Bedroom ventilation and sleep quality

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Preface

The thesis is organized in two parts: the first part puts into context the findings of the Ph.D. thesis in an introductory review; the second part consists of the full papers produced during this Ph.D. study. These papers will be referred to in the text by their number written with the Roman numerals **I-V.** The Ph.D. thesis is based on the following publications:

I. **Fan, X.,** Sakamoto, M., Shao, H., Kuga, K., Ito, K., Lan, L. and Wargocki, P., 2021. Emission rate of carbon dioxide while sleeping. *Indoor air*, *31*(6), pp.2142-2157.

II. **Fan, X.,** Liao, C., Bivolarova, M.P., Mainka, A., Sekhar, C., Laverge, J., Lan, L., Akimoto, M. and Wargocki, P., 2022, May. Air change rates during sleep in Danish bedrooms. In *CLIMA 2022 conference*.

III. **Fan, X.,** Shao, H., Sakamoto, M., Kuga, K., Lan, L., Wyon, D.P., Ito, K., Bivolarova, M.P., Liao, C. and Wargocki, P., 2022. The effects of ventilation and temperature on sleep quality and next-day work performance: pilot measurements in a climate chamber. *Building and Environment*, *209*, p.108666.

IV. **Fan, X.,** Liao, C., Matsuo, K., Verniers K., Laverge, J., Neyrinck, B., Pollet, I., Fang, L., Lan, L., Sekhar, C., and Wargocki, P., 2023 A single-blind field intervention study on improved bedroom ventilation and sleep quality. **Submitted to Science of The Total Environment (under revision)**

V. **Fan, X.,** Liao, C., Bivolarova, M.P., Sekhar, C., Laverge, J., Lan, L., Mainka, A., Akimoto, M. and Wargocki, P., 2022. A field intervention study of the effects of window and door opening on bedroom IAQ, sleep quality, and next-day cognitive performance. *Building and Environment*, *225*, p.109630.

A full list of publications prepared during the Ph.D. study, including first-authored and co-authored publications, can be seen in DTU's webpage: https://www.dtu.dk/english/person/xiaojun-fan?id=139624&entity=publications

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It has been an extraordinary period because the coronavirus pandemic unfortunately occurred, which significantly increased the burden for research activities, especially when human subjects had to be recruited. The Ph.D. thesis could not have been completed without my supervisor, Assoc. Prof. Pawel Wargocki. My deepest gratitude goes to him for his constant support, invaluable guidance, significant input, inspiring encouragement, and great patience. His immense knowledge and enthusiasm for scientific research inspired me to be a good researcher. I have learned a lot from him scientifically and professionally, although there is much more to learn. I would also like to express my appreciation to my co-supervisors, Assoc. Prof. Lei Fang and Ass. Prof. Mariya Petrova Bivolarova, for their vital guidance, treasured support, and timely help with every possible issue and request.

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Xiaojun Fan

Summary

Sleep plays a vital role in maintaining human health and well-being. Previous studies have documented that poor indoor environmental quality (IEQ) in bedrooms disturbs sleep quality, but they were mainly focusing on temperature, noise and light; less attention has been paid to indoor air quality (IAQ) in bedrooms as an essential environmental quality factor. IAQ has been shown to affect human health and performance over the past decades when people are awake. Only a few studies have shown that air pollutant exposure during the night affects sleep quality, and most of them have focused on the effects of ambient (outdoor) air pollution. Research is lacking on how bedroom ventilation and IAQ affect sleep quality and thus next-day cognitive performance and well-being. The present work has attempted to fill this gap.

The main objective of this dissertation was to examine how bedroom ventilation affects sleep quality and next-day cognitive performance. The specific objectives included: 1) to quantify the current ventilation levels in actual bedrooms; 2) to estimate the CO_2 emission rate from sleeping people that can be used to design, control, and operate bedroom ventilation systems; 3) to recommend ventilation rates for bedrooms that will not disturb sleep quality; and 4) to explore ways to improve bedroom ventilation when mechanical ventilation systems are not installed.

A series of experiments were conducted, including climate chamber studies, cross-sectional studies, and field intervention studies. Specifically, a laboratory chamber study was conducted with 11 subjects to measure the CO_2 emission rates from sleeping people and to investigate the effects of increased temperature and reduced ventilation on CO_2 emission, sleep quality and the next-day cognitive performance. Some of these findings were later verified in a four-week-long field intervention study in 29 bedrooms in Belgium where the ventilation rates were remotely controlled by the existing extract ventilation systems; the air entered into bedrooms was delivered by trickle vents installed on the windows. A cross-sectional study was conducted in 84 bedrooms in Denmark to measure the ventilation rates during sleep and to examine whether they impact sleep quality; the measurements lasted for one week. The participants were asked to keep the bedroom settings of their bedroom windows and doors unchanged throughout the measurement period. Subsequently, another field intervention study was carried out in 64 bedrooms participating in a cross-sectional study; measurements were made for an additional week. The intervention was made by opening the windows or internal doors if they had been closed in the first week or closing them if they had been open, to investigate the effects of these interventions on bedroom IAQ, sleep quality and next-day performance.

The results from the experiments in the laboratory and in actual bedrooms consistently show that inadequate bedroom ventilation and consequently poor bedroom IAQ negatively affect sleep quality; they also show that this may affect next-day cognitive performance. Specifically, the results of chamber studies with sleeping people showed

that when ventilation with outdoor air was reduced (as demonstrated by the increased mean CO_2 concentration from 800 ppm to 1,700 ppm), the sleep onset latency increased indicating reduced sleep quality. Self-reported next-day cognitive performance was higher after sleeping with increased ventilation, but it did not change at low ventilation. The analyses of the results from field intervention studies in Belgium showed similar results. The results from 12 bedrooms indicated that when the ventilation was reduced so that mean CO_2 concentration increased from 856 ppm to 1,927 ppm, shorter deep sleep, longer light sleep, and more awakenings were observed. Extended analyses of the results from 23 bedrooms showed that when the ventilation was decreased so that the mean CO_2 concentration increased from 812 ppm to 1,369 ppm, deep sleep was significantly reduced. In the field intervention studies in Denmark, when the windows were open, the bedrooms were ventilated with outdoor air so that the mean CO_2 concentration increased from 761 ppm to 1,820 ppm, sleep duration was significantly longer than when the windows were closed. Objectively measured cognitive performance improved after sleeping with windows open (the CO_2 concentration was 761 ppm), but it did not change after sleeping with windows closed (the CO_2 concentration was 1,820 ppm). In addition to the effects of bedroom ventilation, the chamber studies also showed that increasing the room temperature from 24°C to 28°C, self-reported sleep quality significantly decreased as indicated by subjective ratings made on the Groningen Sleep Quality Scale (GSQS). The subjects also reported feeling more fatigue and sleepier after sleeping at 28 °C compared with 24°C.

Because CO_2 is used as a marker of ventilation and IAQ, the design of ventilation systems requires a knowledge on the rate of occupant CO_2 emission, but very few measurements have been made on sleeping people. The present dissertation bridged this gap by measuring CO_2 emission rates from sleeping people in the chamber. It was on average 11.0 ± 1.4 L/h per person; this emission rate is for healthy adults who did not suffer from chronic sleep disturbance. The measured CO_2 emission rates were not affected by a change in temperature from 24°C to 28°C or when the ventilation was changed so that the mean CO_2 concentration changed from 800 ppm to 1,700 ppm. Small differences between the sexes were observed: the CO_2 emission rate was on average 11.6 ± 1.0 L/h per person for males and 10.7 ± 1.5 L/h per person for females.

The results from the cross-sectional studies showed large variations in bedroom air change rates (ACHs) at night. The median ACH was 0.4 h^{-1} and the interquartile range (IQR) was 0.2-0.9 h^{-1}. 67% of the measured bedrooms did not comply with the highest ventilation requirement of 0.7 h^{-1} stipulated by a European standard. Based on the results obtained in the present study and previously published data, it is recommended that bedroom ventilation with outdoor air should be 10 L/s per person. With an average bedroom size (i.e., 32 m^3 in Denmark), this would correspond to an air change rate of around 1.1 h^{-1}.

Sleeping with windows open reduced the CO_2 concentration and the concentrations of TVOCs and PM_{10}. Under this condition, the perceived air quality was improved, the air

was rated fresher, and the odour intensity was reduced. Sleep duration increased under this condition and the self-reported sleep quality was better. Opening an internal door caused CO_2 concentration to decrease from 2,362 ppm to 1,293 ppm but no other effects were seen. Sleeping with a window open is therefore recommended if no other methods can be used to ventilate bedrooms but only if no other negative effects are introduced such as elevated noise, PM levels, and draught discomfort.

This dissertation investigated bedroom ventilation and its effects on sleep quality. It bridges several current research gaps, provides valuable and helpful references for the design, operation and control of bedroom ventilation, highlights the importance of bedroom ventilation and the urgency of improving it, supplements current knowledge of the effects of bedroom temperature on sleep quality and next-day cognitive performance, and advances research on IEQ in bedrooms in the field of sleep research. All these may help to improve human health and well-being.

Resumé

Søvn spiller en afgørende rolle for menneskers sundhed og velvære. Tidligere undersøgelser har dokumenteret, at indeklimaet i soveværelser kan påvirke søvnkvaliteten, men undersøgelserne fokuserede hovedsageligt på temperatur, støj og lys og langt mindre på luftkvalitet. I vågen tilstand, på arbejdsplads eller i skoler, påvirker luftkvalitet menneskers sundhed og præstationsevne. Endnu har kun få undersøgelser vist, at eksponering for luftforurening i løbet af natten påvirker søvnkvaliteten. De fleste undersøgelser har fokuseret på betydningen af udendørs luftforurening. Der mangler derfor forskning i, hvordan soveværelsets ventilation og luftkvalitet påvirker søvnkvaliteten og derigennem den kognitive præstation og velvære den efterfølgende dag. Dette studium bidrager med denne viden.

Hovedformålet med denne afhandling var at undersøge, hvordan ventilation i soveværelset påvirker søvnkvalitet og næste-dags kognitive præstation. De specifikke mål omfattede: 1) at kvantificere ventilation i soveværelser; 2) at estimere CO_2 emissionsraten fra sovende personer. Emissionsraten kan bruges til at designe og styre ventilationen; 3) at anbefale ventilationsrater for soveværelser, som ikke forringer søvnkvaliteten; og 4) at undersøge metoder til at forbedre ventilation i soveværelser uden mekanisk ventilation.

En række eksperimenter blev udført, herunder klimakammerundersøgelser, tværsnitsundersøgelser og felt-interventionsundersøgelser. Specifikt blev der udført en laboratorieundersøgelse med 11 forsøgspersoner for at måle emissionen af CO_2 fra sovende personer og for at undersøge virkningerne af øget temperatur og reduceret ventilation på CO_2 emissionsrate, søvnkvalitet og næste-dags kognitive præstation. Nogle af disse resultater blev senere verificeret i en fire uger lang interventionsundersøgelse i 29 soveværelser i Belgien, hvor ventilationen blev styret af de eksisterende ventilationssystemer med udsugning. Erstatningsluft blev tilført gennem spalteventiler i vinduerne. Et tværsnitsstudie blev udført i 84 soveværelser i Danmark for at måle ventilationsrater og for at undersøge deres betydning for søvnkvaliteten. Efterfølgende blev endnu et interventionsstudie udført i 64 soveværelser. Interventionen blev foretaget ved at åbne vinduer eller døre, hvis de havde været lukket i den første uge, og lukke dem, hvis de havde været åbne, for at undersøge virkningerne af disse indgreb på soveværelsets luftkvalitet, samt deltagernes søvnkvalitet og næste-dags kognitive præstation.

Resultaterne fra eksperimenterne i laboratoriet og i de faktiske soveværelser viste, at utilstrækkelig ventilation og dermed dårlig luftkvalitet i soveværelset, påvirker søvnkvaliteten negativt. Resultaterne viste også, at dette kan påvirke næste-dag kognitive præstation. Specifikt viste resultaterne af klimakammerundersøgelser med sovende personer, at når ventilationen med udeluft blev reduceret (vist ved at den gennemsnitlige CO_2 koncentration øgedes fra 800 ppm til 1,700 ppm), øgedes tiden før søvnen indtraf, hvilket indikerer nedsat søvnkvalitet. Sammenlignet med bedømmelser

foretaget aften før, var den selvrapporterede næste-dags kognitive præstation højere efter en søvn i soveværelse med øget ventilation, men den ændrede sig ikke når ventilation var lav. Analyserne af resultaterne fra felt-interventionsundersøgelserne i Belgien viste lignende resultater. Resultaterne fra 12 soveværelser indikerede, at når ventilationen blev reduceret, så den gennemsnitlige CO_2 koncentration steg fra 856 ppm til 1,927 ppm, blev der observeret kortere dyb søvn, længere let søvn og flere opvågninger. Resultater fra 23 soveværelser viste, at når ventilationen blev reduceret, så den gennemsnitlige CO_2 koncentration steg fra 812 ppm til 1,369 ppm, blev den dybe søvn reduceret markant. Interventionsundersøgelser i Danmark, hvor vinduerne i soveværelset enten var lukkede eller var åbne og soveværelserne således ventileret med udeluft, resulterede i, at den gennemsnitlige CO_2 koncentration steg fra 761 ppm til 1,820 ppm, og at søvnvarigheden var væsentlig længere, end da vinduerne var lukkede. Sammenlignet med målinger foretaget aften før, blev objektivt målt kognitiv præstation forbedret efter en søvn i soveværelse med åbne vinduer, men den ændrede sig ikke når vinduer var lukkede. Ud over at kvantificere betydningen af soveværelsets ventilation viste klimakammerundersøgelserne også, at ved at øge temperaturen fra 24°C til 28°C, faldt den selvrapporterede søvnkvalitet signifikant som indikeret af subjektive vurderinger foretaget på Groningen Sleep Quality Scale (GSQS). Forsøgspersonerne rapporterede også, at de følte sig mere trætte og søvnige efter at have sovet ved 28 °C sammenlignet med 24 °C.

Fordi CO_2 bruges som markør for ventilation og luftkvalitet, kræver design af ventilationsanlæg en viden om emissionen af CO_2 fra forsøgspersonerne, men der er kun foretaget meget få målinger på sovende mennesker. Derfor gennemførtes i dette studium målinger af CO_2 emissionsrater fra sovende mennesker i klimakammeret. I gennemsnit var emissionsraten 11.0 ± 1.4 l/t pr. person. Emissionsraten gælder for raske voksne, som ikke lider af kroniske søvnforstyrrelser. De målte CO_2 emissionsrater blev ikke påvirket af temperaturændringen fra 24°C til 28°C, eller når ventilationen blev ændret, så den gennemsnitlige CO_2 koncentration i klimakameret ændrede sig fra 800 ppm til 1,700 ppm. Små forskelle mellem kønnene blev observeret: CO_2 emissionsraten var i gennemsnit 11.6 ± 1.0 l/t pr. person for mænd og 10.7 ± 1.5 l/t pr. person for kvinder.

Resultaterne fra tværsnitsundersøgelserne viste store variationer i soveværelsets luftskifte om natten. Medianluftskiftet var 0.4 h^{-1} og interkvartilintervallet var 0.2-0.9 h^{-1}. 67 % af de målte soveværelser opfyldte ikke det højeste ventilationskrav på 0.7 h^{-1} fastsat af en europæisk standard. Baseret på resultaterne opnået i dette og tidligere studier, anbefales det, at soveværelsesventilation med udeluft bør være 10 L/s pr. person. Med en gennemsnitlig soveværelsesstørrelse (32 m^3 i Danmark), ville dette svare til et luftskifte på 1.1 h^{-1}.

At sove med åbne vinduer reducerede CO_2 koncentrationen og koncentrationerne af TVOC og PM_{10}. Den oplevede luftkvalitet blev forbedret, luften blev vurderet til at være friskere, og lugtintensiteten blev reduceret. Ligeledes øgedes søvnens varighed og

den selvrapporterede søvnkvalitet blev forbedret. Åbning af en indvendig dør fik CO_2 koncentrationen til at falde fra 2,362 ppm til 1,293 ppm, men ingen andre effekter blev observeret. Det anbefales derfor at sove med et åbent vindue, hvis ingen andre metoder kan bruges til at ventilere soveværelset, men kun hvis der ikke er andre negative effekter, såsom støj, udendørs luftforurening eller trækgener.

Denne afhandling undersøgte ventilation i soveværelser og betydningen for søvnkvalitet. Den har øget vores forståelse af sammenhængen mellem indeklima i soveværelset og søvnkvalitet, giver værdifulde og nyttige referencer til design og drift af soveværelsesventilation, samt fremhæver sammenhængen mellem søvnkvalitet og næste-dags kognitive præstation. Alt dette kan bidrage til at forbedre menneskers sundhed og velvære.

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List of acronyms

Acronyms	Abbreviated words
Rapid eye movement	REM
Non-rapid eye movement	NREM
Polysomnographic	PSG
Electroencephalogram	EEG
Electrooculogram	EOM
Electromyogram	EMG
Pittsburgh sleep quality index	PSQI
Groningen sleep quality scale	GSQS
Indoor environmental quality	IEQ
Indoor air quality	IAQ
Internet of Things	IoT
Relative humidity	RH
Body mass index	BMI
Air change rate per hour	ACH
Interquartile range	IQR

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1 Introduction and justification

1.1 Why sleep matters?

Sleep is essential for human health as it allows the body to recover and to continue to function effectively by promoting various physiological and cognitive processes. Sleep is as crucial as eating, drinking and breathing. Good sleep quality can enhance our immune system [1], reduce the risk of a series of diseases, such as obesity, hypertension, and cardiovascular [2,3] and alleviate suicidal ideation [4]. Poor sleep quality can increase the morbidity of stressful and depressive symptoms [3,5]. It can also decrease next-day work performance [6,7] and increase the risks of occupational injuries [8], which have been estimated to cause significantly large national economic losses [9].

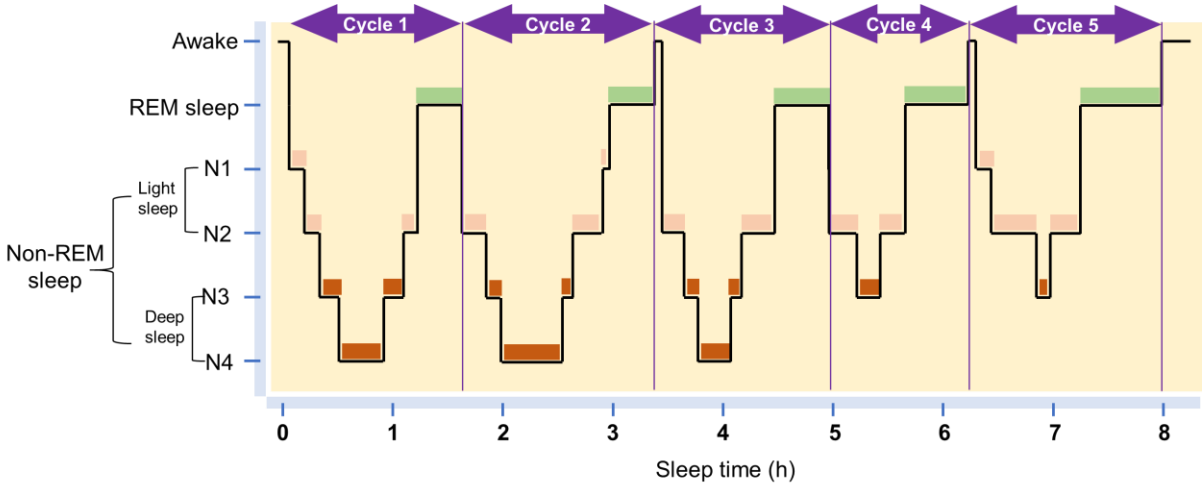


Figure 1.1 Sleep architecture.

1.2 Sleep

The sleep-wake cycle is generally regulated by the homeostatic physiology of circadian rhythm, which is very complex [10]. Even though the body is primarily dormant while sleeping, the brain and the internal body are engaged in several activities. Throughout the time spent asleep, sleep progresses through several iterations of different sleep cycles, each lasting about 90-110 minutes [11,12] and consisting of two general stages: Rapid Eye Movement (REM) and Non-REM (NREM). NREM is further categorized into three (four) sleep stages in sleep medicine: N1, N2, N3 (and N4). N1 and N2 are generally considered together as light sleep. N3 (and N4) are characterized by slow wave activity and are often called deep sleep or slow wave sleep. Figure 1.1 shows the sleep architecture. The length of these stages and the length of sleep and time awake within the total sleep period define the parameters that are used to quantify sleep quality (Table 1-1).

Table 1-1 Sleep quality indicators and their definition.

Indicators	Definition	Better sleep quality
Total sleep period	Total time from being ready to sleep to waking up the following morning	Appropriate range shown in Table 1-2
Sleep onset latency	Total time from being ready to sleep to sleep onset	Shorter sleep onset latency
Wake after sleep onset	Total time of wakefulness during sleep	Shorter wake after sleep onset
Sleep efficiency	Percentage of time in bed actually spent in sleeping	Higher sleep efficiency
Duration of each sleep stage	Total number of minutes scored as N1, N2, N3 (and N4), and REM sleep.	Appropriate range shown in Table 1-2
Total number of awakenings	Sum of the number of awakenings (transition from a sleep stage to a wake epoch) within the sleep period	Lower number of awakenings
PSQI	Self-reported sleep quality over the last month, Maximum score of 21	A global sum of '5' or less [13]
GSQS	Self-reported sleep quality at the previous night. Maximum score of 14	A global sum of '2' or less [14,15]

Sleep is traditionally monitored by measuring biological responses. For this purpose, Polysomnography (PSG) is used, which is a standard method including electroencephalogram (EEG), Electrooculogram (EOG), and Electromyogram (EMG) [16]. Figure 1.2 depicts the electric signals measured by PSG for different sleep stages. Measurements using PSG are usually conducted in sleep clinics with specialized instruments and trained experts, making the PSG expensive and less widely accessible and applicable. Wearing PSG electrodes during sleep may also to some extent disturb a subject's sleep. With the advances in smart technology and big data, unobtrusive solutions (i.e., wearable devices) have attracted great attention for sleep monitoring. They can capture body movements and monitor physiological parameters, including heart rate and skin temperature, and thus provide sleep quality data similar to what the PSG is measuring. In addition, sleep can also be assessed subjectively using specially developed scales, as summarized by Fabbri et al. [17]. The two most frequently used are the Pittsburgh Sleep Quality Index (PSQI) and the Groningen Sleep Quality Scale (GSQS) (Figure 1.3).

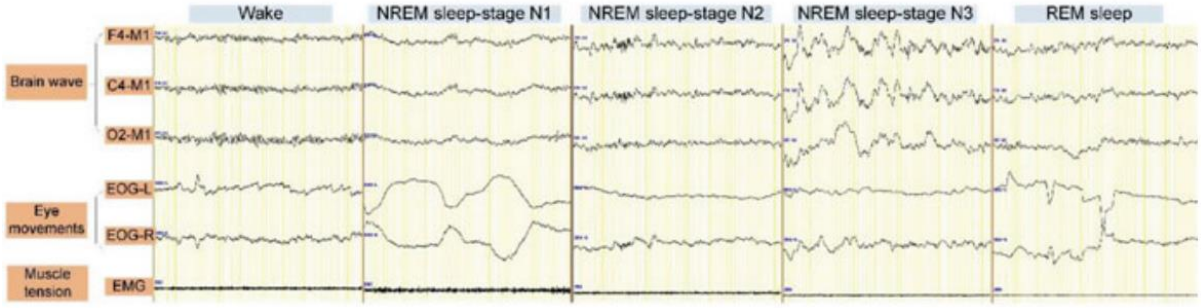


Figure 1.2 PSG features of sleep architecture [18]. The tracings of EEG from three electrodes at the right frontal lobe (F4), right central lobe (C4), and right occipital lobe (O2) refers to the left mastoid (M1). EOG is recorded from the left (L) eye and right (R) eye. EMG is recorded by two leads placed on the chin, one above the jawline and one below.

The Pittsburgh Sleep Quality Index (PSQI)

Instructions: The following questions relate to your usual sleep habits during the past month only. Your answers should indicate the most accurate reply for most days and nights in the past month. Please answer all questions. During the past month

1. When have you usually gone to bed? _____
2. How long (in minutes) has it taken you to fall asleep each night? _____
3. When have you usually gotten up in the morning? _____
4. How many hours of actual sleep do you get at night? (This may be different than the number of hours you spend in bed) _____

5. During the past month, how often have you had trouble sleeping because you…	Not during the past month (0)	Less than once a week (1)	Once or twice a week (2)	Three or more times a week (3)
5.1 Cannot get to sleep within 30 minutes				
5.2 Wake up in the middle of the night or early morning				
5.3 Have to get up to use the bathroom				
5.4 Cannot breathe comfortably				
5.5 Cough or snore loudly				
5.6 Feel too cold				
5.7 Feel too hot				
5.8 Have bad dreams				
5.9 Have pain				
5.10 Other reason(s), please describe, including how often you have had trouble sleeping because of this reason(s):				
6. During the past month, how often have you taken medicine (prescribed or "over the counter") to help you sleep?				
7. During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in the social activity?				
8. During the past month, how much of a problem has it been for you to keep up enthusiasm to get things done?				
	Very good (0)	Fairly good (1)	Fairly Bad (2)	Very bad (3)
9. During the past month, how would you rate your sleep quality overall?				

(A)

Groningen Sleep Quality Scale (GSQS)

1. I had a deep sleep last night	☐ True	☐ False
2. I feel that I slept poorly last night	☐ True	☐ False
3. It took me more than half an hour to fall asleep last night	☐ True	☐ False
4. I woke up several times last night	☐ True	☐ False
5. I felt tired after waking up this morning	☐ True	☐ False
6. I feel that I did not get enough sleep last night	☐ True	☐ False
7. I got up in the middle of the night	☐ True	☐ False
8. I felt rested after waking up this morning	☐ True	☐ False
9. I feel that I only had a couple of hours sleep last night	☐ True	☐ False
10. I feel that I slept well last night	☐ True	☐ False
11. I did not sleep a wink (at all) last night	☐ True	☐ False
12. I did not have trouble falling asleep last night	☐ True	☐ False
13. After I woke up last night, I had trouble falling asleep again	☐ True	☐ False
14. I tossed and turned all night last night	☐ True	☐ False
15. I did not get more than 5 hours' sleep last night	☐ True	☐ False

(B)

Figure 1.3 (A) PSQI, and (B) GSQS.

1.3 Sleep quality

Although there is no accepted definition of the 'quality' of sleep, it is generally derived from the objective measurements made by PSG or subjective ratings using questionnaires mentioned above. Sleep quality can be quantitatively assessed by a collection of indicators as recommended by the National Sleep Foundation in the US. [19]. They also recommend the normative range of these indicators for good sleep quality as a function of age (Table 1-2). It can also be quantified by scores derived from the answers to questions about global sleep quality within a specific period (i.e., GSQS and PSQI) and qualified by people's feeling of their sleep quality using questionnaires (such as the Fatigue questionnaire used in this thesis). Table 1-1 lists some sleep qualtiy indicators and their definition.

Table 1-2 Recommended ranges for good sleep quality across a lifespan [19,20].

Items	Categories	Newborns (0-3 mo)	Infants (4-11 mo)	Toddlers (1-2 y)	Pre-schoolers (3-5 y)	School-aged children (6-13 y)	Teenagers (14-17 y)	Young adults (18-25 y)	Adults (26-64 y)	Older adults (≥65 y)
Sleep duration (h)	Appropriate	14-17	12-15	11-14	10-13	9-11	8-10	7-9	7-9	7-8
	Uncertain	11-13, 18-19	10-11, 16-18	9-10, 15-16	8-9, 14	7-8, 12	7, 11	6, 10-11	6, 10	5-6, 9
	Inappropriate	≤ 11, ≥19	≤ 10, ≥18	≤9, ≥16	≤ 8, ≥14	≤ 7, ≥12	≤ 7, ≥11	≤ 6, ≥11	≤ 6, ≥10	≤ 5, ≥9
Sleep onset latency (min.)	Appropriate	--	0-30	0-30	0-30	0-30	0-30	0-30	0-30	0-30
	Uncertain	--	31-45	31-45	31-45	31-45	31-45	31-45	31-45	31-60
	Inappropriate	--	≥46	≥46	≥46	≥46	≥46	≥46	≥46	≥61
Awakenings (> 5min) (times)	Appropriate	--	--	0-1	0-1	0-1	0-1	0-1	0-1	0-2
	Uncertain	--	--	2-3	2-3	2-3	2	2-3	2-3	3
	Inappropriate	--	--	≥ 4	≥ 4	≥ 4	≥ 3	≥ 4	≥ 4	≥ 4
Wake after sleep onset (min.)	Appropriate	--	--	--	≤ 20	≤20	≤20	≤20	≤20	≤30
	Uncertain	--	--	--	21-50	21-40	21-50	21-40	21-40	≥31
	Inappropriate	--	--	--	≥51	≥41	≥51	≥41	≥41	--
Sleep efficiency (%)	Appropriate	--	≥85	≥85	≥85	≥85	≥85	≥85	≥85	≥85
	Uncertain	--	75-84	75-84	75-84	75-84	75-84	65-84	75-84	75-84
	Inappropriate	--	≤74	≤74	≤74	≤74	≤74	≤64	≤74	≤74
REM sleep (%)	Appropriate	≥41	--	--	--	--	--	--	21-30	--
	Uncertain	21-40	≥11	≥11	≥11	0-100	≥11	≤40	≤20, 31-40	≤40
	Inappropriate	≤20	≤10	≤10	≤10	--	≤10	≥41	≥41	≥41
N1 sleep (%)	Appropriate	--	--	--	--	≤5	≤5	≤5	≤5	--
	Uncertain	--	--	≤20	≤20	6-20	6-20	6-20	6-20	≤25
	Inappropriate	--	--	≥21	≥21	≥21	≥21	≥21	≥21	≥26
N2 Sleep (%)	Appropriate	--	--	--	--	--	--	--	--	--
	Uncertain	--	--	≤80	≤80	≤80	≤80	≤80	≤80	≤80
	Inappropriate	--	--	≥81	≥81	≥81	≥81	≥81	≥81	≥81
N3 sleep (%)	Appropriate	--	--	--	--	21-25	21-25	--	16-20	--
	Uncertain	--	≥11	≥11	≥11	11-20, ≥26	6-20, ≥26	≥6	6-15, ≥21	0-100
	Inappropriate	--	≤10	≤10	≤10	≤10	≤5	≤5	≤5	--

1.4 Bedroom environment and sleep quality

People spend approximately one third of their lifetime sleeping, mostly in bedrooms. A bedroom is a very unique indoor environment compared with other types of rooms and spaces in buildings; for instance, it has the same occupancy and settings all night, making it easier to control. Indoor environmental quality (IEQ) in bedrooms can be generally characterized by thermal, visual, acoustic and indoor air quality (IAQ) conditions [21].

Lan et al. summarized bedroom thermal conditions as characterized by bedroom temperature and its effects on sleep quality [22]. They concluded that both moderate heat and cold exposure significantly reduce sleep quality.

Two reviews summarized the research that has focused on the effects of environmental noise on sleep quality and found that nocturnal noise, especially from public transportation, negatively affects sleep quality [23,24].

Tähkämö et al. conducted a systematic review of how light exposure affects the human circadian rhythm [25]. The results suggested that light exposure in the evening, at night and in the morning affect the circadian cycle of melatonin, which significantly affects sleep quality [26].

A recent review conducted by Canha et al. compared the measured air quality in bedrooms during sleep with guidelines or legislation and found that several air pollutants exceeded their limit values, such as $PM_{2.5}$ and VOCs [27]. However, there are fewer studies on the effects of bedroom IAQ on sleep quality, as summarized by Sekhar et al. [28] and Akimoto et al. [29]

Caddick et al. attempted to recommend the IEQ parameters in bedrooms necessary for optimal sleep by reviewing the published literature [21]. They recommended all forms of noise should remain <35 dB, an air temperature of 17-28 °C, and a relative humidity (RH) of 40-60% in the bedrooms. Complete darkness was also recommended for sleep, avoiding blue light. However, there is no clear recommendation for IAQ except that sea level air quality with adequate ventilation is optimal.

1.5 Bedroom ventilation levels, standards and sleep quality

The energy crisis has increased energy consumption costs, which has led to the tightening of buildings, resulting in reduced ventilation rates and poor IAQ in dwellings since the early 1970s [30]. Over the past decades, there has been increasing research focusing on inadequate ventilation and poor IAQ and their impacts on human health, but mainly in spaces used during the daytime (by people who are awake) [31,32]. Less attention has been paid to IAQ in bedrooms where people generally sleep.

Since 2019 when this dissertation work was launched, bedroom IAQ has attracted increased attention. There have been an increasing number of studies exploring the effects of bedroom ventilation on sleep quality, including chamber studies [41–44], cross-sectional studies [45–49], online surveys [50,51], and field intervention studies [52].

Bedroom IAQ can be affected by many factors. The air pollutants present in bedrooms can have their origin outdoors or indoors. But air pollutants originating indoors are likely to dominate the exposure in bedrooms since outdoor activities are considerably reduced at night. The indoor sources include emissions from the occupants (bioeffluents), building materials and furniture. People normally sleep for 7-9 hours a day, during which they are exposed to similar pollutants for much longer periods than is the case in other indoor environments. Meanwhile, they are unconscious during sleep and cannot make any interventions to improve IAQ in bedrooms. Considering these aspects, bedroom IAQ becomes an even more important topic, as does ventilation that is used to mitigate these effects.

1.5.1 Bedroom ventilation

Ventilation is commonly used to remove and dilute pollutants, and is thus assumed to improve IAQ. Mechanical ventilation systems are more reliable than natural ventilation systems in securing constant ventilation rates with conditioned air or outdoor air. The former uses fans to transport air, but is seldomly installed in bedrooms [30,33,34]. The latter initially refers to specifically designed systems to increase ventilation by natural forces such as temperature differences (buoyancy-driven) [35] and wind (pressure-driven) [36]. But they generally refer to occupants' airing behaviour (window and door opening) in the literature. Opening a window or door can increase ventilation [37–39]. However, people typically sleep with bedroom windows and doors closed, which results in poor bedroom ventilation [40–43].

1.5.2 Ventilation levels in actual bedrooms

Given the importance of ventilation in bedrooms in determining the levels of pollutants, it is disconcerting that only a few studies have focused on measuring ventilation rates in bedrooms; most studies measured CO_2 levels instead [28]. The difficulty in measuring ventilation rates in situ is one of the reasons for this, as discussed in previous publications [44]. Sekhar et al. [28] summarized the studies that measured bedroom ventilation rates and observed that the mean air change rate (ACH) measured in bedrooms was between 0.2 to 4.9 h^{-1} with most cases lower than 0.5 h^{-1}. They also found that bedroom ACHs were lower during the heating season, especially in bedrooms without mechanical ventilation systems and when an air conditioner was running. There are only limited data on actual measured ventilation rates in bedrooms during sleep.

1.5.3 Standards and guidelines on bedroom ventilation

Many standards and guidelines stipulate ventilation and IAQ requirements for buildings [45–49]. However, they do not have specific ventilation requirements for bedrooms; bedroom ventilation is then the result of the overall ventilation requirements for residential dwellings [28]. There is no evidence of whether the prescribed ventilation requirements that are acceptable for the dwellings during the daytime are also sufficient to avoid disturbing sleep at night.

1.5.4 Effects on sleep quality and next-day cognitive performance

An increasing number of epidemiological studies have documented air pollution exposure as a possible cause of various sleep problems in populations across different age groups worldwide, using different measures: they were summarized by Liu et al. in 2019 prior to the start of this Ph.D. study [50]. They concluded that exposure to air pollutants was negatively associated with poor sleep quality in general. While most studies focused on ambient (outdoor) air pollutants; only a few assessed the effects of indoor exposure, specifically examining the relationship between sleep quality and pollutants produced by cooking. Although few in number, previous studies suggest poor IAQ in bedrooms is associated with disturbed sleep quality and reduced next-day cognitive performance. These studies were summarized by Akimoto et al. and Sekhar et al. [28,29]. They proposed a tentative relationship between bedroom IAQ and sleep quality. Mean CO_2 was used as an indicator of the ventilation efficiency and a metric of bedroom IAQ.

The relationship proposes that if CO_2 concentration is below 750 ppm, sleep quality will not be disturbed; that when it is between 750 ppm and 1,150 ppm, sleep quality may be disturbed and that it will be disturbed when the CO_2 is above 1,150 ppm; additionally next-day performance will be negatively affected when the CO_2 concentration is above 2,600 ppm.

It is worth noting that the association between bedroom IAQ and next-day cognitive performance is based on the results from one study conducted by Strøm-Tsjsen et al. who found that the subjects' performance of a test of logical thinking was improved when the bedroom IAQ was improved [51]. There are however other studies that show that poor sleep quality, however caused, has a negative effect on next-day cognitive performance [6,7,52,53]. Guttesen et al. investigated whether behavioural performance was predicted by the overnight consolidation of episodic associations from the previous day by measuring behavioural and electrophysiological indices of episodic encoding after a night of sleep or total sleep deprivation with 30 subjects [52]. They found that sleep supported memory consolidation and next-day learning when compared to sleep deprivation. Lee et al. examined whether sleep improves next-day mindful attention in healthcare workers (61 full-time nurses) and found that it did [7]. Lawson and Lee investigated whether sleep quality was associated with next-day work-to-family

conflicts mediated by work performance [53]. They observed that participants reported better work productivity on the day following a night when sleep quality was better than usual and that this reduced work-to-family conflicts. Awanson et al. examined how sleep impacts work performance based on data from National Sleep Foundation Sleep In America Poll in 2008 and found that the risk for sleep disorders substantially increased the likelihood of negative work outcomes, including occupational accidents, absenteeism, and presenteeism [6]. Unfortunately, no causal conclusions can be drawn from these observed associations.

1.6 CO_2 concentration, bedroom ventilation and IAQ

The most abundant compound produced by human metabolism is CO_2. CO_2 is used to indicate the pollution level likely to be caused by emissions from humans (bioeffluents). It is also widely used as a common indicator of ventilation effectiveness and adequacy and thus of IAQ when occupants are present [54].

CO_2 concentration is mainly measured in bedrooms to indicate bedroom IAQ and the bedroom ventilation rate [27–29]. If outdoor air supply rates are decreased in bedrooms, CO_2 concentration will increase along with the concentrations of other contaminants generated indoors, and the reverse will happen if outdoor air supply rates are increased. Whether CO_2 concentration can be used to indicate bedroom IAQ has not been sufficiently studied. Air pollutants from outdoors and other adjacent rooms indoors can enter bedrooms via ventilation, infiltration, and dispersion and they reduce IAQ. These pollutants are not related to CO_2, making the measurements of CO_2 concentration less reliable as an indicator of bedroom IAQ, especially when considering the negative effects of poor bedroom IAQ on sleep quality. Previous studies have shown that exposure to outdoor $PM_{2,5}$, PM_{10} and NO_2 were associated with poor sleep quality [55,56]. Wei et al. found the exposure to cooking oil fumes from kitchens led to poor sleep quality [57]. When these pollutants are present in bedrooms, the IAQ will be reduced but the CO_2 concentration may not properly indicate their concentrations. Consequently, it is important to examine whether CO_2 can be used as an indicator of bedroom IAQ and ventilation.

1.6.1 CO_2 and ventilation measurements

Standard tracer gas measurements are typically used to measure ventilation rates, including the build-up, steady-state, and decay methods [58,59]. Metabolically generated CO_2 has generally been used as a tracer gas [40,42,60–62]. The build-up and decay methods can determine the average ACH by establishing the CO_2 concentration as a function of time. It is a time-consuming process, which is challenging to apply as a ventilation control strategy. The steady-state method can estimate how ventilation rates change

over time with real-time CO_2 monitoring. However, this approach requires a knowledge of the CO_2 emission rates, as does the build-up method.

1.6.2 CO_2 emission rates for sleeping people

Many studies have reported CO_2 emission rates from people who were awake [63–65], but data from people who were sleeping are scarce. Standards and literature usually assume the CO_2 emission rates from sleeping people. Bekö et al. assumed CO_2 emission rates to be 14 L/h per person for adults and 6 L/h per person for children [42]. The European standard 16798-1 assumes CO_2 emission rates to be 13.6 L/h per person when calculating the design CO_2 concentrations in bedrooms under different prescribed ventilation rates [46]. However, these values cannot be confirmed by a limited amount of actual measurements [42,46,66]. Meanwhile, people remain almost immobile during sleep with very low physical activity levels, so the CO_2 emission rates are mainly affected by environmental factors, such as temperature and ventilation, as shown by recent studies, i.e., [67]. However, no studies have investigated how bedroom temperature and IAQ affect CO_2 emission rates during sleep.

1.7 Rationale

Taking the above knowledge gaps into account, bedroom ventilation and its effects on sleep quality and next-day cognitive performance is clearly a subject of interest because:

1) there is little knowledge on CO_2 emission rates from people who are sleeping and this makes the interpretation of ventilation rate measurements in bedrooms impossible;
2) existing ventilation rates in actual bedrooms are not well documented;
3) little is known on how bedroom ventilation affects sleep quality and next-day cognitive performance;
4) more information is needed on how to improve the ventilation rate in bedrooms without mechanical ventilation systems; and
5) little knowledge exists on the bedroom ventilation rates that would be necessary to avoid disturbing sleep quality.

During this Ph.D. study experimental investigations were carried out to elucidate all of these issues.

1.8 Hypothesis and objectives

The central hypothesis of the present Ph.D. study is that inadequate bedroom ventilation reduces sleep quality and consequently next-day cognitive performance. The main

objective was thus to investigate whether the hypothesis was true or false, using laboratory and field studies.

The following questions were specifically addressed:

- **Research question 1**: Does bedroom ventilation affect sleep quality?
- **Research question 2**: Does bedroom ventilation affect next-day cognitive performance?
- **Research question 3**: What is the CO_2 emission rate from a sleeping person?
- **Research question 4**: What is the bedroom ventilation rate that would avoid disturbing sleep quality?
- **Research question 5**: What are the ventilation rates in actual bedrooms during sleep?
- **Research question 6**: How can bedroom ventilation that is beneficial for sleep quality be achieved without mechanical ventilation systems?
- **Research question 7**: Is CO_2 a good indicator of bedroom ventilation rate and IAQ?

1.9 Thesis structure

This paragraph describes the outline of the present thesis. **Chapter 1** provides the background and cutting-edge knowledge in this dissertation's field that led to the research hypothesis and the research questions. **Chapter 2** is a general introduction to the methodology used in the thesis, including the experimental facilities and approaches, measured outcomes and instruments, and statistical methods. **Chapter 3** presents the main findings of the studies published in the course of this Ph.D. study. It is divided into five subchapters, summarizing the results from each of the 5 publications included in this Ph.D. thesis: Chapter 3.1 presents the measured human CO_2 emission rates while sleeping under different conditions typically occurring in actual bedrooms. Together with previously published findings, bedroom ventilation rate that will avoid sleep disturbance is recommended; Chapter 3.2 summarizes the estimated ventilation rates in actual bedrooms during sleep; Chapter 3.3 investigates how bedroom ventilation affects sleep quality and consequently next-day cognitive performance in a laboratory setting; Chapter 3.4 explores how bedroom ventilation affects sleep quality and consequently next-day cognitive performance in actual bedrooms; Chapter 3.5 assesses different ways of improving bedroom ventilation, and thus sleep quality. The findings of Chapters 5 and 6 also document the recommended ventilation rate for bedrooms. Each subchapter from 3.1 to 3.5 is divided into Methods, Results and Discussion, and Summary sections; **Chapter 4** discusses the main findings of this dissertation, their limitations and practical application; future research studies are suggested; **Chapter 5**

summarizes the main conclusions from the research activities conducted in this dissertation research. Table 1-3 give an overview of this Ph.D. thesis. The published and submitted manuscripts produced in the context of this dissertation research are located at the end of the thesis.

Table 1-3 An overview of this Ph.D. thesis.

Paper No.	Chapters	Research Questions						
		1	2	3	4	5	6	7
Ⅰ	3.1			√	√			
Ⅱ	3.2					√		
Ⅲ	3.3	√	√		√			√
Ⅳ	3.4	√	√		√			√
Ⅴ	3.5	√	√		√		√	√

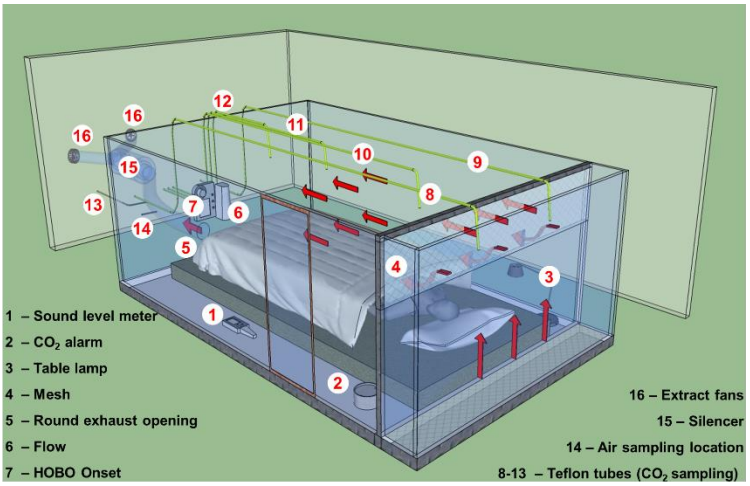
2 Methods

This dissertation consists of a climate chamber study, a cross-sectional study, and two field intervention studies. The methodological approaches used are described in the following sections.

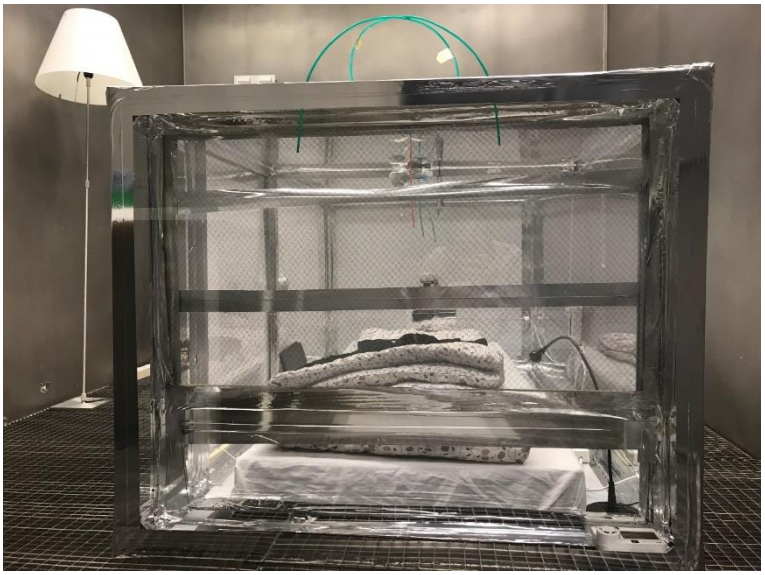
2.1 Experimental design and facilities

The chamber study was conducted in the summer of 2020 in Denmark. A specially designed sleep capsule with a volume of 2.4 m^3 was constructed of reinforced acryl plates that the experimental conditions could be better maintained (Figure 2.1A). The sleep capsule was placed inside a climate chamber equipped with a central ventilation system that can effectively control the IEQ parameters such as temperature and ventilation rate (Figure 2.1B). The subjects slept individually in the capsule for one night under each experimental condition after a first additional night for adaptation [68]. The results obtained in this study were used to calculate the human CO_2 emission rates while sleeping (Paper I) and to explore how bedroom ventilation affects sleep quality and next-day cognitive performance in a well-controlled environment (Paper III).

The cross-sectional study was conducted in Denmark during the heating season in 2020. Special instrument boxes including all the measuring instruments, sensors (Figure 2.2) and instructions used were prepared for the measurements. Invited participants were asked to place the instrument box in their bedrooms at bed height about one meter away from the pillow, ideally on a night table. They slept for one week with the same bedroom environmental settings that they normally have during sleep. The ventilation rates during sleep were estimated based on the rate of decay of the measured CO_2 concentration after they left the bedroom each morning to provide an overview of existing bedroom ventilation rates (Paper II).



(A)



(B)

Figure 2.1 (A) schematic diagram of the sleep capsule, and (B) a snapshot of the empty sleep capsule installed in the climate chamber.

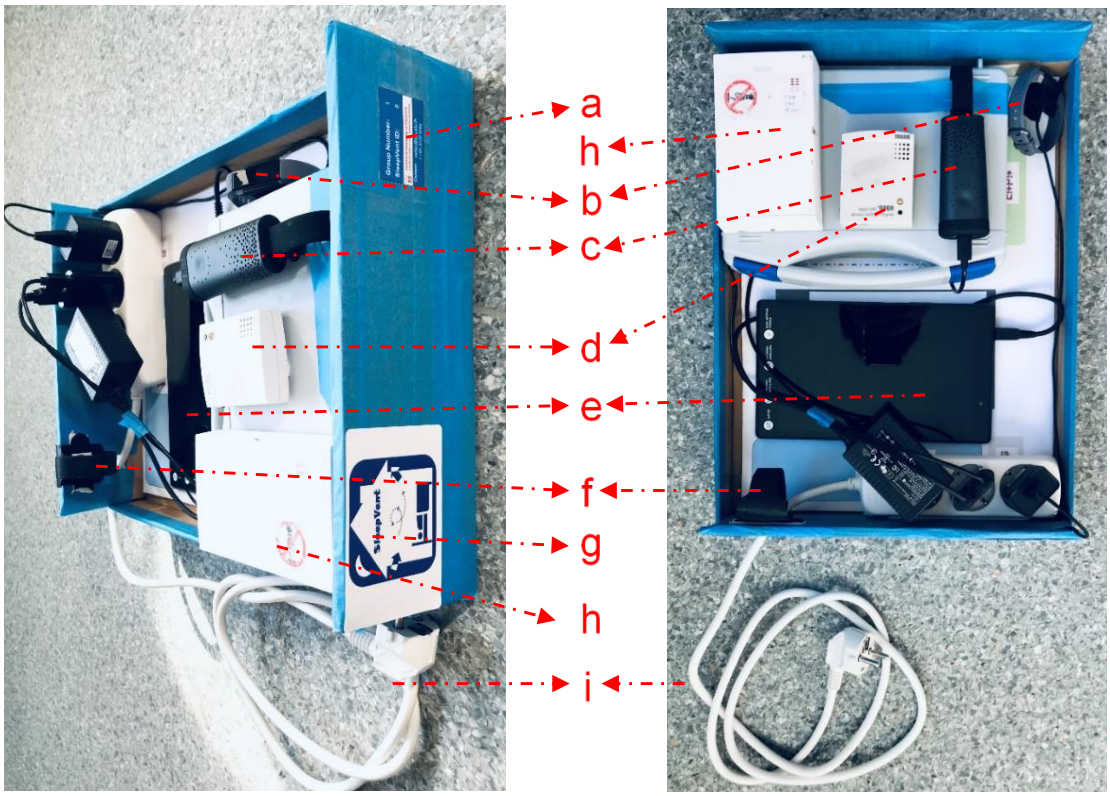


Figure 2.2 Instrument box. (a) Participants' SleepVent ID and Group Number; (b) Actigraphy; (c) Flow; (d) HOBO (light sensor); (e) Tablet; (f) Skin temperature sensor (I-button); (g) Logo; (h) CO2, air temperature and relative humidity sensors and a data logger; (i) The power cable.

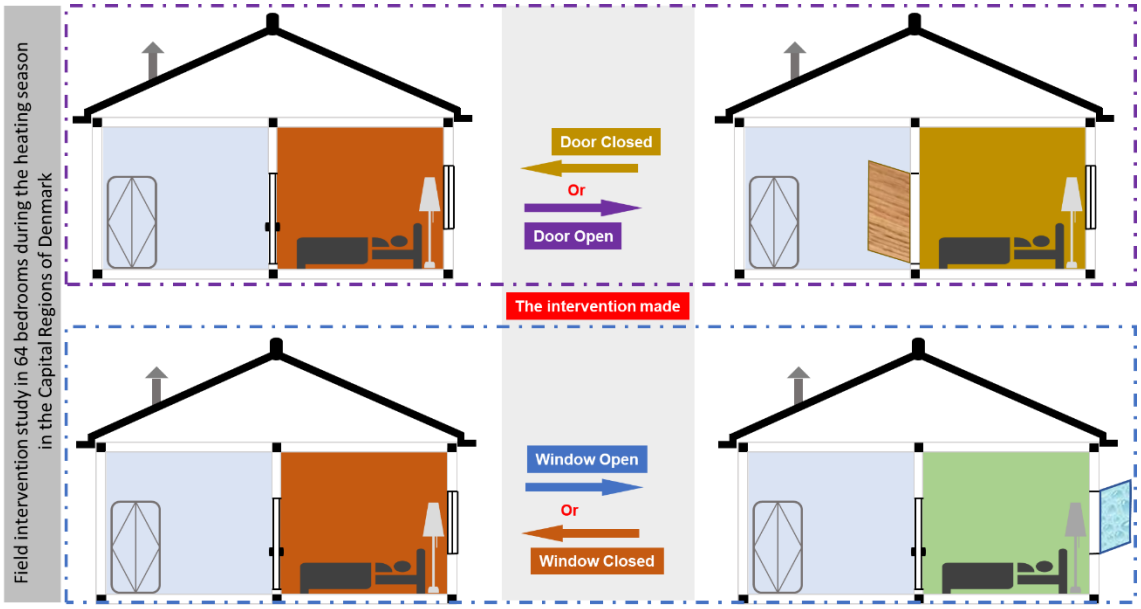


Figure 2.3 The concept of the field intervention study in Denmark.

An intervention study linked to the one-week measurements from the cross-sectional study was then conducted (Figure 2.3): Participants in the cross-sectional study were invited to continue the measurements for another week immediately after the first week and to perform the intervention by opening the windows or doors if they had been closed in the first week or closing them if they had been open (Figure 2.3). The same instrument box was used (Figure 2.2). The measurements from this intervention study were used to explore how these typical airing behaviours affect bedroom IAQ, sleep quality, and next-day cognitive performance (Paper V).

Another field intervention study was performed in Belgium in 2021 (Figure 2.4). People whose bedrooms were mechanically ventilated by an extract ventilation system with trickle vents installed on the windows were recruited. Each participant slept in their bedroom under three different ventilation conditions (low, moderate, and high ventilation rate settings); each condition lasted for one week. During the first week, data was collected but no interventions were made, to familiarize participants with the study protocol and measurements. The experimental conditions were controlled by changing the extract ventilation fan speed remotely. They were established in balanced order of presentation and the participants were not informed when or even whether the changes to bedroom ventilation rate would be executed. Measurements from this study in actual bedrooms were used to validate the effects of ventilation on sleep quality that had been observed in the laboratory setting (Paper IV).

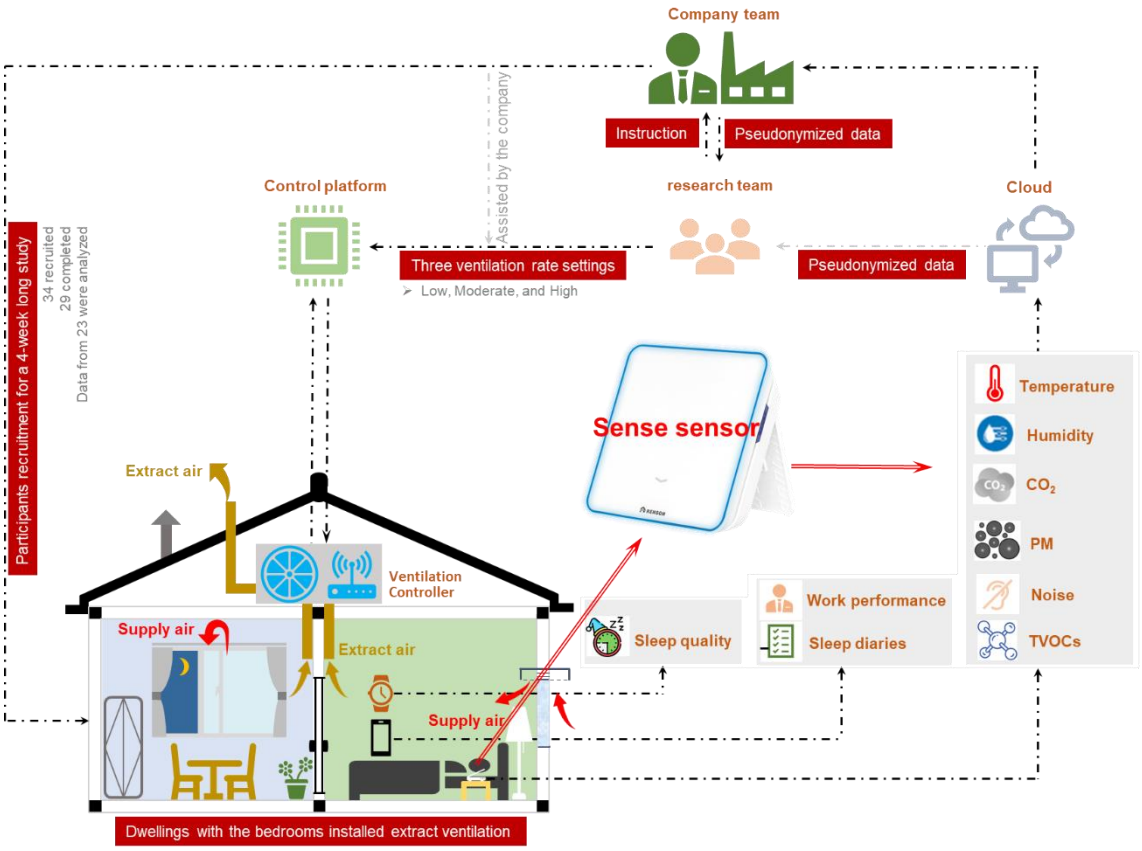


Figure 2.4 Overview of the field intervention study in Belgium.

2.2 Outcome measurements and instruments

Bedroom environmental quality was monitored continuously with different instruments in different studies, but they were all able to measure air temperature, relative humidity, and CO_2 concentration. Selected pollutants (such as TVOCs, PM and NO_2) were also measured.

Sleep quality was objectively measured with closely similar wrist-worn sleep trackers. They were Fitbit Alta HR, Fitbit Charge 2, Fitbit Charge 3, and Fitbit Charge 4, see Figure 2.5. The latest version of Fitbit at the time when the experiments were conducted was used. They all registered total sleep duration, time in bed, the number of awakenings, the duration of any periods during which they were awake after sleep onset, and the duration of any periods of deep sleep, light sleep, and REM sleep. These parameters were all derived by proprietary software analysis of the continuous recordings of heart rate and wrist movement that were subsequently uploaded from the wrist-worn sleep trackers, which the participants wore on the wrist of their non-dominant hand.

(A) (B) (C) (D)

Figure 2.5 Fitbit. (A) HR Alta, (B) Charge 2, (C) Charge 3, and (D) Charge 4.

PSQI is a questionnaire that the participants used to assess their own sleep quality over a one-month interval prior to each study (Figure 1.3A). It was used in each study to collect information that enabled the experimenters to select subjects who were not experiencing any sleep disturbance. A global PSQI score ≤ 5 indicates good sleep quality (Table 1-1). Subjective sleep quality was reported by each participant by completing the GSQS questionnaire (Figure 1.3B). It includes 14 items and its score ranges from 0 to 14. A higher score indicates lower subjective sleep quality. Scores ranging from 0 to 2 points generally suggests unrestricted and undisturbed sleep (Table 1-1).

A 3-minute Baddeley test of grammatical reasoning that examines how well people understand sentences of various levels of syntactic complexity was used to assess cognitive performance [69]. Figure 2.6 shows how to do this test.

Baddeley test

In the following test, there are many short sentences, each followed by a pair of letters (AB or BA). These sentences claim to describe the order of the two letters, i.e., to say which comes first. They can do this in several different ways.

This is illustrated in the following examples:

Sentences	True	False
1. A follows B in AB,		√
2. A follows B in BA,	√	
3. B precedes A in AB,		√
4. B is followed by A in BA,	√	
5. B is preceded by A in BA,		√
6. A does not precede B in BA,	√	

Figure 2.6 Baddeley test.

Two sleep diaries were developed and used, one completed in the evening just before the subjects went to sleep and one in the morning as soon as they woke up. They both included questions on the perceived quality of the IEQ in the bedroom. The evening sleep diary also included questions concerning naps taken, health status, activities (exercise and any electronic devices used before sleep), diet, any measures taken to improve sleep, and sleepiness. The morning sleep diary asked for information on the time the subjects fell asleep and woke up, the number of awakenings during sleep and the reasons for that, sleepiness and finally subjective sleep quality using GSQS. An example of the two sleep diaries used in the chamber study is shown in Appendix 1. In the field studies, the morning sleep diary also obtained information on the number of adults and children in the bedroom during sleep and whether the windows or doors had been open that night. The participants' work performance was subjectively assessed by asking them to complete a questionnaire by marking visual analogue scales – each scale consisted of an ungraduated horizontal line with end labels at the minimum and maximum ratings, but this was only used in the chamber study (Appendix 1).

2.3 Selection of subjects

During the recruitment process, people were asked to complete the online questionnaire that had been used in our previous survey [33]. The questionnaire asked for information on each participant, including the characteristics of their dwelling, bedroom, and surroundings, information on bedroom airing behaviour and the ventilation system, and information about their sleep habits including the PSQI and about their work schedule. In the chamber study, the questionnaire was significantly simplified to collect only information about the subjects since they did not sleep in their own bedrooms.

As a general rule, people with a chronic disease or a sleep disorder were not recruited. Inclusion criteria also consisted of non-smoker, not shift workers, and having a regular lifestyle.

2.4 Statistical analysis

All experiments followed a within-subject design except for the cross-sectional studies. The raw data from each study were screened, processed, and analysed differently based on its objectives. Different statistical methods and models were selected and applied based on the experimental design of each study. All analyses were conducted using the software package IBM SPSS Statistics 22 (SPSS Inc, Chicago, USA).

The effect size was calculated using Cohen's method [70]. There are two different indicators, Cohen's f and Cohen's d. The former is used for outcomes that are statistically compared based on their variance. The latter is used for outcomes that are statistically compared based on their mean values. Cohen's f (d) of 0.1 (0.2), 0.25 (0.5), 0.4 (0.8) define small, medium and large effect size.

3 Results (studies)

3.1 CO_2 emission rates from sleeping people (Paper I)

This part of the study addresses Research Question 3 and 4. The study was conducted in a sleep capsule installed in a climate chamber to measure the CO_2 emission rates from sleeping people and to investigate whether bedroom temperature and ventilation affect the CO_2 emission and sleep quality. Based on the measured CO_2 emission rates and findings from previous studies, ventilation rate for bedroom that would avoid any disturbance of sleep quality was proposed. Detailed descriptions of the methodology, results and conclusions can be found in Paper I. They are summarised in the following sections.

3.1.1 Methods

A chamber study was conducted with eleven (four of them male) college-age (28±4 years old) healthy subjects. Each subject slept in the capsule described in Chapter 2 for four consecutive nights under three conditions, including two temperatures (24 °C and 28 °C) and two ventilation rates resulting in the CO_2 concentrations of 800 ppm and 1,700 ppm under steady state. The RH was not controlled, but the measured mean values were between 40% and 60%. The first night was for adaptation, and the following three were formal experiment nights with a balanced exposure order of the conditions. The capsule consisted of a sleeping space with a volume of 2.2 m^3 and an air plenum with a volume of 0.2 m^3. The conditioned and filtered air from the chamber entered the capsule through the plenum and was then exhausted through a flexible duct with extract fans placed outside the chamber. The ventilation conditions in the capsule were controlled by the extract fans. The temperature in the capsule was controlled and regulated by the chamber's temperature set points, which were all 1 °C lower than the examined temperature conditions due to the heat produced by the subjects sleeping inside.

The air temperature, RH, sound pressure level, and concentration of CO_2, NO_2, TVOCs, $PM_{2.5}$ and PM_{10} in the capsule were continuously monitored. We also measured the subjects' physiological reactions, including skin temperature, core body temperature, heart rate and its variability, and sleep quality. The air from the capsule was sampled with Tenax tubes to explore the chemical pollutants emitted by the sleeping subjects but they are not reported here. The subjects were also asked to fill in a sleep diary every evening and morning to collect their assessments of the environmental quality in the capsule and to perform cognitive performance tasks. The cognitive performance tasks were conducted in the adjacent chamber under neutral conditions.

The ventilation rates during sleep in the capsule were calculated daily based on the decay of the metabolically produced CO_2. The CO_2 emission rates were calculated using a single-zone mass balance model shown in the equation below:

$$CO_2\ emission\ rate\ =\ Ventilation\ rate * (\ C_{in} - C_{out}) \ /\ 1{,}000 \quad (1)$$

Where the *CO_2 emission rate* is in L/h, *Ventilation rate* is in m^3/h, C_{in}: time-average CO_2 concentration at the steady-state period in the capsule during sleep in ppm; C_{out}: CO_2 concentration in the air supplied into the capsule under the period of steady-state in ppm.

Uncertainty analysis of the method used to calculate the CO_2 emission rates was performed to see whether the method is sufficiently sensitive to capture the difference in the emission rates between different conditions [71]. The equation is shown below:

$$\Delta Y\ =\ \sqrt[2]{\sum_{i=1}^{n}(\Delta x_i \times \frac{\partial f}{x_i})^2} \quad (2)$$

Where the derivative terms $\Delta x_i \times \frac{\partial f}{x_i}$ describe the sensitivity of the CO_2 emission rates to the changes in the relative variables.

The outcomes were subjected to either ANOVA with a repeated measures design or Friedman's analysis of variance test. The effect size was also calculated using Cohen's method [70].

3.1.2 Results and Discussion

The calculated CO_2 emission rates and their uncertainty analysis are shown in Figure 3.1. Even though the mean CO_2 emission rate was slightly higher at 28°C than at 24°C, and they were lower at reduced ventilation, resulting in an increased CO_2 of 1,700 ppm compared to the condition where the CO_2 concentration was 800 ppm, the differences did not reach statistical significance (Figure 3.1A). The measured physiological reactions of the subjects during sleep did not differ between conditions, confirming that there is no reason to expect that the CO_2 emission rates would change. This is contrary to what has been observed when people are awake [65,67]. This discrepancy could be because the conditions examined in the present study are insufficient to evoke changes in respiration or metabolism during sleep. More studies are needed to further investigate CO_2 emission rates while sleeping under different temperatures and levels of IAQ.

Since no significant changes in the CO_2 emission rates between conditions were found, the data from all three conditions were averaged. The mean CO_2 emission rate was 11.0±1.4 L/h per person with a range of 7.1 to 14.6 L/h per person. Similar results were obtained in the literature by using previously published data on energy expenditure during sleep and respiratory quotient or reported CO_2 emission rates. We also calculated

CO_2 emission rates using the empirical equations included in current standards [49,72,73] and obtained results similar to those measured in the present study.

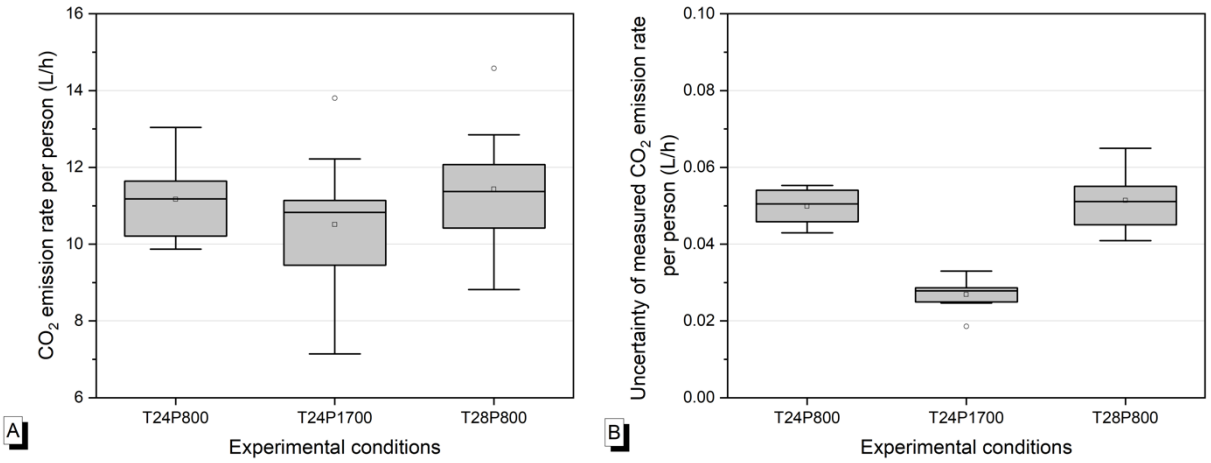


Figure 3.1 (A) Measured CO_2 emission rates and (B) uncertainty analysis of measured CO_2 emission rates under different experimental conditions. The three conditions are abbreviated. For instance, T24P800 refers to an experimental condition with a temperature of 24°C and a ventilation rate that results in a CO_2 concentration of 800 ppm.

The uncertainty was below 0.07 L/h per person (Figure 3.1B), which is lower than the changes in the CO_2 emission rates between different conditions. It indicates that the method used in the present study to calculate the CO_2 emission rates is sufficiently sensitive to capture the changes caused by the experimental conditions. However, slightly higher errors and large variations were observed in the high ventilation conditions compared with the low ventilation conditions. This is because of the reduced precision of estimating ACHs and the shorter time available for this estimation under the high ventilation conditions.

Figure 3.2 shows that the CO_2 emission rates were significantly higher for males than females under low ventilation conditions resulting in a CO_2 concentration of 1,700 ppm, but no gender differences were seen in the other two conditions. This could be due to the higher body surface area of the male subject, who also had a lower body mass index (BMI) than the female subjects. The effects of different body characteristics on the CO_2 emission rates should be examined in future studies. Since there were no significant differences between conditions for either gender, we averaged the CO_2 emission rates for males and females separately: 11.6±1.0 L/h per person for males and 10.7±1.5 L/h per person.

It is worth noting that the CO_2 emission rates in this experiment were measured in an unusual sleeping environment and they were measured for a small group of healthy and young people with normal BMI. Future studies with more diverse subjects conducted

in actual bedrooms will be necessary to validate and extend the applicability of the present results.

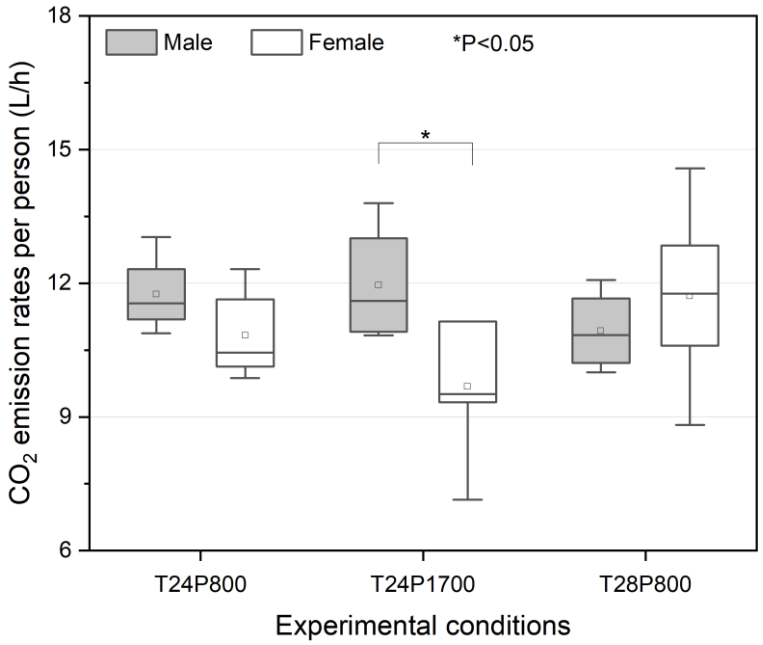


Figure 3.2 CO_2 emission rates by sex under different ventilation conditions. The three conditions are abbreviated. For instance, T24P800 refers to an experimental condition with a temperature of 24°C and a ventilation rate that results in a CO_2 concentration of 800 ppm.

Figure 3.3 shows the outdoor air supply rates as a function of CO_2 concentration in bedrooms, based on the measured CO_2 emission rates during sleep and assuming an outdoor CO_2 concentration of 420 ppm based on the Earth's measured atmospheric CO_2 level (**https://www.co2.earth/**). Considering the CO_2 concentration threshold of < 750 ppm as an indicator of good bedroom IAQ that does not negatively affect sleep quality (see the Introduction section), Figure 3.3 suggest that the bedroom ventilation rate should be higher than 10 L/s per person. If the ventilation rate is below 10 L/s per person, sleep quality may be affected; below 5 L/s per person, sleep quality would be expected to be reduced, as the CO_2 concentration will exceed 1,150 ppm. A ventilation rate lower than 1.5 L/s per person would be expected to affect next-day cognitive performance. It is worth noting that CO_2 is one of the products of human metabolism, and indicates only the indoor pollution level caused by human bioeffluents. If there are other sources of pollution present in bedrooms [33], these recommended values might be different, and this should be investigated in future studies.

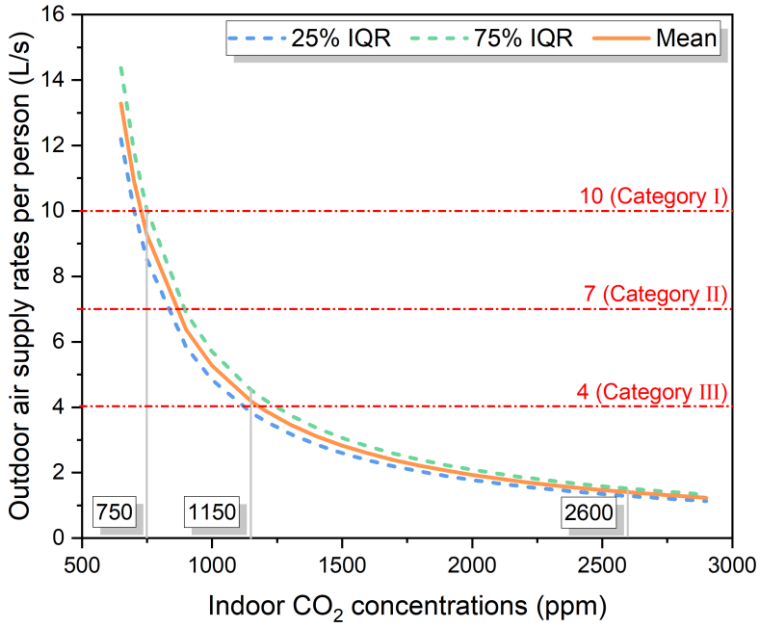


Figure 3.3 Estimated minimum bedroom ventilation rates per person required during sleep at different levels of indoor CO_2 concentration under steady state. The interquartile range (IQR) of the measured CO_2 emission rates and their mean value were used. Bedroom ventilation rate thresholds indicated as CO_2 concentrations proposed by Sekhar et al. are shown considering the impacts on sleep quality and next-day cognitive performance [28]. Ventilation rate requirements in EN16798-1 are presented with red lines [46].

3.1.3 Summary

The CO_2 emission rate was on average 11.0 ± 1.4 L/h per person during sleep. Increasing room temperature from 24 °C to 28 °C or reducing the ventilation rate so that the CO_2 concentration increased from 800 ppm to 1,700 ppm had no effects on the measured CO_2 emission rates and did not change subjects' physiological responses. The conclusion was that a ventilation rate of >10 L/s per person for bedrooms is required if any adverse effects on sleep quality are to be avoided. The present results provide reference values for designing and controlling bedroom ventilation.

3.2 Measured ventilation rates in bedrooms (Paper II)

This part of the study addresses Research Question 5. The study was performed to measure ACHs in actual bedrooms at night (during sleep) to get an overview of existing bedroom ventilation levels. Detailed description of the methodology, results and conclusions can be found in Paper II. Here a summary is presented.

3.2.1 Methods

A cross-sectional study was conducted in the Capital Region of Denmark in 2020, during the heating season. Eighty-four occupants (45 of them male) without significant sleep dysfunction were invited to participate. Their age was on average 32 years old, ranging from 21 to 75 years old and their mean BMI was 22.7 kg/m^2. They slept in their own bedrooms with the heating and ventilation settings they normally adopted during sleep and did not to make any changes throughout the measurement period. An online questionnaire survey that was developed and used in previous studies [33] was used to collect basic information about the participants, their bedrooms, and their sleep quality in the month before starting the study. The bedroom environmental quality and sleep quality were objectively measured using the devices included in an instrument box provided to them and were also subjectively assessed by participants using online sleep diaries (morning and evening sleep diaries). The sleep diaries were completed on only two selected evenings and mornings; the morning sleep diary also collected information about the occupancy and the status of the bedroom windows and doors during sleep. A 3-minute Baddeley test was integrated into the end of each sleep diary to measure the participants' cognitive performance [69]. The instrument box was delivered to each participant at their home with all necessary instruments and documentation for the measurements. The participants were instructed to place the instrument box in their bedrooms at bed height about one meter away from the pillow, ideally on a night table. The measurements lasted for one week, but only the data measured on weekday nights were analysed because work and sleep patterns seemed likely to be different during weekends.

The rate of decay of the concentration of metabolically produced CO_2 was used to estimate ACHs in each bedroom during sleep. The participants were asked to avoid re-entering their bedrooms in the morning for at least 30 minutes after going out and to leave the bedroom conditions as they had been during sleep. We did not concurrently measure the outdoor CO_2 concentration. Instead, the mean value measured after the sleep period and when steady state had been reached in the unoccupied bedroom was adopted. Otherwise, the outdoor CO_2 concentration was assumed to be 420 ppm based on the Earth's measured atmospheric CO_2 level (**https://www.co2.earth/**).

3.2.2 Results and Discussion

Figure 3.4 shows the cumulative probability of the estimated ACHs from 80 Danish bedrooms and the ventilation rates recommended in the applicable standard and based on the findings of this dissertation: one bedroom did not exhibit CO_2 decay; three bedrooms had missing data on CO_2. The results suggest that the median ACH was 0.4 h^{-1} with an IQR of 0.2-0.9 h^{-1}, similar to what had been measured in 500 bedrooms occupied by Danish children [42].

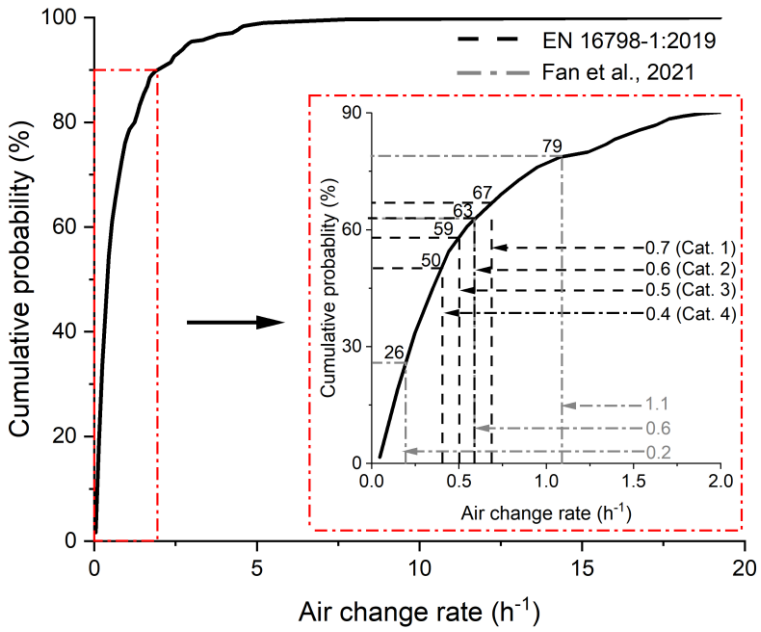


Figure 3.4 Cumulative probability plot of estimated ACHs in bedrooms with an expanded view of ACH <2 h^{-1}. Ventilation rate requirements in EN16798-1 are presented as well [46].

EN16798-1 also stipulates ventilation rates for dwellings in ACH. The requirements are categorized into four: First Category: 0.7 h^{-1}, Second Category: 0.6 h^{-1}, Third Category: 0.5 h^{-1}, and Forth Category: 0.4 h^{-1}. Half of the surveyed bedrooms did not comply with the minimum ventilation rate of 0.4 h^{-1}, and 67% had a ventilation rate lower than 0.7 h^{-1}, the highest ventilation requirement. Since the housing type of the surveyed bedrooms matches well with the distribution of housing type in the Capital Region of Denmark [74] and the bedrooms were randomly selected, the present results indicate that most Danish bedrooms are poorly ventilated, confirming what was concluded by Sekhar et al. [28]. One reason is that fewer than 20% of the bedrooms surveyed were equipped with mechanical ventilation systems [74]. Figure 3.5 shows the measured ACHs by ventilation systems installed in bedrooms. The mean ACH was 0.7, 0.3, and 0.4 h^{-1} for bedrooms with mechanical ventilation systems, natural ventilation systems, and extract ventilation systems, respectively.

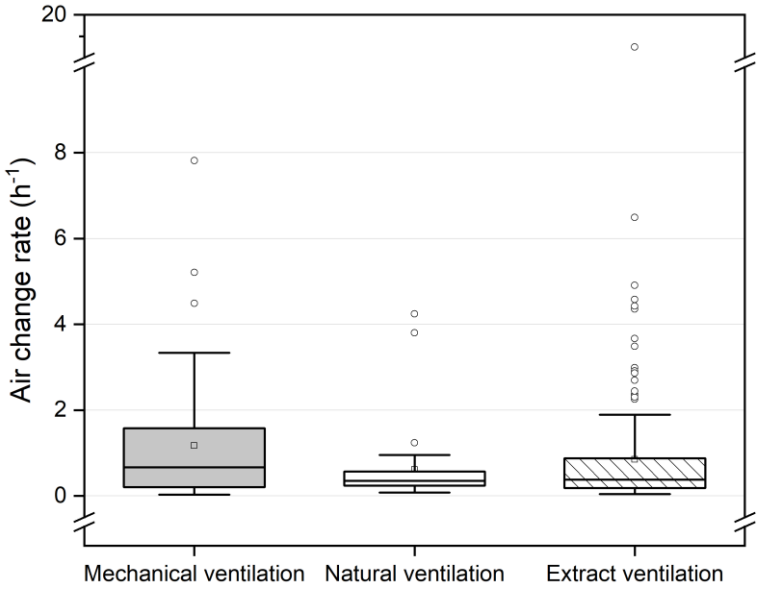


Figure 3.5 Measured ACHs in bedrooms with different ventilation systems. The ventilation type in surveyed bedrooms was identified using the information about the air terminals and trickle vents collected by the online questionnaire. Bedrooms with air terminals were considered to have a fully balanced mechanical ventilation system. Bedrooms with trickle vents and exhaust air terminals in the bathroom or kitchen were considered to have an exhaust ventilation system. Bedrooms were otherwise considered to be ventilated naturally.

In this study, we asked each participant to report the dimensions of their bedrooms and to record the number of occupants in the bedroom on only two days of the week in which measurements were made. We therefore used the median bedroom size of 32 m^3 and the median occupancy of one person in each bedroom during sleep to convert the ventilation rates to ACHs. The mean ventilation rates of 10, 5, and 1.5 L/s per person obtained in Chapter 3.1 then correspond to ACHs of 1.1, 0.6, and 0.2 h^{-1}.

The ACHs in 79% of the bedrooms were lower than 1.1 h^{-1}, indicating that the sleep quality of the occupants sleeping in these bedrooms could have been disturbed; in 26% of the bedrooms the ACHs were lower than 0.2 h^{-1}, indicating that both sleep quality and next-day cognitive performance were likely to have been affected by sleeping in these bedrooms. A paper that reported other results collected in this experiment found that participants did indeed have poor sleep quality [74]. These results highlight the urgency of improving bedroom ventilation. The estimated ACHs are the total airflow for bedrooms, not the outdoor air supply rate. The actual outdoor air supply rate in the bedroom may have been even smaller, exacerbating the negative effects of poor ventilation on sleep quality.

We did not measure the CO_2 concentrations in the ambient air and check the air distribution in bedrooms during sleep, and this should be done in future studies to improve the accuracy of the findings. However, a recent study explored the bedroom air distribution characteristics by deploying the CO_2 sensors at different locations in bedrooms with two different types of ventilation strategy [39]. It found that the location

of the sensors did affect the estimation of the ACHs but concluded that the effects were small when the measurements were close to the breathing zone of the sleeping person. The instructions in the present experiment were that the instrument box that included the CO_2 sensor that should be placed one meter away from the pillow, and as this is within the breathing zone it suggests that our estimates are reliable. The present results are valid for the heating season in a temperate climate zone. Extrapolation to other seasons and climate zones will require further research.

3.2.3 Summary

The median ACH in bedrooms was 0.4 h^{-1}, the minimum ventilation requirement in the European standard. ACHs in 79% of bedrooms did not meet the ventilation rate of 1.1 h^{-1} (corresponding to 10 L/s per person) that would eliminate any risks of disturbed sleep. These measurements indicate that current Danish bedrooms are poorly ventilated and highlight the importance of improving bedroom ventilation.

3.3 Effects of bedroom ventilation on sleep quality and next-day cognitive performance: chamber study (Paper Ⅲ)

This part of the study addresses Research Question 1, 2, 4, and 7. The chamber study was performed to investigate how bedroom ventilation affects sleep quality and next-day cognitive performance in a well-controlled environment. Detailed description of the methodology, results and conclusions can be found in Paper III. Here a summary is presented.

3.3.1 Methods

A study was conducted to investigate the effects of bedroom ventilation on sleep quality in a climate chamber located in the ICIEE laboratory at DTU. Two ventilation rates that resulted in CO_2 concentrations of 800 and 1,700 ppm under steady state were examined, as described also in Section 3.1. Additionally, the effects of temperature on sleep quality were explored. Two temperatures (24 and 28°C) were selected. Data from one subject who rated the air in the capsule to be significantly dry (which was not the case based on the RH measurements) and had significantly low total sleep duration compared to the other subjects were excluded. Data from only ten subjects were included in the final analysis.

The raw data were first screened and pre-processed and then subjected to ANOVA analysis with a repeated measures design. The Greenhouse-Geisser method was used to

adjust the violation of sphericity, and a post hoc analysis was performed using the Bonferroni test. The effect size was also calculated using Cohen's method [70].

3.3.2 Results and Discussion

The general complaint rates of fatigue were higher before sleep under all three conditions (Figure 3.6A). Similar results were seen for sleepiness (Figure 3.6B). The complaint rates of fatigue and sleepiness were lower after sleep than before, but did not reach significance at 28°C. This suggests that subjects did not feel as restored after sleeping at higher temperatures, indicating worse sleep quality.

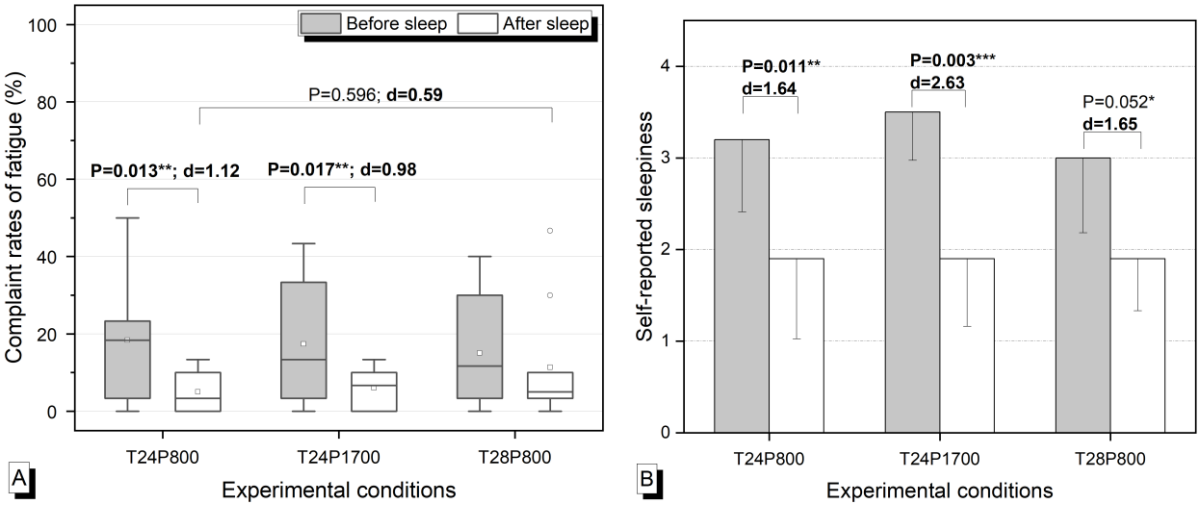


Figure 3.6 (A) The complaint rates of fatigue; and (B) self-reported sleepiness before and after sleep under the three conditions. The three conditions are abbreviated. For instance, T24P800 refers to the experimental condition with a temperature of 24°C and a ventilation rate that results in a CO_2 concentration of 800 ppm. Cohen's d is indicated. ***P<0.01, **P<0.05, *P<0.1

Figure 3.7 shows the objectively measured sleep onset latency and subjective measurements of sleep quality obtained with the GSQS questionnaire. Sleep onset latency was significantly longer when the ventilation was decreased (Figure 3.7A). Similar results were observed by Xu et al. (2020) who also found that reduced ventilation that resulted in the CO_2 concentration increased from 800 ppm to 3,000 ppm significantly reduced sleep quality. Such differences were not observed when the temperature was increased. GSQS scores were higher at 28°C than 24°C, indicating reduced sleep quality (Figure 3.7B). Previous studies show that GSQS scores above two, which was exceeded by the mean score at 28°C, suggest disturbed and restricted sleep [14,15].

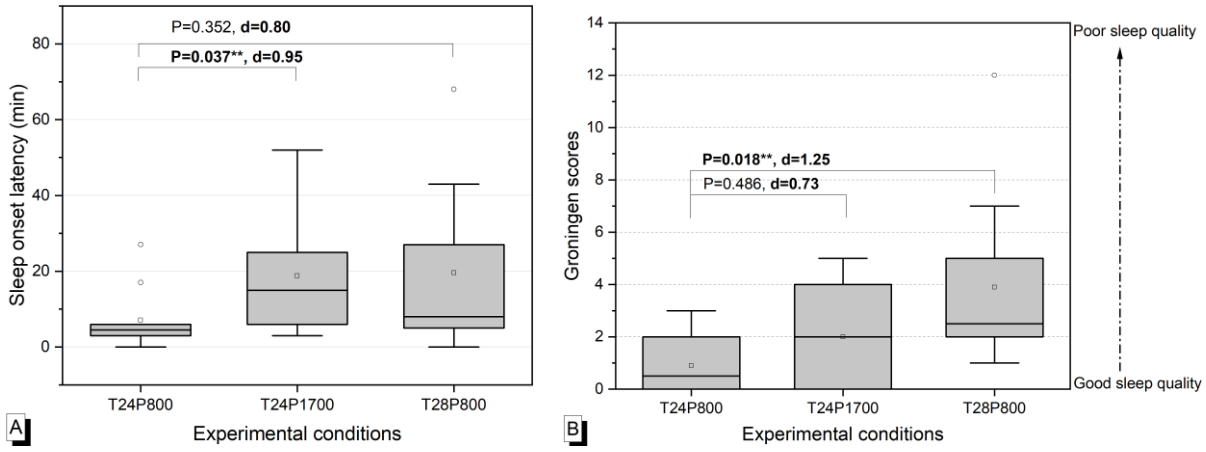


Figure 3.7 (A) Sleep onset latency; and (B) Subjective sleep quality under the three conditions. The three conditions are abbreviated. For instance, T24P800 refers to the experimental condition with a temperature of 24°C and a ventilation rate that results in a CO_2 concentration of 800 ppm. Cohen's d is indicated. **P<0.05

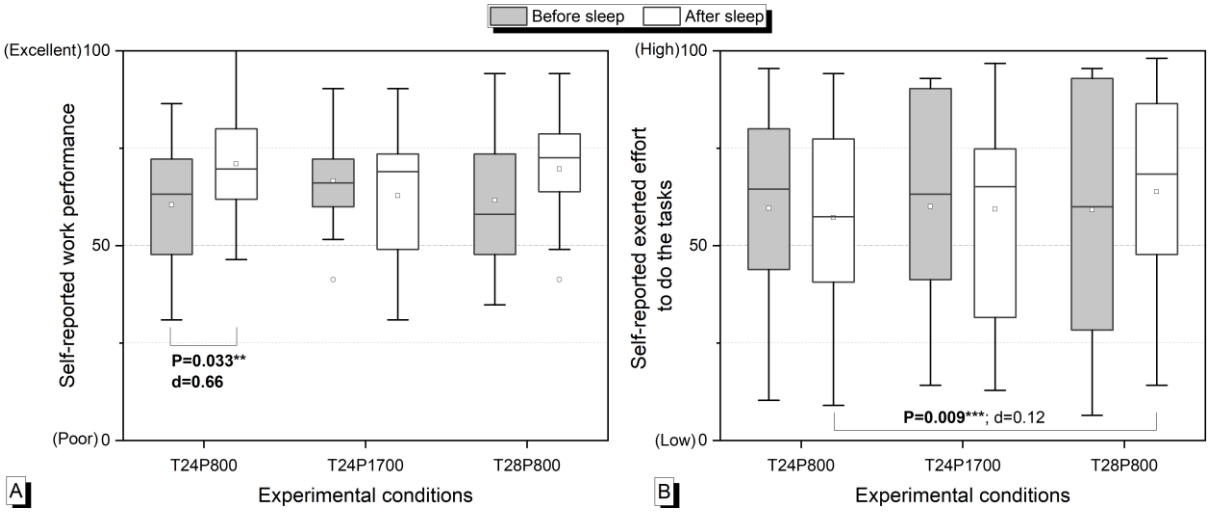


Figure 3.8 Self-reported (A) cognitive performance and (B) exerted effort to do the tasks before and after sleep under the three conditions. The three conditions are abbreviated. For instance, T24P800 refers to the experimental condition with a temperature of 24°C and a ventilation rate that results in a CO_2 concentration of 800 ppm. Cohen's d is indicated. ***P<0.01, **P<0.05

Self-reported work performance is shown in Figure 3.8. It was significantly improved after sleeping at the reference condition with a temperature of 24 °C and high ventilation that resulted in a low CO_2 concentration of 800 ppm, but no such effects were seen under the increased temperature and reduced ventilation conditions (Figure 3.8A). Figure 3.8B shows that the subjects reported that they had to exert significantly more effort to complete the same tasks after sleeping at 28 °C. These results may suggest that their next-day cognitive performance was negatively affected in the present study when either the temperature was increased or the ventilation was reduced. Similar results were observed by Strøm-Tejsen et al., who reported that reduced ventilation negatively

affected the performance of the Baddeley test used in the present study [51]. No effects of sleeping at a raised temperature on next-day cognitive performance have been found in previous studies [75,76]. We cannot make solid conclusions on how next-day performance is affected based on the currently very limited findings. More studies are necessary to explore the effects of bedroom environmental quality on next-day cognitive performance.

3.3.3 Summary

Sleep onset latency increased significantly when the ventilation was reduced so that the CO_2 concentration increased from 800 ppm to 1,700 ppm. Self-reported cognitive performance was not improved although it was after sleeping with better ventilation. Subjective sleep quality was reduced when the temperature was increased from 24°C to 28°C. The present results suggest that increased temperature and reduced ventilation both have negative effects on sleep quality, and that this may have negative effects on next-day cognitive performance.

3.4 Effects of bedroom ventilation on sleep quality and next-day cognitive performance: intervention study in Belgium (Paper IV)

This part of the study addresses Research Question 1, 2, 4, and 7. A single-blind field intervention study was conducted to investigate how bedroom ventilation affects sleep quality and next-day cognitive performance in actual bedrooms. The bedrooms were equipped with extract ventilation systems (with the extract terminals in bedrooms and trickle vents on the windows). Detailed descriptions of the methodology, results and conclusions can be found in Paper IV. Here a summary is presented.

3.4.1 Methods

A four-week-long field intervention study was conducted in 29 bedrooms in October 2021, in Belgium. Participants were recruited based on an online questionnaire about their health condition, bedroom characteristics, work patterns and sleep quality over the past month [33]. All bedrooms were mechanically ventilated by an extract ventilation system with trickle vents on the windows. During the first week, no interventions were made but data were collected to familiarize the participants with the experimental protocol and measurements. In the following weeks, each participant slept for one week under a low, moderate, and high ventilation rate condition corresponding to the target outdoor airflow rates of 3, 10, and 30 m^3/h, respectively. The order of presentation of the experimental conditions was counterbalanced. The conditions were established by

remotely controlling the fan speed in the extract ventilation systems, without informing the occupants and without entering the bedrooms. An instrument package including a bedroom environmental quality monitor and a wrist-worn sleep tracker was sent to each participant by post. Bedroom temperature, RH, the concentrations of CO_2, PM_1, $PM_{2.5}$, PM_4, PM_{10} and TVOCs, and sound pressure level in dB(A) were continuously measured. The participants were instructed to connect the instruments online so that we could access all the measurements. They completed online sleep diaries to record about their assessments of bedroom environmental quality and performed cognitive tasks using Baddeley test on selected mornings and evenings.

The raw data were first screened and pre-processed and then subjected to ANOVA analysis with a repeated measures design. The Greenhouse-Geisser method was used to adjust the violation of sphericity, and the post-hoc analysis was performed using the Bonferroni test. For paired data, the normality of data was explored with a Shapiro-Wilk test. Normally distributed data were analysed with a paired-sample t-test. Otherwise, we used a non-parametric Wilcoxon Matched-Pair Signed-Ranks test. The effect size was also calculated using Cohen's method [70].

3.4.2 Results and Discussion

Although 29 participants completed the measurements, complete data sets were available from only 25 participants. We examined the measured CO_2 concentrations from these 25 participants to verify whether the intervention had been successful. We found that notable differences in measured CO_2 concentration between the low and high ventilation rate settings could be observed in 23 bedrooms. Differences between all three ventilation settings could be observed in only 12 bedrooms. We thus decided to perform analyses separately for these two data sets.

Although we intended to examine the three ventilation rates of 3, 10, and 30 m^3/h in bedrooms, the actual ventilation rates in bedrooms, including infiltration and adventitious ventilation obtained by opening windows [77], if any, differed from these planned settings according to the measured CO_2 concentrations (detailed results can be seen in the Paper IV).

Figure 3.9 shows the objectively measured sleep quality parameters that were found to have significant differences between the three experimental conditions. It shows that when increasing ventilation from low to moderate levels, the number of awakenings and the percentage of light sleep significantly decreased, and the percentage of deep sleep increased significantly. At the low ventilation rate setting the number of awakenings was significantly greater, and the percentage of deep sleep was shorter although the difference was not significant compared to the high ventilation rate setting.

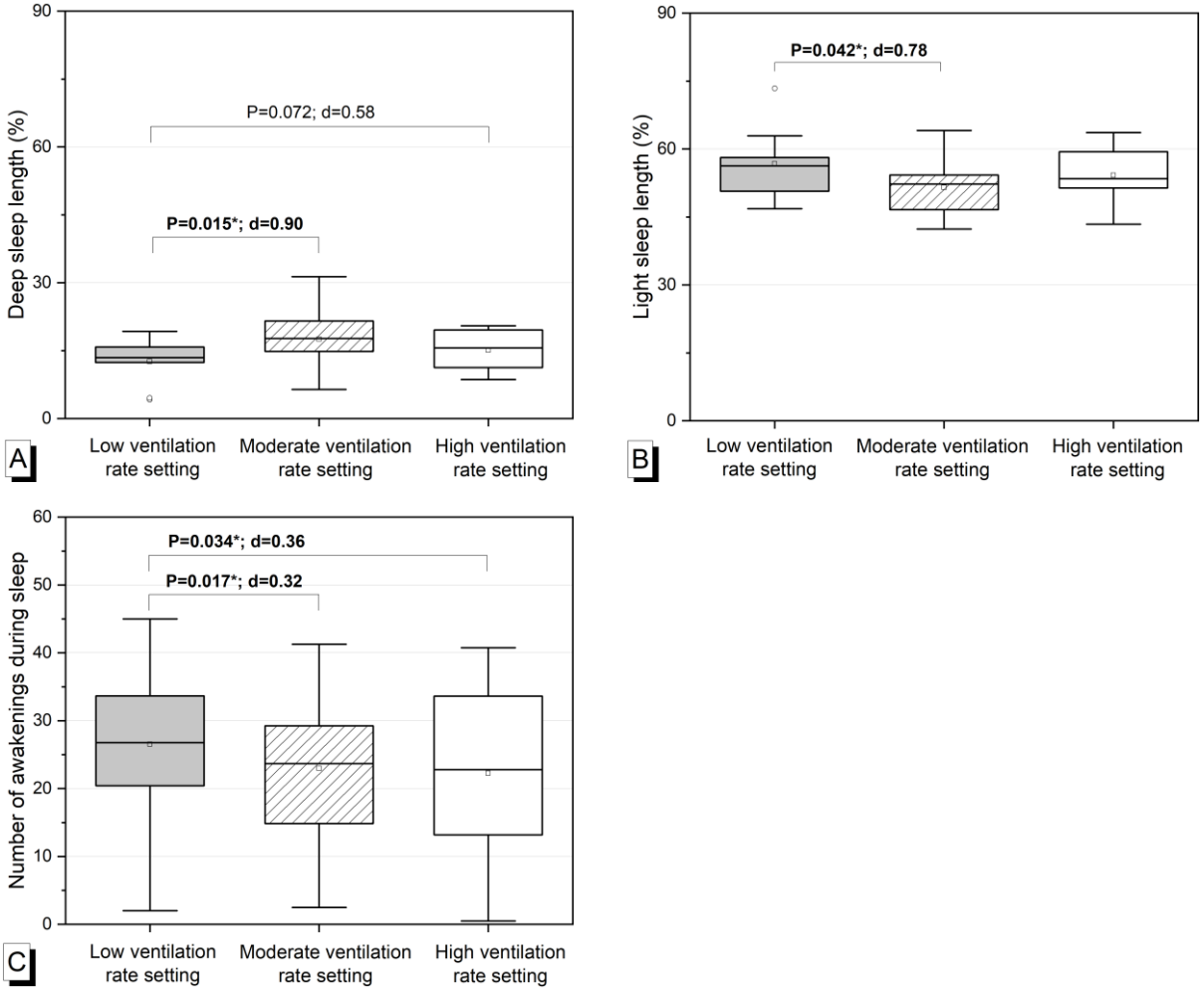


Figure 3.9 (A) Deep sleep; (B) light sleep; and (C) the number of awakenings at three ventilation rate settings. $0.01<*p\leq0.05$

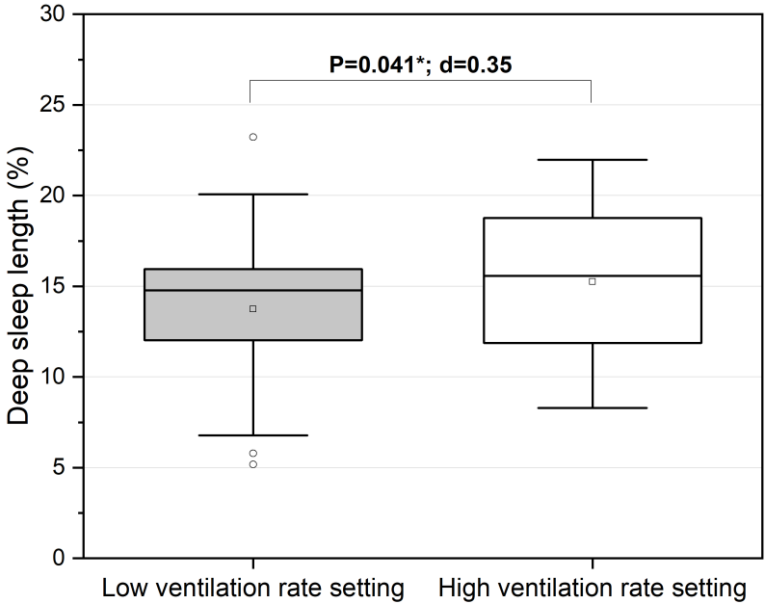


Figure 3.10 Deep sleep at the low and high ventilation rate settings. $0.01<*p\leq0.05$.

Figure 3.10 shows the objectively measured deep sleep at low and high ventilation rate settings. The percentage of deep sleep was significantly shorter at the low ventilation rate setting than at the high ventilation rate setting.

The present results show that the conditions in bedrooms were significantly worse at the low ventilation rate setting, and that this negatively affected sleep quality. Increasing the ventilation rate improved both bedroom IAQ and sleep quality parameters. The former was indicated by lower $PM_{2.5}$, CO_2 and TVOC levels. Sleep quality improved in terms of longer deep sleep, shorter light sleep, and fewer awakenings. The intervention did not change the temperature of the bedroom, so the effects observed in this study can be attributed to the effects of improved IAQ on the human respiratory and autonomic nervous systems as suggested by Yan et al. [78]. Present results are similar to what has been reported in the literature, in laboratory studies [62,78–80], field intervention studies [51,60,81,82] and cross-sectional studies [74,83–85]. We believe that compared with other studies the results in the present study are unique because the effects were observed in actual bedrooms, not dormitories, by changing the set points of an existing mechanical ventilation system. Confirmation in actual bedrooms equipped with a fully balanced mechanical supply and extract system is required.

3.4.3 Summary

The present study investigated and validated the beneficial effects of improved bedroom ventilation on objectively measured indicators of sleep quality. The results support recommendation that a ventilation rate of >10 L/s per person for bedrooms is required to avoid sleep disturbance.

3.5 Windows and doors opening to improve bedroom ventilation (Paper Ⅴ)

This part of the study addresses Research Question 1, 2, 4, 6, and 7. A field intervention study was carried out to investigate how window and door opening affect bedroom IAQ, sleep quality and next-day cognitive performance, and to compare the effects of opening a window or an internal door on bedroom ventilation. Detailed description of the methodology, results and conclusions can be found in Paper IV. Here a summary is presented.

3.5.1 Methods

A field intervention study was conducted from September to December 2020 in the Greater Copenhagen area of Denmark. It was part of a large cross-sectional study

conducted in 84 bedrooms focusing on measuring the bedroom ventilation rates reported in Chapter 3.2 and their effects on sleep quality [74]. Of sixty-four participants who participated in this two-week-long field intervention study, a complete data set was available from only 40. In the first week, participants slept in their bedrooms under the conditions they usually experienced during sleep. In the second week, they were asked to change the bedroom ventilation conditions by opening the doors or windows if they had been closed in the first week or closing them if they had been open in the first week. Whether this intervention had substantively altered bedroom ventilation was determined empirically in a subsequent analysis. The same measurements were made in the second week as in the first week.

We used the 95th percentile of measured CO_2 concentration to determine the success of the intervention. An intervention that caused a difference in the 95th percentile of measured CO_2 concentration that was > 200 ppm was deemed successful, considering the accuracy of the CO_2 sensors and the possibility of incomplete mixing. Twenty-nine bedrooms met this criterion. Among them, the ventilation was changed in 13 bedrooms by opening or closing an internal door with the windows always closed, while in 16 bedrooms it was changed by opening or closing the windows while the internal doors in most of them remained closed.

The data that had been measured more than once each night were subjected to analysis of variance with a repeated-measures design; the Greenhouse-Geisser method was used to adjust the violation of sphericity. A post-hoc analysis was performed using the Bonferroni test. A paired-sample t-test was used for normally distributed data, but we otherwise used the non-parametric Wilcoxon Matched-Pairs Signed-Ranks test. The effect size was also calculated using Cohen's method [70].

3.5.2 Results and Discussion

Table 3-1 summarizes the objectively measured bedroom environmental quality during sleep. Opening either the windows or doors significantly increased the ACH and reduced the CO_2 concentration. The mean NO_2 concentration during sleep increased when the doors or windows were opened; when a window was open, the NO_2 concentration was higher, though not significantly ($P<0.10$). The concentrations of PM_{10} and VOCs decreased significantly when the windows were open. No such effects were observed when an internal door was open.

Mean RH was higher when the windows or doors were closed, but it remained in the range from 40% to 60%. The mean temperature decreased significantly when the windows were open but by an average of only 0.8 °C

Table 3-1 Objectively measured bedroom environmental quality during sleep (Mean±SD). Cohen's d. **P<0.01; *P<0.05.

Parameters	Bedrooms in which the 95th percentile of CO_2 concentration between two weeks differed by > 200 ppm							
	Doors Position				Windows Position			
	Closed	Open	P-value	d	Closed	Open	P-value	d
ACH (h^{-1})	**0.29±0.24**	**0.78±1.14**	**0.007****	**0.62**	**0.34±0.31**	**1.21±1.14**	**<0.001****	**1.08**
95th percentile of CO_2 concentration (ppm) [a]	**2916±960**	**1415±495**	**<0.001****	**2.02**	**2310±944**	**904±406**	**<0.001****	**1.98**
Mean CO_2 concentration (ppm) [b]	**2362±728**	**1293±465**	**<0.001****	**1.80**	**1820±706**	**761±273**	**<0.001****	**2.02**
NO_2 (ppb) [c]	**1.2±1.3**	**4.7±4.5**	**0.043***	**1.14**	3.5±3.8	10.4±12.5	0.056	**0.77**
VOCs (ppb) [c]	198.6±66.1	164.1±49.9	0.086	**0.62**	**205.6±60.7**	**156.0±59.3**	**0.001****	**0.86**
PM_{10} ($\mu g/m^3$) [c]	24.1±24.5	23.1±23.6	0.594	0.04	**46.8±37.1**	**26.3±22.1**	**0.026***	**0.70**
$PM_{2.5}$ ($\mu g/m^3$) [c]	4.7±3.1	4.5±2.9	0.953	0.06	5.4±3.9	3.9±2.5	0.124	0.47
PM_1 ($\mu g/m^3$) [c]	1.9±1.6	1.9±1.5	0.575	0.01	1.8±1.5	1.7±1.2	0.875	0.08
Temperature (°C)	24.7±3.8	24.7±2.9	0.774	0.03	**23.2±1.3**	**22.4±1.9**	**0.008****	**0.51**
Relative humidity (%)	**54±7**	**51±7**	**<0.001****	**0.54**	**53±6**	**48±6**	**0.001****	**0.78**
Illuminance (Lux)	11.3±7.1	12.5±9.3	0.420	0.14	11.4±9.0	10.2±6.2	0.794	0.16

[a] The number of bedrooms with a CO_2 concentration < 1,100 ppm, which according to [28,29] indicates the level below which it is less probable that there are effects on sleep quality: > 200 ppm group: doors closed - 0 bedroom, doors open –3 bedrooms of 13, windows closed – 1 bedroom, windows open 12 bedrooms of 16 bedrooms.

[b] The number of bedrooms with a CO_2 concentration < 1,100 ppm, which according to [28,29] indicates the level below which it is less probable that there are effects on sleep quality: > 200 ppm group: doors closed - 0 bedroom, doors open – 6 bedrooms of 13, windows closed – 2 bedrooms, windows open 13 bedrooms of 16 bedrooms.

[c] Data from six participants with nine nights of measurements was available when the doors were closed or open; Data from 10 participants with 14 nights of measurements was available when the windows were closed or open; Data from 9 participants with 13 nights of measurements was available when the difference in the 95th of CO_2 concentration was ≤200 ppm between two weeks

The bedroom IAQ assessments made by the participants are shown in Figure 3.11. The acceptability of bedroom IAQ increased and the odour intensity decreased when a window was open compared to when a window was closed; no such effects were seen when an internal door was open (Figure 3.11A, C). The perception of air freshness was improved when a window or an internal door were open, while in the case of an open window, the improvement was greater as the air was rated as much fresher (Figure 3.11B).

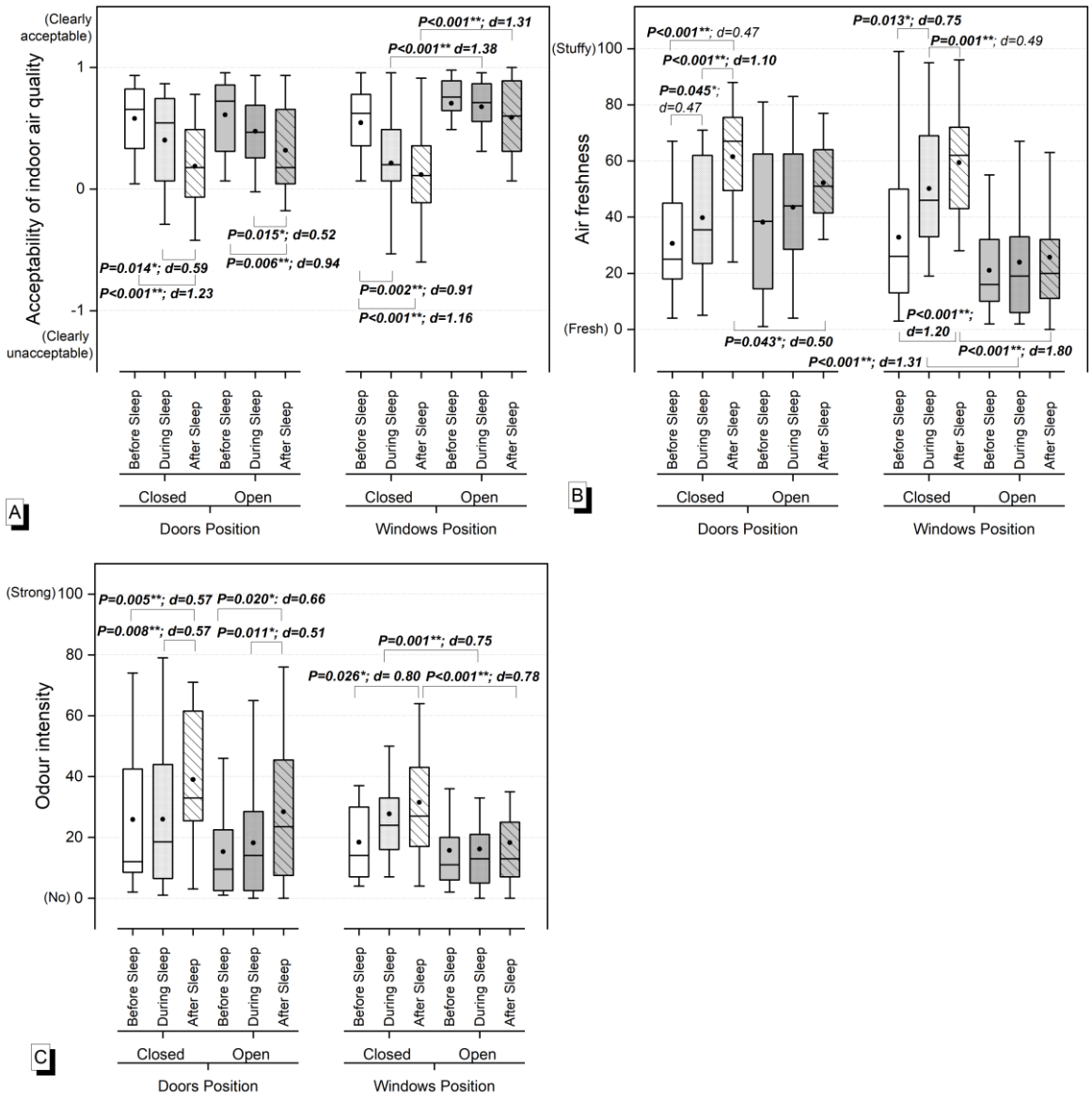


Figure 3.11 (A) The acceptability of IAQ, (B) odour intensity, and (C) air freshness before, during (recalled), and after sleep under the different conditions. Cohen's d is indicated. **P < 0.01; *P < 0.05.

When a window was open, the self-reported sleepiness level in the morning was significantly lower (Figure 3.12A) and the percentage of participants reporting having

enjoyed a ‘deep sleep’ increased (Figure 3.12B) compared with conditions when a window was closed. No such effects were observed when an internal door had been open (Figure 3.12).

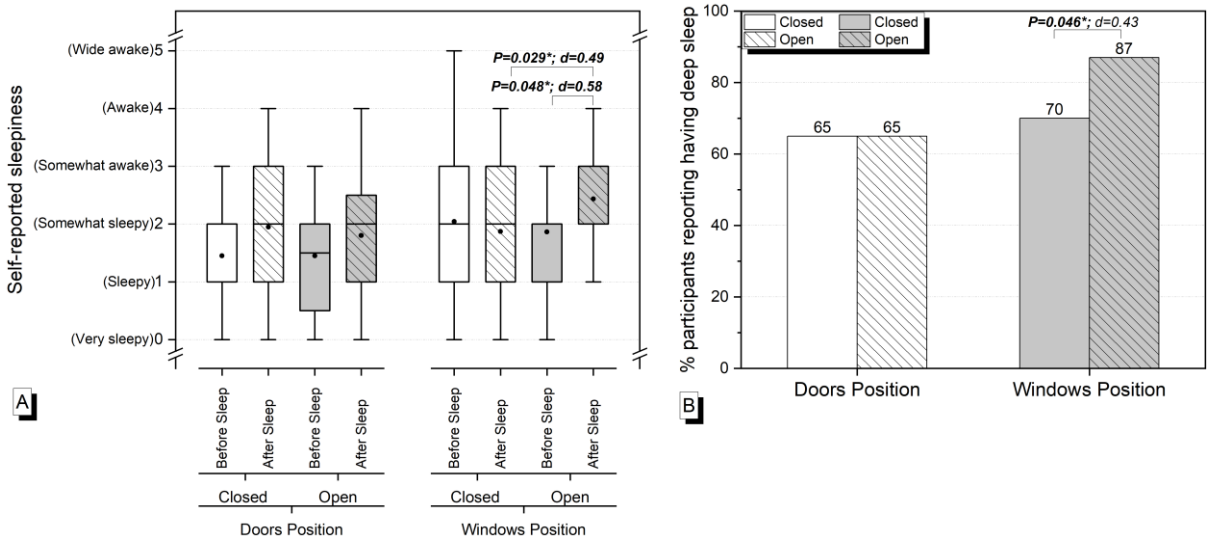


Figure 3.12 (A) Self-reported sleepiness before and after sleep; (B) % of the participants how reported (recalling after sleep) having a ‘deep sleep’ under the different conditions. Cohen’s d is indicated. *P < 0.05

When a window was open, the objectively measured sleep duration was significantly longer (Figure 3.13A), and subjectively rated sleep quality tended to improve (P<0.100) (Figure 3.13B); no such effects were seen when an internal door was open (Figure 3.13).

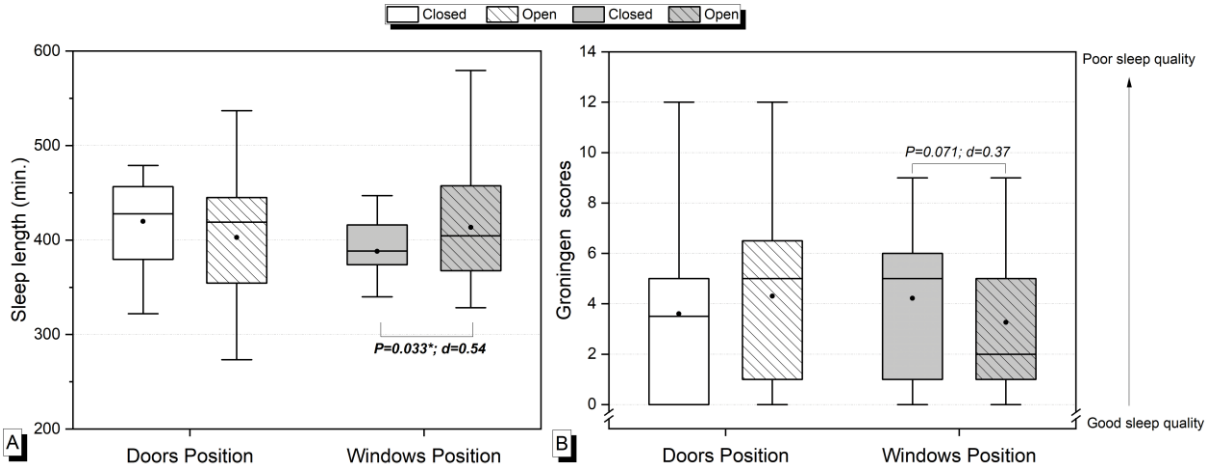


Figure 3.13 (A) Objectively measured sleep length; (B) subjective measurements of sleep quality under the different conditions. Cohen’s d is indicated. *P < 0.05

Scores obtained on the Baddeley test before and after sleep are shown in Figure 3.14. The accuracy was significantly improved after sleeping with a window open. The performance before sleep happened to differ when an internal door was open compared with when it was closed but this difference cannot be attributed to the sleeping conditions.

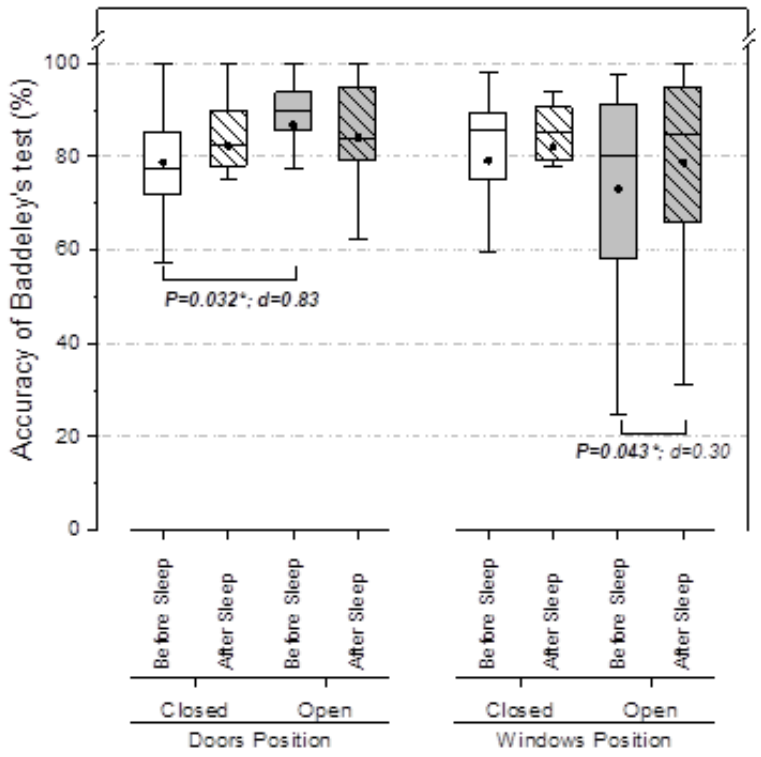


Figure 3.14 The accuracy of Baddeley test under the different conditions. Cohen's d is indicated. *P<0.05.

The present results suggest that opening windows or doors significantly increased bedroom ventilation, reducing CO_2 concentrations during sleep. However, the objectively measured and subjectively rated IAQ in bedrooms was improved only when a window was open, as did sleep quality, which is consistent with the published results [81,82,86]. No such improvements were observed when an internal door was open. We believe that leaving an internal door open did not provide adequate removal or dilution of the pollutants in bedrooms even though we could not confirm this hypothesis with the limited measurements. The reduced levels of CO_2 when an internal door was open suggest that air from other parts of the dwellings was either drawn or diffused into the bedrooms, possibly exposing the sleeping participant to other pollutants drawn for example from the kitchen or bathroom. The CO_2 concentration of this air was low during the sleep period, as other spaces in the dwellings were not occupied, and consequently the bedroom CO_2 concentration was reduced, though not as much as when a window was left open.

3.5.3 Summary

Although opening either a window or an internal door increased bedroom ventilation and reduced the CO_2 concentration, objectively measured and subjectively rated IAQ was improved only when a window was open and this provided benefits for sleep quality. No such effects were seen when an internal door was open. Natural ventilation that is achieved by leaving a bedroom window open is thus recommended as the best way to improve bedroom ventilation if no mechanical ventilation is in operation.

4 General discussion

4.1 Research questions

Research question 1: Does bedroom ventilation affect sleep quality?

Answer: Yes, it does. The results show the benefits of increased bedroom ventilation for sleep quality both as measured objectively (using sleep trackers) and as rated subjectively (on rating scales) (Table 4-1)

Justification and limitations: Experiments performed during the present Ph.D. study found that inadequate bedroom ventilation negatively affected sleep quality by increasing sleep onset latency and awakenings during sleep and reducing sleep duration and deep sleep; these effects were measured using wrist-worn sleep trackers. The results also showed that the participants' subjective sleep quality as assessed by the GSQS questionnaire was also affected. These results are summarized in Table 4-1. The results were obtained both in laboratory experiments and in the participants' own bedrooms. They agree with previous findings in chamber studies [66,78–80], cross-sectional studies [83,84,87–89], online surveys [33,34], and field intervention studies [81]. One study did not observe significant differences in the sleep quality of children sleeping under different ventilation rates in a climate chamber [66]. A plausible explanation for this exception is that the study did not take measures to allow the children to adapt sufficiently to sleeping in an unfamiliar sleeping environment [68].

One limitation of the present work is that sleep quality was measured with wrist-worn sleep trackers. Although previous studies have shown that the sleep trackers used in the present Ph.D. study have a sensitivity comparable with that of the PSG approach [90–92], future studies would be useful to better document their performance against PSG, and such studies are in progress. Another limitation is that noise levels were not measured in the participants' own bedrooms, not even in the field intervention study when the windows and doors were open. Previous studies have found that noise significantly reduces sleep quality [23,24]. Participants rated the noise levels in bedrooms with sleep diaries and they did not report retrospectively having had any problems with noise. The present study did not monitor exposure to daylight on the day prior to the nights when the measurements were made. Research has shown that light exposure affects sleep quality [93]. Although this cannot have biased the findings, the effects of prior light exposure should be investigated in future studies and some are already in progress.

The present research does not provide any evidence on the causative mechanisms for the observed effects or on what pollutants are responsible for the observed effects of changing the bedroom ventilation rate. One study published recently proposed a mechanism for the negative effects of inadequate bedroom ventilation on sleep quality, suggesting that a raised concentration of indoor pollutants negatively affects the respiratory system and the sympathetic nervous activity in such a way as to affect sleep quality [80].

Table 4-1 The effects of bedroom ventilation on sleep quality observed in this Ph.D. thesis.

Papers No.	Context	Ventilation systems	Mean CO_2 concentrations (ppm)	Sleep Quality Objective measurements	Subjective ratings (GSQS)	Self-reported feelings
III	Laboratory	Mechanical ventilation	800 to 1,700	Increased sleep onset latency	No	No
IV	Actual bedrooms	Mechanical ventilation	856 to 1,298 to 1,927 [a]	Reduced deep sleep, increased light sleep, more awakenings	N/A	N/A
			812 to 1,369 [b]	Reduced deep sleep	N/A	N/A
V	Actual bedrooms	Natural ventilation	761 to 1,820 [c]	Reduced sleep duration	Reduced	More sleepiness, reported having less 'deep sleep'
			1,293 to 2,362 [d]	No	No	No

[a] Three ventilation conditions: CO_2 concentrations correspond to high, moderate, and low ventilation rate settings, respectively
[b] Two ventilation conditions: CO_2 concentrations correspond to high and low ventilation rate settings, respectively
[c] The windows were changed from open to closed
[d] The internal doors were changed from open to closed.

Table 4-2 The effects of bedroom ventilation on next-day cognitive performance observed in this Ph.D. thesis.

Papers No.	Context	Ventilation systems	Mean CO_2 concentrations (ppm)	Next-day cognitive performance: Objective measurements		Next-day cognitive performance: Subjective ratings	
				After sleep	Between conditions	After sleep	Between conditions
III	Laboratory	Mechanical ventilation	800 (high ventilation)	No	No	Improved	No
			1,700 (low ventilation)	No		No	
IV	Actual bedrooms	Mechanical ventilation	856 (high ventilation) [a]	No	No	--	--
			1,298 (moderate ventilation) [a]	No		--	
			1,927 (low ventilation) [a]	No		--	
			812 (high ventilation) [b]	No	No	--	--
			1,369 (low ventilation) [b]	No		--	
V	Actual bedrooms	Natural ventilation	761 (Windows open)	Improved	No	--	--
			1,820 (Windows closed)	No		--	
			1,293 (Doors open)	No	Improved only before sleep	--	--
			2,362 (Door closed)	No		--	--

[a] Three ventilation conditions;
[b] Two ventilation conditions.

It is still unknown whether CO_2 is a pollutant that affects sleep quality; levels of CO_2 are high in bedrooms [27,28]. Previous studies have found that exposure to pure CO_2 negatively affects some people when they are awake [94–96]. There are many other air pollutants present in bedrooms, as summarized in two reviews [27,97]. They include CO, TVOCs, formaldehyde, PM, flame retardants, fungi and bacteria. However, none of them have been shown to affect sleep quality, although a survey in Danish bedrooms by Liao et al. found an association between the presence of pollution sources in bedrooms and subjectively assessed sleep quality (PSQI) [33] and some of those sources may emit these pollutants. Recent epidemiological studies have shown that exposure to increased levels of outdoor air pollutants, specifically PM [55,56,98,99], O_3 [98], NO_2 [55,98,99], is associated with subjectively assessed poor sleep quality.

Research question 2: Does bedroom ventilation affect next-day cognitive performance?

Answer: In the present work, no systematic effects on next-day cognitive performance reached statistical significance (Table 4-2).

Justification and limitations: In the climate chamber study, self-reported work performance was not improved after sleeping with a low ventilation rate, while it improved after sleeping with improved ventilation. However, the objectively measured next-day cognitive performance did not change. In the field intervention study in Denmark, next-day cognitive performance improved significantly after sleeping in bedrooms with the windows open, but it did not when the windows were closed. These findings may indirectly suggest the possibility of negative effects on next-day cognitive performance, but no statistical differences in performance between the conditions were seen, which reduce the strength of these observations, and no effects on performance were found in the intervention study in Belgium. These results are summarized in Table 4-2. No effects of reduced ventilation on next-day performance were found in a recent study of children sleeping in a climate chamber, probably because there were no significant effects on their sleep quality, as noted above [66].

These results are different from the ones observed by Strøm-Tejsen et al.[51]. They found that the performance of the Baddeley test was reduced after sleeping in bedrooms with poor ventilation [51]. One reason for the discrepancy could be the exposure levels. In the present studies CO_2 concentrations were at 2,000 ppm or below, while Strøm-Tejsen et al. were examining the effects of CO_2 concentrations of nearly 2,500 ppm. This may suggest that only higher levels of pollutants cause measurable effects on performance. In addition, Strøm-Tejsen et al. did not see the effects in either of their two independent experiments but only when the results from both experiments, i.e., from a total of 30 subjects, were combined. This may suggest that our sample size may have been too small for an effect on next-day performance to reach significance. Other studies have

shown that sleeping poorly does affect next-day cognitive performance [6,7,52,98] and does increase the risk of occupational injury [8].

One limitation of this part of the work is the methodology. In the field studies, the cognitive performance test was performed in the bedroom where the participants had been sleeping, so the observed effects of reduced ventilation could be either due to the resulting poor sleep quality or a direct effect of poor IAQ at the time the test was performed. However, this confounding of two exposures was absent in the chamber study as subjects always performed the tests under neutral conditions.

Previous studies have shown that poor IAQ reduces work performance when people are awake [95,100], so an effect of IAQ on next-day cognitive performance should have been observed. The reason why they were not seen may be the variance caused by the initial sleep inertia or grogginess felt by some people upon awakening. Previous studies have shown that it is associated with significant cognitive performance decrements that dissipate as time awake increases [101]. In the chamber study, the test was always conducted in the first 30 minutes after the subjects woke up and moved to another room, but it was not possible to know when it was performed in the field studies.

Research question 3: What is the CO_2 emission rate from a sleeping person?

Answer: It is on average 11 L/h per person for adults with normal BMI and no sleep disorders.

Justification and limitations: The present Ph.D. study measured the CO_2 emission rates from adults during sleep; it was 11.0±1.4 L/h per person. Similar results were seen in a previous study by White et al. [102] (Figure 4.1).

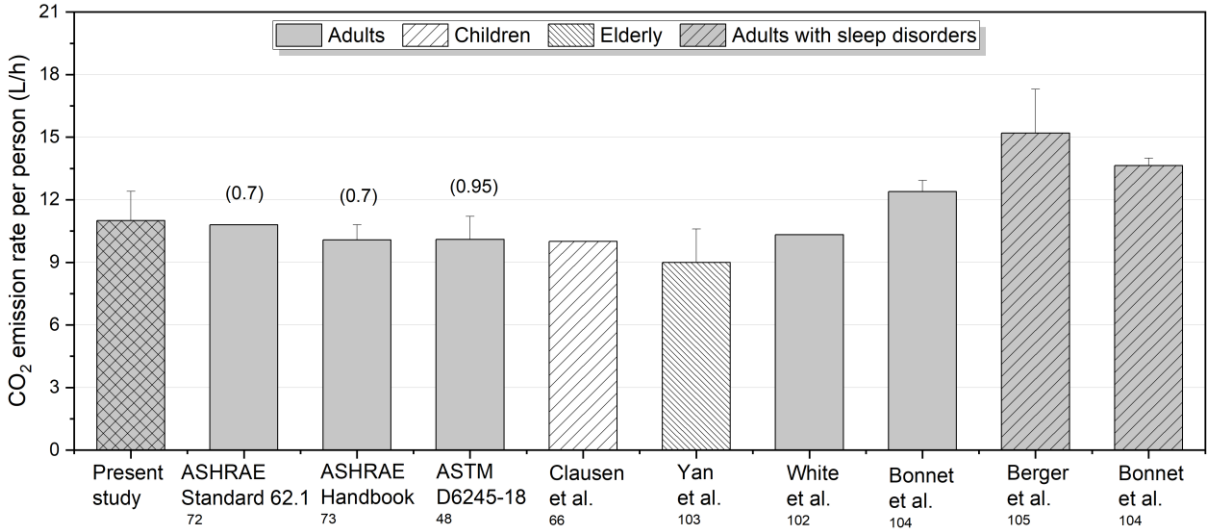


Figure 4.1 Comparisons of CO_2 emission rates measured in the Ph.D. study with those calculated from Standards and previous studies. (MET) presents the metabolic rate (in met) selected when calculating CO_2 emission rates. (Respiratory Quotient was 0.83 in ASHRAE standards and 0.85 in ASTM D6245-18).

The measured CO_2 emission rates were also compared with those calculated using the empirical equations in ASHRAE 62.1 [72], ASHRAE Handbook [73], and ASTM D6245-18 [49]. The results were similar with differences in the range of 2-8% (Figure 4.1). Two recent chamber studies measured the CO_2 emission rates while sleeping from elderly subjects [103] and from children [66]. The mean CO_2 emission rate was 9.0±1.6 L/h per person for the elderly and 10 L/h per person for children aged 10-12, both values lower than was found in the present study.

A higher CO_2 emission rate than estimated in this work was measured in two studies (Figure 4.1). One focused on the effects of fragmented sleep on metabolic rate [104] while the other focused on patients with obstructive sleep apnea [105]. Some of the discrepancies in measured CO_2 emission rates could therefore be explained by fragmented sleep and sleep disorders.

Although small, there were some gender differences: The mean CO_2 emission rate was 11.6±1.0 for males and 10.7±1.5 L/h per person for females. Similar gender differences were reported in previous studies (Figure 4.2) of the effects of age and of sleep problems

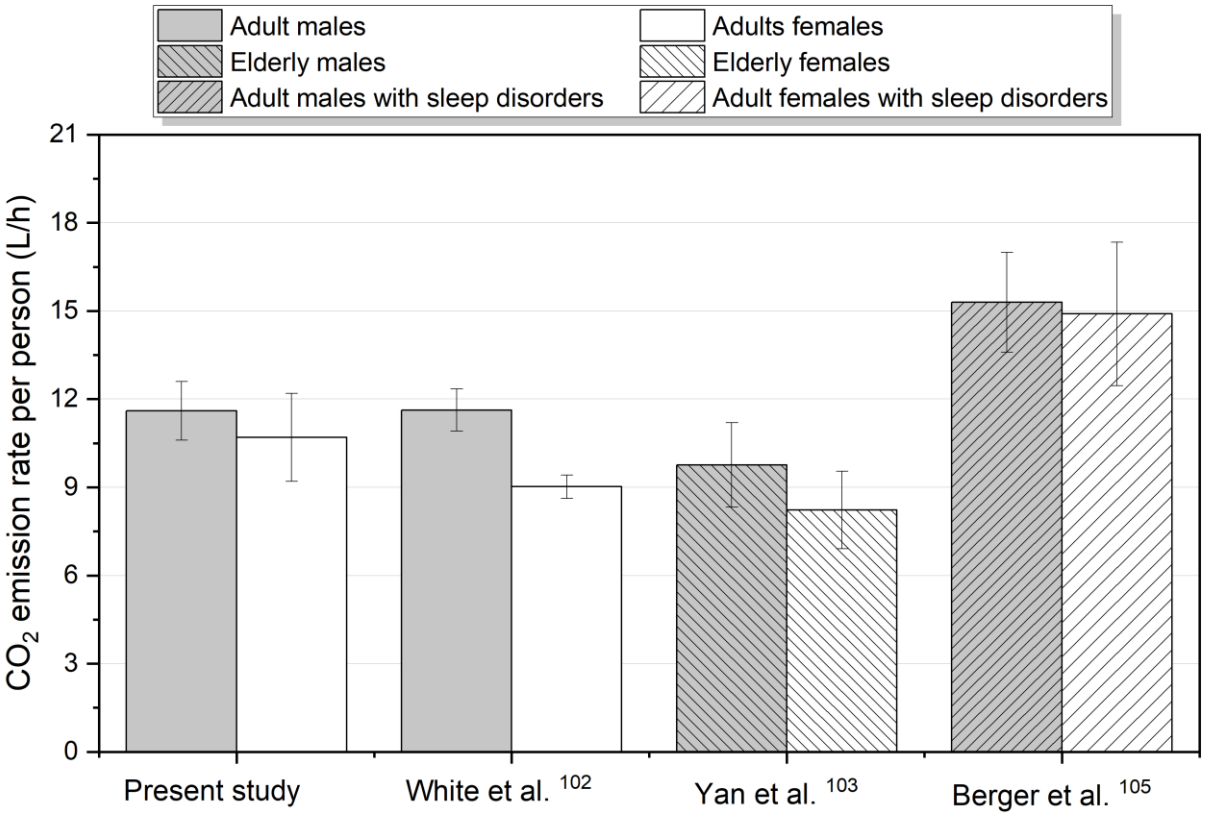


Figure 4.2 The CO_2 emission rates measured in the Ph.D. study and in the previous studies by sex.

One limitation of this study is that the participants all had BMI values in a narrow range (18.5-24.9 kg/m^2). The CO_2 emission rates from people with different BMI values could

be different since it is a function of body size and composition, as discussed in Paper I and in previous studies [63].

The CO_2 emission rates did not change when outdoor air supply rate was reduced so that the resulting CO_2 concentrations increased from 800 to 1,700 ppm. Similar results were reported by Yan et al. who observed that the CO_2 emission rates from the elderly did not change when the outdoor air supply rate decreased so that the CO_2 concentration increased from 763 ppm to 1,229 ppm [103]. However, some effects of IAQ on emission rates have been reported for subjects who were awake [67,106–108]. One plausible explanation is that the respiratory pattern of the sleeping participants in the present study did not change between conditions.

Research question 4: What is the bedroom ventilation rate that would avoid disturbing sleep quality?

Answer: The results from the present study were insufficient to determine the dose-response relationship between bedroom ventilation and sleep quality, but together with previously published data, the present study was able to recommend a ventilation rate of > 10L/s per person.

Justification and limitations: In the present study it was not possible to derive a relationship between bedroom ventilation and sleep quality. However, the tentative relationship proposed by Sekhar et a. [28] and Akimoto et al. [29] was to some extent confirmed and extended. Figure 4.3 and Table 4-3 summarize the findings from previous studies of the effects of bedroom ventilation on sleep quality, including the results from the present study. It shows that the lowest-observed-adverse-effect level of CO_2 is 1,000 ppm, which corresponds to an outdoor air supply rate of 6 L/s per person when the CO_2 emission rate while sleeping is assumed to be 11 L/h per person.

However, it is still unclear what the no-observed-adverse-effect ventilation rate should be since no studies have yet investigated the effects of bedroom ventilation on sleep quality at CO_2 concentrations below 1,000 ppm. Sekhar et al. and Akimoto et al. proposed that when the CO_2 concentration is lower than 750 ppm, sleep quality will not be affected [28,29]. Although there are two studies showing the trend of the change in sleep quality when reducing bedroom ventilation, there is no solid evidence to reject the proposed 750 ppm. Taking account of experimental errors due to the accuracy of the CO_2 sensor and incomplete air mixing in bedrooms, it is reasonable to assume that there should be certain range of CO_2 (below 1,000 ppm) in which sleep quality is still affected. We proposed 200 ppm in the field study in Denmark. This would imply that the no-observed-adverse-effect ventilation rate should be > 10 L/s per person (Figure 3.3), a rate that would keep the CO_2 concentration below 750 ppm to ensure no disturbance to sleep. This should be validated in future studies.

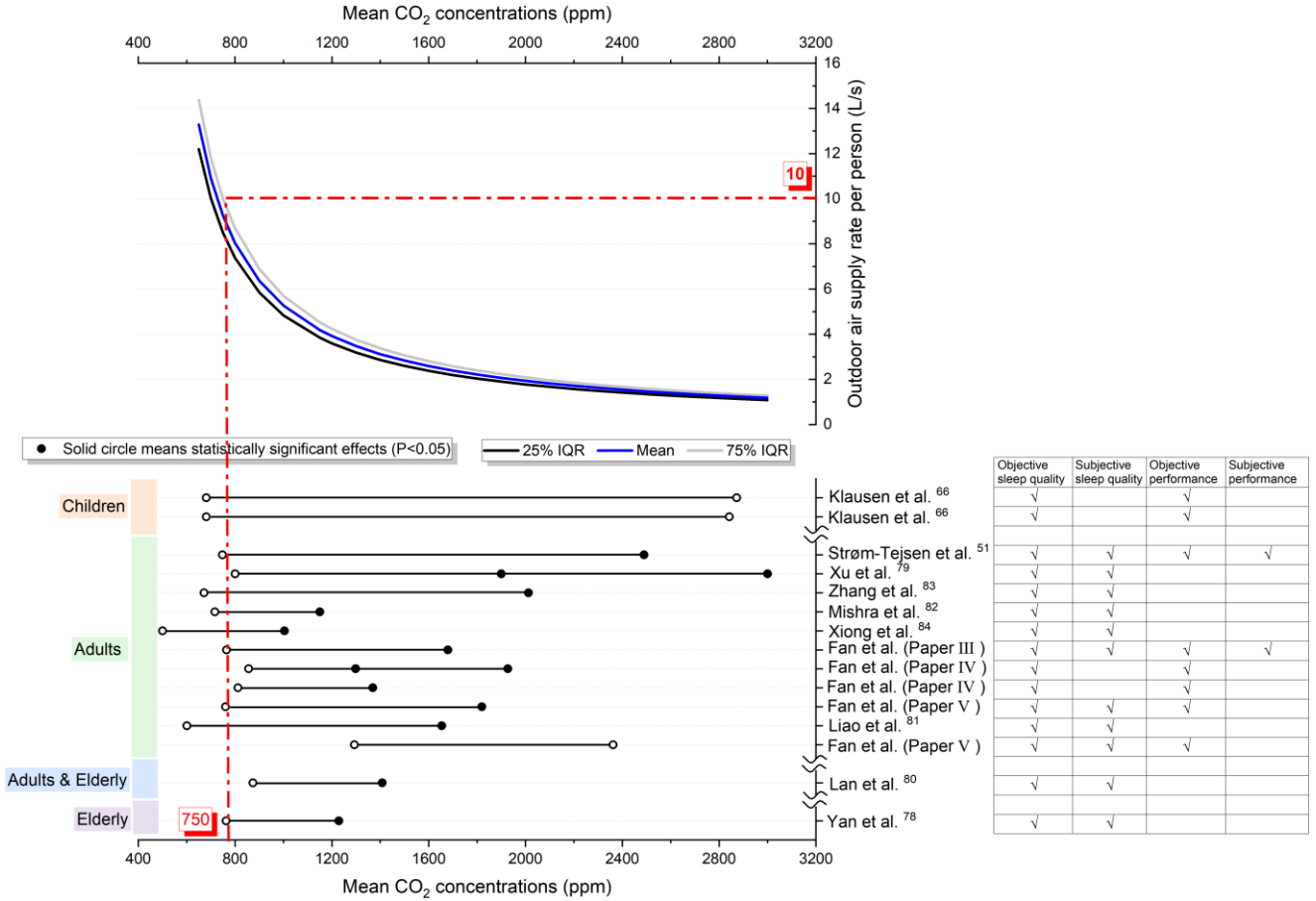


Figure 4.3 Summary of available studies examining the effects of bedroom ventilation (IAQ) on sleep quality and next-day cognitive performance. The table shows the measured outcomes in the present experiments and in relevant studies. Estimated minimum bedroom ventilation rates per person required during sleep at different levels of indoor CO_2 concentration under steady state are presented as well. The IQR of the measured CO_2 emission rates and their mean value were used.

Table 4-3 Ventilation conditions and outcomes of the studies examining the effects of bedroom ventilation on sleep quality.

Ref.	Country	Sample size	Age (y)	Context	Ventilation system	Season	Sleep quality		Next-day cognitive performance	
							Objectively measured	Subjective rated	Objectively measured	Subjectively rated
51 [a]	Denmark	30	20-30	Bedrooms	MV+NV [c]	Autumn, winter	Lower sleep efficiency. Longer sleep onset latency.	Sleepier	Reduced performance of Baddeley test	Less able to concentration next day
79 [a]	China	12	24 ± 1	Laboratory	MV	Summer	Longer Sleep onset latency. Shorter deep sleep.	Poorer sleep quality		
83 [b]	China	104	29.0 ± 11.4	Bedrooms	NV [d]	Spring, Autumn	Lower sleep efficiency. Longer wake after sleep onset.	Poorer sleep quality		
82 [a]	Netherlands	18	21-27	Bedrooms	NV [d]	Winter	Lower sleep efficiency. More number of awakenings.	Less depth of sleep		
84 [b]	Australia	48	36 ± 12	Bedrooms	--	Summer	Shorter deep sleep.	Poorer sleep quality		
Paper III [a]	Denmark	11	28.3 ± 4.1	Laboratory	MV	Summer	Longer sleep onset latency.			Poorer next-day performance
78 [a]	China	16	72 ± 6	Laboratory	MV	Summer	Shorter REM sleep, Shorter deep sleep.			
80 [a]	China	18	24±2, 70±5	Laboratory	MV	Spring, summer	Longer wake after sleep onset. Lower sleep efficiency. Shorter deep sleep.			
Paper IV [a]	Belgium	12	27-64	Bedrooms	MV	Autumn	Longer light sleep. More number of awakenings.			
		23	27-64				Shorter deep sleep			
Paper V [a]	Denmark	16	33±15	Bedrooms	NV [c]	Autumn, winter	Shorter sleep duration.			
81 [a]	Belgium	27	20-33	Laboratory	NV [c]	Spring	More snoring. more number of awakenings.			
Paper V [a]	Denmark	13	28±3	Bedrooms	NV [e]	Autumn, winter				
66 [a]	Denmark	36	10-12	Laboratory	MV MV	-- --				

[a] Intervention studies in the laboratory or in actual bedrooms.
[b] Cross-sectional studies.
[c] Windows opening.
[d] Windows and/or doors opening.
[e] Doors opening.

Although there are many ventilation and IAQ standards and guideline currently in use nationally and internationally, only a few stipulate ventilation rates specifically for bedrooms, as noted by Sekhar et al. [28]; most standards and guideline do not differentiate between ventilation requirements for various rooms in dwellings based on their use, for instance ASHRAE standard 62.2 [47]. Even so, it is likely that these bedroom ventilation requirements do not consider the health effects of bedroom ventilation. Bedroom ventilation is merely the result of ventilation requirements for the entire dwelling [28]. In fact, rooms with different functions in dwellings have different pollution patterns and occupancy that may require different ventilation strategies and rates, which is seldom the case in commercial buildings (non-residential buildings). For example, the kitchen should be ventilated with high ventilation temporarily when cooking since cooking oil fumes affect human health [57]. It would be useful to update current standards and guideline in dwellings based on room function while considering health effects.

One limitation of this work is that recommendation on bedroom ventilation is made assuming that no strong pollution sources are present in bedrooms. Another limitation is that we do not know which indicators of sleep quality are more important than others, or whether the magnitude of the effects on subjectively rated and objectively measured sleep quality are comparable. Previous studies have only shown the consistency of subjective and objective metrics of sleep quality [82].

Research question 5: What are the ventilation rates in actual bedrooms during sleep?

Answer: The median ACH (IQR) in 80 typical bedrooms in Denmark was estimated to be 0.4 (0.2-0.9) h^{-1} during sleep in the heating season.

Justification and limitations: The median ACH in bedrooms during sleep was estimated to be 0.4 h^{-1}, which is similar to what was measured in 500 bedrooms in Denmark [42]. A greater proportion of the 500 bedrooms had a high ventilation rate than was found in the present study. This may be because they were all children' bedrooms. Similar ACHs were also found in bedrooms in Sweden [109], France [110] and China [40,41]. However, Bekö et al. observed a high ACH in 56 Danish bedrooms: the median ACH was 1.2 h^{-1} [111]. Half of the bedrooms in the present study did not meet the minimum ventilation rate of 0.4 h^{-1} prescribed by EN16798-1, and only 33% met the highest recommended minimum ventilation rate of 0.7 h^{-1}. These findings emphasize the urgency and importance of improving bedroom ventilation.

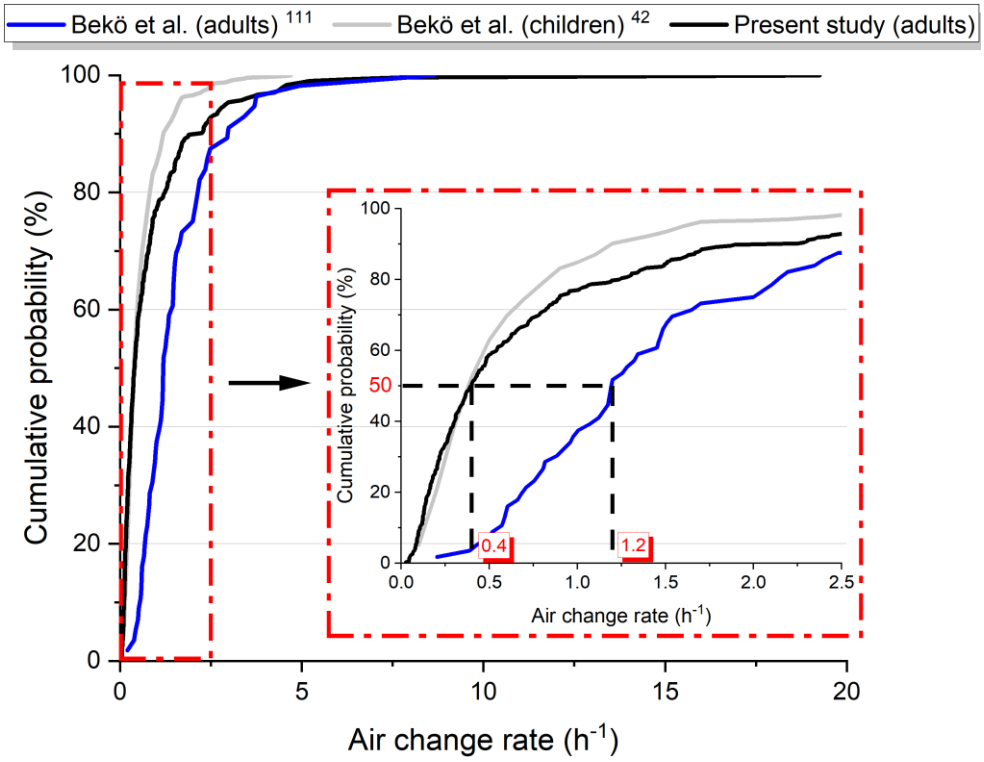


Figure 4.4 Comparisons of the estimated ACHs in bedrooms in the present study with those in previous studies conducted during the heating season in the same region [42,111], with an expanded view of ACH <2.5 h^{-1}.

The present research supplements current knowledge of ventilation rates in bedrooms and will thus help to facilitate the establishment of bedroom ventilation standards. One limitation of the data is that the calculation method used here can only estimate the total airflow into the bedrooms, including airflows from other functional rooms in dwellings – the ACHs were calculated using decay of human metabolically produced CO_2.

The ventilation rate value recommended for bedrooms in this dissertation is the outdoor air supply rates, which means that the pollution concentrations in the measured bedrooms could be even worse. In addition, this work was conducted during the heating season in Denmark when the outdoor temperature is generally low. The airflows and airing behaviour of the participants (opening windows and doors) may differ from other seasons, leading to different bedroom ventilation rates [37,39]. Previous studies have shown that the ventilation rates in bedrooms differ between seasons, especially that in the summer periods the bedroom ventilation rates are higher than in winter [41]. Future studies in other seasons are required to make it possible to derive ventilation rates in bedrooms that are representative of occupants' long-term exposure to pollutants.

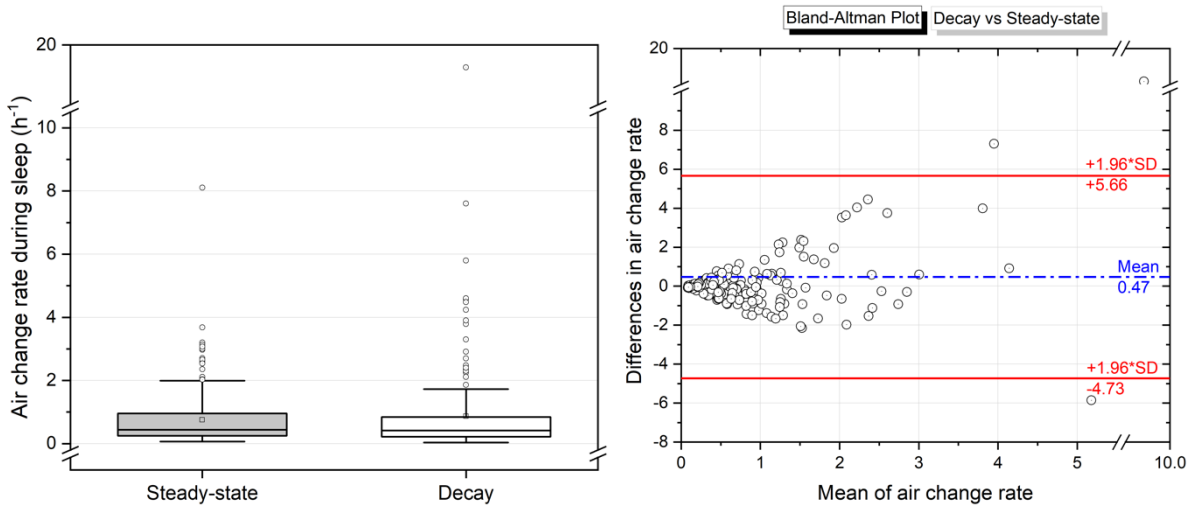


Figure 4.5 (A) Estimated ACHs using decay and steady-state methods, and (B) Bland-Altman plot for the ACHs of decay and steady-state methods. A Bland-Altman plot is a graphical method to determine whether two different methods can be used interchangeably [112].

Another limitation is that the estimations of ACHs were made using the CO_2 decay assuming that the ACHs were the same as during sleep, as the bedroom settings were kept unchanged (window and door status unchanged). To check this limitation, the ACHs were estimated in bedrooms using the CO_2 emission rate of 11 L/h per person during sleep and using the 95th percentile of the CO_2 concentration. Median ACH was not different from the decay method (Figure 4.5). Because the methods agreed, this may suggest good applicability of CO_2 emission rates in ACHs estimation in bedrooms during sleep, although this requires further investigation.

Research question 6: How can bedroom ventilation that is beneficial for sleep quality be achieved without mechanical ventilation systems?

Answer: The present study shows that clean outdoor air should be used for bedroom ventilation as window opening improved sleep quality but opening an internal door did not.

Justification and limitations: For bedrooms without mechanical ventilation systems, natural ventilation augmented by opening windows and doors is the only way to increase bedroom ventilation. Window opening is recommended to improve bedroom ventilation because sleeping with the window open improves bedroom IAQ and benefits sleep quality. No such effects can be expected when an internal door is left open.

Many factors can reduce the desirability of opening a window so most people prefer to sleep with the window closed [33,42,83,87,113]. One is that opening a window may allow noise from outdoors, i.e., transportation noise, to become more audible in a bedroom and that this may negatively affect sleep quality [114–117]. Another is the possible effects on room temperature, especially in winter, when opening a window may decrease the

bedroom temperature and thereby reduce sleep quality [22,78,118–120]. Window opening may also allow the penetration of light, especially the daylight in the morning, that also reduces sleep quality [93,121]. Another disadvantage is that outdoor pollutants may enter bedrooms through an open window and reduce sleep quality [50]. All these negative effects on sleep quality may offset the benefits of increasing bedroom ventilation. In the present study, these confounders were to some extent controlled by the experimental design.

Taking the above limitations into considerations, ventilation systems that supply conditioned air or clean outdoor air into bedrooms and remove air pollutants from bedrooms seem to be the most appropriate solution.

One limitation of the present research is that the participants knew about the intervention made. This could bias their responses (a Hawthorne effect) [82]. As the openings of windows or doors is commonly assumed to improve bedroom ventilation, the participants who generally opened a bedroom window or door may have expected that this would produce a positive effect. On the other hand, the many participants who generally slept with a bedroom window or door closed may have had the opposite expectation, removing or at least reducing the bias due to the Hawthorne effect.

Research question 7: Is CO_2 a good indicator of bedroom ventilation rate and IAQ?

Answer: CO_2 is a good indicator of IAQ only if pollutants other than human emissions are absent.

Justification and limitations: Reduced CO_2 concentration indicates increased bedroom ventilation, but it does not always mean improved bedroom IAQ. In the chamber study, when the ventilation rate was reduced, CO_2 and TVOCs increased, and subjects rated the air stuffier. Similar results were seen in the field intervention study in Belgium. In these studies, CO_2 is a good marker of bedroom ventilation and IAQ since the sleeping places were ventilated with outdoor air or conditioned air and no other strong pollution sources were present. If the outdoor air supply rates are reduced in bedrooms, the CO_2 concentration will increase along with the concentration of other pollutants generated indoors [54].

In the field intervention study in Denmark, opening windows or doors significantly reduced the CO_2 concentration during sleep, which is conventionally interpreted to indicate that in both cases bedroom ventilation and IAQ improved. However, the objectively measured and subjectively rated bedroom IAQ was improved only when the windows were open, not when the internal doors were open. The reduced CO_2 concentrations measured when the internal doors were open imply that air from adjacent rooms of the dwelling entered the bedrooms although this could not be documented by the limited measurements made. The CO_2 concentration of this air was low during the sleep period, as other spaces in dwellings were not occupied, and consequently the

bedroom CO_2 concentration was reduced. However, there were no improvements in IAQ in this case. This may be because other air pollutants were transported into the bedrooms by the air entering from other parts of the dwellings. CO_2 is thus not a good metric of IAQ in this case. To characterize bedroom IAQ better, the concentrations of as many pollutants as possible should be measured, together with the CO_2 measurements.

4.2 General Limitations

This dissertation research comprehensively investigated bedroom ventilation and its effects on sleep quality and next-day cognitive performance. Although the results are either cross-verified or compatible with data published in previous studies, they still have some limitations. One important limitation is the small sample size, especially in the climate chamber studies, in which only 11 subjects participated. Running sleep studies is not only time-consuming and costly but it is also difficult to recruit subjects. In the field invention study in Belgium, the recruitment invitation was sent to several thousand potential participants but fewer than 10% responded, and only 34 met the selection criteria. To supplement the statistical significance analysis, the effect size was calculated in the present study to show the practical implication of the outcomes.

Another limitation is that only healthy adults without sleeping disorders were recruited. They are not representative of the entire population. Previous studies have shown that the elderly have worse sleep quality than that of younger occupants [80]. The findings of this dissertation will have to be extended by recruiting larger groups of people, including participants of different ages and people with sleeping disorders in future studies.

The results in the present work are based on either one-night measurements in the climate chamber studies or one-week measurements in the field studies under each experimental condition. No repetitions were made, nor were longer exposures monitored.

Some factors could not be controlled. For example, psychological factors, including life stress, depression, mood and anxiety symptoms, have been shown to be associated with sleep dissatisfaction [3]. Also, the sociodemographic factors (i.e., income, education level, and state of residence) were not considered, nor potential disturbance of sleep quality by any other persons who shared the bedroom with the participant. Future studies should consider how to control these external factors. However, it seems likely that poor bedroom IAQ would exacerbate these negative effects.

4.3 Practical implications

The practical implications of the present dissertation research are as follows:

- Bedrooms should be well ventilated (> 10 L/s per person) to avoid reduced sleep quality.
- Existing bedrooms should be retrofitted to increase ventilation and improve IAQ.
- When bedrooms are not mechanically ventilated, window opening is a good way to improve bedroom ventilation, while opening an internal door is not.
- CO_2 concentration can be generally used as an indicator of bedroom ventilation and IAQ but should not be used when the air entering bedrooms is polluted.
- Assumed CO_2 emission rates of 11 L/h per person while sleeping can be used to estimate bedroom ventilation rates and can be integrated into algorithms for the operation and control of bedroom ventilation systems that use measurements of CO_2 concentration as a control feedback signal.
- Increasing bedroom ventilation improves sleep quality and next-day cognitive performance, both having economic implications [9].

4.4 Recommendations for future studies

Future studies avoiding the limitations identified in the present work are recommended, such as studies with more diverse subjects and measurements in actual bedrooms in different seasons. It will help to reproduce and extend the applicability of the findings from this Ph.D. thesis. Other recommended studies for future are as follows:

- A bedroom ventilation rate that would avoid any reduction of sleep quality was recommended in this Ph.D. thesis. Future studies are needed to further investigate and validate the observations since the no-observed-adverse-effect bedroom ventilation rate is still unknown.
- More measures to improve bedroom IAQ for good sleep quality should be explored. One way is to retrofit existing bedrooms by installing mechanical ventilation systems to supply clean outdoor air. Another way is to use air cleaners and purifiers that produce air equivalent to clean outdoor air. How these methods will affect bedroom IAQ and sleep quality and what their energy costs would be should be determined. Improved bedroom environmental quality that ensures good sleep quality and better next-day performance should be able to justify the increased energy costs.
- The world is currently facing two global crises: the pandemic and climate change. The former has focused attention on the importance of ventilation while global warming has focused attention on energy conservation and the effects of raised temperatures. This Ph.D. thesis has investigated the ventilation of bedrooms but has also documented that increased temperatures in bedrooms can negatively

affect sleep quality. How climate change would affect sleep quality should be addressed in the future studies.

- Previous studies have shown that sleep loss can cause large economic costs in terms of reduced GDP due to reduced labour productivity [9]. It is still unknown what the economic burden of poor sleep quality would be when caused by inadequate bedroom ventilation and other bedroom environmental quality factors.
- There is not yet enough published data for a consensus on how bedroom ventilation affects next-day cognitive performance. Very few studies have investigated the effects of thermal conditions in bedrooms on next-day cognitive performance [76]. Future studies should closely address this subject and try to identify the mechanisms causing any observed effects.
- With this Ph.D. thesis, bedroom thermal, visual, acoustic, and IAQ environments were investigated separately. However, we sleep in bedrooms where all these aspects could affect our sleep quality concurrently. How they interact and affect sleep quality should be studied.
- CO_2 can be used as a marker of bedroom ventilation and IAQ, but it is not always reliable. Additional markers are needed to better characterize bedroom ventilation and IAQ.
- Only one recent study explored whether CO_2 affects sleep quality and it found that exposure to increased CO_2 concentration by dosing the supply air with pure CO_2 did not affect children's sleep quality [66]. Future studies are needed to investigate this further.
- CO_2 is one of the products of human metabolism. There are many other products. Previous studies have made chemical measurements to identify the pollutants emitted by people when they are awake [122,123], but there has been no such study of emissions from people who are asleep. This should be measured in future studies.
- Epidemiologic studies have established associations between multiple air pollutants and sleep quality. The indoor air pollutant(s) in bedrooms that have negative effects on sleep quality should be identified in future research.
- Many models available in the literature can be used to predict thermal comfort based on measurements and perceptions, but these are all based on data from people who were awake. During sleep, we cannot provide feedback to express our thermal sensation, making it impossible to obtain subjective estimates of thermal comfort in real time. Future studies could try to determine whether thermal comfort ratings obtained retrospectively, after waking, are valid.

5 Conclusions

This dissertation presents the results of studies examining bedroom ventilation and its effects on sleep quality and next-day cognitive performance. Sleep quality was measured objectively by wrist-worn sleep trackers and subjectively through questionnaires. Bedroom IAQ was monitored objectively with sensors and was subjectively rated by the participants. The main conclusions are as follows:

- Existing bedrooms are poorly ventilated. The bedroom median ACH during sleep was 0.4 h^{-1}, corresponding to the lowest minimum ventilation requirement prescribed by EN16798-1.
- Increased bedroom ventilation improves IAQ in bedrooms during sleep. When bedroom ventilation was increased by increasing fan speed in the mechanical ventilation system or by opening a window, the measured concentrations of air pollutants were reduced (CO_2, TVOCs, $PM_{2.5}$ and $PM_{2.5}$) and subjectively rated air quality was improved (increased perceived air freshness, reduced odour intensity and improved perceived air quality).
- Increasing the bedroom ventilation reduced the CO_2 concentration, but this does not mean that the IAQ in the bedrooms was improved to the same extent. The air that enters bedrooms can not only remove the air pollutants originating in bedrooms but can also transport contaminants that negatively affect sleep quality from the surroundings into bedrooms. When an internal door was open, the bedroom ventilation increased, resulting in reduced CO_2 concentrations, but no improvements in IAQ were observed, either by objective measurements or by subjective perceptions. Bedroom IAQ should therefore be characterized by measurements as much as possible.
- Poor bedroom ventilation negatively affects sleep quality. When bedroom ventilation was reduced, several different sleep quality indicators were negatively affected: longer sleep onset latency, reduced time spent asleep, shorter duration of deep sleep, more awakenings, reduced subjective sleep quality, and poorer self-reported sleep quality.
- Bedroom ventilation may have an effect on next-day cognitive performance. The indirect evidence suggests that the next-day cognitive performance is negatively affected after sleeping in a poorly ventilated bedroom. However, no direct results showing that increased bedroom ventilation provides benefits to cognitive performance were obtained.
- The ventilation rate for bedrooms should be > 10 L/s per person, which would avoid any negative effects on sleep quality. This value was estimated by assuming the measured CO_2 emission rate of 11 L/h per person during sleep.

- Natural ventilation achieved by opening a window is recommended to improve bedroom ventilation if there are no other ways available. Sleeping with the window open improved bedroom IAQ and provided benefits for sleep quality. No such effects were seen when sleeping with an internal door open.
- The present results were obtained for healthy and mainly young adults, so they need to be verified for other groups, especially for people with sleep disorders. They were obtained in a region with a temperate climate and during the heating season in places where outdoor pollution is low. Extension of this research to other climates and regions with higher outdoor air pollution and to periods outside the heating season is required.

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Emission rate of carbon dioxide while sleeping

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Abstract

Humans emit carbon dioxide (CO_2) as a product of their metabolism. Its concentration in buildings is used as a marker of ventilation rate (VR) and degree of mixing of supply air, and indoor air quality (IAQ). The CO_2 emission rate (CER) may be used to estimate the ventilation rate. Many studies have measured CERs from subjects who were awake but little data are available from sleeping subjects and the present publication was intended to reduce this gap in knowledge. Seven females (29 ± 5 years old; BMI: 22.2 ± 0.8 kg/m^2) and four males (27 ± 1 years old; BMI: 20.5 ± 1.5 kg/m^2) slept for four consecutive nights in a specially constructed capsule at two temperatures (24 and 28°C) and two VRs that maintained CO_2 levels at ca. 800 ppm and 1700 ppm simulating sleeping conditions reported in the literature. The order of exposure was balanced, and the first night was for adaptation. Their physiological responses, including heart rate, $pNN_{50,}$ core body temperature, and skin temperature, were measured as well as sleep quality, and subjective responses were collected each evening and morning. Measured steady-state CO_2 concentrations during sleep were used to estimate CERs with a mass-balance equation. The average CER was 11.0 ± 1.4 L/h per person and was 8% higher for males than for females ($P < 0.05$). Increasing the temperature or decreasing IAQ by decreasing VR had no effects on measured CERs and caused no observable differences in physiological responses. We also calculated CERs for sleeping subjects using the published data on sleep energy expenditure (SEE) and Respiratory Quotient (RQ), and our measured CERs confirmed both these calculations and the CERs predicted using the equations provided by ASHRAE Standard 62.1, ASHRAE Handbook, and ASTM D6245-18. The present results provide a valuable and helpful reference for the design and control of bedroom ventilation but require confirmation and extension to other age groups and populations.

KEYWORDS
human CO_2 emission rates, physiological responses, sleeping conditions, temperature, ventilation

1 | INTRODUCTION

Occupants are one of the many pollution sources in buildings and are sometimes even a major source of pollution.[1] The abundant pollutant emitted by humans is carbon dioxide (CO_2), a human metabolism product. In the absence of other markers, its concentration indoors is frequently used as an indicator of the ventilation rate (VR) (when occupants are present)[2] and the degree of air mixing (ventilation efficiency) as well as indoor air quality (IAQ). Poor IAQ as indicated by a high CO_2 concentration has been shown to affect sleep quality and consequently next-day work performance.[3–5] An increasing number of studies link bedroom ventilation to sleep quality.[3–7] A knowledge of the CO_2 emission rate (CER) of sleeping occupants is necessary when estimating bedroom ventilation rate from the measured CO_2 concentration, to determine whether the bedroom ventilation is adequate.

Many published studies have determined CERs and the factors affecting them,[8–14] but in most of these studies, the subjects were awake. It was found that CERs were affected by physical activity level,[8] age,[8,14] and sex[8,14] as expected. Recently, it has also been shown that CERs can be affected by environmental factors[9–13] such as temperature causing thermal discomfort and poor IAQ documented by the elevated levels of CO_2. With regard to sleeping people, there is, however, very little published information on the CER; most studies, whose results were analyzed later in the present paper, reported only sleep energy expenditure (SEE); only three studies reported CERs of subjects who were asleep.[15–17] White et al,[15] investigated the relationship between metabolic rate and breathing during sleep. They found that the CER was 11.6 ± 0.7 L/h per person and 9.0 ± 0.4 L/h per person for healthy males and females, respectively, and that they were closely linked to respiratory ventilation. Bonnet et al[16] tested the effects of fragmented sleep on metabolic rate. The reported CER from healthy subjects who were asleep was 12.4 ± 0.5 L/h per person. CERs were slightly higher during fragmented sleep compared with that during normal sleep, which could be due to elevated activity-induced energy expenditure (EE) during fragmented sleep. The CER during recovery sleep after fragmented sleep was similar to the value obtained during normal sleep. Berger et al,[17] measured the acute kinetics of CO_2 accumulation and CO_2 elimination during sleep in patients with obstructive sleep apnea and addressed interapnea ventilatory compensation for the maintenance of CO_2 homeostasis during periodic breathing. They reported that the CER from sleeping subjects was 15.3 ± 1.7 L/h per person and 14.9 ± 2.4 L/h per person for males and females, respectively.

Different methods have been developed for estimating CER. It is typically derived from metabolic rate using an empirical equation provided by the ASHRAE Handbook in the field of indoor environment.[18] In other fields, i.e. in medicine, the gas exchange method is adopted to determine the CER by measuring the difference between inspired and expired CO_2 volume.[19] This is the basis of the indirect calorimetry method, which has been regarded as the gold standard by which EE is accurately calculated from respiratory gas exchange measurements and urinary nitrogen excretion in a respiratory chamber.[20] It also measures whole-body oxygen consumption (V_{O2}) in addition to CER, both being converted to a caloric equivalent EE according to the equation developed by Weir (1949)[21]:

$$EE = (3.94 * V_{o2}) + (1.1 * CER). \quad (1)$$

The respiratory quotient (RQ), which is the ratio of CER/V_{O2}, can be used as an indicator of substrate use since different pathways are used for fats, carbohydrates, and proteins.[19] Consequently, CER can be calculated from the following equation:

$$CER = \frac{EE}{(3.94/RQ) + 1.1}. \quad (2)$$

In practice, CER is generally derived from the physical activity levels according to the empirical equations given by ASHRAE standard 62.1[22] and ASTM D6245-18.[23] The former shows the relationship between the CER and metabolic rate, while the latter is based on the study of Persily and Jonge,[14] who summarized the methods used to estimate CER in the past and proposed a new approach to estimate the CER for different age and sex groups and physical activity levels that were based on human metabolism and exercise physiology. Using the activity level for sleep, the CER from sleeping occupants can be estimated. Finally, CER during sleep can also be estimated by performing measurements of CO_2 under controlled environmental conditions during sleep.

The primary objective of the present study was to measure CER from sleeping people. The measured CERs were then compared with CERs estimated using published data on SEE; the studies reporting SEE were identified and reviewed. Furthermore, considering that the thermal conditions and IAQ affect CER for awake people, as described above, we also explored whether CER from sleeping people was influenced by these parameters.

Practical Implications

- The CO_2 emission rate from sleeping people was determined in the present paper.
- The determined CO_2 emission rate can be used to estimate ventilation rates in bedrooms based on the measurements of CO_2 concentrations. This applies to estimating outdoor air supply rates and the total dilution level obtained by the outdoor air and air from the other rooms in dwellings.
- Furthermore, the CO_2 emission rate from sleeping people can also be used in algorithms for demand control ventilation in bedrooms based on the measured CO_2 concentrations.

2 | METHODS

2.1 | Facilities

A special sleep capsule was designed with the dimensions 2.4 × 1.1 × 0.9 m to create a space for the subjects to sleep in. It was constructed from transparent reinforced acryl plates attached to aluminum rails (Figure 1); sealing on both the inside and outside was achieved with aluminum tape. A door to the capsule was installed on one side. The capsule was installed in a stainless-steel climate chamber[24] that provided control of thermal conditions and air quality indicated by CO_2 concentration inside the capsule.

The schematic diagram of the sleep capsule is shown in Figure 1A. The capsule consisted of two volumes divided by a partition consisting of an acrylic plate in the lower part and open mesh in the upper part (the length of the mesh was within 20 cm off the ceiling of the capsule). The larger volume was used for sleeping (2.2 × 1.1 × 0.9 m) and the smaller one as a plenum for the air used to ventilate the occupied section of capsule (0.2 × 1.1 × 0.9 m). On the exterior wall opposite the plenum, a round opening was made in the lower part. A flexible exhaust duct connected this opening to the outside of the stainless-steel climate chamber, where extract fans were installed at the end of the duct to ensure the airflow in the capsule as stable as possible; to reduce the noise, a silencer was mounted upstream of the fans.

The sleeping arrangement inside the capsule consisted of a mattress (1.98 × 0.79 × 0.12 m), a cotton quilt (1.88 × 1.20 × 0.03 m), a pillow (0.56 × 0.38 × 0.11 m), bedclothes and a table lamp. The bedclothes together with the pajamas and towels were cleaned every day using fragrance-free washing powder.

A sensor connected to an alarm was installed inside the capsule in case the concentration of CO_2 should increase above 5000 ppm (due to failure of the ventilation system); the alarm was never activated during the experiments.

The capsule was ventilated by the air in the stainless-steel climate chamber. The chamber was equipped its own ventilation system, which has the upward airflow with low velocity that is similar to the displacement ventilation principle—filtered and conditioned air

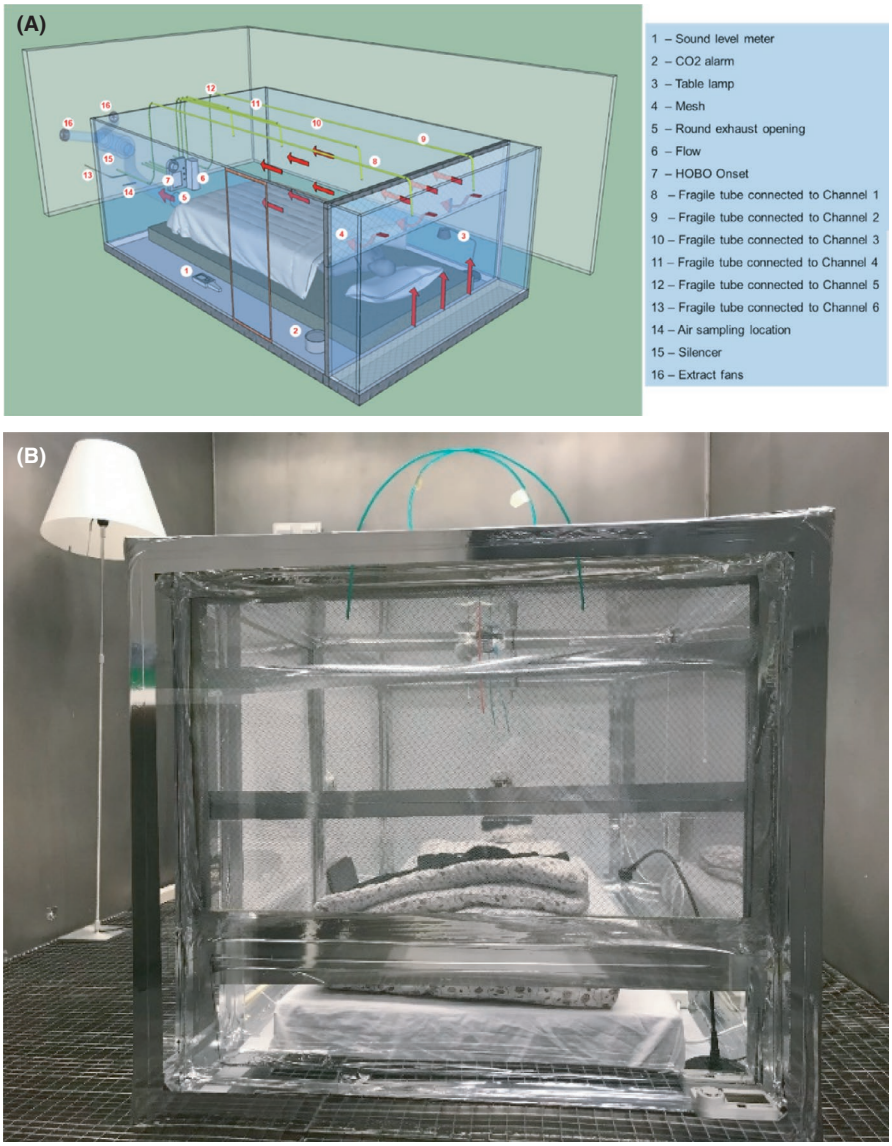

FIGURE 1 (A) A schematic diagram of the capsule (the red arrows show the airflow); (B) A snapshot of the empty capsule

was supplied into the underfloor plenum and entered the chamber through a perforated floor beneath a stainless-steel grid.[24] The air in the climate chamber was exhausted through four outlets in the ceiling. The climate chamber air entered the capsule through the plenum which, as mentioned earlier, was exhausted through a flexible duct with extract fans. No mixing fans were installed inside the capsule, but a fairly uniform CO_2 concentration in the capsule was obtained as documented by measurements of CO_2 at different locations when a subject was sleeping in the capsule (Figure 2).

Before the experiments with each new subject, the chamber was cleaned and "baked" by keeping the temperature in the stainless-steel climate chamber at 40°C. The capsule together with the equipment used was sanitized to conform to the COVID-19 pandemic regulations currently in force; the experiments were carried out in Denmark from June to August 2020.

2.2 | Experimental conditions

Three conditions were established (Table 1), consisting of two air temperatures and two levels of IAQ indicated by two CO_2 concentrations. The temperatures were 24°C (T24) and 28°C (T28). They represent a neutral and a warm thermal environment during sleep. T24 is within the temperature range recommended by EN16798-1,[25] and T28 is above this range. Both are within the range of temperatures measured in actual bedrooms according to two recent reviews.[5,26] CO_2 concentrations of 800 ppm (P800) and 1700 ppm (P1700) to represent two levels of IAQ were selected and established by changing the VR. (In the present study, "ppm" means ppm by volume, "ppmv"; but we write "ppm" for simplicity; the concentration expressed in "ppmv" is also called the mixing ratio.) They were both within the range of 428–2585 ppm measured in bedrooms, as summarized by two recent reviews[5,26] and represent ventilation in the highest and the lowest category of indoor environment of bedroom and office/living room, respectively, according to EN16798-1.[25] The higher concentration of CO_2 resulted from the lowest VR that could be controlled in the capsule, and the lower concentration was selected to avoid an unacceptably high level of fan noise.

The temperature set points of the chamber were all 1°C lower than the selected temperature conditions that we wanted to create in the capsule considering the heat produced by the subjects during sleep, namely 23°C at T24 and 27°C at T28. The measured temperature in the capsule during sleep reached the intended levels (Table 1).

2.3 | Subjects

Eleven college-age healthy individuals were recruited (Table 2). They were non-smokers, without chronic diseases, asthma, allergy, or hay fever; they did not take any medication or sleeping pills during the experimental period. The exclusion criteria included a history of alcohol or substance abuse, shift work, transmeridian travel within the past four weeks, body mass index (BMI) outside the normal range of 18.5–24.9 kg/m^2, and the presence of any eating, sleeping, or neurological disorders. They completed the Pittsburgh Sleep Quality Index (PSQI)[27] questionnaire, which was used to avoid recruitment of subjects with significant sleep disorders experienced during the past month; the average PSQI was 6 ± 2 indicating only slight sleep disturbance of any recruited subject over the past month. A recent survey in Denmark showed a similar average PSQI for >500 subjects.[28] The experiments were arranged to avoid the exposure of female subjects during their menstrual period.

One day before the experiments and on each experimental day, the subjects were asked to refrain from consuming caffeine and alcohol, spicy food, and intense physical activity. The subjects were instructed to avoid deodorants, perfumes, or perfumed hygienic products, to keep to a similar diet and use the same means of transport to the laboratory throughout the entire experimental session. The use of deodorants was reduced as we also carried out chemical measurements of emissions from the subjects participating in the experiments.

The subjects used pajamas selected so that they felt thermally neutral at 23°C when awake. Because the temperature at which people feel comfortable has been shown to be higher during sleep than while awake,[29] it was believed that obtaining thermal comfort when awake would also ensure thermal comfort during sleep. The subjects wore the same pajamas throughout the entire experiment.

The subjects went to bed at their preferred time and were not forced to wake up at any specified time in the morning. This was to maintain their habits and their usual circadian rhythm.

2.4 | Measurements

The air temperature and relative humidity were continuously measured and recorded every 30s by a HOBO data logger (Onset Computer Corp.) placed close to the exhaust opening in the capsule. The data logger had a built-in temperature sensor (range: 0–50°C, accuracy: ±0.21°C) and a humidity sensor (range: 1–90%, accuracy: ±2%).

The sound pressure level was measured every second with the sound level meter (B&K 2245, Brüel & Kjær, Corp., range: 16–141 dB(A), accuracy: ±0.1 dB(A)); it was placed on the floor in the center of the capsule next to the mattress.

The CO_2 concentration was measured continuously with an Innova 1412i Photoacoustic Multi-gas Monitor (Luma-Sence Technologies A/S, range: 15–15 000 ppm; accuracy: ±3% of readings). Six locations in the capsule were monitored: Two were uniformly distributed along the width of the capsule in the air plenum (channels 1–2), three were uniformly distributed along the length of the sleeping space (channels 3–5, channel 3 over the respiratory zone of subjects, channel 4 in the middle of the capsule, and channel 5 over the anterior calf of the subjects), and one was in the exhaust duct of the capsule (channel 6). CO_2 concentrations measured by channels 1, 2, and 6 were used to calculate CER. The CO_2 monitoring locations of channels 1–2 were 10 cm off the ceiling of the capsule in the plenum, which was the center of the suppling opening to the

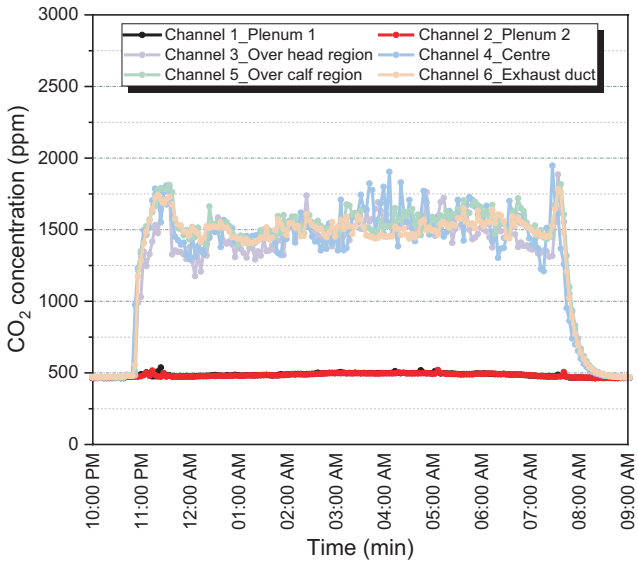

FIGURE 2 An example of measured CO_2 concentration at different locations in the capsule

capsule; and channels 3–5 were 20 cm off the ceiling of the capsule, and channel 6 was in the center of the exhaust duct.

A low-cost sensor was used to monitor NO_2, TVOCs, $PM_{2.5,}$ and PM_{10} (Flow, Plume laboratory). The accuracy of the Flow is at 90%–95% correlation with static reference monitors in benchmark tests for the core pollutants it measured as stated by Plume. (https://blog.plumelabs.com/2019/06/21/how-accurate-is-flow/). It was placed next to the HOBO data logger.

The air from the capsule was sampled on Tenax tubes in the exhaust duct before the subjects entered the capsule and toward the end of the sleeping period. The total volume of air sampled was 9.0 L, and the sampling rate was 0.3 L/min. The air sampled on the Tenax tubes was analyzed using TD-GC-MS for the VOCs present in the capsule. These measurements will be reported separately.

The core body temperature (CBT) of subjects during sleep was monitored continuously and recorded every second by a non-invasive portable sensor (CORE, greenTEG AG Inc., accuracy: ±0.26°C). The sensor was attached to the chest by adhesive medical tape. Skin temperatures on the chest, wrist, anterior thigh, anterior calf, and upper arm were recorded every minute using Pyrobuttons (DS1922L, range: 0–125°C, accuracy: ±0.2°C). The sensors were attached to the skin by adhesive medical tape. Mean skin temperature (MST) was calculated as the weighted average.[31]

Heart rate was continuously monitored using a commercial chest belt (Suunto). The measurements were also used to determine heart rate variability (HRV) by calculating the percentage of adjacent inter-beat intervals differing by >50 ms (pNN_{50}), which is an index of HRV indicating the balance between the parasympathetic and sympathetic functions of the autonomic nervous system.[31]

Sleep quality was monitored using low-cost sleep trackers including two actigraphy watches placed on the wrist (Fitbit Charge 3 and GetFit X10 pro), two finger rings (Motiv ring and Oura Heritage), an under-sheet belt (Beddit 3), and a monitor placed on the pillow (Sleepace). Sleep quality was also rated by the subjects on the Groningen Sleep Quality Scale (GSQS) each morning. These measurements will be reported separately.

The subjects filled in a sleep diary every evening and morning. They rated the indoor environmental quality in the capsule and their sleepiness. They also performed the N-back test examining working memory and the 3-min grammatical reasoning test. The tasks were presented on a PC in the adjacent chamber[24] before they went to sleep and after they woke up; they were self-paced. These measurements will be reported separately.

2.5 | Experimental protocol

A training session was completed before the exposures began, during which the subjects were familiarized with the experimental protocol, the chamber, the capsule, and the content and scales of all the sleep diaries and tasks. They practiced the cognitive tasks six times and were informed what they should do during the experiments. Physiological and sleep quality measurements were not performed, but the instruments were presented and explained to the subjects.

Each subject slept in the capsule for four consecutive nights. The first night was for adaption and the next three nights were used to study the effects of temperature and IAQ (indicated by CO_2 concentration). We did not use the measurements from the first night. The order of presentation of the conditions during the three subsequent nights was balanced across subjects to eliminate the carryover effects and systemic bias due to exposing subjects to the conditions in the same order. The condition during their first night was T24P800.

The experimental procedure is shown in Figure 3. Subjects were asked to have their last meal at least 4 h before their habitual bedtime and to arrive at the laboratory at least 2 h before their habitual bedtime; the latter was determined by recording the sleep-wake cycle using a wrist-actigraphy watch (Fitbit) and by questioning the subjects. Upon arriving, the subjects took a shower; they used a paraben-, perfume- and colorant-free liquid shower and shampoo (Neutral, Unilever Denmark), brushed teeth with a perfume-free toothpaste (Zendium Classic, Unilever Denmark); these hygiene products were provided for them. After that they put on pajamas and the sensors for registering physiological functions were attached; the sleep trackers were also attached.

Once the performance tests were completed, the subjects entered the capsule and it was sealed from the inside by the subjects. The lights in the chamber were then turned off but they could still use the small table lamp in the capsule. After about 30 min, they completed the evening sleep diary and went to sleep. Upon waking up in the morning, the subjects completed the morning sleep diary and then transferred from the capsule to an adjacent chamber. The doors to the capsule were resealed from the outside, and the decay of CO_2 in the capsule was monitored. The subjects completed the cognitive tasks in the adjacent chamber. The sensors were then removed, and the subjects changed out of their pajamas and into normal clothing.

TABLE 1 Planned and measured parameters in the sleep capsule under different experimental conditions

	Planned conditions		Measured parameters during sleep (mean ± SD)								
Nominal conditions	T (°C)	CO_2 concentration (ppm)	T (°C)	CO_2 concentration (ppm)	SPL (dB(A))	PSPL (dB(A))	RH (%)	Absolute humidity (g/m^3)	NO_2 (ppb)	TVOCs[a] (ppb)	$PM_{2.5}$ (ug/m^3)	PM_{10} (ug/m^3)
T24P800	24	800	23.7 ± 0.2	771 ± 34	51.1 ± 4.8	70.4 ± 2.5	48 ± 2	10.3 ± 0.5	1.9 ± 2.5	160.4 ± 37.3	2.7 ± 1.2	6.5 ± 1.6
T24P1700	24	1700	24.0 ± 0.2	1671 ± 121	47.6 ± 2.0	68.4 ± 1.2	57 ± 3	12.4 ± 0.7	1.7 ± 1.3	191.2 ± 15.6	2.3 ± 0.7	6.9 ± 1.4
T28P800	28	800	28.0 ± 0.2	795 ± 75	50.6 ± 5.0	70.1 ± 2.6	40 ± 3	10.8 ± 0.7	2.8 ± 2.4	176.7 ± 12.2	2.7 ± 1.3	6.8 ± 1.7

Abbreviations: PSPL, peak sound pressure level; RH, relative humidity; SPL, sound pressure level; T, Temperature.
[a]Total volatile organic compounds.

The door to the capsule could be sealed both from the inside and outside. Subjects were instructed how to seal the door during the training session. They were told that they could leave the capsule when it was necessary, for example, when they had to go to the toilet or felt anxious. They could also contact the experimenter on duty throughout the entire night, but no one subject did. One subject went to the toilet (twice) during the entire experiment but no other subject did.

2.6 | Consent

The experiments were approved under the general permission of the Ethics Review Board issued for experiments performed by the International Centre for Indoor Environment and Energy (KA04741). Verbal and written informed consent were both obtained from each subject. The study followed General Data Protection Regulation (GDPR).

2.7 | Calculation of ventilation rates and CO_2 emission rates

Ventilation rate was calculated separately for each experimental session by measuring the rate of decay of the concentration of metabolic CO_2 after each subject left the sleeping capsule[32–34] assuming that VR did not change whether the subjects were present or absent in the capsule; the rate of decay of CO_2 was used to estimate air change rate (ACH). Figure 4 shows an example of the measurements of CO_2 under two experimental conditions (T24P800 and T24P1700); the time periods used for estimating CER and ACH using the decay of CO_2[32–34] are indicated. The ACH was used to derive VR using the volume of the part of the capsule in which the subjects had been sleeping.

CER was calculated using a single-zone mass-balance model (equation 3)[35]: The steady-state concentration of CO_2 was used (Figure 4) and the VR using the decay of CO_2 estimated for the same day on which the steady-state concentration of CO_2 was measured.

$$\mathrm{CER} = \mathrm{VR} * (C_{\mathrm{steady}} - C_{\mathrm{a}})/1000. \quad (3)$$

Where CER in L/h, VR in m^3/h, C_{Steady}: time-average CO_2 concentration at the steady-state period in ppm, C_{a}: ambient CO_2 concentration in ppm under the period of steady state.

2.8 | Uncertainty analysis

The uncertainty of the estimated CERs was calculated following the uncertainty analysis in ISO Standard[36]:

$$\Delta Y = \sqrt[2]{\sum\nolimits_{i=1}^{n} \left(\Delta X_i \frac{\partial f}{X_i}\right)^2} \quad (4)$$

where the derivative terms $\Delta X_i \frac{\partial f}{X_i}$ describe the sensitivity of CERs to the changes in the related variables. The uncertainty of estimated CERs

TABLE 2 Anthropometric data of subjects

Subject No.	Sex	Weight (kg)	Height (m)	Age (years)	BSA (m^2)	BMI (kg/m^2)	PSQI
1	Male	67.8	1.80	27	1.86	20.9	3
4	Male	67.6	1.72	28	1.79	22.9	4
9	Male	57.2	1.73	25	1.68	19.1	8
10	Male	63.2	1.81	29	1.81	19.3	4
Males mean		64.0 ± 4.3	1.77 ± 0.04	27 ± 1	1.78 ± 0.07	20.5 ± 1.5	5 ± 2
2	Female	56.8	1.58	28	1.57	22.8	6
3	Female	64.0	1.68	38	1.72	22.7	5
5	Female	50.1	1.56	30	1.47	20.6	7
6	Female	59.0	1.61	22	1.61	22.8	6
7	Female	55.6	1.60	32	1.57	21.7	7
8	Female	65.8	1.69	24	1.75	23.0	4
11	Female	57.8	1.63	28	1.61	21.8	9
Females mean		58.4 ± 4.9	1.62 ± 0.05	29 ± 5	1.62 ± 0.09	22.2 ± 0.8	6 ± 1
All means		60.4 ± 5.4	1.67 ± 0.08	28.3 ± 4.1	1.68 ± 0.11	21.6 ± 1.4	6 ± 2

Note: BSA: Body surface area calculated by DuBois equation.[30]

consists of these variables: (1) uncertainty in the ACH estimation, which was obtained from statistical regression based on the decay of CO_2 (standard error); (2) uncertainty in the CO_2 measurements: based on the manufacturer's stated accuracy for the Innova instrument, 24 ppm and 51 ppm were assumed to the error in the CO_2 concentration at high and low ventilation condition, respectively; (3) uncertainty in the estimated volume of the capsule. The capsule volume was calculated by the multiplication of length, width, and height. Given the confined space of capsule, the net volume of the capsule was corrected for the volume of the bedding but no correction was made for other items in the capsule or for the subjects themselves; the uncertainty was assumed to be 5%.

2.9 | Statistical analysis

The data were first tested for normality using a Shapiro-Wilk test. Normally distributed data were subjected to analysis of variance in a repeated-measures design. The differences induced by various conditions and by sex were tested in post hoc analysis using the Bonferroni test. Non-normally distributed data were analyzed using Friedman's analysis of variance and the Wilcoxon signed-rank test to examine the effects of the conditions in the capsule on CERs, while the Mann-Whitney U test was applied to examine sex effects. The relationships between the CERs and BMI and BSA were analyzed by applying linear regression. The significance level was set at $p = 0.05$ (2-tail).

3 | RESULTS

The parameters describing environmental conditions in the capsule monitored during sleep are shown in Table 1. The measured air temperature and CO_2 concentration were maintained at the intended levels. The RH was not controlled so it was lower at the raised temperature and the higher VR as expected. The sound pressure level was somewhat higher at the higher VR, indicating that the silencer did not wholly remove noise from the extract fans outside the climate chamber. The measured $PM_{2.5}$ and PM_{10} levels during sleep were similar in all three conditions; the NO_2 was slightly higher at higher temperature and increased VR. The TVOCs levels were higher at lower VR and higher temperature as would be expected.

The calculated ventilation rates at each experimental condition are shown in Table 3 and Figure 5. The calculated VR was relatively stable in the low ventilation condition, but a larger variation was seen in the two higher ventilation conditions.

The calculated CO_2 emission rates are shown in Table 3 and Figure 6. The average CER was 11.0 ± 1.4 L/h per person. The CER was not affected by either increasing temperature from 24 to 28°C or reducing IAQ indicated by increased CO_2 concentration from 800 to 1700 ppm. The detailed calculated CERs for each subject were summarized in Table S1.

The results of the uncertainty analysis of estimated emission rates of CO_2 are shown in Figure 7. The uncertainty was always <0.07 L/h per person. The relative errors caused by this uncertainty were below 0.5% (Table S1). Slightly higher error and larger variation were observed in the high VR conditions compared with that of the low VR condition.

There were no statistically significant differences in the measured physiological parameters between the different conditions (Table 3).

3.1 | Previously published data allowing estimation of CO_2 emission rates from sleeping subjects

Nineteen papers published in the literature provide information that allows estimation of CER from sleeping subjects. They were found

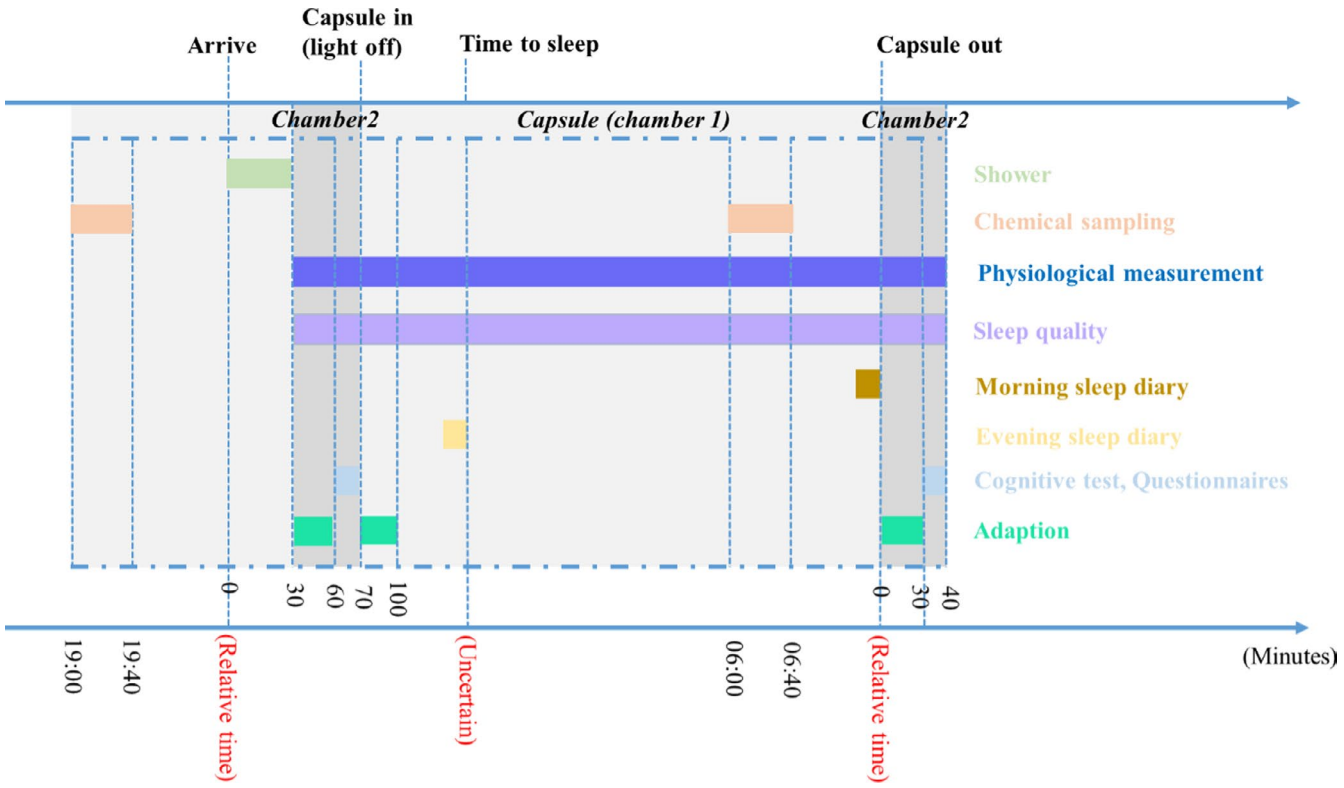

FIGURE 3 Experimental procedure

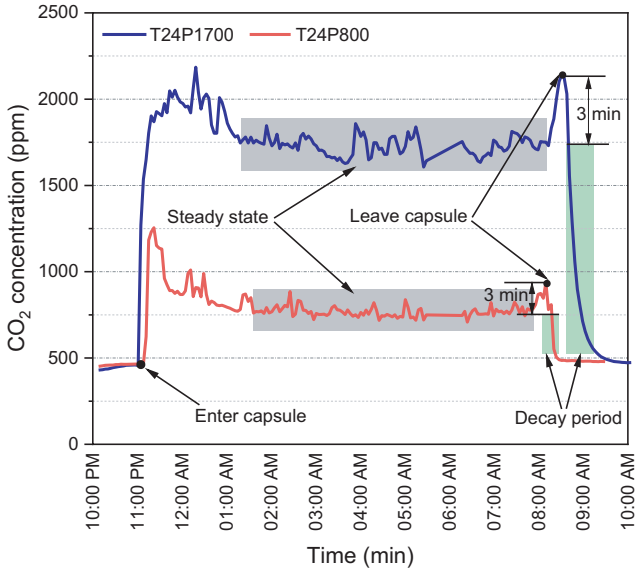

FIGURE 4 An example of the measured CO_2 concentration

by performing a literature search in the Web of Sciences. Fifteen of them provide information on both SEE and RQ (Table 4) while key information was missing in the other four so they could not be used (Table S2). Among them, three listed in the Introduction section provided information on CER.[15–17]

Five studies[15,17,37–39] were carried out when subjects slept normally. Three of them explored the relationships between the SEE and sleep stages for healthy subjects,[37–39] one[15] reported the calculated CER from 21 healthy subjects and determined the relationship between SEE and respiratory ventilation, and one[17] reported CERs from 11 subjects with severe obstructive sleep apnea who slept in the daytime (37–137 min) while the interapnea ventilation compensation for the maintenance of CO_2 homeostasis during periodic breathing was measured. In this study, the estimated CERs were higher than in the other studies. These two studies also found that males emitted more CO_2 than females as expected.[15,17]

Four studies[40–43] were performed when subjects slept normally while the effects of daylight exposure, snack time, the nutritional value of dinner and body weight were examined. One of them[43] investigated the effects of daylight exposure on the SEE of 15 healthy adults and found that hourly SEE and RQ were unaffected. Additionally, this study retrospectively analyzed the data from a night shift work simulation but these data could not be used because only the 24-h average EE and RQ were provided, that is, including periods when the subjects were not asleep. In one study,[40] eleven subjects consumed a selected snack either during the daytime (at 10 AM) or the nighttime (at 11 PM) and SEE was measured. It showed that the snack taken at 11 PM significantly decreased fat oxidation which might explain the slightly higher CER under this condition compared with the daytime snack condition. One study[41] showed that substrate oxidation during sleep was affected by the micronutrition composition of dinner and consequently CERs during sleep were about 4% higher after consuming a high carbohydrate dinner than after a high fat dinner. In one study,[42] three groups of subjects were recruited with low, moderate, and high body weight and it was

TABLE 3 Calculated VRs and CERs and physiological measurements under the experimental conditions (mean ± SD)

Parameters	T24P800	T24P1700	T28P800	P_T	P_{VR}
Ventilation rate (L/s per person)	11.2 ± 0.9	2.5 ± 0.3	11.6 ± 1.7	–	–
CO_2 emission rate (L/s per person)	11.2 ± 0.9	10.5 ± 1.7	11.4 ± 1.5	1.000	0.696
Heart rate (bpm)	62 ± 7	61 ± 6	62 ± 9	1.000	1.000
pNN_{50} (%)	19.5 ± 9.9	16.4 ± 13.2	28.1 ± 19.4	1.000	1.000
CBT (°C)	36.7 ± 0.2	36.7 ± 0.1	36.7 ± 0.2	1.000	1.000
MST (°C)	33.3 ± 1.1	33.8 ± 0.5	33.7 ± 0.4	0.213	0.155
Wrist skin temperature (°C)	33.3 ± 0.6	33.2 ± 0.7	33.7 ± 0.4	0.259	1.000

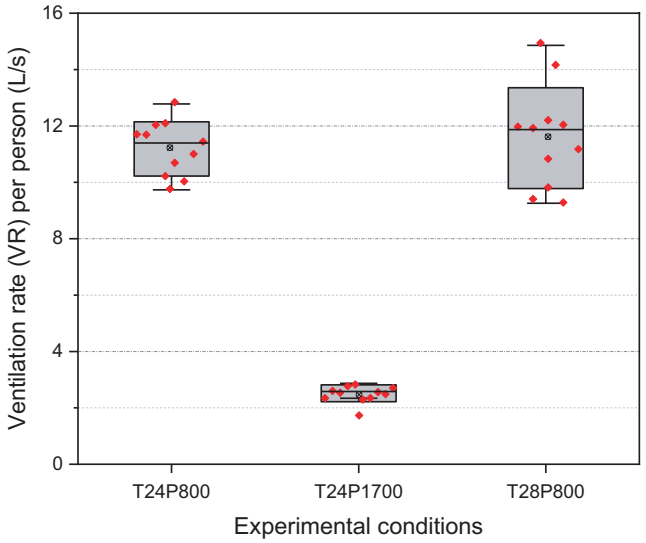

FIGURE 5 Calculated VRs at different conditions in the sleep capsule; box plots are shown

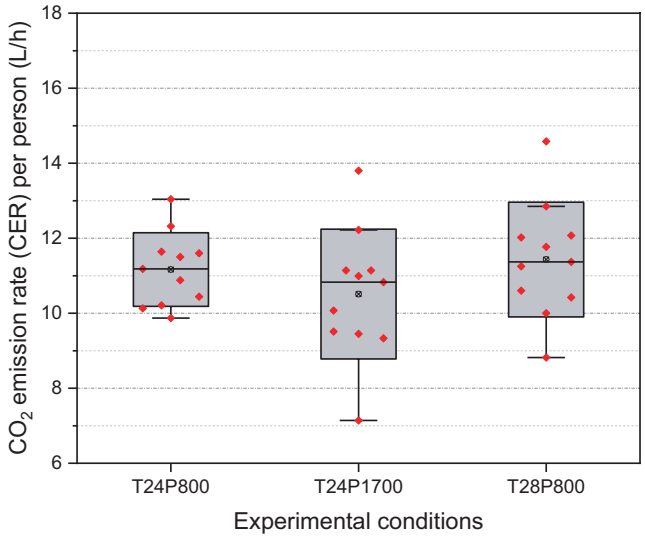

FIGURE 6 Estimated CERs at different conditions; box plots are shown

observed that SEE increased with body weight; this study also found that males emitted about 34–42% more CO_2 than females. Higher CER for males was also seen in two other studies as mentioned earlier.[15,17]

The effects of reduced sleep length on SEE were investigated in three studies.[44–46] Subjects were asked to sleep for 3.5–4 h (short sleep) or 7–9 h (long sleep). Two studies[44,45] observed that CERs were 3–6% higher during a short sleep, but the third study[46] obtained the opposite result.

Two studies investigated the effects of fragmented sleep on the SEE of 12–15 healthy subjects.[16,47] Fragmentation of sleep was accomplished with either approximately hourly wake-up calls or tones which were controlled to be "on" for 3s and then "off" for 3s through an earphone insert earpiece taped into their preferred ear. These interferences disappeared only when subjects responded to them by either turning them off or in the presence of EEG evidence of arousal. In this studies, calculated CERs were slightly higher during fragmented sleep compared with that during normal sleep, which could be due to the elevated activity-induced EE during fragmented sleep. The CER during recovery sleep after fragmented sleep was similar to what was observed during normal sleep.

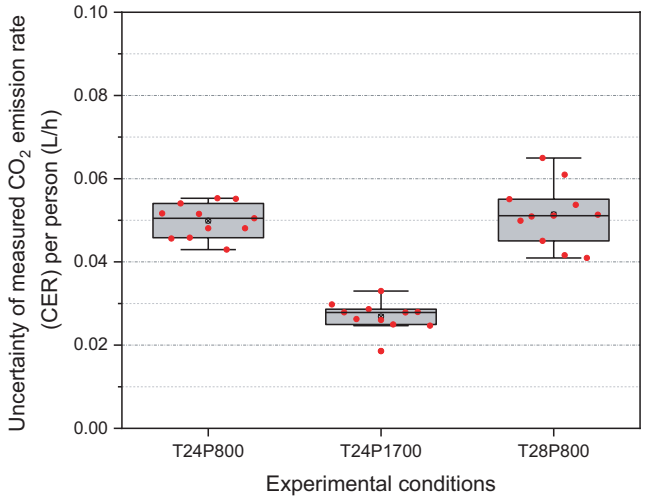

FIGURE 7 Calculated uncertainty of estimated CERs; box plots are shown

One study[48] examined the effects of sleep deprivation on the SEE of 7 healthy subjects. The CERs were similar during normal sleep and recovery sleep after sleep deprivation but were higher during fragmented sleep. This seems reasonable as the CER during sleep

deprivation can be regarded as the same as from subjects who are awake and engaged in light activitiy.[8,14,22,23,49]

Table 4 summarizes the details of the studies and the summary of estimated CER. The following conclusions can be drawn from these published data: (1) The snack time and composition of dinner before sleep slightly affect CERs (<5%), and body weight has a significant influence on CER while sleeping (14–33%) but daytime light exposure has no effects on CER. (2) The results are inconsistent regarding the effects of sleep length on CER while sleeping. If they do exist, they are small—below 5%. (3) CER is higher by 1–10% during fragmented sleep compared with normal sleep. (4) CER is higher by 30–40% when sleep deprived compared with normal sleep. (5) CER for males is slightly higher than for females (Fig. S1). CERs ranged from 9.7 to 20.2 L/h per person for male subjects (Mean ± SD 12.1 ± 0.8 L/h per person) while for female subjects they were between 7.8 and 15.2 L/h per person (Mean ± SD 9.2 ± 0.4 L/h per person).

4 | DISCUSSION

We present CER values of people while sleeping that were estimated experimentally and calculated using previously published SEE and RQ or CER values. The subjects in the present study slept normally although they were in a confined space. Their average total asleep time recorded with the wrist-actigraphy watch (Fitbit) was 473 ± 50 min; total asleep time of 420–540 min is regarded as adequate for normal sleep.[50] Our estimated CERs were between 7.1 and 14.6 L/h per person (Figure 6), which were similar to the 7.8–20.2 L/h per person reported in the literature (Table 4). The differences could be due to the purpose of the research as both fragmented and deprived sleep affect CERs, and they are also higher for subjects with higher body weight. Length of sleep and sleep disturbance, daytime light exposure, snack time, and composition of dinner seem not to affect CERs. The CERs derived in the present study are similar to those calculated using the empirical equations presented in ASHRAE Standard 62.1,[22] ASHRAE Handbook,[18] and ASTM D6245-18[23] with differences in the range of 2–8% (Figure 8). Figure 8 shows additionally that CERs during sleep are about 31–45% lower than when subjects are awake and performing light office work while seated. The metabolic rates (MET values) that were assumed, as shown in Figure 8, are different but they are for the same activity. ASHRAE standard 62.1 refers to ASHRAE Handbook[18] which defines the metabolic rate at met = 0.7 for sleeping and met = 1.0 for light office work while ASTM D6245-18 refers to a compendium[51] defining metabolic rate met = 0.95 for sleeping and met = 1.5 for light office work. The potential reasons for different metabolic rates estimated using different methods are discussed elsewhere.[14]

The present results show that neither increased temperature between 24°C and 28°C nor exposure to reduced IAQ as indicated by increasing the CO_2 concentration from 800 ppm to 1700 ppm should affect CERs. Physiological measurements did not differ between the different conditions in the present study, confirming that there is no reason to expect that CERs would differ. This is contrary to what has been observed during wakefulness.[10–12,49] Probably, the respiratory pattern of subjects during sleep did not change between conditions in the present study. Previous studies of subjects who were awake have documented reduced respiration in a polluted environment[52,53] and at high temperature.[54] Further studies are required to monitor the respiratory pattern during sleep at different temperatures and levels of IAQ.

Although small we saw sex differences in the measured CERs in the present experiments: They were on average 11.6 ± 1.0 L/h per person for males and 10.7 ± 1.5 L/h per person for females. Figure S2 shows that at T24P1700 CERs were significantly higher for males than females. In the other two conditions, CERs were higher for males in one of them and for females in the other one but the difference did not reach formal significance. Higher CERs for males during sleeping were also seen in the other studies summarized in Table 4 and Figure S1, which is consistent with the data for people who are awake.[9,10] Westerterp et al,[42] found that SEE and therefore the calculated CERs increased when the body weight increased from low to high (Table 4); males in the present experiments had higher body weight (Table 2). Zhang et al,[55] found on the other hand higher SEE for subjects with higher BMI; females in the present experiment had higher BMI. We created Figure 9 (and Fig. S3) to examine the effects of the body size area (BSA) and BMI on CERs: Both were found to be positively correlated with CERs. In the present study, the BSA of males was higher but BMI was lower than for females which could explain the inconsistent findings at different conditions. However, the main reason limiting the generalization of the present results is that the CERs were measured for only eleven subjects.

We estimated bedroom VRs using CERs determined in the present study assuming an outdoor CO_2 level of 420 ppm (https://www.co2.earth/) (Figure 10). We used the levels of CO_2 proposed in the tentative relationship relating bedroom IAQ with sleep quality and next-day work performance[5]: <750 ppm representing the range for undisturbed sleep quality, >750 ppm representing the range for possibly disturbed sleep quality, >1150 ppm for the range with disturbed sleep quality, and >2600 ppm showing the range at which sleep quality and next-day work performance are affected.[5] Our estimation shows that a VR in bedrooms of >10 L/s per person would be needed to avoid sleep disturbance, a VR <10 L/s per person may affect sleep quality, <5 L/s per person will affect sleep quality, and <1.5 L/s per person will affect both sleep quality and next-day work performance. These estimations are tentative and require validation in future studies, some of which are already in progress. As CO_2 is also a marker for the resulting concentration of other emissions (mainly exhaled bioeffluents), these VRs may be different if there are other strong sources of pollution in bedrooms.

A limited number of ventilation standards prescribe VRs in bedrooms. These standards have been summarized by Sekhar et al. (2020)[5]. The requirements define VRs in L/s, L/s.m^2, h^{-1}, CO_2 level and L/s per person. To make a comparison with the results shown in Figure 10, we used the requirements from the standards that prescribe VRs in L/s per person. For other recommendations, we would have to make assumptions regarding dwelling/bedroom size,

TABLE 4 An overview of the papers providing information allowing calculation of CERs (mean ± SD) for sleeping subjects

Ref. no.	Authors	Year	Sex	Subject no.	Age	BMI (kg/m^2)	BSA (m^2)	VR (L/s)	T (°C)	RH (%)	Conditions	CER (L/h per person)	Group
37	Fontvieille et al[a]	1994	Male	18	33 ± 7	30.2 ± 8.9	1.98 ± 0.10	0.8–0.8	25.0	N/A	Normal sleep	11.2 ± 0.5	I
			Female	11	28 ± 5	30.6 ± 13.2	1.40 ± 0.12						
38	Kayaba et al[a]	2017	Male	25	23 ± 3	23 ± 2	N/A	1.2	25.0 ± 0.5	55 ± 3	Normal sleep	11.5 ± 0.2[b]	
			Female	4									
39	Katayose et al[a]	2009	Male	12	23 ± 1	23.6 ± 1.1	1.85 ± 0.02	1.2	25.0 ± 0.5	55 ± 3	Normal sleep	10.7 ± 0.8[b]	
15	White et al[c]	1985	Male	11	47 ± 17	24.6 ± 3.6	1.94 ± 0.12	N/A	20.0–22.0	N/A	Normal sleep	11.6 ± 0.7[b]	
			Female	10	45 ± 17	23.4 ± 3.5	1.67 ± 0.11					9.0 ± 0.4[b]	
17	Berger et al[c]	2000	Male	8	44 ± 8	42.7 ± 8.8	2.30 ± 0.17[d]	N/A	N/A	N/A	Normal sleep - subjects with severe apnea	15.3 ± 1.7	
			Female	3	37 ± 8	60.4 ± 11.3	2.41 ± 0.38[d]					14.9 ± 2.4	
40	Hibi et al[a]	2013	Female	11	23 ± 1	20.6 ± 2.6	1.56 ± 0.04	1.2	25.0	50.0	Normal sleep - daytime snack (10 AM)	8.7	II
											Normal sleep - nighttime snack (11 PM)	8.9	
41	Yajima et al[a]	2014	Male	10	25 ± 1	22.6 ± 0.8	1.81 ± 0.01	13	25.0 ± 0.5	55 ± 3	Normal sleep - high carbohydrate dinner	11.4 ± 1.1	
											Normal sleep - high fat meal dinner	10.9 ± 1.2	
42	Westerterp et al[e]	1991	Male	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Normal sleep - low weight subjects	N/A	
				3	36 ± 2	22.7 ± 2.4	1.84 ± 0.05				Normal sleep - normal weight subjects	14.4 ± 1.2[f]	
				3	30 ± 7	49.3 ± 8.8	2.78 ± 0.11				Normal sleep - high weight subjects	20.2 ± 1.6[f]	
			Female	3	36 ± 9	15.1 ± 0.7	1.40 ± 0.01				Normal sleep - low weight subjects	7.8 ± 0.6[f]	
				3	32 ± 7	22.1 ± 0.8	1.76 ± 0.04				Normal sleep - normal weight subjects	10.2 ± 0.4[f]	
				3	22 ± 4	46.0 ± 1.3	2.36 ± 0.05				Normal sleep - high weight subjects	15.2 ± 2.4[f]	
43	Melanson et al[a]	2018	Male	8	23 ± 3	22.4 ± 2.0	1.76 ± 0.05	N/A	N/A	22–23	Normal sleep – daytime typical room white light exposure	10.6 ± 1.0	
			Female	7									

(Continues)

TABLE 4 (Continued)

Ref. no.	Authors	Year	Sex	Subject no.	Age	BMI (kg/m^2)	BSA (m^2)	VR (L/s)	T (°C)	RH (%)	Conditions	CER (L/h per person)	Group
											Normal sleep – daytime bright white light exposure		
											Normal sleep – daytime blue-enriched white light exposure		
44	Klingenberg et al[a]	2012	Male	21	17 ± 1	21.0 ± 1.8	1.81 ± 0.05	N/A	N/A	N/A	Short sleep (4h)	12.6 ± 0.4	III
											Long sleep (9h)	12.3 ± 0.3	
45	Shechter et al[a]	2013	Female	10	28 ± 2	26.0 ± 0.5	1.76 ± 0.01	1.3	24.0 ± 0.5	N/A	Short sleep (4h)	10.0 ± 0.1	
											Long sleep (8h)	9.5 ± 0.1	
46	Hibi et al[a]	2017	Male	9	23 ± 2	22.2 ± 3.0	N/A	1.2	25.0	50	Short sleep (3.5h)	9.9 ± 0.2	
											Recovery sleep after short sleep (7h)	9.7 ± 0.1	
											Long sleep (7 h)	10.3 ± 0.3	
											Recovery sleep after long sleep (7 h)	9.9 ± 0.3	
16	Bonnet et al[c]	1991	Male	12	18–28	N/A	N/A	N/A	N/A	N/A	Normal sleep (7.5)	12.4 ± 0.5	IV
											Fragmented sleep (7.5)	13.6 ± 0.4	
											Recovery sleep (7.5)	12.6 ± 0.5	
47	Hursel et al[a]	2011	Male	15	24 ± 4	24.1 ± 1.9	2.01 ± 0.04	N/A	N/A	N/A	Normal sleep (8 h)	13.7 ± 0.2	
											Fragmented sleep (8 h)	13.8 ± 0.2	
48	Jung et al[a]	2011	Male Female	5 2	22 ± 5	22.9 ± 2.4	N/A	N/A	22.5 ± 0.02	N/A	Habitual sleep (8 h)	12.0 ± 0.6	V
											Sleep deprivation (0 h)	15.6 ± 0.3	
											Recovery sleep (8 h)	11.11 ± 0.6	

[a]IC method.

[b]Averaged value of different sleep stages.

[c]Tight-fitting face mask method.

[d]Body surface area extracted from literature, others calculated by DuBois equation.[30]

[e]Using isotope ratios to calculate the CER, then converting to EE assuming an energy equivalent of 531 kJ/mol.

[f]Using mean 24-h measured respiratory quotient of 0.85.

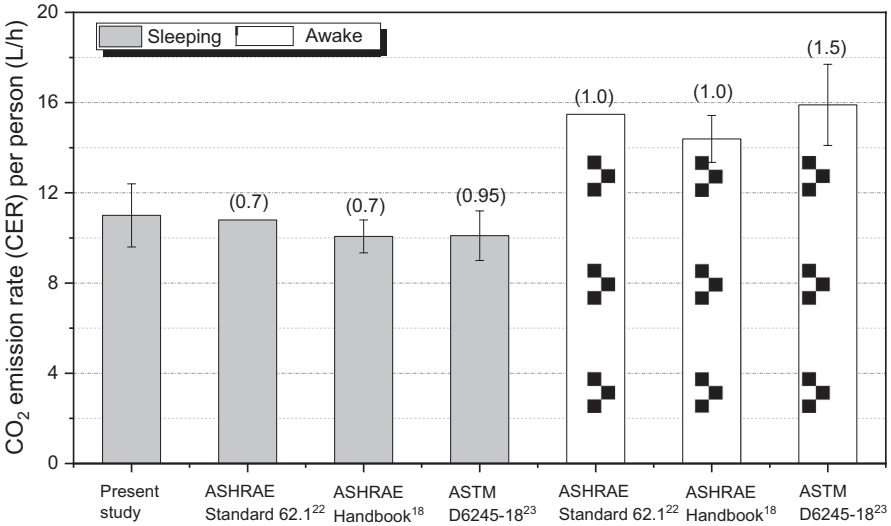

FIGURE 8 Comparison of CERs estimated in the present experiment with CERs calculated using ASHRAE 62.1, ASHRAE Handbook, and ASTM D6245-18; (MET) represents the metabolic rate (in met) selected when calculating CERs. (RQ was 0.83 in ASHRAE Handbook and 0.85 in ASTM D6245-18)

volume, and occupant density and we chose not to make them. With regard to recommendations in bedrooms, a VR of 7.2 L/s per person is recommended by TEK17 (2017)[56] in Norway and 5.6 L/s per person by ÖNORM H 6038 (2014)[57] in Austria. Four standards prescribe VRs for the whole dwelling between 4.2 and 10 L/s per person (EN 16798–1:2019,[25] ÖNORM H 6038:2014,[57] GB/T 18883:2002,[58] and Japan Building Standard Law 1950[59]). These recommendations can according to Figure 10 result in some disturbance of sleep quality. It is worth noting that EN 16798–1:2019[25] stipulates CO_2 levels (380–950 ppm above outdoors or 800–1370 ppm assuming CO_2 outdoors at 420 ppm) in bedrooms assuming a CER of 13.6 L/s per person during sleep when the VR is 4, 7, 10 L/s per person for cat. I, II, and III of indoor environmental quality. The measured CER in the present study is lower than the CER used by EN 16798–1 so with these three VRs the CO_2 levels will be lower than stipulated by the standard. Generally, Figure 10 implies that bedrooms should have a VR corresponding to the highest category of indoor environmental quality in buildings according to EN16798-1[25] to ensure no risk of disturbed sleep. This is compatible with the VR recommended by Pettenkofer (1858)[60] (who recommended a maximum CO_2 concentration in bedrooms of 700 ppm) but should be investigated further.

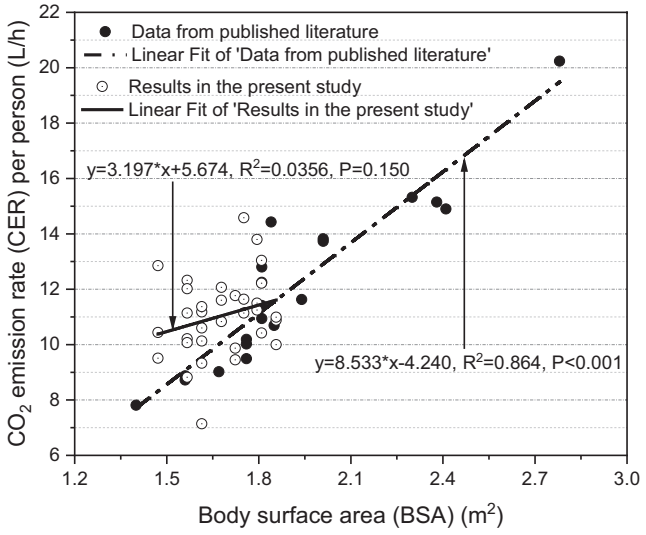

FIGURE 9 The relationship between CERs and BSA

4.1 | Limitations and experimental conditions

The measured temperature and CO_2 concentration in the capsule during sleep were maintained at the intended levels. CO_2 concentration in the present study was only used as an indicator of IAQ mainly affected by bioeffluents emitted by subjects sleeping in the capsule. The changes in IAQ were confirmed by the measurements of TVOC (Table 1). The variation of estimated VR was larger at higher ventilation conditions because the period for estimating the ACH using decay curve was shorter leading to errors. In the future, other methods for measuring air supply rate should be used. We did not measure the air velocity in the capsule near the subjects during sleep, but the subjects did not complain of drafts.

The limitation of the present study is that only young and healthy individuals with normal BMI were recruited. They are not representative of the entire population as they did not include subjects with any sleep disorder or with high or low BMI, or any other age group. Even though the measurements were performed with only eleven subjects, the results are compatible with the results either published in the literature or estimated using reported SEE and RQ.

The sleep conditions were not typical as the subjects slept in such a confined space in the present study, although we included an initial night for adaptation, as in the previous studies.[61] We calculated the CER during this first night and it was on average 10.8 ± 2.1 L/h per person and thus similar to what occurred during the other nights.

Even though only eleven subjects took part, the measurements of CO_2 concentration and estimated CERs were consistent from night to night. In general, the accuracy was high (uncertainty <0.07 L/h per person corresponding to the errors <0.5%). Slightly higher uncertainty and variation were observed at higher VRs due to the reduced

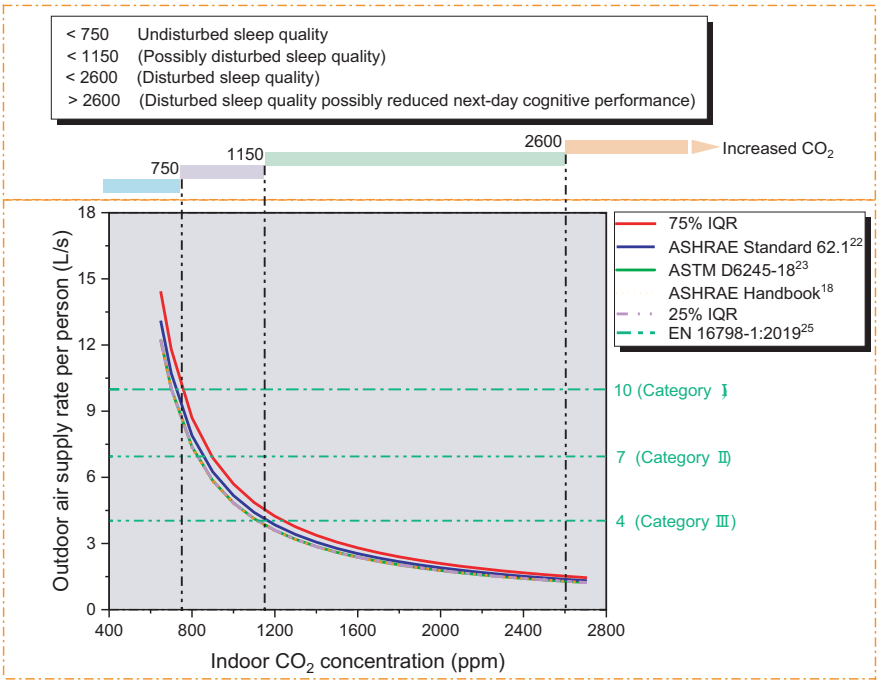

FIGURE 10 Calculated minimum required VRs per person during sleep at different levels of indoor CO_2. (1) The interquartile range (IQR) of CERs measured in the present study was used (10.1–11.9 L/h per person); VRs in the EN 16798-1[25] for bedrooms are presented as well

precision of estimating ACHs and the shorter time available for its estimation. The variation in measured CO_2 was also low (<10%).

Further studies with more and more diverse subjects are necessary to reproduce and extend the applicability of the present results.

5 | CONCLUSIONS

- CO_2 emission rates (CERs) from eleven subjects while sleeping were measured in the present study. The average CO_2 emission rate was estimated to be 11.0 ± 1.4 L/h per person; the subjects slept normally with no major disturbances. It was similar to the values calculated using published data on the sleep energy expenditure (SEE) and Respiratory Quotient (RQ) of subjects. It was also similar to the values calculated using ASHRAE Standard 62.1, ASHRAE Handbook, and ASTM D6245-18.
- Measured CO_2 emission rates did not change when the temperature was increased from 24°C to 28°C or when the ventilation rate was reduced so that CO_2 level increased from 800 ppm to 1700 ppm. No significant physiological changes were observed.
- Published studies of sleep energy expenditure (SEE) show that CO_2 emission rates from sleeping subjects are not affected by the length of sleep or by daytime light exposure. Sleep fragmentation and deprivation, body weight, snack time, and the nutritional composition of dinner have been shown to change CO_2 emission rates (CERs) during sleep. Slightly higher CO_2 emission rates from sleeping male subjects have been reported in the literature and were found in the present study.
- The present results provide usable data for prescribing and controlling bedroom ventilation. Their applicability will have to be extended by exposing larger groups with different ages that include subjects with chronic sleeping disorders.

DATA AVAILABLE STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

Xiaojun Fan involved in conceptualization, investigation, formal analysis, methodology, validation, visualization, writing-original draft preparation & reviewing and editing. Mitsuharu Sakamoto involved in conceptualization, formal analysis, methodology, and writing-reviewing and editing. Huiqi Shao involved in conceptualization, methodology, and investigation. Kazuki Kuga involved in conceptualization, methodology, and writing-review and editing. Kazuhide Ito and Li Lan involved in writing-review and editing. Pawel Wargocki involved in conceptualization, data curation, funding acquisition, investigation, methodology, project administration, resources, supervision, and writing-review and editing.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Paper 2

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Air change rates during sleep in Danish bedrooms

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Abstract. The ongoing project 'Bedroom Ventilation and Sleep Quality' investigates the effects of bedroom ventilation on sleep quality and next-day cognitive performance. As part of the project, 84 bedrooms in the Greater Copenhagen area of Denmark were inspected during the 2020 heating season. In the first week, participants slept under environmental conditions that they typically experienced during sleep; in the second week, they slept with the interventions made by opening/closing either the door, or window, or both. As an essential part of the study, the CO_2 concentration in bedrooms was continuously measured. The bedroom window and door status during sleep were obtained the following morning via sleep diary. The air change rates per hour (ACHs) in bedrooms were estimated using the occupant-produced CO_2 concentration decay method. Mechanical ventilation was rarely installed in bedrooms; extract ventilation in the bathroom and kitchen was predominant. Participants typically slept with both bedroom window and door closed. The median ACH was 0.40 h^{-1} during sleep under habitual conditions. Opening either the window or door increased bedroom ACH during sleep, but window opening led to better ventilation than the door opening, which was verified by the intervention. These results suggest that the ventilation in most bedrooms is currently insufficient compared with the ventilation requirements prescribed by limited standards, highlighting the urgency to look at its impact on sleep quality and improve bedroom ventilation.

Keywords. Bedroom Ventilation, Air change rate, Airing behaviour, Residential buildings, Sleep

1. Introduction

Sleep is essential for our health and well-being by enabling human bodies to function well. Previous studies have shown that inadequate ventilation in bedrooms adversely affects sleep quality [1–3], which in turn increases the risk of a series of health-related diseases, such as obesity and chronic diseases [4], etc., and reduces the next-day cognitive performance [3,5].

In light of the difficulties in ventilation rate measurements on-site, for example, air mixing indoors and methods limitations, CO_2 concentration during sleep is typically measured in most studies as a proxy of ventilation in bedrooms, as summarized by Akimoto et al. [6]. Limited studies attempted to characterize bedroom ventilation by measuring the air change rate using the tracer gas method as summarized by Sekhar et al. [7]. They found that the mean air change rate (ACH) varied largely from 0.2 to 4.9 h^{-1}. A large number of surveyed bedrooms did not meet the ventilation requirements stipulated by ASHRAE and European Standards [8][9].

Buildings worldwide are being built tightly due to the energy crisis. Consequently, the ventilation rates in dwellings are reduced, especially in areas where the central heating system is installed. Occupants generally sleep with the bedroom door and window closed in these areas during the heating season, further decreasing the bedroom ventilation during

sleep.

This study is part of a large field investigation on the effects of bedroom ventilation on sleep quality and next-day cognitive performance conducted in the Greater Copenhagen area of Denmark during the heating season in 2020. This paper presents the results of the estimated ACHs using the occupant-produced CO_2 concentration decay method to provide an overview of the actual bedroom ventilation and characterize how occupants' airing behaviours affect ACHs during sleep. Other measurements will be reported separately.

2. Method

A cross-sectional field study was conducted from September to December 2020 in the Greater Copenhagen area of Denmark. Eighty-four participants were recruited based on the answers to a recruitment questionnaire, which collected the information on candidates, characteristics of bedrooms and dwellings, and sleep quality over the past month prior to participating in this study. Participants could choose to take part in either one-week or two-week measurements: only weekdays (Monday evening to Friday morning) were considered. The participants were asked to sleep under their habitual sleep conditions in the first week; in the second week, they were instructed to make interventions by opening or closing the bedroom door, or window, or both at night. Among them, 64 participated in two-week measurements.

The CO_2 concentration was measured continuously in bedrooms at an interval of 5 min. Sixteen measuring units, each comprising a CO_2 sensor (GMW90R, Vaisala Corp., Finland) and a data logger (HOBO UX120-006M, Onset Computer Corp., USA), were used in the present study. The measuring range of the sensor was 0-5000 ppm with an accuracy of ±30 ppm + 2% of reading. The air temperature and relative humidity were recorded simultaneously. The CO_2 sensor was calibrated prior to the study.

Each bedroom was installed with one unit. The unit was placed at a similar height of the bed and one meter away from the head region when participants lay down. Participants reported the status of the bedroom door and window via an online sleep diary in the morning, which they were asked to fill out twice, two weekdays' morning of each week.

The ACH was estimated for every weekday night by measuring the decay of the human-produced CO_2 concentration after the participants left the bedrooms assuming that the ACH did not change if the bedroom door and window status were kept the same as the previous night. Participants were asked not to make any changes to the bedroom window and door after waking up and to avoid re-entering the bedrooms at least within 30 min. after leaving to allow the decay of CO_2 concentration to be built up. The outdoor CO_2 concentration throughout the measuring period was not recorded. Instead, the mean value at a steady-state during daytime when the bedrooms were not occupied was used. Otherwise the outdoor CO_2 concentration was assumed to be 420 ppm as used by the previous study to estimate the ventilation rate under different CO_2 levels [10]

3. Results and Discussions

Fig. 1 shows the cumulative probability of estimated ACHs in bedrooms during habitual sleep conditions. The median ACH was 0.40 h^{-1}, ranging from 0.03 h^{-1} to 19.25 h^{-1}, similar to the value measured in 500 children's bedrooms of Denmark [11].

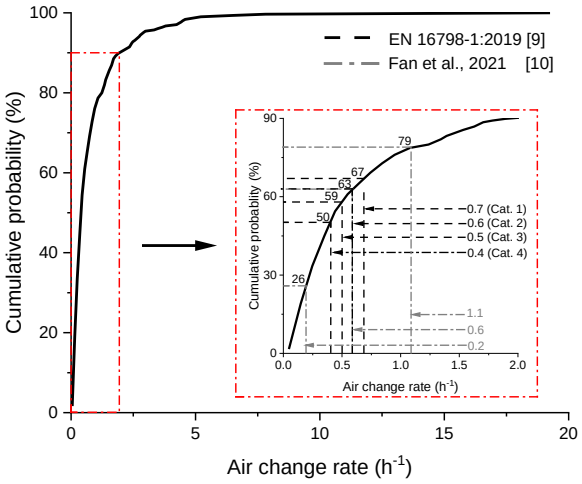

Fig. 1 – Cumulative probability plots of estimated ACHs in bedrooms during habitual sleep conditions. Bedroom ventilation stipulated by EN 16798-1 [9] and recommended by Fan et al. [10] are also presented.

Sekhar et al. reviewed 17 international and national standards and building regulations on ventilation requirements for bedrooms and found that most existing standards do not prescribe specific ventilation requirements for bedrooms; the requirements for bedroom ventilation is simply the application of ventilation requirements for the whole dwellings [7]. Among others, the European standard specifies the total ventilation (including infiltration) of 0.4, 0.5, 0.6, 0.7 h^{-1} for Categories 4 to 1 respectively for entire dwellings [9]. These values are used for benchmarking in the present study.

Half surveyed bedrooms had an ACH lower than 0.4 h^{-1} during sleep, the minimum ventilation requirement stipulated by EN 16798-1 [9]. If an ACH of 0.7 h^{-1} is used as the criterion for bedroom ventilation, 79% of bedrooms did not comply with the ventilation requirement.

Based on the tentative relationship between bedroom ventilation (indicated by CO_2 levels) and sleep quality established by Sekhar et al. [7], Fan et al. recommended the bedroom ventilation rates considering the adverse effects on sleep quality assuming that the CO_2 emission rate during sleep was

11.0 L/h per person [10]. To avoid sleep disturbance, the ventilation rate in bedrooms should be >10 L/s per person, corresponding to a CO_2 level of < 800 ppm. A ventilation rate of < 10 L/s per person may affect sleep; < 5 L/s per person, corresponding to a CO_2 level of >1150 ppm, will affect sleep; <1.5 L/s per person, corresponding to a CO_2 level of >2600 ppm, will affect both sleep quality and next-day cognitive performance. The corresponding ACH was estimated to be 1.1, 0.6, and 0.2 h^{-1} (the median bedroom volume and occupancy during sleep were 32 m^3 and one person in the present study). 79% of bedrooms had an ACH < 1.1 h^{-1} suggesting that occupants sleeping in these bedrooms may suffer from sleep disturbance; 26% was lower than 0.2 h^{-1} indicating that both sleep quality and next-day cognitive performance of occupants sleeping in these bedrooms might be affected already. These results highlight the urgency of improving bedroom ventilation and the importance of investigating its effects on sleep quality.

Window and door opening significantly affect bedroom ventilation [12–14]. According to the habitual airing behaviours, the sample size obtained can be categorized into four different scenarios of natural ventilation in bedrooms: (1) Scenario 1, Window Closed and Door Closed; (2) Scenario 2, Window Closed and Door Open; (3) Scenario 3, Window Open and Door Closed; and (4) Scenario 4, Window Open and Door Open.

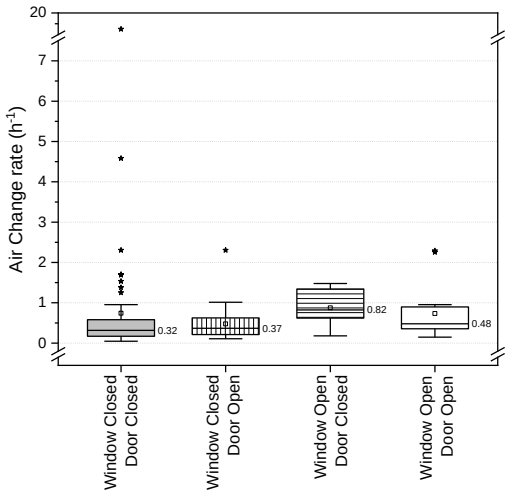

Fig. 2 – Estimated ACHs in different scenarios during the habitual sleep conditions.

Fig. 2 presents the estimated ACHs at different scenarios during the habitual sleep conditions. The lowest ACHs during sleep were found for Scenario 1 with a median value of 0.32 h^{-1} in Scenario 1; while the highest ACHs were observed for Scenario 3 with a median value of 0.82 h^{-1}. Window and door opening improved the bedroom ventilation, as expected. In contrast, the median ACH was 0.48 h^{-1} at Scenario 4 during sleep, which is in between Scenario 2 and 3. Similar results were observed under Scenario 2 and 3 but not Scenario 4 [12]. The plausible explanation for this divergence would be the opposite air movement directions from the window and the door. Further studies are necessary to investigate it.

We estimated the ventilation type in surveyed bedrooms using the information about the air terminals and trickle vents collected by the recruitment questionnaire. Bedrooms with air terminals were considered to have a fully balanced mechanical ventilation system. Bedrooms with trickle vents and exhaust air terminals in the bathroom or kitchen were considered to have mechanical ventilation with exhaust only. Bedrooms with other cases were considered to be ventilated naturally.

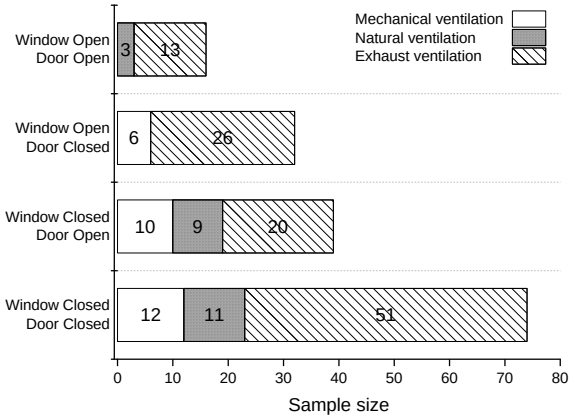

Fig. 3 – The distribution of sample size in terms of the ventilation system of the surveyed bedrooms in different scenarios. The sample size is larger than the number of occupants as more than one sample came from one participant.

The distribution of sample size based on the bedroom ventilation system is shown in Fig. 3. Most ACHs were estimated from bedrooms only with exhaust ventilation; only a few bedrooms were installed with a fully balanced mechanical ventilation system. The choice of opening or closing the window or door seems to be independent of the bedroom ventilation system.

It can also be seen that most samples were from bedrooms in Scenario 1; only a few samples were from bedrooms in Scenario 4; as expected. This study was conducted in wintertime in Denmark when the outdoor temperature was lower. Occupants prefer to avoid air draught and keep the bedroom warm during sleep by closing both the window and door, resulting in poor ventilation. More attention should be paid to bedroom ventilation during sleep, especially in these areas with central heating systems in winter. The sample size from the bedrooms with the door open was similar to those with the window open.

The locations of the surveyed bedrooms were deduced from postcodes collected from the recruitment questionnaire. The distribution of the sample size based on the locations is shown in Fig. 4. Most samples in the present study were from bedrooms located in suburban regions. There was only a small number of samples from bedrooms located in urban regions. The composition of the sample size in each Scenario was similar.

Both the characteristics of the ventilation system in surveyed bedrooms and information on the airing

behaviour during sleep explain the observed low ACHs during sleep under habitual conditions in the present study.

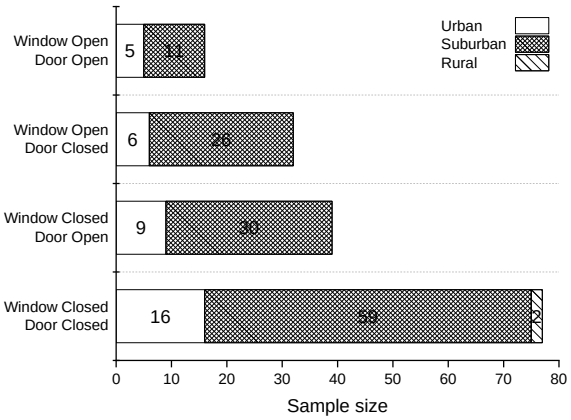

Fig. 4 – The sample size distribution in terms of the locations of the surveyed bedrooms in different scenarios. The sample size is large than the number of occupants as more than one sample came from one participant. The areas of the bedrooms with the first two numbers of postcodes 25 or below are regarded as urban regions; suburban regions refer to the areas with the first two numbers of postcodes 26-31, 34-36, 40, 50-52, 70, 80-82, and 90-92; and the other areas in the Capital Region of Denmark are rural.

The ACHs obtained from two-week measurements with the interventions are depicted in Fig. 5. This analysis is a within-subject comparison. The median ACHs were approx. 0.3 h^{-1} in Scenario 1 during sleep, which was similar to 0.32 h^{-1} measured during habitual sleep conditions. The median ACHs increased from 0.27 h^{-1} to 0.39 h^{-1} in Scenario 2. When opening the window only, the median ACHs increased from 0.32 h^{-1} to 1.14 h^{-1}. The median ACHs were only increased by 27% when opening both the window and door, which was similar to the estimated value under the conditions with the door open.

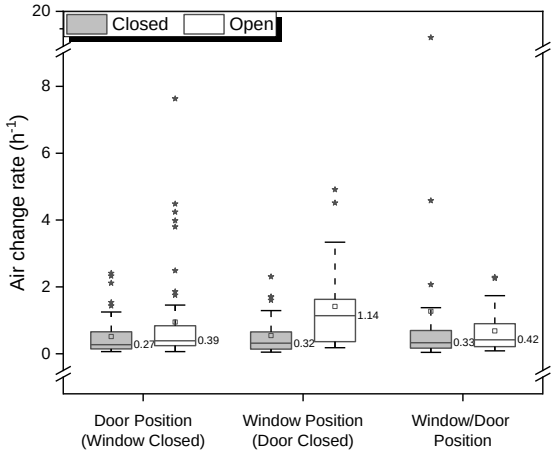

Fig. 5 – Estimated ACHs before and after interventions made by opening or closing either the door, or window, or both.

These results from the intervention part verify the observations from the habitual sleep conditions. The findings of the present study suggest that opening either the door, or the window, or both increases the ACH. However, the open window leads to better ventilation than the open door, as may be expected. Similar results were found by Mishra et al.[13]. It is worth noting that opening both window and door in the present study did not further improve the ventilation in bedrooms compared with only opening the window or door. A follow-up study is necessary to investigate the reasons behind that and the optimal conditions to increase the bedroom ventilation by opening both.

4. Limitation

This study was conducted during the heating season in Denmark, where the outdoor temperature in winter is low. The airing behaviour of participants during sleep may be different in other seasons, resulting in different ventilation. More future studies are needed to investigate it further.

The ACH was estimated by the decay of human metabolically produced CO_2 concentration. Its accuracy depends on the CO_2 measurement, elapsed time for decay, and air mixing in bedrooms. In addition, if the window and door status after sleep is the same as they are during sleep, it is also crucial to estimate the ventilation rate during sleep precisely by the CO_2 decay after sleep. The outdoor CO_2 level was not measured throughout the entire measuring period in the present study. We also did not check the air mixing. It would be useful to monitor the outdoor CO_2 concentration simultaneously and deploy more sensors at the different locations in bedrooms. Besides, we asked participants not to re-enter their bedroom within 30 min. after leaving it, which may lead to large uncertainty of the ACH estimation due to the limited data points available as the CO_2 concentration was registered every five min., especially at the high ventilation conditions where the decay would be quickly established. A more extended decay period could contribute to a more accurate estimation of the ACH.

The ACHs estimated in the present study are the total airflow into the bedroom, including airflows from adjacent spaces, especially when the bedroom door was open as an intervention. In light of no CO_2 measurements conducted in the adjacent spaces, especially outside the bedroom door, we assumed that the CO_2 concentration in the air supplied into bedrooms from adjacent spaces was equal to that in the outdoor air.

Even though we identified the ventilation systems of surveyed bedrooms based on the information about the air terminals and trickle vents, we did not check if they were operated appropriately throughout the entire measuring period. The previous study has shown that the ACH can be further enhanced by operating the exhaust ventilation system when opening the door in bedrooms [15]. In the present study, we did not observe that. It may be because the extraction systems were not in operation during

sleep. It would be helpful to check the operations of the ventilation systems in bedrooms during sleep in future studies to investigate the bedroom ventilation with different ventilation systems installed.

5. Conclusions

This work estimated the ACHs in bedrooms during sleep and explored how bedroom window and door opening affects ventilation. Extract ventilation was predominant in surveyed bedrooms; only a few had mechanical ventilation installed. Most participants slept with both the window and door closed. There was only a small number of participants who kept the bedroom window or door open during sleep, even less with both the window and door open. During habitual sleep conditions, the median ACH was 0.40 h^{-1}, ranging from 0.03 h^{-1} to 19.25 h^{-1}. Bedroom ventilation with closed door and window resulted in the lowest ACH, but window or door opening increased bedroom ACH, and window opening led to better ventilation than the door opening. This was verified by the results from intervention. The median ACH increased from 0.27 h^{-1} to 0.39 h^{-1} by only opening the door and from 0.32 h^{-1} to 1.14 h^{-1} by only opening the window. However, both window and door opening only slightly increased ventilation from 0.33 h^{-1} to 0.42 h^{-1}. During habitual sleep settings, half the surveyed bedrooms did not meet the minimum ventilation requirement prescribed by European Standard; 79% of bedrooms had an ACH of <1.1 h^{-1}, including 26% lower than 0.2 h^{-1}. Future studies are required to investigate whether the sleep quality is disturbed after sleeping under the insufficiently ventilated bedrooms and how window and door opening will affect the bedroom ventilation and sleep quality.

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Data Statement

The datasets generated during and/or analysed the current study are not publicly available but are/will be available by contacting the first author upon reasonable request.

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Paper 3

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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.

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.

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.

2. Methods

2.1. Subjects

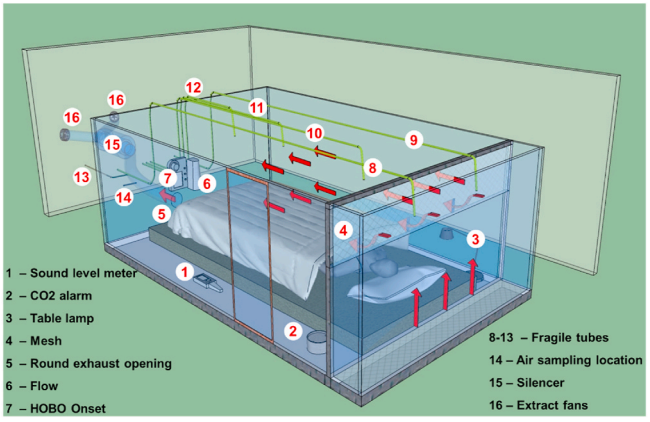
Eleven healthy subjects without sleep disorders [30] were recruited and slept a night under each of the experimental conditions. The data from one subject were excluded as she perceived the air in the capsule to be extremely dry (which was not the case as illustrated in Table 2) and her TST deviated 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.



(A)

(B)

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.

$$MST = 0.2{*}T_1 + 0.2{*}T_2 + 0.3{*}T_3 + {*}0.3{*}T_4 \quad (1)$$

- 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.

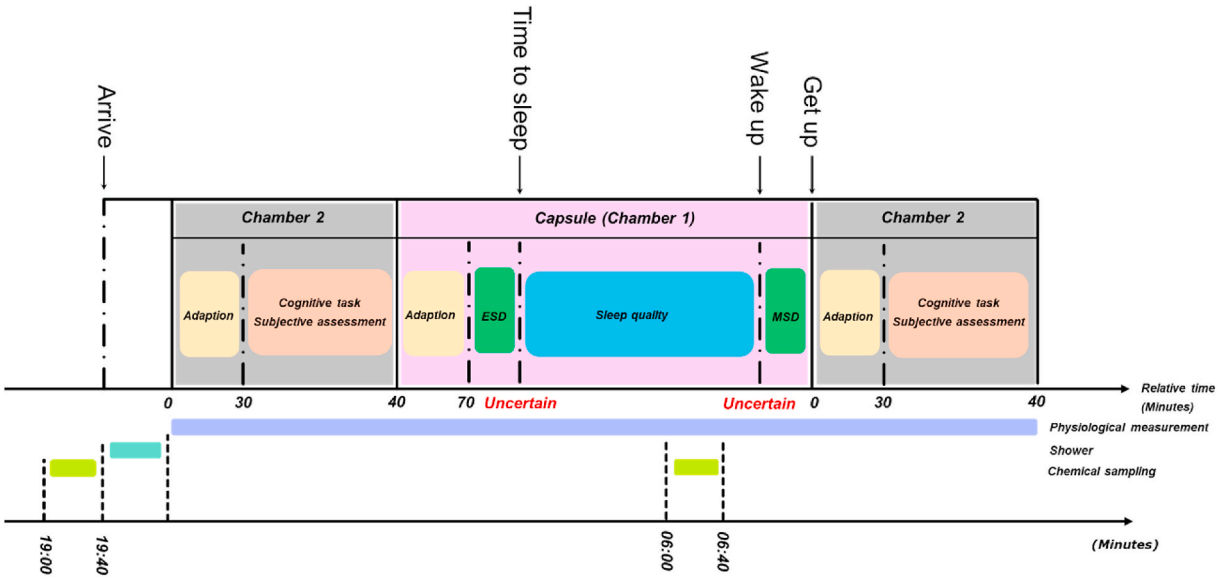


Fig. 2. Experimental procedure. ESD: evening sleep diary; MSD: morning sleep diary.

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].

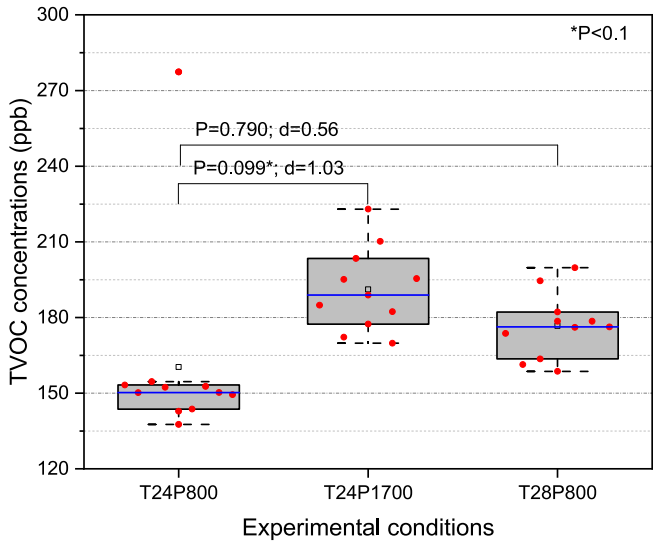


Fig. 3. Measured TVOC concentrations at different conditions in the capsule during sleep. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

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

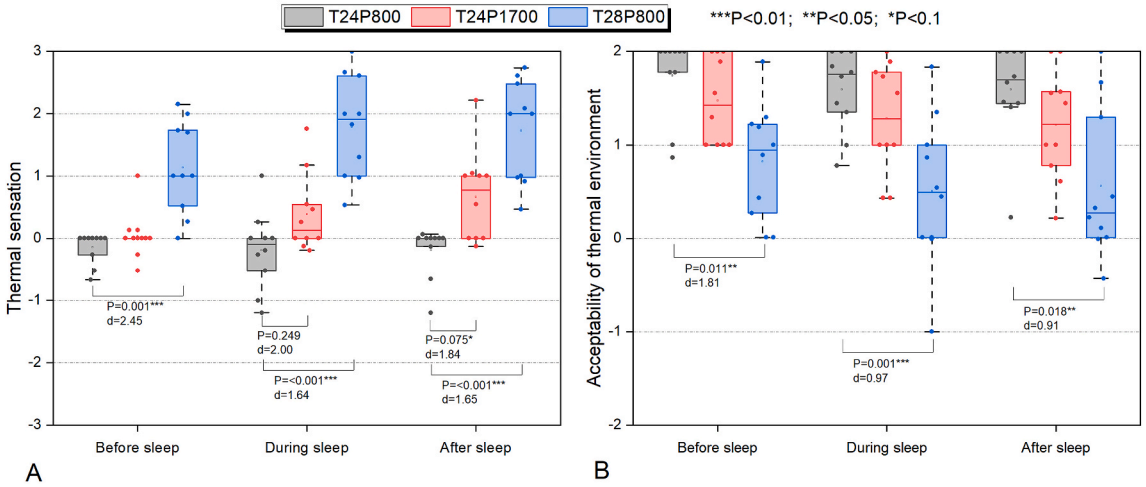


Fig. 4. (A) Thermal sensation; and (B) acceptability of thermal environment before, during (recalled), and after sleep under the different conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

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

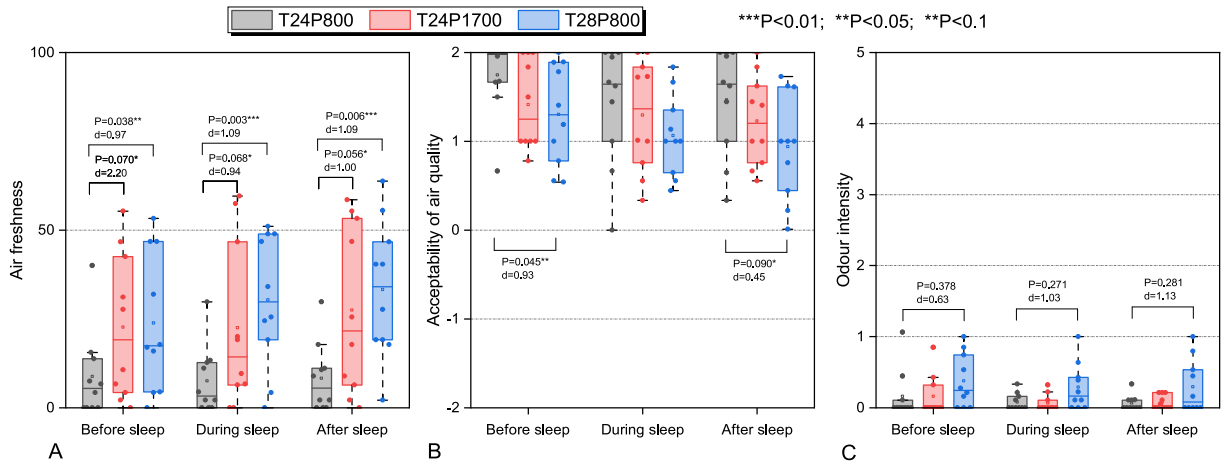


Fig. 5. Ratings of (A) air freshness; (B) acceptability of air quality; and (C) odour intensity before, during (recalled), and after sleep under the different conditions. Cohen's d is indicated; its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

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.

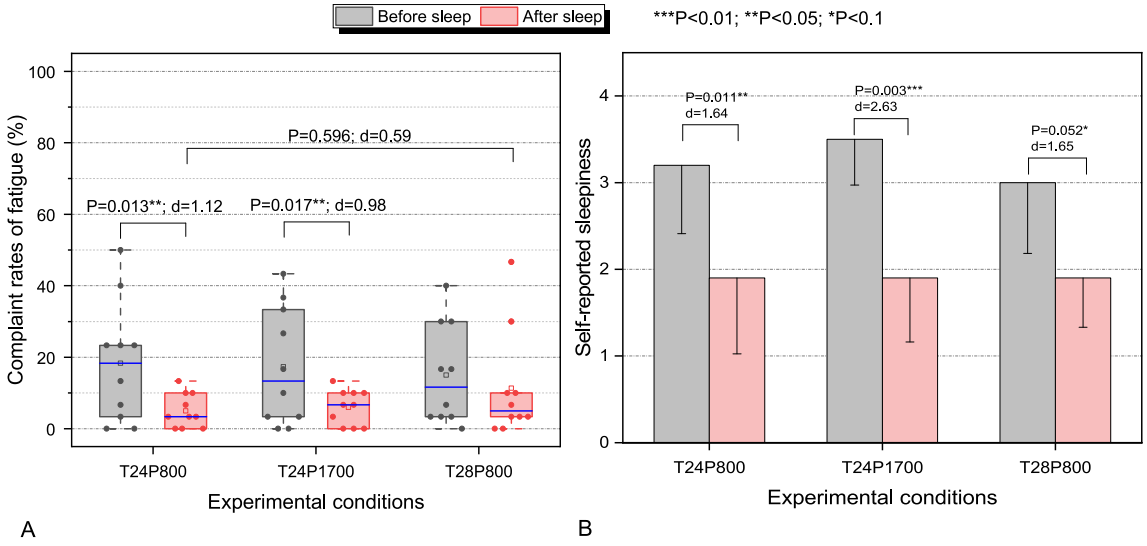


Fig. 6. (A) The complaint rates of fatigue; and (B) sleepiness before and after sleep under the three conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

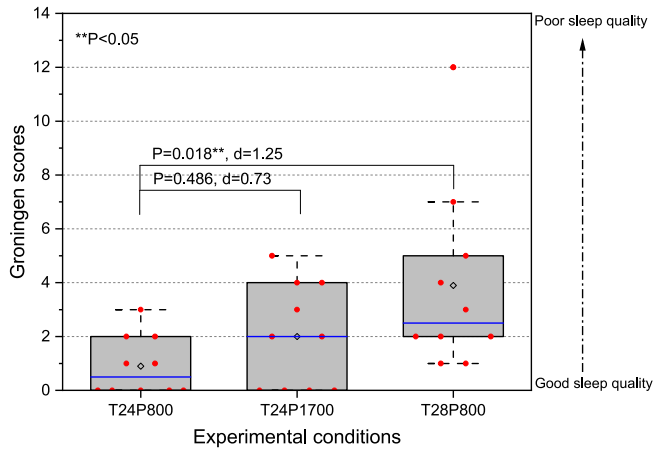


Fig. 7. Subjective measurements of sleep quality in the three conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

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].

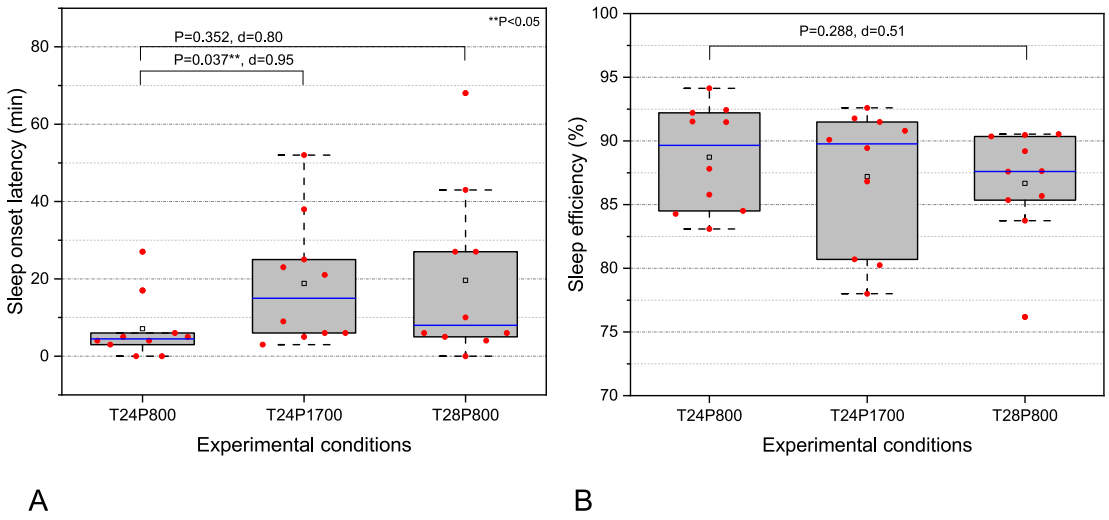


Fig. 8. (A) Sleep onset latency and (B) sleep efficiency under three conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

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

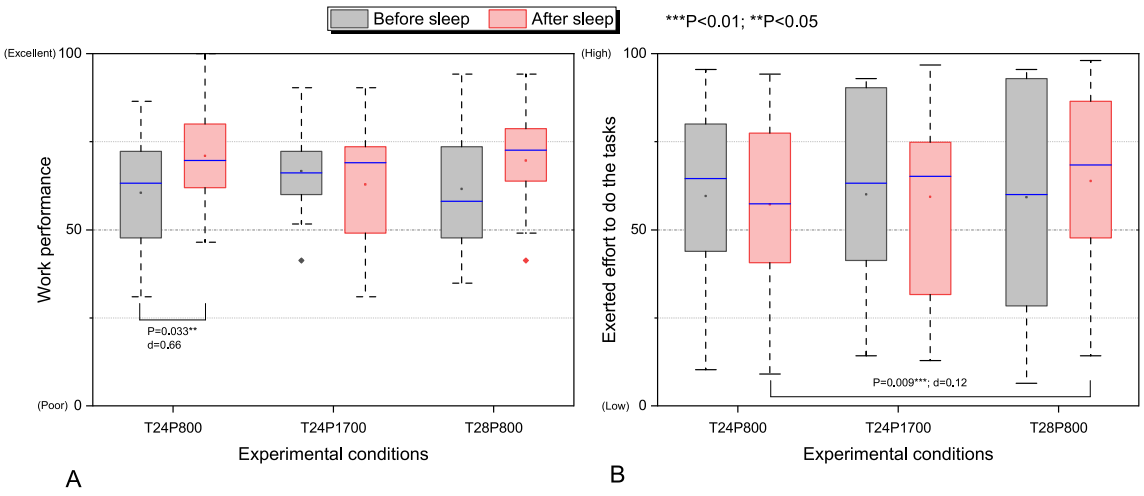


Fig. 9. Self-reported (A) work performance; and (B) exerted effort to do the tasks before and after sleep under the three conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

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.

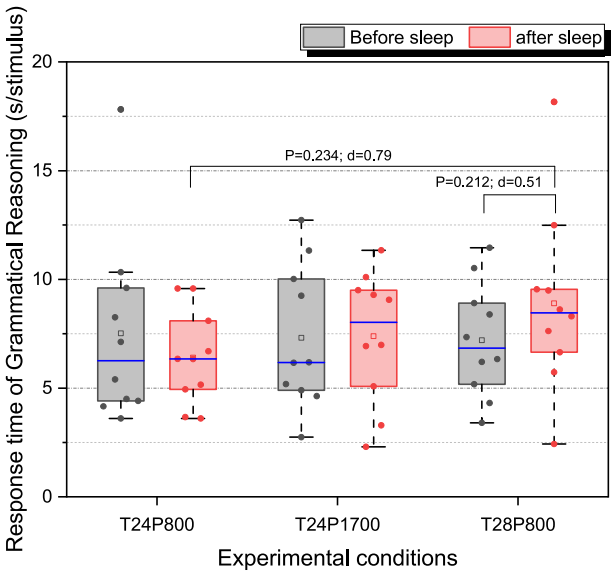


Fig. 10. The response time in the Grammatical Reasoning test before and after sleep under three conditions. Cohen's d is indicated. Its values of 0.2, 0.5, 0.8 indicate the small, medium, and large ES.

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.

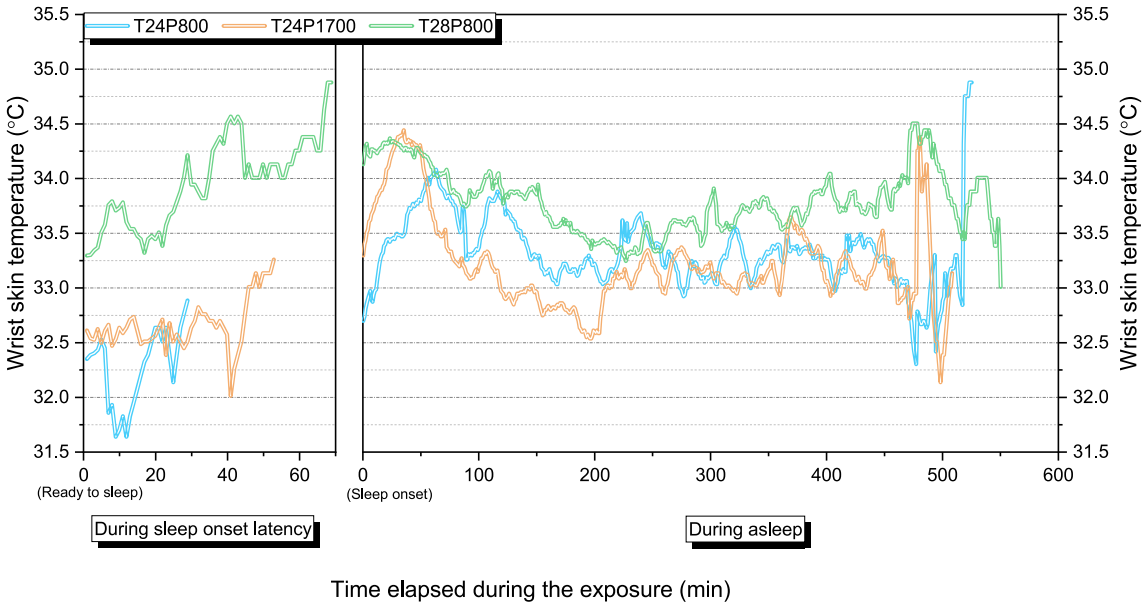


Fig. 11. Wrist skin temperature in each condition during sleep.

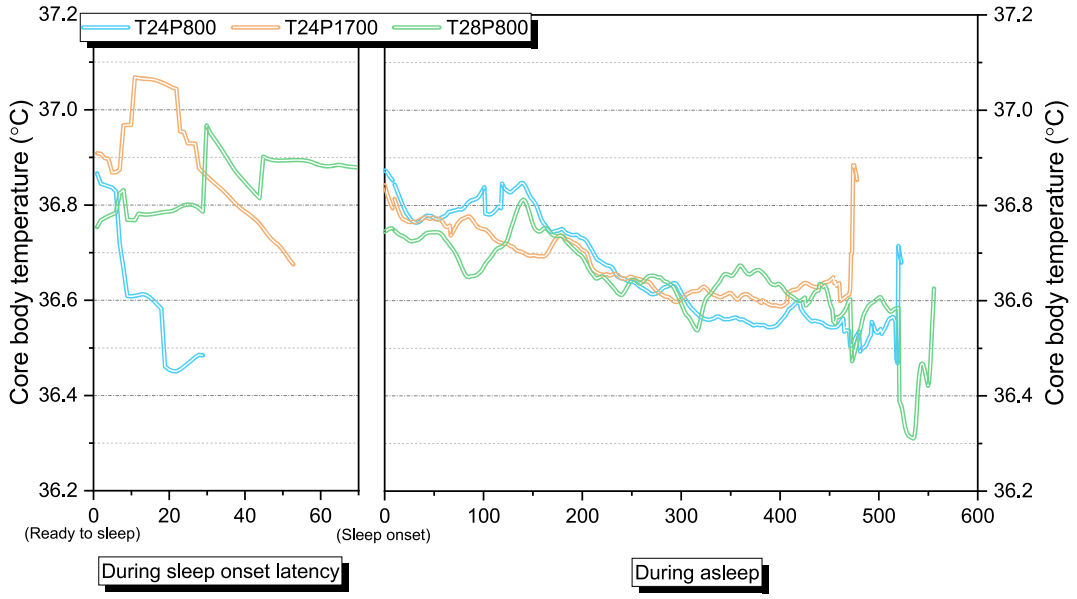


Fig. 12. Core body temperature in each condition during sleep (Temperature effects: $P > 0.1$; $d < 0.5$; ventilation effects: $P > 0.1$; $d < 0.5$).

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.

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Paper 4

Fan, X., Liao, C., Matsuo, K., Verniers K., Laverge, J., Neyrinck, B., Pollet, I., Fang, L., Lan, L., Sekhar, C., and Wargocki, P., 2023 A single-blind field intervention study on improved bedroom ventilation and sleep quality. **Submitted to Science of The Total Environment (under revision)**

A single-blind field intervention study of whether increased bedroom ventilation improves sleep quality

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ABSTRACT

A four-week-long field intervention experiment was conducted in twenty-nine bedrooms with extract ventilation systems and air inlet vents. During the first week no interventions took place. In the three weeks that followed, each participant slept for one week under a low, medium, and high ventilation rate condition (target outdoor airflow rates were 3, 10 and 30 m^3/h respectively) in balanced order. These conditions were established by covertly altering the fan speed of the exhaust ventilation system without changing other settings. Participants were not informed when or even whether the changes to bedroom ventilation would be executed. The bedroom environmental quality was monitored continuously and sleep quality was monitored using wrist-worn trackers. Tests of cognitive performance were conducted in the evening and morning. The estimated actual ventilation rates based on measured carbon dioxide (CO_2) concentrations were higher than the nominal values. In twelve bedrooms where clear differences in air quality between the three conditions occurred, as indicated by the measured CO_2 concentrations, participants had significantly less deep sleep, more light sleep and more awakenings in the low ventilation rate condition. In twenty-three bedrooms where a clear difference in ventilation rate between the high and low setting conditions was observed, as confirmed by the measured CO_2 concentrations, the duration of deep sleep was significantly shorter in the low ventilation rate condition. No differences in cognitive performance between conditions were observed. In the low ventilation rate condition, the concentrations of CO_2 and $PM_{2.5}$ increased, as did the relative humidity, while bedroom temperatures remained unchanged. The present results, which were obtained in actual bedrooms, confirm the findings in previous studies of a positive effect of increased ventilation on sleep quality. Further studies with larger populations and better control of bedroom conditions, particularly ventilation, are required.

Keywords: *Bedroom air quality ; Mechanical extract ventilation; Sleep quality; Outdoor air supply rate; Field intervention*

1. INTRODUCTION

Sleep is vital for a well-functioning life. Poor sleep quality has been associated with increased morbidity for a series of diseases including inflammation and cardiovascular diseases (Miller and Cappuccio, 2007; Ohayon et al., 2017) and suicidal ideation (Wu et al., 2022). It has also been shown to affect next-day work performance negatively (Lee et al., 2021; SWANSON et al., 2011). These effects have been estimated to cause significant economic losses (Hafner et al., 2016).

The National Sleep Foundation in the U.S. recommends sleeping for 7 to 9 hours every night (Hirshkowitz et al., 2015). This means that about one-third of the typical lifetime of a person is spent in those environments where sleeping takes place, which predominantly are bedrooms in dwellings. It is therefore crucial that bedroom environmental quality does not reduce sleep quality (Ohayon and Zulley, 2001). Several recent studies have shown that thermally uncomfortable environments, poor bedroom air quality and inadequate bedroom ventilation all decrease sleep quality (e.g., (Fan et al., 2022a, 2022b; Lan et al., 2021, 2019, 2014; Pan et al., 2012; Strøm-Tejsen et al., 2016; Xu et al., 2020; Yan et al., 2022b)).

Bedroom ventilation and its effects on sleep quality have only recently been in focus (e.g., (ASHRAE Residential Buildings Committee, 2022)). Bedroom ventilation can be improved by opening a window or door, by specially designed natural ventilation, or by a dedicated mechanical ventilation system, i.e., mechanical extract ventilation with outdoor air inlet vents to the bedroom or a fully balanced system with supply and exhaust ventilation (Liao et al., 2021a; Sekhar et al., 2020a, 2020b). Current standards and guidelines often stipulate ventilation rates for the entire dwelling and generally lack specific recommendations for the ventilation of bedrooms (Sekhar et al., 2020a). An attempt to provide some recommendations was recently made, in which a tentative relationship between sleep quality and bedroom ventilation indicated by the carbon dioxide (CO_2) concentration was developed based on published data, although they were limited (Akimoto et al., 2021; Sekhar et al., 2020a). The association suggests that bedroom ventilation should ensure that the CO_2 concentration remains ≤ 800 ppm, which would correspond to a ventilation rate of at least 10 L/s per person using published CO_2 emission data from sleeping people (Fan et al., 2021). According to this relationship, ventilation rates at which CO_2 levels are ≥ 1,150 ppm would consistently disturb sleep and ≥ 2,600 ppm would additionally reduce next-day work performance. More research is needed to validate this proposed relationship.

The effects of bedroom ventilation on sleep quality have been investigated in chamber studies and field experiments. In the former, the participants did not sleep in their own bedrooms but in specially constructed sleeping capsules or chambers or spaces adapted to serve or mimic bedrooms where ventilation and other indoor environmental parameters could be controlled (Fan et al., 2022b; Lan et al., 2021; Xu et al., 2020; Yan et al., 2022b). These studies showed positive effects of increased ventilation on sleep quality: wake time after sleep onset decreased (Lan et al., 2021), sleep onset latency decreased (Fan et al., 2022b; Xu et al., 2020), sleep efficiency increased (Lan et al., 2021), REM sleep increased (Yan et al., 2022b), deep sleep increased (Xu et al., 2020; Yan et al., 2022b), and subjectively rated sleep quality as assessed by the Groningen Sleep Quality Scale (GSQS) or other methods improved (Fan et al., 2022b; Xu et al., 2020). One study additionally investigated how noise from the ventilation system impacted sleep quality and found that it significantly decreased deep sleep and REM sleep, and increased light sleep (Lan et al., 2021). In these laboratory studies, besides sleep quality, several physiological responses were monitored to provide information that could be used to describe the underlying mechanisms. They included measurements of skin temperature (Fan et al., 2022b; Lan et al., 2021; Yan et al., 2022b), heart rate and its variability (Fan et al., 2022b; Yan et

al., 2022b), core body temperature (Fan et al., 2022b), respiration rate (Yan et al., 2022b), blood pressure (Yan et al., 2022b), and salivary biomarkers (Lan et al., 2021; Yan et al., 2022b). The suggested mechanisms underlying the effects of poor bedroom ventilation on sleep quality include the effects of pollutants on respiratory function and the autonomous nervous system (Yan et al., 2022b), but more supportive information is still required.

The findings from laboratory experiments require validation in actual bedrooms because they are usually based on measurements performed in environments that are not normally used for sleeping and often based on the measurements performed over one night only. Field studies have therefore been carried out to examine the relationship between bedroom ventilation and sleep quality (Fan et al., 2022a; Liao et al., 2022, 2021b; Mishra et al., 2018; Strøm-Tejsen et al., 2016; Xiong et al., 2020; Xu et al., 2021; Yan et al., 2022a; Zhang et al., 2021). Many of these studies were cross-sectional (Liao et al., 2022; Xiong et al., 2020; Xu et al., 2021; Yan et al., 2022a; Zhang et al., 2021). In these studies, sleep quality and bedroom environmental quality were monitored and subsequently their correlations were examined using statistical modelling, taking into account that sleeping conditions were changing randomly from night to night and these changes could affect sleep quality. To better explore the effects of bedroom ventilation in actual settings, some field studies used an intervention approach where bedroom ventilation was changed from week to week in a systematic fashion (Fan et al., 2022a; Mishra et al., 2018; Strøm-Tejsen et al., 2016) except for one study in which each condition was measured on only two consecutive nights (Liao et al., 2021b). In most of these studies, bedroom ventilation was varied by either opening or closing the windows or doors in actual bedrooms. Their results showed that door opening, in contrast to window opening, did not provide benefits for sleep quality even though CO_2 concentration decreased. The conclusion was that bedrooms should be ventilated with clean outdoor air. One limitation of these studies was that participants were aware of the interventions so that this could bias their responses, at least their subjective ratings, due to expectation: they knew that the windows or doors were open or closed. It was also impossible to identify the airflow direction in the bedrooms, which is crucial for assessing the effect of ventilation (Sekhar et al., 2020b). Field studies examining the effects of improved ventilation by mechanical ventilation systems are lacking. In a study to address this gap that showed positive effects of increased ventilation on sleep quality (Strøm-Tejsen et al., 2016), ventilation was changed by operating or idling inaudible fans supplying outdoor air to bedrooms; the study was performed with students in a dormitory building. In this study and in many other studies to date students were recruited to sleep in chambers or measurements were made in student dormitory buildings and not in conventional dwellings (Fan et al., 2022b; Liao et al., 2021b; Mishra et al., 2018; Strøm-Tejsen et al., 2016; Xu et al., 2020). This may limit the application of the findings and their extrapolation to other population groups and settings.

The present study aimed to examine the effects of improved ventilation on sleep quality and next-day performance while avoiding some of the limitations that characterized the studies described above. It was a single-blind field experiment in which systematic interventions affecting outdoor air supply rates were made. To ensure realism, the study was performed in dwellings occupied by the general public rather than on students in dormitory buildings. Bedroom ventilation was modified by changing the set point of the extract ventilation systems installed in the dwellings, and the occupants of the dwellings participating in the experiment were not informed when these changes would be made.

2. METHODS

2.1 Approach

The experiments were performed in October 2021 in Belgium, where during this period there were no COVID-19 lock-down or severe pandemic restrictions. The bedrooms selected for the study were all ventilated by mechanical ventilation systems where the ventilation rate could be changed without informing the occupants or entering the dwellings. To meet this objective, we identified a suitable pool of centralized exhaust ventilation systems in Belgium. These systems were installed individually in each dwelling and ensured ventilation with outdoor air through "trickle" vents (small air inlets) at each window; the extract fan was installed in the central unit and could be remotely controlled and surveyed via the manufacturer's specially developed control platforms. The manufacturer of these systems (Renson Ventilation NV) agreed to participate in the study. Occupants who had the system installed in their bedrooms were invited to participate in the present experiment. Three different mechanical extract airflow rates were set in each bedroom in successive weeks, each condition lasting for one week, following a reference week in which data was obtained but no interventions took place. Each occupant participating in the study received a set of instruments consisting of a bedroom environmental quality monitor and a wrist-worn sleep tracker; they were sent by ordinary mail so that experimenters did not need to enter the dwellings. The participants kept the instruments as a token of appreciation of their participation in this study once the measurements had been completed. They registered the instruments online so that the study team could access all the measurements through the Cloud. In addition, they registered for two online surveys (called morning and evening sleep diaries) to collect their subjective judgments of bedroom environmental quality and performed cognitive tasks on specified evenings and mornings. All data were pseudonymized. Because of the GDPR rules, all contacts between the participants and the study team were conducted by the manufacturer of the systems, who followed our instructions regarding the experimental protocol.

2.2 Participants

Prior Power Analysis (G*Power) was performed to determine the minimum sample size with the following settings: ANOVA with repeated measurements within factors, effect size of 0.5, a statistical power of 0.8, a non-sphericity correction factor of 0.5, and a correlation among repeated measures of 0.5. This indicated that fifteen participants was the minimum size.

The study invitation was sent via an existing telephone Application (referred to in the following as the "app") as a push notification to several thousand customers who had installed the ventilation system in their dwellings and were using the app to control it; 172 agreed to participate (response rate <10%), and 34 who met the selection criteria were recruited; two of them shared the same bedroom. They were divided into three groups to ensure proper balancing and sufficient sample size even if there were some unexpected problems. Of the 34 participants, 29 completed the four-week measurements but usable data for analysis were available for only 23 participants, which is still higher than the minimum sample size of 15. All the occupants who agreed to participate completed an online questionnaire during the recruitment process. The questionnaire was used to collect anthropometric data, information on health conditions and dietary habits, the characteristics of their bedrooms, dwellings, and surroundings, the bedroom ventilation system and airing behaviour, work pattern and sleep habits including the questions allowing derivation of the Pittsburgh Sleep Quality Index (PSQI) describing whether they had experienced any problems with sleep over the past month prior to the study. A similar questionnaire has been used in previous studies (Fan et al., 2022a; Liao et al., 2022, 2021a). Table 1 summarizes the anthropometric data of all 29 participants who completed the measurements. All the participants were daytime workers, free of chronic disease (such as asthma,

rhinitis, hay fever, eczema, headache, and diabetes), with no hearing/smelling impairment, and were not taking any medication or sleeping pills during the experimental period. The exclusion criteria included a history of alcohol or drug abuse and any significant sleep disorder over the past month.

Most participants were males, non-smokers, had been living in Belgium for ≥ 2 years prior to this study, had no children living at home throughout the measurements, and did not experience sleep problems (for all PSQI (Buysse et al., 1989) was below 8 and for the majority it was below 5). The BMI of these participants was ≥18.5 kg/m^2. Half the participants were below 40 years old and half of the total were office workers.

None of the participants lived in a dormitory and the majority had bedrooms on the first floor in either detached or row houses. Most buildings had been renovated over one year prior to the experiment or had not been refurbished at all. Less than half of the bedrooms were single-occupied during the measurement period.

The recruited participants were provided with all necessary information about the study and detailed instructions via email and videos posted on a YouTube channel (https://www.youtube.com/@jonatan7988/featured). They were asked to keep their lifestyle unchanged during the entire experiment.

We additionally invited 12 occupants whose bedrooms did not have the mechanical ventilation system to participate in this study as a control group. However, complete data from only two participants were obtained. We therefore decided not to report these data.

2.3 Measurements

Measurements included objectively measured and subjectively rated bedroom environmental quality, sleep quality, and cognitive performance. They were all performed in bedrooms and by the participants themselves; the study team did not enter their bedrooms. As indicated earlier, all necessary details about the bedrooms such as location and airing behaviour were collected through the online survey.

The bedroom environmental quality was continuously monitored at intervals of 5 minutes with the Sense unit (Renson Inc, Belgium). It had a built-in temperature sensor (accuracy: ±0.2°C; range: 0 to 65 °C), a humidity sensor (accuracy: ±2%; range: 10 to 90%), a carbon dioxide (CO_2) sensor (accuracy: ±30 ppm + 3% of reading; range: 400 to 5,000 ppm), and particulate matter (PM) sensors allowing measurements of particles with an aerodynamic diameter ≤ 1 µm (PM_1), 2.5 ($PM_{2,5}$), 4 µm (PM_4), and 10 µm (PM_{10}) (accuracy: ± 10 µg/m^3; range: 0 to 100 µg/m^3); all sensors were factory calibrated. The Sense unit also provided measurements of the total concentration of volatile organic compounds (TVOCs), although as we could not verify the quality of measurement or what types of pollutants caused the response of the sensor we did not use these data in the main analyses; they are however presented for reference in the Supplementary Information (SI). The Sense unit also measured sound pressure level in dB(A) but as the measured data were unreliable they were not used in the main analyses although as in the case of TVOCs they are presented for reference in the SI.

Upon receipt, the participants paired the Sense unit with the dedicated App on their Internet-connected smartphone or tablet and placed it at bed height about 1 m away from the pillow, preferably on a night table as in previous studies (e.g., (Canha et al., 2017; Fan et al., 2022a; Liao et al., 2022)). The Sense unit was always switched on and data were automatically transferred to the Cloud; in this way the study team had access to all the measured data.

Together with the Sense unit, the participants received sleep trackers to register their sleep quality. The sleep tracker was a wrist-worn actigraphy watch that also recorded heart rate (Fitbit Charge 4); it was worn on the non-dominant wrist. It registered total sleep duration, time in bed, number of awakenings, and sleep architecture (total time awake after sleep onset, deep sleep, light sleep and Rapid Eye Movement (REM) sleep). Upon receipt, the participants paired the sleep tracker with the App on their Internet-connected smartphone/tablet using the pre-defined login and password; in this way sleep data were sent to the Cloud and could be accessed by the study team.

Cognitive performance was measured using a 3-minute version of the Baddeley test of grammatical reasoning to examine how well people understand sentences of various levels of syntactic complexity (Baddeley, 1968). The test was used in previous studies measuring the effects of bedroom ventilation on sleep quality (Fan et al., 2022b, 2022a). The online version of the test created with ClassMarker was performed by the participants immediately before they went to sleep in the evening and after they woke up in the morning.

Two sleep diaries, including an evening sleep diary and a morning sleep diary similar to the ones used in the previous studies (e.g., (Fan et al., 2022a)), were used in the present study. The participants filled in the evening sleep diary immediately before going to sleep and the morning sleep diary immediately after waking up; the diaries were online and were to be completed on any two weekdays every week. However, as there was a considerable amount of missing data, we decided not to report the results from these diaries or to report them in the SI.

We also estimated the ventilation rates in bedrooms on the nights when the bedroom occupancy was available from the morning sleep diary, based on a mass balance model. The CO_2 emission rate was assumed to be 11 L/h per person for sleeping adults (Fan et al., 2021) and 10 L/h per person for sleeping children (Klausen et al., 2023). The outdoor CO_2 concentration was assumed to be 420 ppm (https://www.co2.earth/). The calculated 95^{th} percentile of measured CO_2 ($CO_{2\text{-}95\%tile}$) was used to indicate steady-state CO_2 concentration (Fan et al., 2022a).

248 Table 1 Description of participants and their bedrooms.

Items	29 participants who completed the study	23 participants for whom usable data were available [a]	12 participants for whom usable data were available [b]
Sex			
Male	23	17	12
Female	6	6	0
Age (y)			
≤ 40 (27-40)	14	13	6
> 40 (41-64)	15	10	6
BMI (kg/m²)			
< 18,5	2	2	0
18,5-24,9	10	8	6
>24,9	17	13	6
Time resident in Belgium			
≤ 1 year	3	2	1
≥ 2 years	26	21	11
Smoking			
Yes	3	2	1
No	26	21	11
The age of the youngest child at home			
No child at home	21	16	7
6-15 (y)	8	7	5
Working/studying from home			
Yes, I work/study in other functional room at home	13	11	7
No, I work/study in office	16	12	5
Sleeping alone during weekdays, excluding holidays			
Yes, I sleep alone	11	9	4
No, I sleep with spouse or partner	18	14	8
Dwelling type			
Multistory apartment building	6	4	2
Row-house (joined to another house)	11	9	5
Detached house (not joined to another house on either side)	12	10	5
Bedroom floor			
0 (Ground floor)	3	3	1
1	22	17	10
> 1	4	3	1
Major bedroom renovations (e.g. change of window(s), carpet(s), bedroom furniture(s), etc.)			
New building	5	4	2
Yes, in the last 6 months	1	1	1
Yes, 6 months to 1 year ago	3	3	1
Yes, over 1 year ago	8	7	4
No, it has not been renovated	12	8	4
PSQI score			
≤ 5	20	17	10
6-8	9	6	2

249 [a] Notable differences in CO_2 concentrations were observed between low and high ventilation rate settings.
250 [b] Notable differences in CO_2 concentrations were observed across the three ventilation rate settings.
251

252 ## 2.4 Ventilation conditions

253 The bedrooms in the present study were ventilated with outdoor air that was drawn into the bedroom
254 by the extract ventilation system through trickle vents mounted on windows. Each dwelling had its
255 own dedicated ventilation system. The ventilation system consisted of an EC (Electronically
256 Commutated) fan with control dampers connected externally. The system was connected to the Cloud
257 through the Internet and could be controlled remotely. The fan had a large impeller and a high-tech
258 active variable pressure-controlled operation so the ventilation rate could be changed by altering the
259 fan speed without noticeable changes in the noise level.

The ventilation rate was changed by remotely changing the fan speed using the specially developed control platform without the necessity to enter the dwelling. The changes were made every Friday so that each participant had slept three nights at the new ventilation rate setting before the actual measurements of sleep quality commenced; this was done to ensure adaptation to the new airflow setting. The participants were not informed when the ventilation rate was changed. They were asked to set the trickle vent on the window at the minimum opening and not to change its position during the entire experiment. They were also asked to keep the doors and windows to the bedrooms closed to reduce the risk that the air from other rooms could enter the bedroom and disturb the intended interventions and to reduce noise disturbance.

We intended to study the effects of three ventilation rates: low, moderate and high. With the help of and after consulting with the engineers from the manufacturer of the ventilation system, we estimated that the lowest ventilation rate that could be reasonably controlled would be 3 m^3/h and the highest ventilation rate which would not create noise problems and cold draught would be 30 m^3/h. We supplemented these two ventilation rates with a moderate level corresponding to 10 m^3/h to create a logarithmic progression. With one person sleeping in a bedroom these three extract flowrates would correspond to CO_2 concentrations of above 3,000 ppm and below 800 ppm under steady-state conditions for the low and the high ventilation rate setting, respectively. The actual total ventilation rates, including infiltration and adventitious ventilation obtained through open windows, if any, (Schiavon, 2014) that were estimated from the measured CO_2 concentrations differed from these intended settings; they are presented in Tables 2 and 4 and Figures 2 and 5. This gave rise to some analytical limitations, as described below.

We did not control other conditions in bedrooms and only monitored changes to some parameters describing bedroom environmental quality that could occur as a result of changing the ventilation rates or for any other uncontrolled reasons. As this study was scheduled in October in Belgium, the impact of outdoor temperature changes was expected to be low and the measurements (Tables 2 and 4) confirmed this to be the case.

2.5 Experimental design

The study lasted for four weeks. During the first week data was obtained but no interventions were made, in order to familiarize participants with the study protocol and measurements. During this week, the ventilation conditions were the result of the settings made by the participants. From then on, the ventilation rates were remotely changed every Friday in a Latin Square design with the participants divided into three groups to balance the order in which the three conditions were encountered. Only data from four nights during each week - Monday night to Friday morning - were analyzed.

This study conformed to the guidelines in the Helsinki Declaration. A digital consent form was obtained from each participant prior to the study. All the personal data from the participants were pseudonymized to comply with the General Data Protection Regulation (GDPR). Our experimental protocol was approved by the ethical committee of the Faculty of Engineering and Architecture at Ghent University (Application No. HBC.2020.2520). Participants were informed that they could withdraw from the study at any time and two participants did withdraw. We also created a “hot-line” where the participants could post their queries.

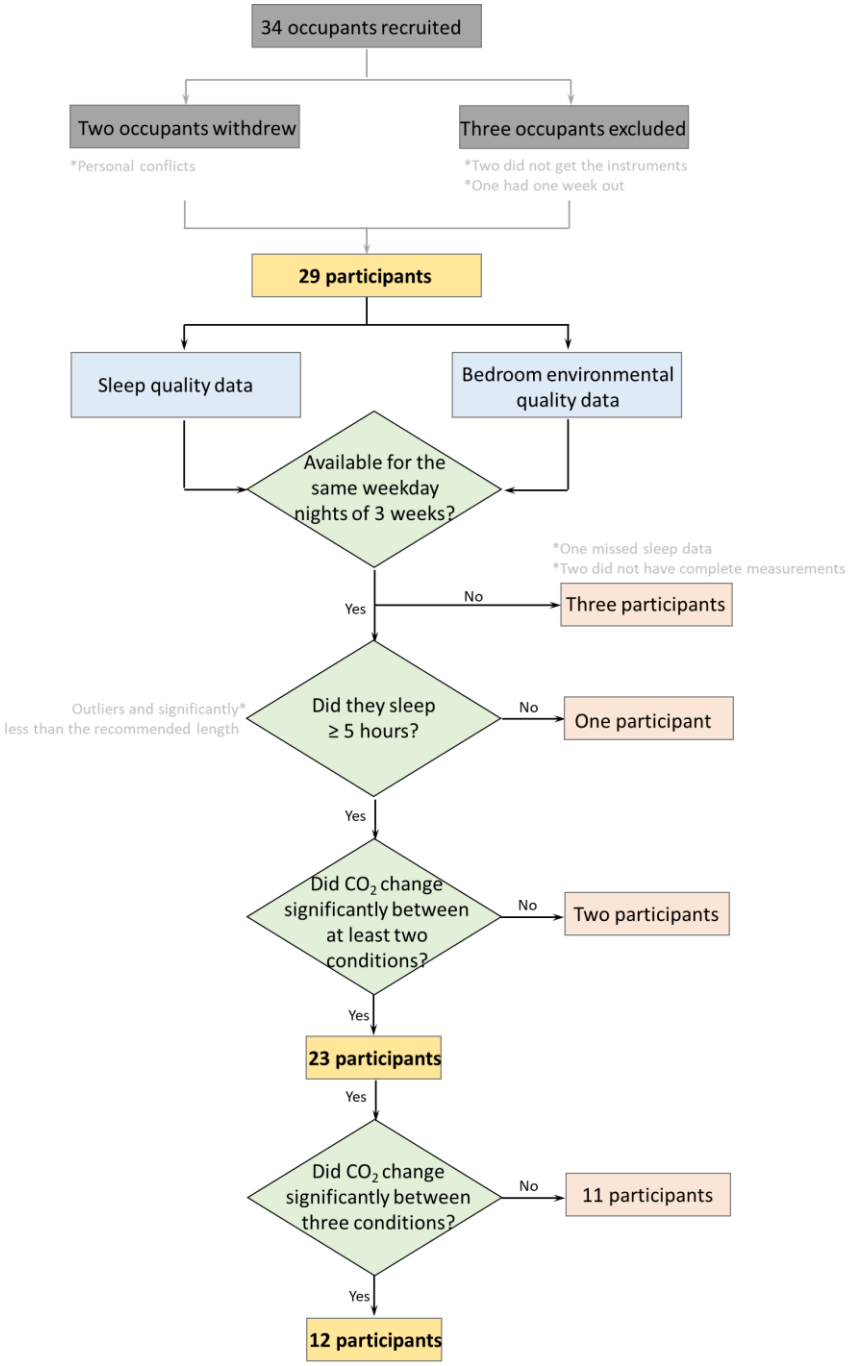

Figure 1. The flow chart describing the data screening and pre-processing.

2.6 Selection of data for the analyses

The process of data selection is shown in Figure 1. Thirty-four participants were recruited. A full set of measurements was available for twenty-nine participants; in the case of other participants recruited for the experiment, the instruments were lost in shipment for two of them, one did not sleep in his/her bedroom during one of the weeks, and two withdrew. We also excluded three participants with missing data and one who slept for less than 5 hours, as this is significantly less than what is recommended by the National Sleep Foundation in the U.S. (Hirshkowitz et al., 2015). Consequently,

we examined the data from 25 bedrooms and found that in two bedrooms, there had been no significant differences in the measured CO_2 levels between conditions, indicating that the intervention had been unsuccessful; we were unable to find out why and so excluded these data. Data from 23 bedrooms was thus available for the analysis.

We found that clear differences between the three different ventilation rate settings could only be observed in 12 bedrooms while notable differences between the low and high ventilation rate settings were found in all of the 23 bedrooms selected as described above. We therefore decided to perform analyses separately for these two data sets. Table 1 shows the characteristics of participants in these 23 and 12 bedrooms.

We used $CO_{2\text{-}95\%tile}$ during sleep as a method to evaluate the success of the intervention; this concentration is used as a proxy for the ventilation rate (Fan et al., 2022a). The time-series CO_2 concentration measured during sleep was also compared between conditions to verify the success of the intervention. The data from each participant in a given ventilation rate setting were then averaged and analyzed.

2.7 Statistical analysis

We used IBM SPSS Statistics 27 software for the data analysis. ANOVA analysis with a "within-subject" design was used to examine the effects of changing the ventilation rate. The Greenhouse-Geisser method was used to adjust the violation of sphericity, and a post-hoc analysis was performed using the Bonferroni test. For paired data, the normality of the data was determined with a Shapiro-Wilks test. Normally distributed data were analysed with a paired-sample t-test. Otherwise, we used a non-parametric Wilcoxon Matched-Pair Signed-Ranks test. The significance level was set at p=0.05 (1-Tail).

The effect size was calculated using Cohen's method (Cohen, 1988). Cohen's d was calculated based on the mean values; it distinguishes between small (d=0.2), medium (d=0.5), and large (d=0.8) effect sizes. Cohen's f was calculated based on the variance; it also distinguishes between small (f=0.1), medium (f=0.25), and large (f=0.4) effect sizes.

3. RESULTS

3.1 Twelve bedrooms

The conditions measured during sleep in 12 bedrooms where clear differences in CO_2 concentration were observed between all three ventilation rate settings are shown in Table 2. Changing the ventilation rate significantly changed CO_2 concentration, both average CO_2 concentration ($CO_{2\text{-}avg}$) and $CO_{2\text{-}95\%tile}$ and relative humidity with a large effect size, all being higher at the low ventilation rate setting, as expected. Neither the concentrations of PM nor temperature changed significantly between all three conditions as a result of changing the ventilation rate. $PM_{2.5}$ concentrations were below the 24-hour mean guideline of 15 $\mu g/m^3$ and lower than the annual guideline value of 5 $\mu g/m^3$ recommended by WHO (World Health Organization, 2021).

Table 2. Measured bedroom environmental parameters during sleep at three different ventilation rate settings (Mean±SD). **p≤0.01.

Parameters	Low ventilation rate setting	Moderate ventilation rate setting	High ventilation rate setting	F	P	Cohen's f
$CO_{2\text{-Avg}}$ (ppm)	1927±460	1298±296	856±118	37.46	**<0.001****	**0.42**
$CO_{2\text{-95\%tile}}$ (ppm)	2527±633	1540±373	983±150	43.41	**<0.001****	**0.80**
PM_1 (μg/m^3)	2.9±1.9	2.9±0.8	2.4±0.5	0.78	0.418	0.25
$PM_{2.5}$ (μg/m^3)	3.3±2.0	3.2±0.9	2.6±0.5	1.03	0.346	0.28
PM_4 (μg/m^3)	3.4±2.0	3.2±1.0	2.6±0.5	1.27	0.293	0.30
PM_{10} (μg/m^3)	3.4±2.0	3.2±1.0	2.6±0.5	1.31	0.284	0.31
Temperature (°C)	22.2±1.3	22.1±1.3	22.0±1.3	0.98	0.356	0.27
Relative humidity (%)	57±7	54±4	53±6	9.71	**<0.001****	**0.50**

Figure. 2 depicts the estimated ventilation rates using a mass balance model at the three different ventilation rate settings. The estimated ventilation rates in bedrooms were on average 5-9 m^3/h higher than the extract ventilation rate setpoints. The ventilation rate at the low ventilation rate setting was on average 11 m^3/h although the extract rate set point was 3 m^3/h, 19.1 m^3/h at moderate ventilation rate setting although the extract rate set point was 10 m^3/h, and 34.5 m^3/h at high ventilation rate setting although the extract rate set point was 30 m^3/h. As bedroom volume varied considerably between participants, these outdoor air supply rates resulted in a wide range of bedroom air change rate (ACH) per hour, but the median ACH values were estimated from the available data to be 0.3 h^{-1}, 0.4 h^{-1} and 0.7 h^{-1}, respectively, for the low, moderate, and high ventilation rate settings, as shown in Figure S1A in the SI. It also shows the ACH values estimated in the first week, in which the median ACH was 0.7 h^{-1}, the same as at the high ventilation rate setting.

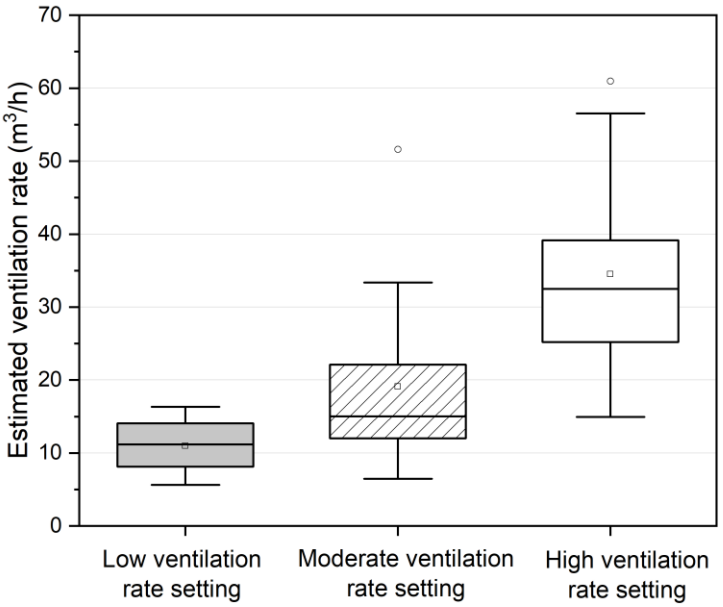

Figure 2. The estimated ventilation rates in bedrooms at the three ventilation rate settings.

Figure 3 shows the changes in measured CO_2 and relative humidity at the three different ventilation rate settings and their variation at each ventilation rate setting. Increasing the ventilation rate

significantly reduced CO_2 concentration with a large effect size. At the low ventilation rate setting $CO_{2\text{-}Avg}$ was in the range of 1324-2787 ppm, while at the high ventilation rate setting it was in the range of 708-1043 ppm. The relative humidity was significantly higher at the low ventilation rate setting with a medium effect size; it was generally between 50% and 60% on average.

Table 3 shows the results of objectively measured sleep quality and the appropriate range for good sleep quality recommended by the National Sleep Foundation in the U.S. (Hirshkowitz et al., 2015; Ohayon et al., 2017). Participants in this study generally had a good sleep quality: their sleep length, sleep efficiency and sleep onset latency were on average within the recommended ranges. The percentage of deep and REM sleep were both slightly lower than the recommended range but within the range that could indicate either good or bad sleep quality. Significant differences were observed for the number of awakenings and the percentage of light sleep and deep sleep with a large effect size. The post-hoc analysis is shown in Figure 4. It shows that when increasing ventilation from low to moderate, the number of awakenings (close to medium effect size) and the percentage of light sleep (close to large effect size) significantly increased, while the percentage of deep sleep decreased significantly with a large effect size. At the low ventilation rate setting the number of awakenings was significantly more with an effect size close to medium, the percentage of deep sleep was shorter with a medium effect size although the difference was not significant when compared to the high ventilation rate setting.

There were no significant differences in the performance of the Baddeley test between the three different ventilation rate settings as shown in Table S1 in the SI.

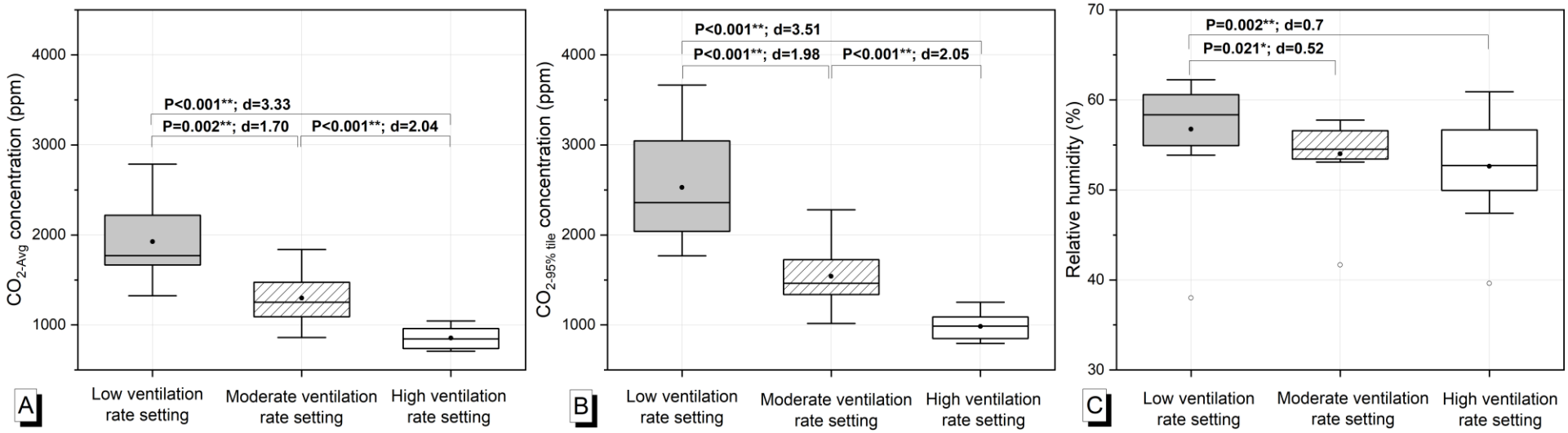

Figure 3. (A) $CO_{2\text{-}Avg}$ concentration; (B) $CO_{2\text{-}95\%tile}$ concentration; (C) relative humidity at the three different ventilation rate settings. **p≤0.01; 0.01<*p≤0.05.

Table 3. Measured sleep quality parameters at the three ventilation rate settings and recommendations for good sleep quality. **p≤0.01; 0.01<*p≤0.05.

Sleep quality parameters	Low ventilation rate setting	Moderate ventilation rate setting	High ventilation rate setting	F	P	Cohen's f	Recommended range for good sleep quality [a]
Duration of sleep (min.)	426.4±31.8	414.6±37.5	424.4±43.8	0.69	0.515	0.24	420-540 min
Sleep onset latency (min.)	4.8±4.9	4.8±6.0	6.6±12.3	0.21	0.815	0.13	≤ 30 min
No. of awakenings	27±12	23±11	22±13	5.80	**0.009****	**0.48**	N/A [b]
Sleep efficiency (%)	87.8±2.4	88.5±2.9	87.7±3.5	0.60	0.560	0.22	≥ 85%
REM sleep (%)	19.1±5.2	20.2±5.6	18.7±4.4	0.79	0.469	0.27	Between 21-30%
Wake after sleep onset sleep (%)	11.6±2.9	10.7±2.8	12.0±1.8	1.02	0.379	0.30	N/A [b]
Light sleep (%)	56.8±7.4	51.5±6.7	54.2±5.8	3.83	**0.041***	**0.46**	N/A [b]
Deep sleep (%)	12.6±4.8	17.5±6.7	15.1±4.4	5.77	**0.012***	**0.49**	Between 16-20%

[a] Recommendations for adults by National Sleep Foundation in the U.S. (Hirshkowitz et al., 2015; Ohayon et al., 2017)

[b] The definition by National Sleep Foundation in the U.S. is different from what was registered by the sleep tracker.

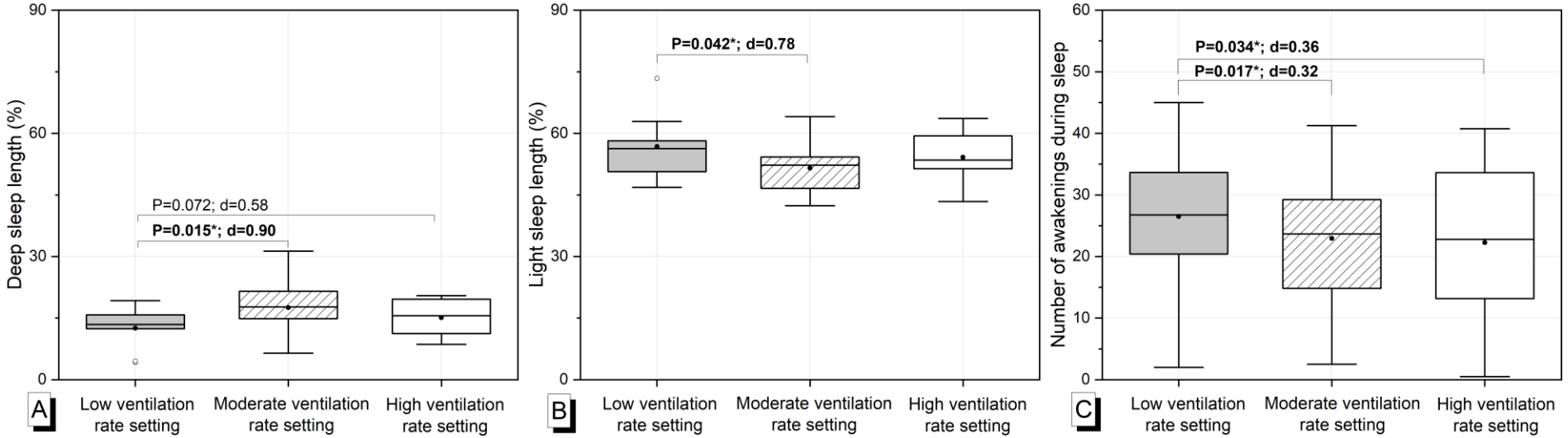

Figure 4. (A) Deep sleep; (B) light sleep; and (C) the number of awakenings at the three ventilation rate settings. 0.01<*p≤0.05.

3.3 Twenty-three bedrooms

Measured environmental conditions in the 23 bedrooms where clear differences in measured CO_2 concentration were observed between the low and high ventilation rate settings are shown in Table 4. Besides the significant differences in CO_2 concentration and relative humidity with a large effect size, corresponding to what was observed for 12 bedrooms (Table 3), the concentration of $PM_{2.5}$ was significantly higher with a large effect size at the low ventilation rate setting, although it was still on average lower than the 24-hour guideline value set by WHO (World Health Organization, 2021).

Table 4. Measured bedroom environmental parameters during sleep at the high and low ventilation rate settings (Mean±SD). **p≤0.01; 0.01<*p≤0.05.

Environmental parameters	Low ventilation rate setting	High ventilation rate setting	P	Cohen's d
$CO_{2\text{-Avg}}$ (ppm)	1369±433	812±166	**<0.001****	**1.74**
$CO_{2\text{-95\%tile}}$ (ppm)	1703±636	928±201	**<0.001****	**1.68**
PM_1 (μg/m^3)	3.1±1.9	2.3±0.6	0.057	0.54
$PM_{2.5}$ (μg/m^3)	3.3±2.1	2.5±0.6	**0.047***	**0.54**
PM_4 (μg/m^3)	3.4±2.1	2.6±0.6	0.057	0.54
PM_{10} (μg/m^3)	3.4±2.1	2.6±0.6	0.057	0.54
Temperature (°C)	22.6±1.4	22.4±1.6	0.061	0.1
Relative humidity (%)	55±6	52±5	**<0.001****	**0.55**

Figure. 5 depicts the estimated ventilation rates using a mass balance model for the low and high ventilation rate settings. The ventilation rate was on average 20.2 m^3/h at the low ventilation rate setting, which is much higher than the intended level of 3 m^3/h, and 43.0 m^3/h at the high ventilation rate setting, which is considerably higher than the intended level of 30 m^3/h. The median ACH at the high ventilation rate setting was 0.7 h^{-1}, the same as in the first week (Figure S1B in the SI). It was 0.4 h^{-1} at the low ventilation rate setting.

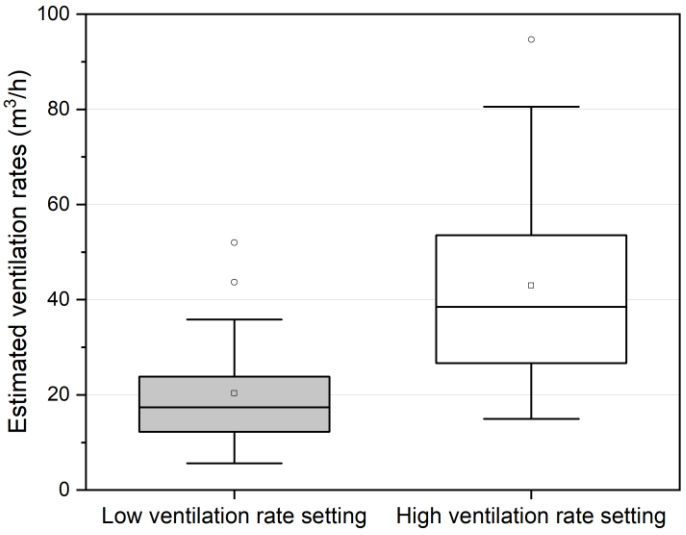

Figure 5 Estimated ventilation rates during sleep at the low and high ventilation rate settings.

Table 5. Measured sleep quality parameters at the low and high ventilation rate settings (Mean±SD) and recommendations for good sleep quality. 0.01<*p≤0.05.

Sleep quality parameters	Low ventilation rate setting	High ventilation rate setting	P	Cohen's d	Recommended range for good sleep quality [a]
Duration of sleep (min.)	421±44	427±38	0.865	0.13	420-540 min
Sleep onset latency (min.)	5.2±5.6	6.7±7.5	0.601	0.23	≤ 30 min
No. of awakenings	26±9	25±10	0.248	0.08	N/A [b]
Sleep efficiency (%)	87.0±2.6	87.4±2.1	0.247	0.18	≥ 85%
REM sleep (%)	19.2±4.5	19.1±3.9	0.401	0.02	Between 21-30%
Wake after sleep onset sleep (%)	12.1±2.9	11.3±2.1	0.106	0.30	N/A [b]
Light sleep (%)	55.0±6.4	54.3±5.7	0.318	0.11	N/A [b]
Deep sleep (%)	13.7±4.6	15.2±4.1	**0.041***	**0.35**	Between 16-20%

[a] Recommendations for adults by National Sleep Foundation in the U.S. (Hirshkowitz et al., 2015; Ohayon et al., 2017)

[b] The definition by National Sleep Foundation in the U.S. is different from what was registered by the sleep tracker.

The objectively measured sleep quality at the low and high ventilation rate settings is summarized in Table 5. This table also shows the appropriate range for good sleep quality as recommended by the National Sleep Foundation in the U.S. (Hirshkowitz et al., 2015; Ohayon et al., 2017). The sleep onset latency and sleep efficiency were on average < 30 min. and > 85%, respectively, indicating good sleep quality. The percentage of REM and deep sleep was in the "uncertain" range, which may indicate good or bad sleep quality. The percentage of deep sleep was significantly shorter at the low ventilation rate setting, with an effect size close to medium. No other sleep quality parameters differed significantly between conditions.

There were no significant differences between conditions in the performance of the Baddeley test at the low and high ventilation rate settings (Table S1 in the SI).

4. DISCUSSION

The present results show that at the low ventilation rate setting the conditions in the bedrooms were the worst, and that they had negative effects on sleep quality. Increasing the ventilation rate improved both bedroom air quality and the sleep quality parameters. The former was indicated by lower $PM_{2.5}$ and CO_2 levels; TVOCs were also reduced (Figure S2 in the SI) but as indicated in the Methods section we did not consider these results as reliable as they could be influenced by the levels of relative humidity and we could not verify which pollutants caused the sensor response. Improved sleep quality was indicated by more deep sleep, less light sleep and fewer awakenings. The intervention did not change the temperature so the effects observed in this study can be attributed to improved air quality that probably affected the human respiratory system and the autonomic nervous system, as suggested by Yan et al. (Yan et al., 2022b), so as to have a negative effect on sleep quality. However, no mechanism can be identified because no physiological measurements were carried out. The present results are similar to what have been reported in the literature, in the case of laboratory studies (Fan et al., 2022b; Lan et al., 2021; Xu et al., 2020; Yan et al., 2022b), field intervention studies (Fan et al., 2022a; Liao et al., 2021b; Mishra et al., 2018; Strøm-Tejsen et al., 2016) and cross-sectional studies (Liao et al., 2022; Xiong et al., 2020; Yan et al., 2022a; Zhang et al., 2021). We believe that compared with other studies the results in the present study are unique because the effects were

observed in bedrooms in actual dwellings, not in dormitories or laboratories, with adult participants and by changing the set-points of a pre-installed extract ventilation system. Confirmation in bedrooms with a fully balanced mechanical system is still required.

No significant effects on next-day work performance were observed in the present study, nor were such effects observed by Fan et al. (Fan et al., 2022a, 2022b) who also used the Baddeley test to examine cognitive work performance. These results differ from the findings observed by Strøm-Tejsen et al. who found that the performance of the Baddeley test was reduced after sleeping in bedrooms with poor ventilation (Strøm-Tejsen et al., 2016). This discrepancy is probably caused by differences in exposure conditions. In the present study and in the studies of Fan et al. (Fan et al., 2022a, 2022b), the $CO_{2\text{-Avg}}$ concentrations were below 2,000 ppm while in the study of Strøm-Tejsen et al. (Strøm-Tejsen et al., 2016) they reached nearly 2500 ppm, which may suggest that higher levels of pollutants are needed to cause measurable effects on performance. There could also be other reasons for these differences and this should be further investigated in future studies. It is important to note that in the present study and in the study of Strøm-Tejsen et al. (Strøm-Tejsen et al., 2016) the effects of poor sleep and exposure to poor air quality on work performance could not be separated, whereas in the study of Fan et al. (Fan et al., 2022b), the Baddeley test was always performed under neutral conditions outside the bedroom after sleeping under different ventilation conditions. Future experiments should attempt to discriminate between the effects on performance attributable to poor sleep quality and exposure to poor bedroom air quality during the test of cognitive performance.

The present study does support to some extent the tentative relationship between bedroom ventilation (as indicated by the $CO_{2\text{-Avg}}$ concentration) and sleep quality proposed in two recent reviews (Akimoto et al., 2021; Sekhar et al., 2020a). The relationship predicts that no effects of bedroom ventilation on sleep quality are to be expected at a $CO_{2\text{-Avg}}$ concentration below 800 ppm, while concentrations above 1,150 ppm would be expected to cause significant negative effects on conventional measures of sleep quality. In the present study, the $CO_{2\text{-avg}}$ concentration at the low ventilation rate setting was above 1,300 ppm and it was ca. 800 ppm at the high ventilation rate setting. More research is needed to determine the bedroom ventilation rate at which no disturbance to sleep quality would occur due to poor air quality. At present it would appear that concentrations of $CO_{2\text{-Avg}}$ below 800 ppm or a ventilation rate above 10 L/s per person would meet this goal (Fan et al., 2021).

All of the bedrooms in the present study had extract ventilation with trickle vents installed on the windows. This means that the bedrooms were ventilated directly with outdoor air. A previous intervention study in Denmark showed that ventilating bedrooms with outdoor air by opening the windows improved sleep quality, but this was not observed when they were ventilated with air from other rooms in the dwelling by opening an internal door (Fan et al., 2022a). We can assume that no air from other rooms in the dwellings entered the bedroom in the present study because we asked participants to sleep with the internal door to the bedroom closed. The air used for ventilating bedrooms in the present study was assumed to be clean (although it was not filtered) as shown by the levels of PM. This solution should only be used in areas with low outdoor air pollution. Additionally, this ventilation principle can allow penetration of ambient noise into the bedroom. This was observed by e.g. Strøm-Tejsen et al. where subjects reported higher noise levels when the windows were open (Strøm-Tejsen et al., 2016). We could not verify whether the ambient noise influenced the sleep quality in the present study. However because the windows were closed and the opening of the trickle vent was unchanged (and kept at the lowest setting) there is no reason to expect changes in the noise penetrating from outdoors under the different exposure conditions in the present experiment. The noise caused by the ventilation system did not differ between the ventilation rate settings when the ventilation settings were determined in empirical trials prior to the experiment, although we could

not verify these assumptions because the measurements of sound pressure levels by the Sense unit (Figure S3 in the SI) were unreliable and only limited data on noise was included in the diaries kept by the participants. The available data from the Sense unit indicated no difference in the measured acoustic conditions between the conditions established in the bedrooms.

The relative humidity was lower at the higher ventilation rate settings, as would be expected, but the change in relative humidity was very small. The range of average relative humidity levels in the exposures was 52% to 57%. We therefore do not expect that changes in relative humidity played an important role in the present experiments.

One limitation of the present work is that the actual ventilation rates in bedrooms were within such a moderate range. This could influence the outcomes and the ability of the study to detect effects on sleep quality and cognitive performance. Because of the experimental protocol, we did not enter the measured bedrooms to measure the ventilation rates that were established at the three different settings. However, we were able to show significant and substantial differences between the ventilation rates resulting from the highest and the lowest ventilation rate settings in the 23 out of 25 bedrooms that had complete data and in the 12 bedrooms where we could use the data at all three ventilation rate settings, and although twelve bedrooms was slightly fewer than the required minimum sample size of 15 indicated by the Power Analysis, we could still show significant differences between conditions in some measures of sleep quality.

Another important limitation of the study was that because of missing data we could not ensure proper balancing of exposures among all participants. As shown in Table 6, we used a Latin Square Design in which the conditions would be changed according to the predetermined sequence in 12, 11 and 11 bedrooms. The data available did not meet our objective of proper balancing (Table 6) but it is not possible to determine whether this had any effects on the observed results.

Table 6 Balanced order of exposure to the three conditions and sample size.

Group No.	Experimental conditions				Sample size			
	Week 1	Week 2	Week 3	Week 4	Planned	completed	Three ventilation rate settings	Two ventilation rate settings
1	Reference	c	a	b	12	8 [d]	4	5
2		a	b	c	11	10 [e]	2	8
3		b	c	a	11	11	6	10

[a] Low ventilation rate setting
[b] Moderate ventilation rate setting
[c] High ventilation rate setting
[d] Two withdrew; one did not receive the measurement unit; one had one week not sleeping in the surveyed bedroom
[e] One did not receive the measurement unit

An important feature of the present study is that the participants were blind to the conditions because they were not informed when the bedroom ventilation was changed. In most previous studies, e.g. (Fan et al., 2022a; Liao et al., 2021b; Mishra et al., 2018), the participants were asked to open or close the windows or doors themselves so the results could be influenced by expectation.

Although we recruited 34 participants, only the measurements from 23 bedrooms were usable and we could not use the data from the diaries because only a limited number of usable responses were available. The recruitment invitation was sent to several thousand potential participants, but less than 10% responded, and only 34 met the selection criteria. These numbers show how difficult it is to

perform field studies of the type described in the present paper. It is more feasible to perform studies of the effects of bedroom conditions on sleep quality in "living labs" (simulated dwellings) or in climate chambers.

The present results are valid for healthy adults (27-64 years old) who do not have significant sleep disturbance (PSQI<8) and for outdoor weather conditions with moderate temperatures. Extrapolation to other groups and other climatic conditions requires further research. The observed effects on sleep quality occurred on average within the range of sleep quality parameters recommended by the U.S. National Sleep Foundation (Hirshkowitz et al., 2015; Ohayon et al., 2017). The long-term consequences of these results for health and general well-being must be examined in future studies. Our population was too small and our exposures were too short for it to be possible to draw sound conclusions on long-term effects on the general population.

5. CONCLUSIONS

Despite the difficulties in performing field intervention measurements in actual bedrooms, the present study was able to confirm the previously reported benefits of improved bedroom ventilation for objectively measured indicators of sleep quality and it supports the importance of maintaining a minimum ACH of 0.5 h^{-1} in bedrooms. A median ventilation rate below this level increased the concentrations of $PM_{2.5}$ and CO_2 in bedrooms, indicating that the concentrations of other air pollutants, especially bioeffluents, were also higher. The study was a single-blind intervention with participants who had no sleep disorders. Similar studies of different populations in different climates and better control of ventilation are still required.

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Paper 5

Fan, X., Liao, C., Bivolarova, M.P., Sekhar, C., Laverge, J., Lan, L., Mainka, A., Akimoto, M. and Wargocki, P., 2022. A field intervention study of the effects of window and door opening on bedroom IAQ, sleep quality, and next-day cognitive performance. *Building and Environment*, *225*, p.109630.

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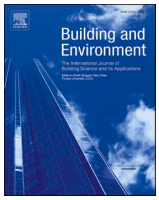

A field intervention study of the effects of window and door opening on bedroom IAQ, sleep quality, and next-day cognitive performance

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ABSTRACT

Indoor Air Quality (IAQ) and sleep quality measurements over a period of two weeks were performed all night in 40 bedrooms in Denmark during the heating season. In the first week, the bedroom conditions were typical of what participants would normally experience during sleep. In the second week, the participants were asked to open the doors or windows if they had been closed or the opposite. A change in the 95th percentile of the measured CO_2 concentration by more than 200 ppm in the expected direction on the same weekdays of the two-week measurement period was taken to indicate that an effective intervention had taken place. The measurements in the 29 bedrooms that met this criterion were grouped depending on how the windows or doors had been manipulated. Objectively measured and subjectively rated bedroom IAQ improved when the windows were open except that the NO_2 concentration was slightly higher. Sleep was longer under this condition and sleep quality was subjectively assessed to be better. Similar effects were not observed when the doors were open although the 95th percentile of CO_2 concentration decreased by as much as when the windows were open. No effects were seen in the 11 bedrooms in which the change to the bedroom conditions made by the participants did not change the CO_2 concentration by at least 200 ppm, as would be expected. The present study provides evidence that sufficient dilution and/or removal of pollutants is necessary to ensure good bedroom IAQ and good sleep quality.

1. Introduction

Sleep plays a central role in human health and well-being [1]. Good sleep quality enhances our immune system [2] and reduces the risk of obesity [3,4] and chronic diseases [3]. It also improves next-day cognitive performance (e.g. concentration, reaction time, and comprehension [5,6]) and reduces the risk of occupational injuries [7–10], all of which have economic implications.

Although limited in number, existing studies show that poor indoor air quality (IAQ) in bedrooms negatively affects sleep quality; these studies mainly focused on how changing bedroom ventilation will affect sleep quality. The IAQ in bedrooms is often characterized by measuring carbon dioxide (CO_2) which is a marker of ventilation effectiveness in the presence of building occupants [11]. Recently Sekhar et al. [12] and Akimoto et al. [13] summarized these studies and found that CO_2 levels in many bedrooms are high indicating inadequate ventilation and implying poor bedroom IAQ. They also proposed a tentative relationship between bedroom CO_2 concentration during sleep and sleep quality. This relationship suggests that CO_2 concentration should be < 800 ppm to avoid negative effects on sleep quality, that between 800 ppm and 1100 ppm sleep quality may be negatively affected, that levels above 1100 ppm have consistently been shown to have negative effects on sleep quality and that sleeping at levels >2600 ppm is likely to reduce next-day cognitive performance. Recent studies by Fan et al. [6] and Lan et al. [14] support these conclusions.

A few studies measured IAQ and pollutants in bedrooms. Canha et al. summarized these studies in a review and found that most studies

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Abbreviations

IAQ	Indoor Air Quality
CO_2	Carbon dioxide
VOCs	Total volatile organic compounds
SI	Supplementary information
SD	Standard deviation
PSQI	Pittsburgh sleep quality index
RH	Relative humidity
NO_2	Nitrogen dioxide
PM_1	Particulate matter with the aerodynamic diameter ≤1 μm
$PM_{2.5}$	Particulate matter with the aerodynamic diameter ≤2.5 μm
PM_{10}	Particulate matter with the aerodynamic diameter ≤10 μm
REM	Rapid eye movement
GSQS	Groningen sleep quality scale

measured mainly CO_2; in some studies particles, carbon monoxide, total volatile organic compounds (VOCs), and formaldehyde were also monitored [15]. Some of these pollutants exceeded limit values prescribed by standards and guidelines [16,17], although their impact on sleep quality has not yet been elucidated [18].

Ventilation is typically used to improve bedroom IAQ. Mechanical ventilation is not a common method for ventilating bedrooms [19–21]. In the Swedish housing stock, 59% of 3696 houses did not have any form of mechanical ventilation system [20]. 75% of 304 surveyed homes in Finland were naturally ventilated [21]. A recent survey in Denmark found that 40% of 475 bedrooms were naturally ventilated [19]. Natural ventilation is a method of increasing ventilation by specially designed systems that use natural forces, such as wind-driven [22] and buoyancy-driven ventilation [23], but we could not find any information on their use in the above-mentioned studies in Finland [21] or Denmark [19]. We therefore assume that natural ventilation was achieved by the opening of windows by building occupants, sometimes enhanced by opening doors. Sekhar et al. [12] reviewed international and national standards and guidelines that prescribe bedroom ventilation and concluded that many bedrooms do not meet existing ventilation requirements. This was especially the case during the heating season for bedrooms classified as having natural ventilation; in such bedrooms, window opening is the only way to increase bedroom ventilation and improve IAQ [24–30].

Although opening a window by building occupants, usually referred to as natural ventilation, is a common mean of improving IAQ in bedrooms, people may not always do so. In a recent survey in Denmark, 70% of 510 respondents preferred to keep the bedroom window closed during sleep [19]. The doors to a bedroom can also be kept open to improve IAQ, although in the above-mentioned survey in Denmark as many as 48% of respondents slept with the doors closed [19]. Similar results were observed for bedrooms in China [28,29,31]. A field study conducted in China during spring and autumn observed that both the window and door in 41% of 104 bedrooms were closed during sleep, and only 52% kept either the window or door open [32]. A Norwegian survey observed that only 39% of 1001 respondents opened bedroom windows at night [33]. A study conducted in 500 bedrooms in Denmark showed that a window was open in only 20% of the bedrooms at night, although in most of them the bedroom door was kept open [26]. This was probably because the measurements were made in children's bedrooms.

Only a few field intervention studies have been conducted to investigate the effects of window and door opening on bedroom ventilation, IAQ, and sleep quality [5,30,34–36]. Canha et al. [30] explored the effects on IAQ during sleep of four different window and door configurations in one naturally ventilated bedroom. They found that ventilation rates were increased significantly by opening the window, door, or both, resulting in a lower level of some pollutants, particularly CO_2. However, they also observed the presence of some pollutants that originated outdoors or from other parts of a dwelling, especially particulate matter. Strøm-Tejsen et al. [5] showed that increasing the ventilation rate by opening the window or turning on inaudible outdoor air inlet fans in dormitory rooms reduced sleep onset latency, increased sleep efficiency, improved subjectively rated sleep quality, improved next-day cognitive performance and reduced CO_2 concentration during sleep. Laverge and Janssens [36] reported that window opening in eight naturally ventilated dormitory rooms caused participants to report being more rested and reduced the measured duration of light sleep. The measured CO_2 concentration was also reduced. Liao et al. [35] found in a study with 27 subjects that window opening reduced snoring and the number of awakenings at night. Mishra et al. [34] observed that window or door opening in 17 bedrooms resulted in deeper sleep as reported by the participants; lower CO_2 concentrations were found, and the objectively measured number of awakenings at night decreased, sleep efficiency increased.

The studies mentioned above either did not monitor sleep quality, were cross-sectional or generally carried out in dormitories with students [5,30,34–36]. Not all of them focused on the effects of window and door opening on the levels of different pollutants in bedrooms and sleep quality. Concentration of CO_2 was a major metric used to characterize bedroom IAQ, however the effect on IAQ could be different, depending on whether the doors or windows were open even though both actions can have similar effects on CO_2 levels in bedrooms. Taking these limitations into account, our study was designed to supplement the evidence on the types of benefits that can be expected when sleeping with bedroom doors or windows open.

2. Method

2.1. Approach

The present field intervention study was carried out between September and December 2020 in the Capital Region of Denmark, where the climate is typical of a temperate zone. It is part of a large cross-sectional field measurement conducted in 84 bedrooms and focusing on bedroom ventilation and sleep quality [37]. A subset of these measurements is analysed in this study, focusing on how an intervention in bedroom ventilation affected IAQ and sleep quality. Participants slept in their own bedrooms for two consecutive weeks. In the first week, they slept under their normal bedroom conditions. In the second week, they were asked to change the bedroom ventilation conditions by opening bedroom windows or doors during the night if they had been closed in the first week, or closing them during the night if they had been open in the first week. Whether this intervention had substantively altered bedroom ventilation was determined empirically in a subsequent analysis. An online questionnaire was used to collect information on the participants, their bedrooms and sleep quality in the previous month prior to taking part in this study. The bedroom environment and each participant's sleep quality were monitored continuously using instruments and were subjectively rated by each participant in online sleep diaries that were completed on selected evenings and mornings. The intervention that was made at the end of the first week was also recorded in the sleep diary. In addition, wrist skin temperature was measured. The instruments were installed in a box that was supplied together with an envelope containing all the necessary information about the study. A short grammatical reasoning test was presented at the end of each sleep diary to objectively quantify cognitive performance before and after each night's sleep.

2.2. Participants

The participants in the present study were recruited primarily from among the respondents to an online survey that was conducted in early 2020 [19]. As too few replied to the invitation, we recruited more participants by posting the invitation on social media. A total of 84 participants were recruited. Each participant received a DKK 30 voucher for the coffee shop and among all participants, we randomly selected six who received an actigraphy watch. As a general rule, we did not recruit volunteers if they had reported a chronic disease or a sleep disorder when completing the online questionnaire that had been used in an online survey in 2020 [19].

Of the 84 recruited, 64 participated in the two-week measurements during which an intervention was made in the second week but a complete set of measured data was obtained from only 40 participants. The measurements performed in their bedrooms were used for the analyses. Table 1 summarises the information about all 40 participants and after grouping them according to the intervention type. The average age of participants in each subgroup was similar, although the standard deviation (SD) was large; any potential effect on sleep quality caused by age or other external factors was eliminated by the within-subjects design in which only responses from the same participant under different conditions were compared. Detailed information on all 64 participants who participated in this study is presented in Table S1 in the Supplementary Information (SI).

2.3. Measurements

2.3.1. Physical measurements of the bedroom environment

Sixteen boxes, in which instruments for measuring CO_2, air temperature, relative humidity (RH) and a data logger, a light sensor and a tablet with a 4-G internet connection provided by either a SIM card or a router had been installed contained also an actigraphy watch, a skin temperature sensor attached to a wristband made of Velcro and a multi-divider socket, were prepared and used in the study (Fig. S1 in the SI). In eight of the boxes a portable IAQ monitor had also been installed.

Air temperature, RH, and CO_2 concentration were continuously monitored at intervals of 5 min using a Vaisala GMW90R (Vaisala Corporation, Finland) connected to a HOBO UX120-006 M 4-channel analogue data logger (Onset computer corporation, USA). The HOBO U12-012 data logger had a built-in light sensor (Onset computer corporation, USA), which measured and recorded the illuminance every 5 min. Selected pollutants (VOCs, nitrogen dioxide (NO_2), particulate matter with the aerodynamic diameter $\leq$1 μm (PM_1), 2.5 μm ($PM_{2.5}$), and 10 μm (PM_{10})) were measured by the IAQ monitor Flow 2 (Plume Labs, France) at intervals of 1 min, as in two of our previous studies [6, 39]. The accuracy and specifications of all the instruments are listed in Table S2 in the SI. The CO_2 sensors were calibrated just before the study began, while the other sensors were factory calibrated.

The participants were instructed to plug in the box, to keep it plugged in throughout the entire measuring period, and to place it at bed height about 1 m away from the pillow, preferably on a night table as recommended in the Instruction shown in Fig. S2 in the SI [30].

2.3.2. Objective measurement of sleep quality

Wrist-worn actigraphy watches were used to measure objective sleep quality. These were either Fitbit Charge 2 or Fitbit Alta HR models. Both of them have a sensitivity comparable with polysomnography, as was documented in a study with subjects suffering from obstructive sleep apnea [40]. Total sleep duration, time in bed, number of awakenings, the duration of any periods awake after sleep onset, and the duration of any periods of deep sleep, light sleep, and Rapid Eye Movement (REM) sleep were all derived by proprietary software analysis of the continuous records of heart rate and wrist movement that were subsequently uploaded from the wrist-worn units, which the participants wore on the non-dominant hand.

2.3.3. Subjective responses and questionnaires

During recruitment, participants completed the online questionnaire that had been used in our previous survey [19]. The questionnaire obtained information about each participant, including the characteristics of their dwelling, bedroom and surroundings, information on bedroom airing behaviour and the ventilation system, and information about sleep habits including the questions whose answers could be used to derive the PSQI.

Ten minutes before sleep, participants completed an evening sleep diary. It consisted of questions concerning the number of nap times and their length throughout the day, perceived sleepiness at the time of answering the question and earlier during the daytime, activities (exercise and screen time before sleep), diet, smoking, any measures taken to facilitate sleep, health status, estimated time of going to sleep, and the perceived quality of the bedroom environment.

Ten minutes after waking up, the participants completed a morning sleep diary. This obtained information on the time the participants woke up, the number of awakenings during sleep and the reasons for any awakenings, the number of adults and children in the bedroom during that night, the perceived quality of the bedroom environment during sleep and when answering the questions, whether any bedroom

Table 1
Anthropometric information about the 40 participants (Mean ± SD).

Items		In total[a]	Bedrooms in which the 95th percentile of CO_2 concentration between two weeks differed by					
			>200 ppm				≤200 ppm	
			Doors Open vs Closed		Windows Open vs Closed			
Nights No. where the data was obtained		58	20		23		15	
Participants No		40	13[c]		16		11	
Sex		40	Females	Males	Females	Males	Females	Males
			7	6	7	9	5	6
Age (y)		32 ± 12	28 ± 4	28 ± 3	30 ± 10	35 ± 18	28 ± 10	27 ± 5
Body Mass Index (kg/m^2)		22.8 ± 3.6	22.2 ± 3.2	26.6 ± 3.5	20.0 ± 1.4	24.4 ± 3.8	20.8 ± 1.8	21.8 ± 2.6
Living in Denmark	≥1 year	36	6	6	6	8	4	6
	<1 year	4	1	0	1	1	1	0
Smoker		2	0	0	1	1	0	0
Chronic diseases	Yes	3	0	1	1	0	1	0
	No	36	7	5	6	9	4	5
Shift worker	Yes	5	0	0	1	0	2	2
	No	34	7	6	6	9	3	3
PSQI[b]		6 ± 3	5 ± 2	6 ± 5	6 ± 2	5 ± 3	6 ± 2	5 ± 1

[a] Two participants did not answer all the questions.
[b] Pittsburgh Sleep Quality Index [38].
[c] Two participants shared bedroom.

windows or doors had been open that night, current sleepiness level and finally, subjective sleep quality as indicated by the answers to the questions in the Groningen Sleep Quality Scale (GSQS) [41]. A question regarding deep sleep was reported separately as it did not count toward the total GSQS score.

Subjective assessments of the bedroom environment included thermal sensation, odour/noise/light intensity, air freshness/dryness, and the acceptability of the thermal/IAQ/acoustic/visual environments. These assessments and scales had been used in previous studies [6]. The scales marked by the participants are shown in the SI together with the scoring of the scales. Sleepiness was assessed on a six-point Likert scale as follows: very sleepy (0), sleepy (1), somewhat sleepy (2), somewhat awake (3), awake (4), and wide awake (5); mean values were calculated to represent the level of sleepiness: the lower the mean, the sleepier the participant.

Evening and morning sleep diaries were available both in Danish and English and accessible online through links or QR codes. The participants were asked to complete these diaries at least twice a week and on the same two days in each week from Monday night to Friday morning to reduce potential bias caused by any systematic differences in activities on different weekdays.

2.3.4. Cognitive performance

Once a sleep diary had been completed, a 3-min version of Baddeley's test was presented to the participant. Baddeley's test is a grammatical reasoning test measuring how well a participant understands the relationship between objects as described in words and is used frequently to measure cognitive performance [42]. It has been used previously to measure cognitive performance after sleeping in poor IAQ conditions [5,6].

2.3.5. Physiological measurements

Skin temperature on the dominant hand's wrist was measured continuously during sleep and recorded at intervals of 5 min. An iButton DS1922L (Maxim integrated; USA) sensor was used and attached to a wristband made of Velcro. Skin temperature has been shown to be a good marker of thermal sensation so we used it in our study [43–45]. No other physiological measurements were performed, although they might have been useful, to maintain the realism and ensure that sleeping conditions were not disturbed, for example by additional sensors.

2.3.6. Estimation of ventilation rates

Metabolically generated CO_2 was used to estimate ventilation rates from the rate of decay of the measured CO_2 concentration each morning [39,46,47]. The participants were asked to avoid re-entering their bedroom for at least 30 min and to leave the bedroom conditions as they had been during the previous night during this period. The 95^{th} percentile of the CO_2 concentration during sleep was also calculated and used to estimate the ventilation rate. This was assumed to be close to the steady-state CO_2 concentration.

The above methods can provide an estimate of the total ventilation rates in bedrooms but they cannot provide an estimate of the proportion of outdoor air supplied to each bedroom.

2.4. Experimental procedure

The participants received detailed instructions via email and in the envelope supplied together with the instrumentation box; videos with all the necessary instructions were posted on YouTube (https://www.youtube.com/channel/UC8luzg7Uifjcd-217HuOmMA/videos).

Fig. 1 shows the measurement procedure for each night during the two-week-long experimental period; evening and morning sleep diaries were not taken every night.

Participants were asked to maintain their daily sleep patterns and lifestyle routines. They were also asked to provide a photograph or a sketch showing the dimensions of their bedroom, the location of the bed, windows, doors, instrument box, and any outdoor air inlets. We checked either the sketches or photos from the participants and found that they were placed as instructed. Two researchers could be contacted at any time throughout the period if there were any queries but this did not occur.

The present study conformed to the guidelines in the Helsinki Declaration. Written informed consent was obtained from each participant. The data collected via online questionnaires were pseudonymized and stored on the Technical University of Denmark (DTU) server to comply with the General Data Protection Regulation (GDPR) requirements. Our proposal was approved by DTU and archived under DOCX 19/1002413. Participants were informed that they were free to discontinue their participation at any time but this did not occur.

2.5. Screening and classification of measured data

Although the measurements were made over a period of two weeks, only data from the nights for which the sleep diary data were available to identify the status of the windows and doors clearly are reported here; all other data will be reported separately.

Measurements from the two-week measurements were available for 64 bedrooms. We screened raw data and excluded the measurements from 24 bedrooms because they were incomplete (Fig. S3 in the SI). The reasons for exclusion were as follows: for two participants only a single week of objectively measured sleep data was available; three participants had no historical CO_2 data; two participants completed their sleep diaries in only one week; four participants did not have objectively measured sleep data and a completed sleep diary for the same weekday nights in both weeks; four participants made an intervention that was not comparable between weeks (for example they opened the doors with the windows closed in the first week, while in the second week they opened the windows with the doors closed); one participant did not make any interventions; the rest either did not report making the intervention or the changes in CO_2 concentration did not match the intervention they claimed to have made, e.g., the CO_2 concentration was higher when they had reported sleeping with open windows or doors.

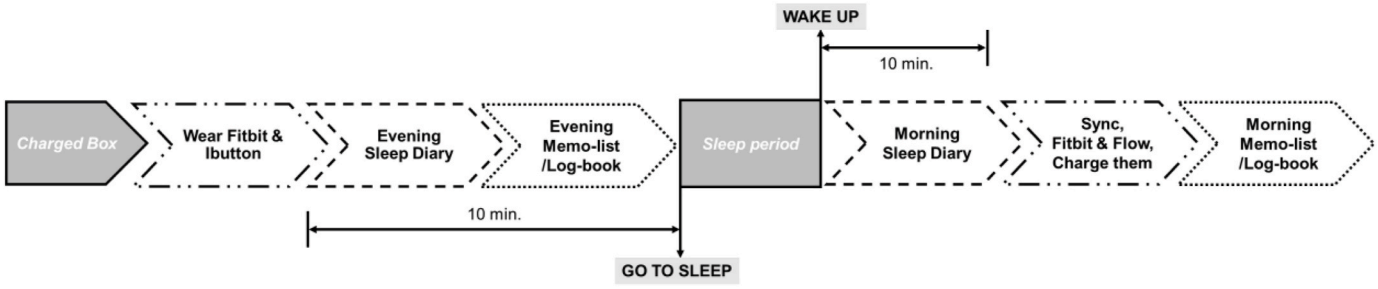

Fig. 1. An example of the experimental procedure with the sleep diaries for one night. Participants adopted these procedures without completing the sleep diaries on the other nights each week.

We thus used data from only 40 participants in the analyses. We compared the 95th percentile of CO_2 concentration for the same weekday nights in each of the two weeks. The bedrooms in which the difference in the 95th percentile of CO_2 concentration was >200 ppm were used in the analysis of the effects of an intervention; we chose 200 ppm considering the accuracy of the CO_2 sensors and to account for the possibility of incomplete mixing, and to ensure that there was a measurable change in bedroom ventilation. Twenty-nine bedrooms met this criterion.

As our focus was on the effects of open bedroom doors and windows, the data from the 29 bedrooms in which the 95th percentile CO_2 differed by > 200 ppm between weeks were compared between two conditions depending on the window and door status in each of the two weeks. In one group, consisting of 13 bedrooms, the doors were either open or closed each week, while the windows were always closed. In another group consisting of 16 bedrooms, the windows were either open or closed during each week while the doors in most of the bedrooms were closed. In one bedroom the door was always open independently of whether the windows were open or closed; in four bedrooms the windows were open together with open doors while the doors were closed when the windows were closed.

The data from the 11 bedrooms in which the 95th percentile CO_2 differed by ≤ 200 ppm between weeks were analysed for any difference in effect between two cases: Closed condition (the windows and doors were closed except for one bedroom where the doors were open for two weeks); Open condition (windows or doors were open). These analyses were treated as a form of control as no effects were expected considering that the CO_2 concentration differed so little between the two weeks, indicating that the intervention had not affected bedroom ventilation to any meaningful extent.

Information about the participants in each of these three groups is shown in Table 1. The detailed characteristics of window and door opening are presented in Table S3 in the SI.

2.6. Analysis

A Shapiro-Wilk test was used to examine whether the data were normally distributed. For normally distributed data, a paired-samples *t*-test was used, but we otherwise used the non-parametric Wilcoxon Matched-Pairs Signed-Ranks test. The data that had been measured more than once each night were subjected to analysis of variance with a repeated-measures design; the Greenhouse-Geisser method was used to adjust the violation of sphericity. Post-hoc analysis was performed using the Bonferroni test. The statistical analyses were performed using IBM SPSS Statistics 22 (SPSS Inc, Chicago, IL, USA). The significance level was set at P = 0.05 (2-tail). In the analyses, the status of window and door opening were independent variables while all other parameters measured or reported by the participants were dependent variables.

The effect size was calculated using Cohen's method [48]. Cohen's f examining the practical importance of outcomes based on their variance defines the small (0.1), medium (0.25), and large (0.4) effect sizes [49]. Cohen's d examining the practical importance of outcomes by comparing the mean values also defines small (0.2), medium (0.5), and large (0.8) effect sizes [49]. Small, medium, and large effect sizes imply that 58%, 69%, and 79% of the results were higher than the mean value, respectively [49].

Considering the limited number of participants within each subgroup after data screening in the present study, Bonferroni post-hoc analysis was also performed when the effect size (Cohen's f) of intervention effects, time effects, or the interaction of intervention and time was large.

3. Results

The characteristics of the 40 bedrooms from which data were analysed are summarized in Table 2. They were primarily non-smoking spaces located in multi-story apartment buildings in suburban areas but a few were in a student dormitory building. Many of the buildings had been constructed before the 1980s and after the 2010s. The average volume and floor area of the bedrooms were approximately 36 m^3 and 13 m^2, respectively. According to the incidence of air terminals reported by the participants, most of the bedrooms had exhaust ventilation. We did not verify this information or whether the ventilation systems were in operation at night to avoid the need to enter the bedrooms. More than half of the bedrooms were singly occupied during the measurement period. The information for all 64 surveyed bedrooms is presented in Table S4 in the SI.

Table 3 shows the objectively measured bedroom environmental quality during sleep. The air change rate was on average lower than the statutory minimum of 0.5 h^{-1} when the doors and windows were closed but when they were open it increased considerably. The mean 95th percentile of CO_2 concentration (and the mean CO_2 concentration) during sleep was reduced from 2916 ppm to 1415 ppm (mean concentration was reduced from 2362 ppm to 1293 ppm) when the doors were open and from 2310 ppm–904 ppm (mean from 1820 ppm–761 ppm)

Table 2
Information about surveyed bedrooms (Mean ± SD).

Items		In total[a]	Bedrooms in which the 95th percentile of CO_2 concentration between two weeks differed by		
			>200 ppm		≤200 ppm
			Doors Open vs Closed	Windows Open vs Closed	
Building types	Detached house	9	1	5	3
	Row-house	3	0	3	0
	Multi-story apartment building	24	11	8	5
	Others, (i.e. cottages)	2	0	0	2
Non-smoking dwellings	Yes	38	12	15	11
	No	2	1	1	0
Built year of the dwellings	Before 1960	10	6	3	1
	1961–1981	4	2	1	1
	1982–1995	1	0	1	0
	1996–2009	2	0	2	0
	After 2010	7	1	4	2
	Don't know	15	4	5	6
Dwellings' location[b]	Urban	8	0	4	4
	Suburban	31	12	12	7
	Rural	1	1	0	0
Living in dormitory	Yes	9	1	4	4
	No	30	12	12	6
Bedroom located floor	<0 (basement)	0	0	0	0
	Ground floor (0)	16	9	6	1
	≥1st floor	23	4	10	9
Bedroom size (m^3)		36 ± 12	36 ± 12	32 ± 11	35 ± 14
Bedroom ventilation[c]	Mechanical ventilation	8	2	1	5
	Exhaust ventilation	28	8	15	5
	Natural ventilation	3	3	0	0
Occupants in bedrooms during sleep	1	25	4	13	8
	≥2	15	9	3	3

[a] Two participants did not answer all the questions.
[b] Residential location was deduced from the zip codes. Urban regions refer to the areas with the first two numbers of zip codes 25 or below; suburban regions refer to the areas with the first two numbers of postcodes 26–31, 34–36, 40, 50–52, 70, 80–82, and 90–92, and the other areas in the capital region of Denmark are rural.
[c] Bedrooms with air terminals were considered to have a fully balanced mechanical ventilation system, bedrooms with trickle vents and air terminals in the bathroom were considered to have mechanical ventilation with exhaust only; others were naturally ventilated bedrooms.

Table 3
Objectively measured bedroom environment during sleep (Mean ± SD). Cohen's d. **P < 0.01; *P < 0.05.

Parameters	Bedrooms in which the 95th percentile of CO_2 concentration between two weeks differed by											
	>200 ppm								≤200 ppm			
	Doors Position				Windows Position				Closed[b]	Open[c]	P-value	d
	Closed	Open	P-value	d	Closed	Open	P-value	d				
Air change rate (h^{-1})	**0.29 ± 0.24**	**0.78 ± 1.14**	**0.007****	**0.62**	**0.34 ± 0.31**	**1.21 ± 1.14**	**<0.001****	**1.08**	0.77 ± 0.58	1.24 ± 1.4	0.875	0.44
95th percentile of CO_2 concentration (ppm)[d]	**2916 ± 960**	**1415 ± 495**	**<0.001****	**2.02**	**2310 ± 944**	**904 ± 406**	**<0.001****	**1.98**	1067 ± 516	1017 ± 530	0.083	0.10
Mean CO_2 concentration (ppm)[e]	**2362 ± 728**	**1293 ± 465**	**<0.001****	**1.80**	**1820 ± 706**	**761 ± 273**	**<0.001****	**2.02**	**975± ±462**	**893 ± 425**	**0.015***	0.19
NO_2 (ppb)[a]	**1.2 ± 1.3**	**4.7 ± 4.5**	**0.043***	**1.14**	3.5 ± 3.8	10.4 ± 12.5	0.056	**0.77**	4.0 ± 4.3	4.0 ± 4.8	0.695	0.01
VOCs (ppb)[a]	198.6 ± 66.1	164.1 ± 49.9	0.086	**0.62**	**205.6 ± 60.7**	**156.0 ± 59.3**	**0.001****	**0.86**	170.9 ± 26.8	169.1 ± 46.6	0.867	0.05
PM_{10} (μg/m^3)[a]	24.1 ± 24.5	23.1 ± 23.6	0.594	0.04	**46.8 ± 37.1**	**26.3 ± 22.1**	**0.026***	**0.70**	23.1 ± 24.9	20.0 ± 18.8	0.701	0.14
$PM_{2.5}$ (μg/m^3)[a]	4.7 ± 3.1	4.5 ± 2.9	0.953	0.06	5.4 ± 3.9	3.9 ± 2.5	0.124	0.47	4.1 ± 3.1	3.8 ± 2.9	0.701	0.13
PM_1 (μg/m^3)[a]	1.9 ± 1.6	1.9 ± 1.5	0.575	0.01	1.8 ± 1.5	1.7 ± 1.2	0.875	0.08	1.7 ± 1.5	1.6 ± 1.4	0.223	0.04
Temperature (°C)	24.7 ± 3.8	24.7 ± 2.9	0.774	0.03	**23.2 ± 1.3**	**22.4 ± 1.9**	**0.008****	**0.51**	24.3 ± 1.3	23.7 ± 1.8	0.175	0.36
Relative humidity (%)	**54 ± 7**	**51 ± 7**	**<0.001****	**0.54**	**53 ± 6**	**48 ± 6**	**0.001****	**0.78**	44 ± 8	42 ± 10	0.278	0.20
Illuminance (Lux)	11.3 ± 7.1	12.5 ± 9.3	0.420	0.14	11.4 ± 9.0	10.2 ± 6.2	0.794	0.16	8.9 ± 6.3	10.0 ± 8.6	0.638	0.14

[a] Data from six participants with nine nights of measurements was available when the doors were closed or open; Data from 10 participants with 14 nights of measurements was available when the windows were closed or open; Data from 9 participants with 13 nights of measurements was available when the difference in the 95th of CO_2 concentration was ≤200 ppm between two weeks.
[b] The windows and doors were both closed except for one bedroom with the doors open.
[c] The windows or doors were open.
[d] The number of bedrooms with the CO_2 concentration <1100 ppm, which according to Refs. [12,13] indicates the level below which it is less probable that there are effects on sleep quality: > 200 ppm group: doors closed - 0 bedroom, doors open −3 bedrooms of 13, windows closed – 1 bedroom, windows open 12 bedrooms of 16 bedrooms; < 200 ppm group: closed - 7 bedrooms, open - 7 bedrooms of 11 bedrooms.
[e] The number of bedrooms with the CO_2 concentration <1100 ppm, which according to Refs. [12,13] indicates the level below which it is less probable that there are effects on sleep quality: > 200 ppm group: doors closed - 0 bedroom, doors open – 6 bedrooms of 13, windows closed – 2 bedrooms, windows open 13 bedrooms of 16 bedrooms; < 200 ppm group: closed - 8 bedrooms, open - 9 bedrooms of 11 bedrooms.

when the windows were open.

Mean RH was significantly higher when the doors and windows were closed, and the mean RH was in the range of 40–60%. The mean temperature decreased significantly when the windows were open but by only 0.8 °C.

The mean NO_2 concentration during sleep increased when either the doors or windows were open; when a window was open, the NO_2 concentration was higher, though not significantly ($P < 0.10$). The concentrations of VOCs and PM_{10} were significantly lower when the windows were open, indicating that they originated indoors. Boor et al. summarized in a review that particles could be suspended by body movements in bed [50], which is likely to explain the observed higher PM_{10} concentration with the windows closed. Door opening also tended to reduce the level of VOCs ($P < 0.10$). The concentrations of $PM_{2.5}$ and PM_1, and the illuminance level were unaffected by either intervention.

In the bedrooms in which the 95th percentile CO_2 concentration differed by ≤ 200 ppm between weeks it still decreased when the windows and/or doors were opened although it remained in the range of 900-1100 ppm. No other measurements differed between weeks in this failed intervention group.

Subjective ratings of the bedroom environment are shown in Table S5 in the SI. Significant differences in the ratings following post-hoc analysis are summarized in Figs. 2 and 3. The acceptability of bedroom IAQ increased (Fig. 2A), and the odour intensity decreased

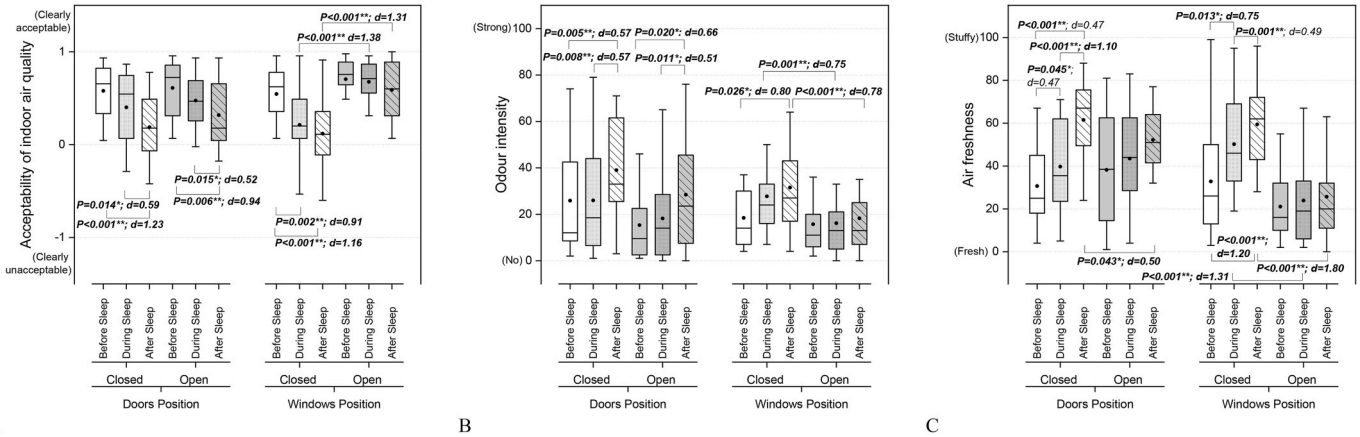

Fig. 2. (A) The acceptability of IAQ; (B) odour intensity; and (C) air freshness before, during (recalled), and after sleep under the different conditions. Cohen's d. **P < 0.01; *P < 0.05.

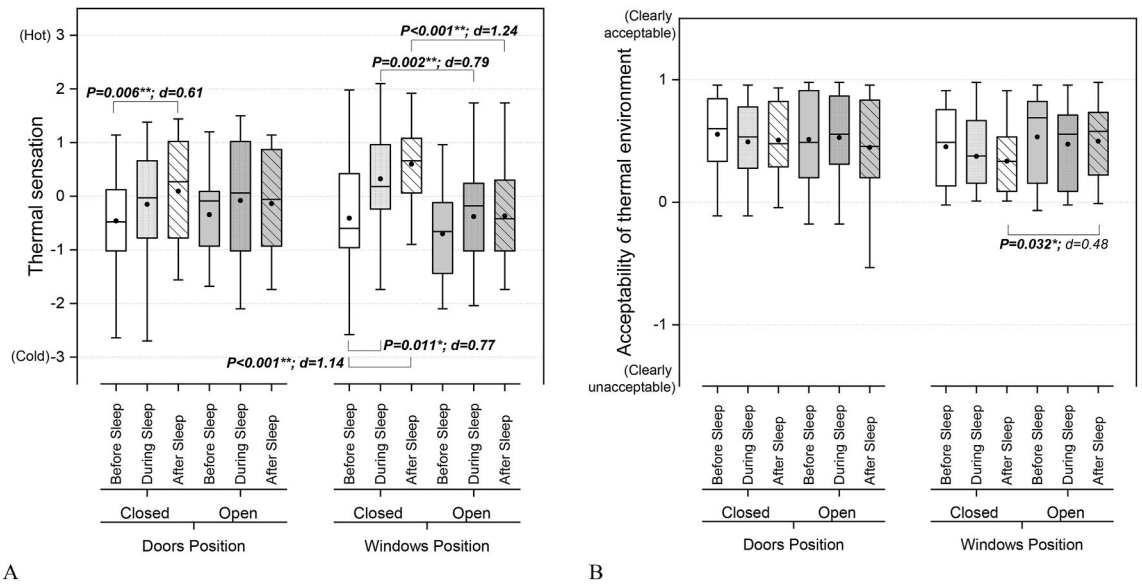

Fig. 3. (A) Thermal sensation; and (B) acceptability of the thermal environment before, during (recalled), and after sleep under the different conditions. Cohen's d. **P < 0.01; *P < 0.05.

(Fig. 2B) when the windows were open compared with the condition when they were closed; door opening did not produce similar effects. There was a small but significant improvement in the ratings of air freshness when the doors were open, while in the case of window opening the improvement was greater and showed that the air was rated as much fresher (Fig. 2C). Thermal sensation decreased when the windows were open from around neutral to slightly cool; no such effect was observed when the doors were open (Fig. 3A). There were no significant differences between weeks in the measured wrist skin temperature (Fig. S4 in the SI). However, the skin temperature was from the sleep period, and the acceptability of the thermal environment, which was rated while awake, improved when the windows were open, again with no similar effects when the doors were open (Fig. 3B). No other significant differences were observed.

The acceptability of the IAQ decreased, and the odour intensity increased in the morning compared with the evening, independent of the status of the doors. Similar changes were observed when the windows were closed. The air was rated to be stuffier, and the thermal sensation was warmer when the doors and windows were closed. The perceived light intensity increased after sleep compared with before sleep independently of the window status (Fig. S5A in the SI). The subjective responses made by participants did not differ between weeks in the failed intervention group (Table S5 and Fig. S6 in the SI).

Objectively measured sleep quality was compared with what is currently recommended by the U.S. National Sleep Foundation [51]. The results are tabulated in Table S6 in the SI and show that the sleep quality of the participants in the present study would not be regarded as poor.

There were no significant differences in objectively measured

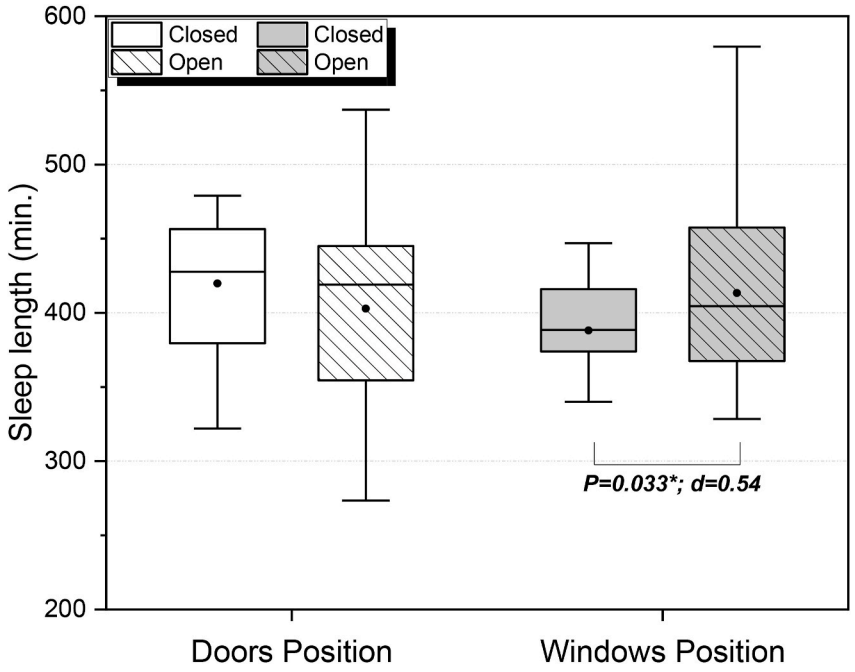

Fig. 4. Objectively measured sleep length under the different conditions. Cohen's d. *P < 0.05.

parameters defining sleep quality (Table S6 in the SI) except for sleep duration, which was significantly longer when the windows were open (Fig. 4). There were no differences in objectively measured sleep quality between weeks in the failed intervention group.

Subjectively rated sleep quality tended to improve when the windows were open ($P < 0.10$); no similar effect was seen when the doors were open (Fig. 5). Self-reported sleepiness is summarized in Table S7 in the SI. Significant post-hoc results are shown in Fig. 6. The self-reported sleepiness level was lower when the windows were open; similar effects were observed in the morning compared with the evening in this condition; no other differences were seen. The percentage of participants reporting having a deep sleep increased when the windows were open; no such effect was seen when the doors were open (Fig. 7). There was no difference in self-reported number of awakenings during sleep and the reasons for waking up were random, which supports the realism of this study (Table S8 in the SI). There were no significant effects on subjectively reported sleep quality, sleepiness level or depth of sleep in the failed intervention group (Table S7 and Figs. S7–8 in the SI).

The performance of Baddeley's test before and after sleep is shown in Fig. 8 and Table S9 in the SI. There was a significant decrease in the percentage of errors after sleeping with windows open. We observed that the performance before sleep differed when the doors were open compared with when they were closed but this difference cannot be attributed to the sleeping conditions. There were no significant differences in performance before and after sleep in the failed intervention group.

4. Discussion

Our results show that opening windows or doors significantly reduced CO_2 concentration during sleep. This is conventionally interpreted to indicate that in both cases bedroom IAQ improved. However, this was not the case as shown by other measurements. Only when the windows were open did the participants rate bedroom IAQ better. Sleep quality also improved in this condition, which is consistent with the published studies reviewed in the Introduction section [34–36]. No such improvements were seen when the doors were open. We believe that door opening did not provide adequate removal and dilution of pollutants in bedrooms even though we were not able to confirm this hypothesis with the limited measurements that were made. The reduced levels of CO_2 when the doors were open suggest that air from other parts of the dwelling was either drawn or diffused into the bedrooms. The CO_2 concentration of this air was low during the sleep period, as other spaces in the dwelling were not occupied, and consequently the bedroom CO_2 concentration was reduced, though not by as much as when the windows were open (Table 3).

As shown in the review by Canha et al., bedroom air during sleep contains numerous pollutants whose levels are higher than the limit values prescribed by the standards and guidelines [15]. These pollutants can enter bedrooms from other parts of the dwelling [30]. For example, cooking oil fumes originating from the kitchen were associated with overall poor sleep quality [52]. Additionally, exposure to increased PM_{10} concentration was significantly associated with increased obstructive sleep apnea [53], which may disturb sleep. A recent cross-sectional study showed that sleep stages were affected during exposures to NO_2, $PM_{2.5}$, and O_3; as a result some decreases in cognitive capacity were observed [54]. Finally, Chen et al. concluded that long-term exposures to $PM_{2.5}$, PM_{10}, and NO_2 were associated with poor sleep quality in rural China [55]. If proper removal or dilution of these and other pollutants is not achieved by the air that enters bedrooms, no improved bedroom IAQ and sleep quality should be expected. This may have been the case when the internal doors were open in the present study, even though the total concentration of VOCs was lower. On the other hand, window opening was able to provide sufficient dilution and removal of some of these pollutants. For example, the present study showed that the total concentration of VOCs and PM_{10} levels were lower and perceived IAQ was improved when the windows were open. However, window opening increased NO_2 concentration, which thus presumably originated outdoors. This could counteract the positive effect of reduced exposure to other pollutants because exposure to NO_2 can increase the risk of sleep apnea [56]. Future studies should closely look at the impact of outdoor air pollution on sleep quality and consequently

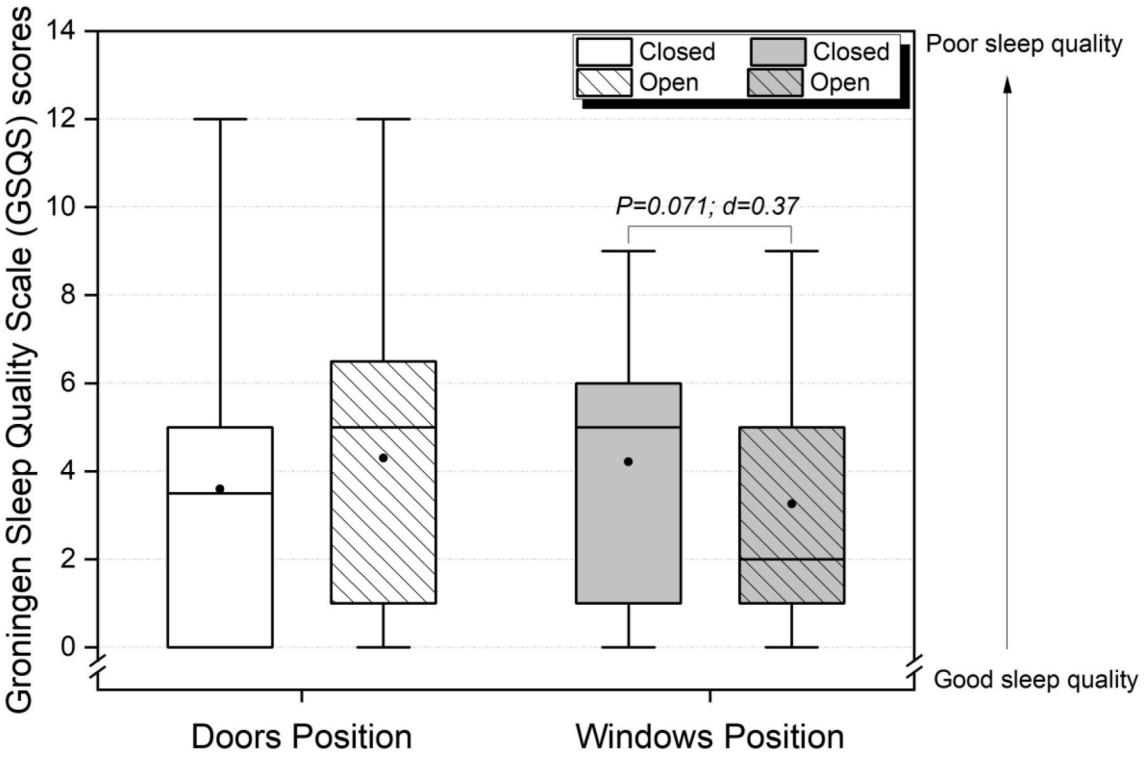

Fig. 5. Subjective measurements of sleep quality under the different conditions. Cohen's d.

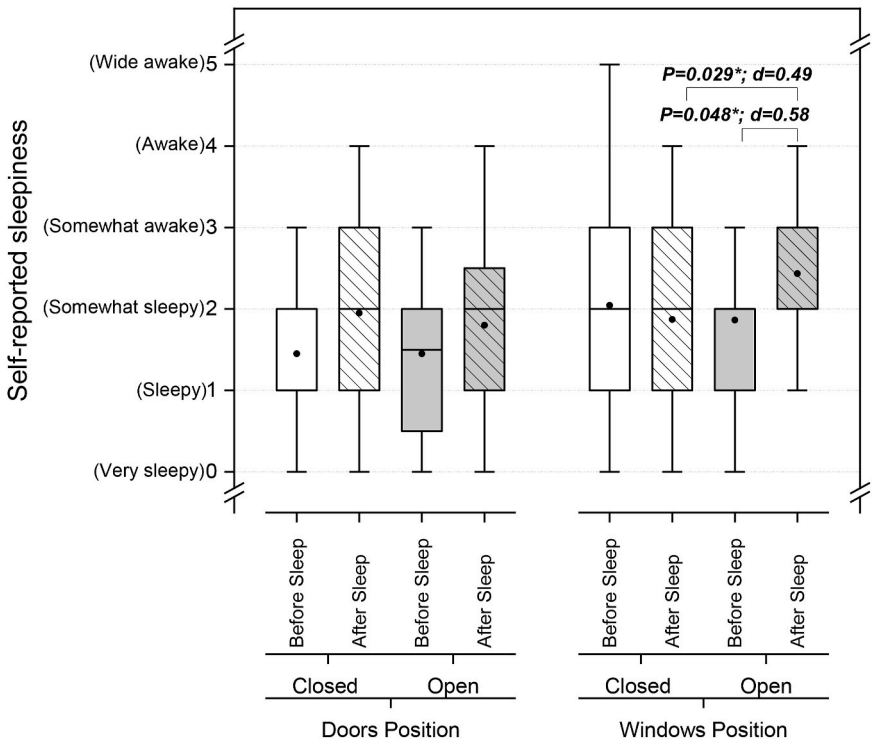

Fig. 6. Self-reported sleepiness before and after sleep under the different conditions (Mean ± SD). Cohen's d.*P < 0.05.

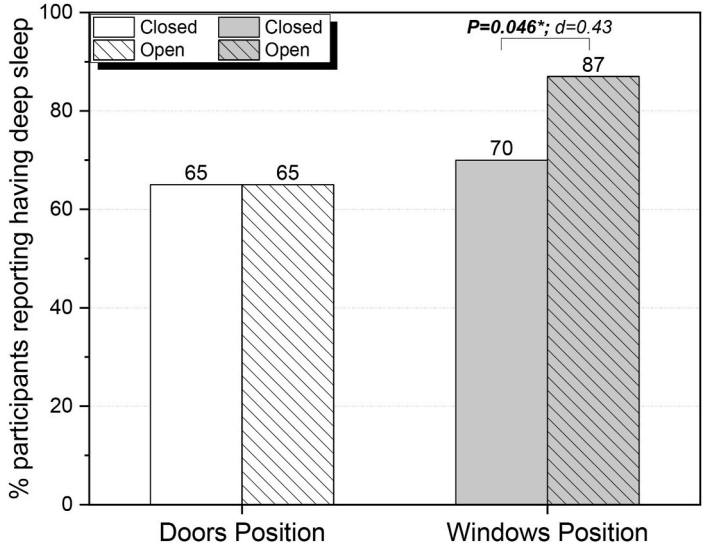

Fig. 7. of the participants who reported (recalling after sleep) having a "deep sleep" under the different conditions. Cohen's d. *P < 0.05.

examine measures that should be taken to reduce their levels.

It is worth noting that in an earlier study involving multiple CO_2 measurements in a bedroom having windows with fully open trickle vents, Sekhar et al. showed that the bedroom was better ventilated by the incoming outdoor air through the trickle vents, which was further enhanced with the assistance of a kitchen hood or bathroom extraction fan if an internal bedroom door was open [25]. We are unable to verify whether this occurred in the present study because the operation of ventilation systems during the measurements period was not checked, as mentioned earlier. The CO_2 measurements just outside the bedroom door would help characterize the airflow direction in future studies.

It is reasonable to assume that the expectations of participants could bias the results of the present study particularly their subjective responses (a Hawthorne effect) [34]. As opening a window or a door is usually assumed to improve bedroom IAQ, the participants might expect that they have positive effects but no such effects on subjective responses were found. Additionally, in the failed intervention group in which bedroom IAQ remained unchanged even though doors and windows were opened, no positive or negative effects of expectation on subjective responses were found. Another reasonable hypothesis is that becoming familiar with the routines of the experiment during the first week might have helped the participants to sleep better in the second week. If so, as more participants went from open to closed windows in the second week than in the reverse direction (10 versus 6, respectively, as shown in Table 4; details summarized in Table S3 in the SI), this might have spuriously appeared to favour closed windows. That open windows were

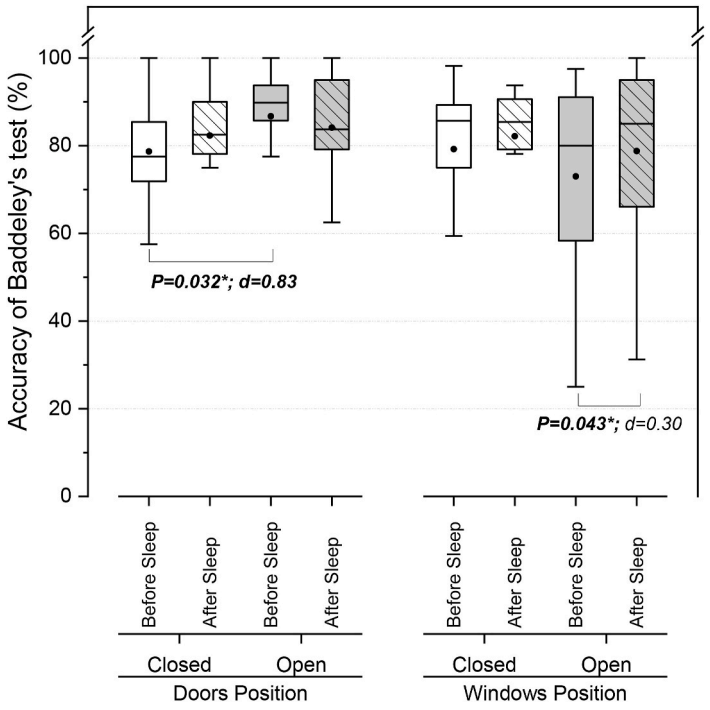

Fig. 8. The accuracy of Baddeley's test under the different conditions (Mean ± SD). Cohen's d. *P < 0.05.

Table 4
The number of participants (nights of measurements each week) who changed the doors and windows from open to closed and vice versa between weeks.

First week to second week	Bedrooms in which the 95th percentile of CO_2 concentration between two weeks differed by		
	>200 ppm		≤200 ppm
	Doors Open vs Closed	Window Open vs Closed	Open vs Closed[a]
Changing from open doors to closed doors	5 (8)	- -	- -
Changing from closed doors to open doors	8 (12)	- -	- -
Changing from open windows to closed windows	- -	10 (15)	- -
Changing from closed windows to open windows	- -	6 (8)	- -
Changing from open windows or doors to closed windows and doors	- -	- -	5 (7)
Changing from closed windows and doors to open windows or doors	- -	- -	6 (8)

[a] Closed: the windows and doors were both closed except for one bedroom with the doors open; Open: the windows or doors were open.

found to result in better sleep is thus a conservative conclusion.

The present results support the tentative relationship between bedroom ventilation (as indicated by mean CO_2 level) and sleep quality that has been recently suggested [12,13]. According to this relationship, no effects on sleep quality would be predicted in bedrooms with doors open, as observed in the present study. The present results support the recommendation that the outdoor air supply rate in bedrooms should be > 10 L/s per person [39] to ensure that sleep quality is undisturbed and that the resulting CO_2 concentration is below 750 ppm.

A change in the 95th percentile of the CO_2 concentration that was less than 200 ppm was insufficient to produce any measurable changes in the outcomes in the present study, lending support to the analysis. There could be many reasons why the change in the 95th percentile of the CO_2 concentration after the intervention was lower than 200 ppm in 11 bedrooms. The most plausible reason is that five of them had mechanical ventilation and five had extract ventilation, so opening windows or doors would have had a very limited effect on CO_2 levels which were already low. The recently published paper analysing all results from the present study collected in the first week showed that the CO_2 concentration measured in bedrooms with mechanical ventilation was lower compared with bedrooms with other types of ventilation [37], which further supports this interpretation.

An apparent effect on next-day cognitive performance was seen in the present study at a mean CO_2 level of 1800 ppm, lower than the 2600 ppm suggested by the above authors as the threshold for such effects. However, although next-day cognitive performance improved significantly after sleeping in bedrooms with windows open and did not improve significantly after sleeping with windows closed, which is compatible with a beneficial effect of sleeping with open windows, no significant difference in performance could be shown between the conditions with windows open and closed. The present results therefore do not constitute an extension of the findings of Strøm-Tejsen et al. [5] to lower CO_2 concentrations.

In the present experiment, cognitive performance was measured in the bedroom, i.e., with the same IAQ as during the sleep period, so the observed effects of poor bedroom IAQ could be due either to the resulting poor sleep quality or to a direct effect of poor IAQ at the time the test was performed; the latter effect has been documented in many studies [57,58]. These two effects cannot be separated in the present experiment.

The CO_2 level is generally used to estimate the ventilation rate and IAQ [12,13,15]. Reduced CO_2 concentration in the present study did indicate increased dilution, but it was not a good predictor of bedroom IAQ (Fig. 2 and Table 3). CO_2 may not always be a good marker of IAQ as indicated in the recently published ASHRAE's Position Document [59]. Future studies should consider measuring other contaminants as well as CO_2 to obtain a better estimate of bedroom IAQ.

The present results show that ventilation with outdoor air results in improved bedroom IAQ and sleep quality. This suggests that effective measures must be taken to ensure sufficient delivery of clean outdoor air to bedrooms. These measures include mechanical ventilation, natural

ventilation in which windows are operated automatically as a function of different parameters, or simply providing the possibility of opening windows to occupants for airing the bedrooms. As described in the Introduction section and as shown by Sekhar et al. [12], most bedrooms are ventilated only by voluntary window opening, which cannot take place while asleep even if bedroom IAQ becomes worse during the night. The effectiveness of ventilation by window opening depends on many factors, among which outdoor conditions and wind pressure differences play the most important role. Window opening can be discouraged by conditions outside the building, including perceived security and ambient noise as well as privacy considerations. In areas with high outdoor air pollution, window opening can even make the IAQ in bedrooms worse by allowing outdoor pollutants to enter the bedroom. Finally, window opening can allow rain to enter and may increase bedroom temperature during hot weather, or increase energy use for heating during cold weather. On the other hand, retrofitting bedrooms with mechanical ventilation may involve technical difficulties and can be costly. In the absence of mechanical ventilation or specially designed natural ventilation systems, other means of improving bedroom IAQ could be considered [60]. One way would be the use of air cleaners. However, information on their application for improving bedroom IAQ is limited [61,62] and no data are available on whether their use would improve sleep quality. Future studies should closely address this matter and focus on other methods and retrofits that would result in improved bedroom IAQ.

5. Limitations

To keep the realism, the study was performed in actual bedrooms on weekdays. This has significant implications because not all potentially disturbing factors could be controlled. Yet, the present study was an intervention performed in two subsequent weeks, and we compared the measurements obtained in one week against the measurements in the other week and performed analyses as within-subject comparisons. We believe that this approach to some extent controlled for external factors. A similar approach was used successfully in previous studies examining the effects on work performance in the laboratory [63] and in the field [64], as well as in the study examining the effect of bedroom ventilation on sleep quality and next-day cognitive performance [5].

With the window open, the relative humidity and temperature in bedrooms during sleep were lower. This could potentially affect sleep quality [6,44] and bedroom IAQ [65], but we were unable to separate these effects in the subsequent analyses. Yet, participants did not report thermal discomfort in any of the conditions examined so the influence of these small differences in thermal conditions on sleep quality is expected to be minor.

We did not measure noise levels. However, most of the surveyed bedrooms were located in suburban areas where the ambient noise levels during sleep can generally be assumed to be low. Consequently, window opening should not have caused much sleep disturbance due to external noise. In support of this conclusion, participants rated the noise intensity as low and the acoustic environment in bedrooms as highly acceptable.

Window opening can increase air speed and cause draft problems. We did not assess the effects of these two parameters. If anything, they would be expected to reduce the positive effects that were observed when the windows were open in the season when the present study was performed.

The estimation of ventilation rates from the decay rate of metabolically generated CO_2 requires several assumptions including the level of CO_2 in the air supplied to bedrooms and good mixing within the bedrooms. The estimated ventilation rate reflects the local conditions where the CO_2 concentration was measured and should not be assumed to apply to the entire volume of the bedroom. A discussion of air distribution and exposure is important in this context, as depending on the sleep position and air distribution, which can be influenced by the position of the bed in relation to the window and the door, the actual exposure of participants could be different from what was estimated from the measured CO_2 concentration [25,50,66,67]. We were not able to examine the air distribution in the bedrooms. However, as we compared the effects of high and low levels of CO_2 in the same bedrooms, our results are valid even without a knowledge of air mixing. In future studies it would be useful to measure the actual exposures of sleeping occupants and the air distribution in bedrooms.

Our results are based on a smaller number of observations than was intended. One reason is that we used stringent inclusion criteria, including that the sleeping diaries should have been completed on the same weekday night in each week of the two-week measurements and that the intervention must have changed the 95^{th} percentile of CO_2 by more than 200 ppm. Confirmation in studies with a larger sample size and longer duration would be useful.

We did not collect full information about the buildings, bedrooms and participants. One of the reasons was that the participants already had to perform many measurements and provide many responses and we did not want to further inconvenience them. Also, some information could be considered as sensitive and the participants might have been unwilling to share it with us or might even have withdrawn from participating in this study if they were requested to provide it. In future studies it would be useful to collect more information on climatic data and building location, the economic status of the participants, their occupation and the type of bedding used, including an estimation of its thermal insulation, and the use of curtains, etc, so that this information can be included as additional variables in the statistical models. Intervention studies like the one presented in this paper can control for many of these factors as the responses from the same participants were compared. In bedrooms with more than one participant it would be useful to collect data from both occupants, if both agree to participate in the monitoring program.

The present study was conducted during the heating season in a temperate climate zone. Consequently the findings require verifications in other climate zones and periods of the year before they can be widely applied.

6. Conclusions

A field intervention study was conducted in bedrooms during the heating season. The effects of bedroom door and window opening on IAQ, sleep quality, and next-day cognitive performance were determined. Sleeping with the window open improved bedroom IAQ and provided benefits for sleep quality. No such effects were observed when sleeping with the door open. The present study provides evidence that bedroom ventilation with outdoor clean air resulting in improved bedroom IAQ is important for sleep quality.

CRediT authorship contribution statement

Xiaojun Fan: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chenxi Liao:** Methodology, Investigation, Conceptualization. **Mariya P. Bivolarova:** Investigation. **Chandra Sekhar:** Writing – review & editing. **Jelle Laverge:** Writing – review & editing. **Li Lan:** Writing – review & editing. **Anna Mainka:** Writing – review & editing. **Mizuho Akimoto:** 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.

Data availability

Data will be made available on request.

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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.2022.109630.

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Appendix 1 Questionnaires used in the chamber study

Evening Sleep Diary

Name:	
Date:	Time:

(*Please use "√" to mark the cycle, for example* ✓):

1. Your sleep environment Now is as follows:

Hot	No odour	Air fresh	Too dark	Too dry	Too quiet
Warm	Slight odour				
Slightly warm	Moderate odour				
Neutral	Strong				
Slight cool	Very strong				
Cool	Overwhelming	Air stuffy	Too bright	Too humid	Too noisy
Cold					

2. The conditions in this sleep environment Now could be described as follows:

	Thermal comfort	Perceived air quality	Acoustic comfort	Visual comfort
Clearly acceptable				
Acceptable				
Just acceptable				
Just unacceptable				
Unacceptable				
Clearly unacceptable				

3. How many times did you take a nap today? (Write '0' if you did not take a nap.)

   _____ times

   The total nap time was:

   _____ minutes

4. How sleepy were/are you:

	Wide awake	Somewhat awake	Somewhat sleepy	Very sleep
Now	○	○	○	○
Throughout the day	○	○	○	○

5. When did you exercise today for at least 20 min?

In the morning	In the afternoon	In the evening	At night	Did not exercise
○	○	○	○	○

6. At what time did you have your last meal (dinner/supper) today?

Before 18:00	18:00 – 20:00	20:00 – 21:00	After 21:00
○	○	○	○

7. Did you consume the following during or after your last main meal? (Mark all that apply)

Coffee	Tea	Caffeinated beverages (e.g. cola)	Alcohol	None of them
○	○	○	○	○

8. Was your last main meal heavy

Yes	No
○	○

9. Were you engaged with electronic devices with an illuminated screen for at least 10 min., approximately within 1 hour before going to sleep? (e.g. smartphone, tablet, etc.)

Yes	No
○	○

10. Did you take/use any of the following NOW to help you sleep? (Mark all that apply)

Pills	Herbal tea	Essential oil	Others: _____	I didn't use anything to help me sleep
○	○	○	○	○

11. Are you feeling your usual self NOW? (feel well, healthy, not stressed, not depressed, etc.)

Yes	No
○	○

Morning Sleep Diary

Name:	
Date:	Time:

(*Please use "√" to mark the cycle, for example* ✓):

1. At what time did you go to bed/sleep yesterday? _____
2. What time did you wake up this morning? _____
3. How many times did you wake up during the night last night? _____
4. How many times did you get out of bed during the night last night? _____
5. <u>WHEN YOU WOKE UP</u> this morning, your sleeping environment was as follows:

Hot	No odour	Air fresh	Too dark	Too dry	Too quiet
Warm	Slight odour				
Slightly warm	Moderate odour				
Neutral	Strong				
Slight cool	Very strong				
Cool	Overwhelming	Air stuffy	Too bright	Too humid	Too noisy
Cold					

6. <u>WHEN YOU WOKE UP</u> this morning, the conditions in your bedroom could be described as follows:

	Thermal comfort	Perceived air quality	Acoustic comfort	Visual comfort
Clearly acceptable				
Acceptable				
Just acceptable				
Just unacceptable				
Unacceptable				
Clearly unacceptable				

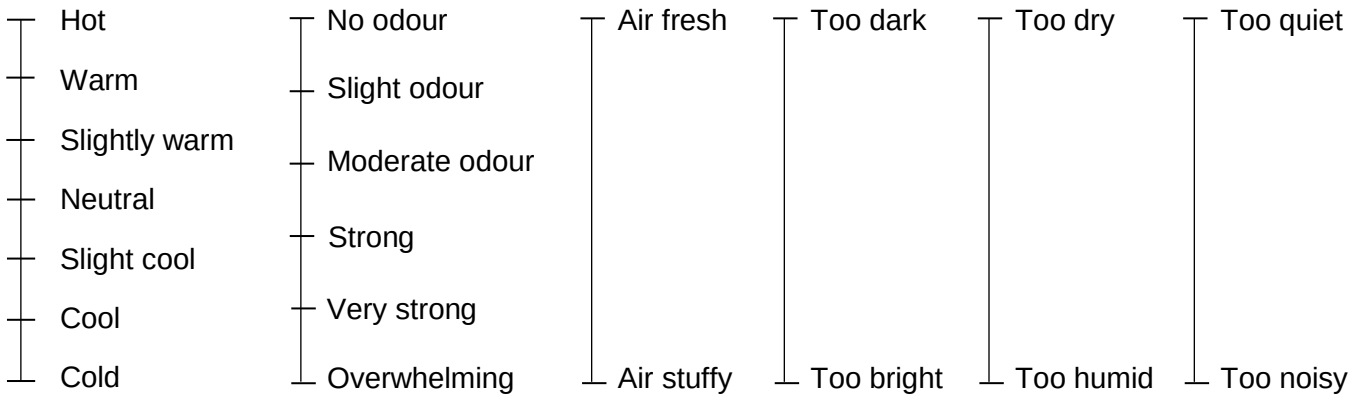
7. When you woke up this morning, you felt:

Wide awake	Somewhat awake	Somewhat sleepy	Very sleep
○	○	○	○

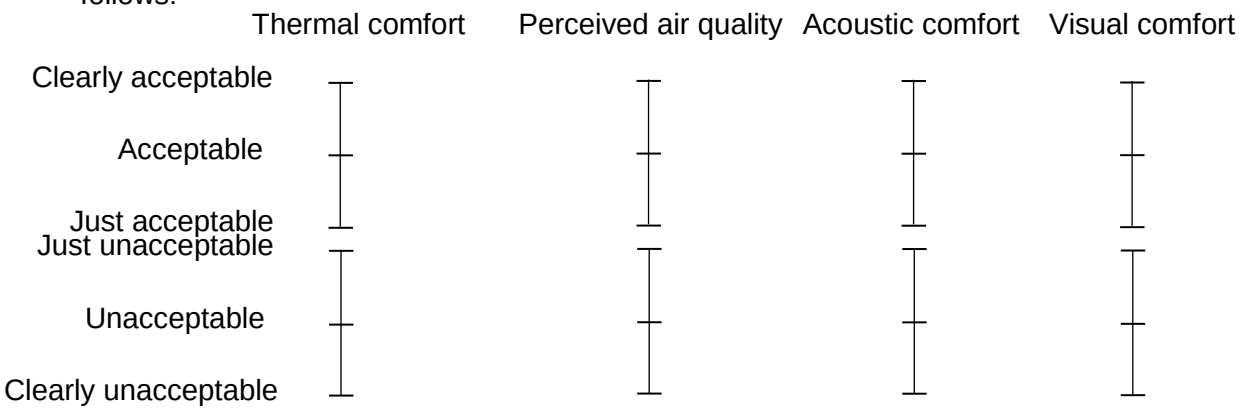
8. Last night, you woke up because of

- ○ Stress
- ○ Snoring
- ○ Sleep environment (e.g. bed temperature, relative, noise, light, and air quality)
- ○ Physical discomfort (e.g. muscle pain, headache, etc.)
- ○ Other: _____
- ○ Not applicable (did not wake up)

9. DURING LAST NIGHT, your sleep environment was as follows:



10. DURING LAST NIGHT, the conditions your **sleep environment** could be described as follows:



11. How did you sleep last night?

1) I had a deep sleep last night	☐ True	☐ False
2) I feel that I slept poorly last night	☐ True	☐ False
3) It took me more than half an hour to fall asleep last night	☐ True	☐ False
4) I woke up several times last night	☐ True	☐ False
5) I felt tired after waking up this morning	☐ True	☐ False
6) I feel that I did not get enough sleep last night	☐ True	☐ False
7) I got up in the middle of the night	☐ True	☐ False
8) I felt rested after waking up this morning	☐ True	☐ False
9) I feel that I only had a couple of hours' sleep last night	☐ True	☐ False
10) I feel that I slept well last night	☐ True	☐ False
11) I did not sleep a wink (at all) last night	☐ True	☐ False
12) I did not have trouble falling asleep last night	☐ True	☐ False
13) After I woke up last night, I had trouble falling asleep again	☐ True	☐ False
14) I tossed and turned all night last night	☐ True	☐ False
15) I did not get more than 5 hours' sleep last night	☐ True	☐ False

Time:	00
Subject No.	Fatigue

Do you feel any of the following symptoms right now?

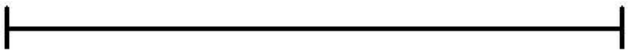
Please put a circle around - Yes - Y or No - N. For example:

My eyes are getting tired	Ⓨ/ N

1. My eyes are getting tired	Y / N	16. I feel giddy	Y / N
2. The small muscles around my eyes are twitching	Y / N	17. I feel unwell	Y / N
3. I can't stop yawning	Y / N	18. I am starting to feel drowsy	Y / N
4. Breathing takes an effort	Y / N	19. I feel like lying down	Y / N
5. I feel thirsty	Y / N	20. My head is drooping	Y / N
6. My voice is probably hoarse	Y / N	21. I have a headache	Y / N
7. Talking would take some effort	Y / N	22. I can't think clearly	Y / N
8. My back hurts	Y / N	23. My mind is blank	Y / N
9. I am sitting badly	Y / N	24. I can't concentrate	Y / N
10. My shoulder muscles are tense	Y / N	25. I am starting to forget things	Y / N
11. I feel stiff and clumsy	Y / N	26. I am uncertain	Y / N
12. My legs are getting tired	Y / N	27. I am starting to feel nervous	Y / N
13. I would be unsteady on my feet	Y / N	28. I am worried	Y / N
14. My whole body is getting tired	Y / N	29. I am losing interest in my work	Y / N
15. My limbs are shaking	Y / N	30. I feel impatient	Y / N

Time:	00
Subject No.	WEE

Your willingness to exert effort right now? Mark the scale

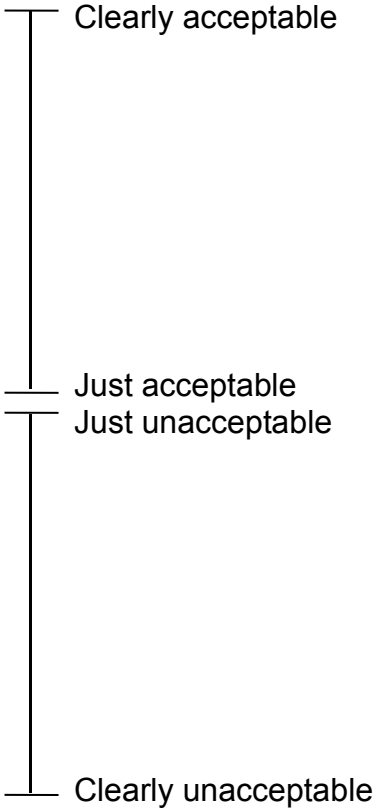
Not at all  Extremely

Date:	
Name: Subject No.	PAQ

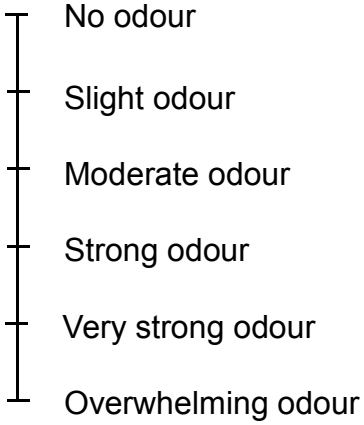
Imagine that you in your daily work are exposed to the air that you perceive at present

1. How do you assess the air quality?

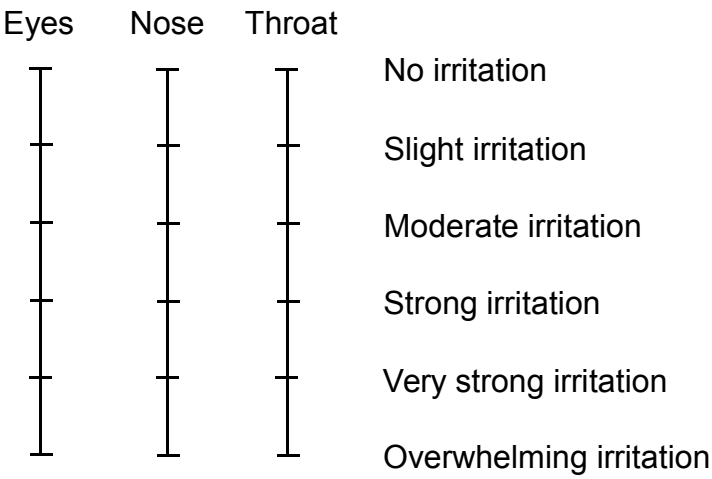
Notice the distinction between acceptable and unacceptable.



2. Assess odour intensity.

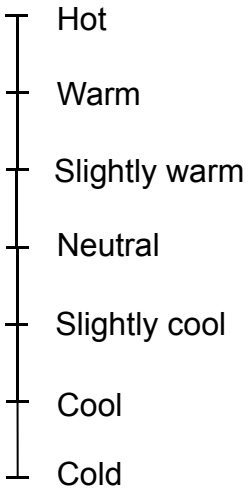


3. Assess irritation in

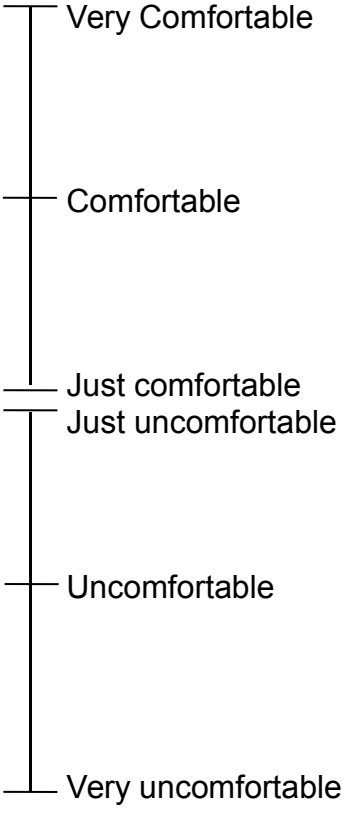


Date:	
Name: Subject No.	TC

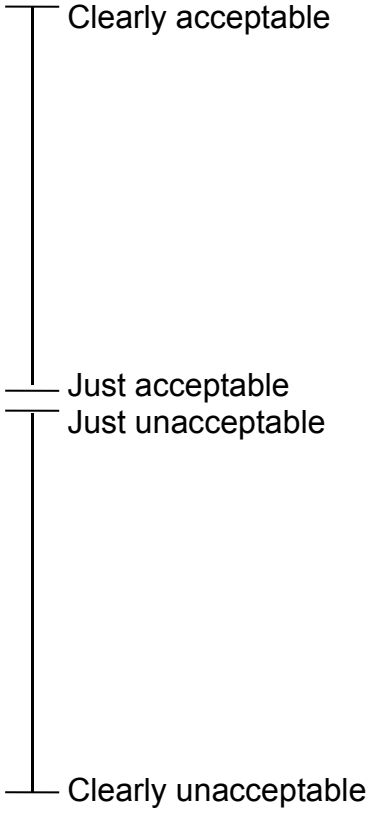
1. How is your thermal sensation <u>at this moment</u>?



2. How do you asses <u>the thermal comfort</u> right now (temperature, air movement, air humidity)?



3. How do you asses <u>the thermal environment</u> right now (temperature, air movement, air humidity)?



Date:	
Name: Subject No.	SBS

Right now, my environment can be described as follows:
（please tick the scales below at the place that best represents how you feel at this moment）

Too humid	———	Too dry
Air stuffy	———	Air fresh
Too dark	———	Too bright
Too quiet	———	Too noisy

Right now, I feel as follows:
（please tick the scales below at the place that best represents how you feel at this moment）

Nose dry	———	Nose running
Throat dry	———	Throat not dry
Skin dry	———	Skin not dry
Eyes dry	———	Eyes not dry
Eyes aching	———	Eyes not aching
Severe headache	———	No headache
Difficult to think	———	Head clear
Dizzy	———	Not dizzy
Feeling bad	———	Feeling good
Tired	———	Rested
Hard to concentrate	———	Easy to concentrate
Depressed	———	Positive
Alert	———	Sleepy

Date:	
Name: Number:	SEPX

Assess the tasks and your performance

The tasks seemed:

Very easy ——— Very hard (demanding)

My level of effort was:

Very low ——— As high as I could exert

The time pressure was:

No time pressure ——— High time pressure

I worked at:

0% ——— 100% of my full capacity

My performance was:

Poor ——— Excellent