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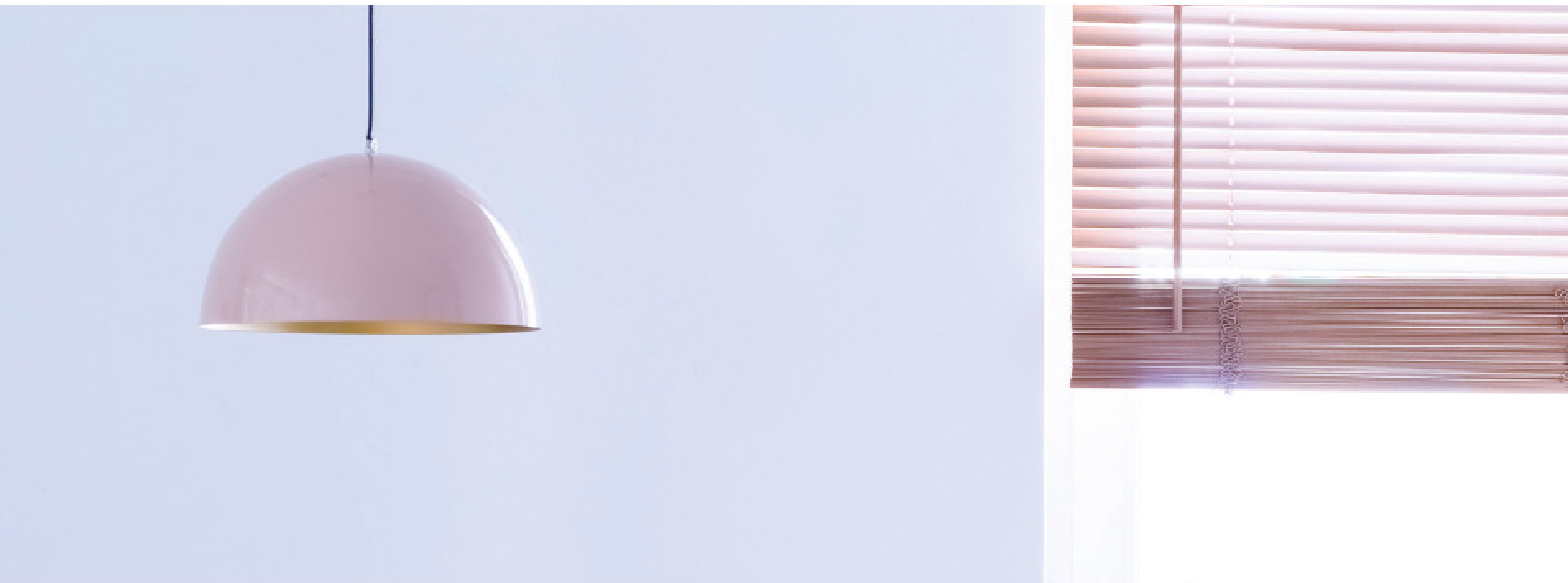

Associations between Bedroom Ventilation and Sleep Quality

Chenxi Liao

Doctoral dissertation submitted to obtain the academic degree of
Doctor of Engineering

Supervisors

Prof. Jelle Laverge, PhD* - Prof. Pawel Wargocki, PhD**

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Faculty of Engineering and Architecture, Ghent University

** Department of Civil Engineering
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Chenxi Liao

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Nomenclature

Acronyms

AASM	American Academy Of Sleep Medicine
AC	Air Conditioning
ACR	Air Change Rate
AH	Absolute Humidity
AHI	Apnea-Hypopnea Index
AI	Arousal Index
ANT	Attentional Network Task
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAMSE	Children, Allergy, Milieu, Stockholm, Epidemiology
BMI	Body Mass Index
BR	Building Regulation
CI	Confidence Interval
CNHS	California New Home Study
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COVID	Corona Virus Disease
DTU	Technical University Of Denmark
ECG	Electroencephalogram
EEG	Electroencephalogram

EMG	Electromyography
EOG	Electrooculography
ER	Error Rate
ERB	Ethical Review Board
ESD	Evening Sleep Diary
$ETCO_2$	End-Tidal CO_2
FL	Flow-Limited
FWO	Research Foundation - Flanders
GDPR	General Data Protection Regulation
GSQS	Groningen Sleep Quality Scale
HENGH	Healthy Efficient New Gas Home
HF	High Frequency
HR	Heart Rate
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
ICC	Intraclass Correlation Coefficients
IEQ	Indoor Environmental Quality
IQR	Interquartile Range
ISIAQ	International Society of Indoor Air Quality and Climate
KSS	Karolinska Sleepiness Scale
LF	Low Frequency
ML	Machine Learning
MRT	Mean Radiant Temperature

MSD	Morning Sleep Diary
MV	Mechanical Ventilation
NO_2	Nitrogen Dioxide
NOA	Number Of Awakenings
NREM	Non-Rapid Eye Movement
NV	Natural Ventilation
O_2	Oxygen
O_3	Ozone
ODI	Oxygen Desaturation Index
OV	Other Ventilation
PLMS	Periodic Limb Movement of Sleep
PM	Particle Matters
PM_1	Particle Matters with a diameter of 1 micrometre or less
PM_{10}	Particle Matters with a diameter of 10 micrometres or less
$PM_{2.5}$	Particle Matters with a diameter of 2.5 micrometres or less
PMV	Predicted Mean Vote
POMS	Profile Of Mood States
PPD	Predicted Percentage of Dissatisfied
PSG	Polysomnography
PSQI	Pittsburgh Sleep Quality Index
PSS	Perceived Stress Scale
PV	Personalized Ventilation
OR	Odds Ratio

REM	Rapid Eye Movement
RH	Relative Humidity
RMSE	Root Mean Square Error
RQ	Research Question
RT	Reaction Time
SBS	Sick Building Syndrome
SD	Sleep Diary
SDB	Sleep-Disordered Breathing
SE	Sleep Efficiency
SET	Sleep End Time
SHAP	Shapley Additive Explanation
SL	Sleep Latency
SO_2	Sulphur Dioxide
SST	Sleep Start Time
ST	Sleep Tracker
T	Temperature
TE-AD	Thermoelectric Air Duct Cooling
TIB	Time In Bed
TMD	Total Mood Disturbance
TRT	Analysis Duration
TST	Total Sleep Time
TV	Television
TVOC	Total Volatile Organic Compound

VLF	Very Low Frequency
VOC	Volatile Organic Compound
WASO	Wake After Sleep Onset
WBGT	Wet Bulb Globe Temperature
WC	Window Closed
WHO	World Health Organization
WO	Window Open

Symbols

ρ	Correlation efficient

Units

L/s	Volume flow rate
m^3/h	Ventilation flow rate
h^{-1}	Air change rate - times per hour
m^3/hour/person	Ventilation flow rate

Subscripts and superscripts

Cat.	Category
min	minute

Summary

The main objective of the PhD study was to explore bedroom ventilation and its impact on sleep quality. In particular, it documents how bedroom occupants rate bedroom air quality and their sleep quality, together with physical parameters and objective sleep quality measurements.

To meet this objective, the following research actions were undertaken: (1) a review was performed to have an overview of bedroom ventilation situations from current literature, indoor air quality standards from different countries and associations between bedroom ventilation and sleep quality reported in previous studies; (2) an experiment to quantify the effects of the window opening on sleep quality in the university dorm was designed and performed. A total of 27 subjects participated; (3) an online questionnaire survey, whose QR code was posted in the universities, public libraries and a residential community in the capital region of Denmark was prepared, distributed and analysed. A total of 517 responses were received; (4) a field study was designed and conducted in the heating season in Denmark to examine the real conditions in bedroom environments, sleep quality among occupants and how occupants rate bedroom air quality. In total, 75 occupants participated in this study.

The results of the literature and standard review indicated that the reported mean (or median) CO_2 levels in the majority of cases were generally within the ranges prescribed by the European CEN standard. The reported ranges of mean CO_2 concentrations and mean air change rates were 428-2,585 ppm and 0.2-4.9 h^{-1}, respectively. The air change rates in the heating season are generally much lower than 0.7 h^{-1}, which is the highest total ventilation put forward in both the CEN and ASHRAE standards. Four ranges of CO_2 levels and their corresponding effects on sleep quality were tentatively proposed based on the current literature. The CO_2 levels under 750 ppm were proposed as the range with undisturbed sleep quality; 750-1150 ppm as the range with possibly disturbed sleep quality; 1,150-2,600 ppm as the range with disturbed sleep quality and >2,600 ppm as the range with disturbed sleep quality with possible reduced next-day cognitive performance. The proposed ranges need further validation.

Window opening improved air quality in bedrooms during sleep based on the results of the experiment on the effects of the window opening on sleep quality. Snoring was more prevalent when sleeping with windows closed compared to sleeping with windows open. Sleeping with windows closed tended to be affected by a higher number of awakenings compared to sleeping with windows open. Subjective sleep quality and next-day performance were not significantly different between sleeping with windows open and closed. In addition, Fitbit Charge 2, the sleep tracker utilized in this experiment, was compared with home polysomnography, and it showed good agreement in sleep start time, sleep end time, total sleep time, and time in bed. The scoring of light sleep time and sleep latency were in moderate agreement; and sleep efficiency tended to be in poor agreement between the two types of devices. Time awake, REM time, deep sleep (N3) time, REM in percent, light sleep (N1+N2) in percent, and deep sleep (N3) in percent were not in significant agreement.

The survey study, which was conducted in the heating season, suggested that bedroom occupants were disturbed by stuffy air during night-time sleep in the heating season in Danish residences. Mechanical ventilation (balanced mechanical ventilation) tended to reduce sleep disturbance caused by stuffy air and by feeling "too cool" compared to the exhaust (unbalanced mechanical ventilation) and natural ventilation types in bedrooms. The presence of carpet in bedrooms caused more sleeping disturbed by stuffy air. People who were disturbed by stuffy air or by feeling "too warm" opened windows more frequently during the day or night, but the bedroom airing behaviours were not significantly associated with sleep quality. Subjective sleep quality based on the Pittsburgh Sleep Quality Index (PSQI) was poorer with an increased number of reported sleep disturbances caused by stuffy air, noise, "too warm" and "too cool". Moreover, the presence of objects such as carpet, TV set, printer and fish tank (39.5%) in bedrooms was negatively associated with subjective sleep quality. A field measurement was needed to validate the results.

The field measurement study in the heating season in the capital region of Denmark showed that bedroom perceived air quality was rated poorer after sleep among those who slept with both window and door closed compared to those who slept with either window or door open. The bedroom occupants, who slept with either window or door open, had significantly better subjective sleep quality, compared to those who slept with both window and door closed. A similar result was also found for the association between perceived air quality and subjective sleep quality. However, subjective sleep quality was not correlated with objective sleep quality, and the bedroom occupants had a higher percent of deep sleep with an increase of CO_2 levels in the range from 450 to 1200 ppm on average. These results suggest that tempered levels of CO_2 during sleep would be beneficial to deep sleep. This finding was opposite to the result of subjective sleep quality and the findings in previous studies. Bedroom air pollution levels should be studied more in detail to further investigate and understand the association between bedroom ventilation and sleep quality.

To summarize, bedroom occupants reported stuffy air as a sleep disturbance and those who slept with either window or door open had better subjective sleep quality, compared to those who slept with window and door closed. Sleeping with windows and doors closed induced a higher percentage of snoring and a higher number of awakenings compared to sleeping with windows open. The mechanical ventilation system in bedrooms was positively associated with less disturbance by stuffy air or feeling "too cool" during sleep, compared to the other ventilation types. Nevertheless, tempered levels of CO_2 around 1200 ppm were associated with more deep sleep (%) compared to the CO_2 levels below 1200 ppm.

The present conclusions need further validation, in particular where they contradict previous studies. Future studies are suggested to measure sleep- and ventilation- related air pollutants in bedrooms, such as NO_2 and O_3, and figure out the mediating role ventilation plays between exposure to these pollutants and sleep quality.

Samenvatting

Het hoofddoel van het doctoraatsonderzoek was het onderzoeken van slaapkamerventilatie en de impact ervan op de slaapkwaliteit. Het gevoerde onderzoek documenteert hoe slaapkamerbewoners de luchtkwaliteit in de slaapkamer en hun slaapkwaliteit beoordelen, samen met fysieke parameters en objectieve metingen van de slaapkwaliteit.

Hiertoe werden de volgende onderzoeksacties ondernomen: (1) er werd een literatuurstudie uitgevoerd om een overzicht te krijgen van gerapporteerde slaapkamerventilatie uit de huidige literatuur, van binnenluchtkwaliteits- en ventilatienormen uit verschillende landen, en van associaties tussen slaapkamerventilatie en slaapkwaliteit; (2) er werd een experiment opgezet en uitgevoerd om de effecten van het openen van het slaapkamerraam op de slaapkwaliteit in een studentenhuis te kwantificeren. In totaal namen 27 proefpersonen deel; (3) een online vragenlijstonderzoek, waarvan de QR-code werd opgehangen in universiteiten, openbare bibliotheken en een residentiële wijk in de hoofdstedelijke regio van Denemarken, werd voorbereid, verspreid en geanalyseerd. Er werden in totaal 517 reacties ontvangen; (4) er is een veldstudie opgezet en uitgevoerd in het stookseizoen in Denemarken om de werkelijke omstandigheden in slaapkameromgevingen en de slaapkwaliteit van de bewoners te onderzoeken alsmede in kaart te brengen hoe de bewoners de luchtkwaliteit in de slaapkamers beoordelen. In totaal namen aan deze studie 75 personen deel.

De resultaten van de literatuurstudie gaven aan dat de gerapporteerde gemiddelde (of mediane) CO_2-niveaus in de meeste gevallen min of meer binnen de door de Europese CEN-norm voorgeschreven waarden lagen. De gerapporteerde gemiddelde CO_2-concentraties en gemiddelde ventilatievouden waren respectievelijk 428-2.585 ppm en 0,2-4,9 h^{-1}. De ventilatievouden in het stookseizoen zijn over het algemeen veel lager dan 0,7 h^{-1}, wat het hoogste totale ventilatievoud is dat wordt vooropgesteld in zowel de CEN- als de ASHRAE-normen. Op basis van de huidige literatuur werden vier categorieën van CO_2-niveaus en overeenkomstige effecten op de slaapkwaliteit voorlopig voorgesteld. De CO_2-niveaus onder 750 ppm komen dan overeen met ongestoorde slaapkwaliteit; 750-1150 ppm komt overeen met mogelijk gestoorde slaapkwaliteit; 1.150-2.600 ppm met gestoorde slaapkwaliteit en > 2.600 ppm met gestoorde slaapkwaliteit met mogelijk verminderde cognitieve prestaties de volgende dag. De voorgestelde categorieën moeten verder worden gevalideerd.

Uit de resultaten van het experiment waarbij de effecten van het openen van het slaapkamer raam op de slaapkwaliteit werden onderzocht, blijkt dat het openen van het slaapkamerraam de luchtkwaliteit in slaapkamers tijdens de slaap verbeterde. Snurken kwam vaker voor bij het slapen met gesloten ramen in vergelijking met slapen met open ramen. Slapen met gesloten ramen leek te leiden tot een hoger aantal episodes van ontwaken in vergelijking met slapen met open ramen. Subjectieve slaapkwaliteit en prestaties de volgende dag waren niet significant verschillend tussen slapen met open en gesloten ramen. Daarnaast werd Fitbit Charge 2, het sporthorloge dat in dit experiment werd gebruikt, vergeleken met thuispolysomnografie. Beide types toestellen vertoonden een goede overeenkomst wat de starttijd, de eindtijd, de totale duur van slaap en de tijd in bed betreft; lichte slaaptijd en slaaplatentie waren in matige overeenstemming; Voor tijd wakker, REM-tijd, diepe slaap (N3) tijd, REM in procent, lichte slaap (N1+N2) in procent en diepe slaap (N3) in procent was er geen significante overeenstemming, terwijl slaapefficiëntie meestal slecht met elkaar overeenstemde.

De resultaten van de enquêtestudie, die werd uitgevoerd in het stookseizoen, suggereren dat de deelnemers tijdens de nachtelijke slaap in het stookseizoen in Deense woningen last hadden van benauwde lucht. Mechanische ventilatie was gecorreleerd met een verminderde verstoring van de slaap veroorzaakt door benauwde lucht of een "te koel" gevoel in vergelijking met de afvoer- en natuurlijke ventilatietypes in slaapkamers. De aanwezigheid van tapijt in slaapkamers was gecorreleerd met meer slaapstoornissen door benauwde lucht. Mensen die last hadden van benauwde lucht of 'te warme' omstandigheden openden overdag of 's nachts vaker ramen, maar het raamopeningsgedrag in de slaapkamer was niet significant gecorreleerd met de slaapkwaliteit. De subjectieve slaapkwaliteit op basis van de Pittsburgh Sleep Quality Index (PSQI) was slechter met een verhoogd aantal gerapporteerde slaapstoornissen veroorzaakt door benauwde lucht, lawaai, "te warm" of "te koel". Bovendien was de aanwezigheid van tapijt, tv, printer en aquarium (39.5%) in slaapkamers negatief gecorreleerd met subjectieve slaapkwaliteit. Een veldonderzoek was nodig om de resultaten te valideren.

Het veldonderzoek in het stookseizoen in de hoofdstad van Denemarken toonde aan dat de waargenomen luchtkwaliteit in de slaapkamer na het slapen slechter werd beoordeeld bij degenen die sliepen met zowel raam als deur gesloten in vergelijking met degenen die sliepen met raam of deur open. De deelnemers die sliepen met een raam of een deur open, hadden een significant betere subjectieve slaapkwaliteit in vergelijking met degenen die sliepen met zowel raam als deur gesloten. Een vergelijkbaar resultaat werd ook gevonden voor de relatie tussen waargenomen luchtkwaliteit en subjectieve slaapkwaliteit. De subjectieve slaapkwaliteit was echter niet gecorreleerd met de objectieve slaapkwaliteit, en de slaapkamerbewoners hadden een hoger percentage diepe slaap bij toenemende gemiddeld CO_2-niveaus tussen de 450 en 1200 ppm. Op basis van deze resulaten zouden getemperde niveaus van CO_2 tijdens de slaap gunstig zijn voor de diepe slaap. Deze bevinding was tegengesteld aan het resultaat van de subjectieve slaapkwaliteit en de bevindingen in eerdere onderzoeken. Luchtverontreinigingsniveaus in de slaapkamers moeten daarom meer in detail worden bestudeerd om het verband tussen slaapkamerventilatie en slaapkwaliteit verder te onderzoeken en te begrijpen.

Samenvattend: deelnemers rapporteerden benauwde lucht als een slaapstoornis en degenen die sliepen met raam of deur open hadden een betere subjectieve slaapkwaliteit dan degenen die sliepen met raam en deur gesloten. Slapen met ramen en deuren gesloten veroorzaakte een hoger percentage snurken en meer ontwaken in vergelijking met degenen die sliepen met open ramen. Een mechanische ventilatiesysteem in slaapkamers was nuttig om minder gestoord te worden door benauwde lucht of een "te koel" gevoel tijdens de slaap, in vergelijking met de andere ventilatietypes. Desalniettemin waren getemperde CO_2-niveaus van omstreeks 1200 ppm gunstig voor meer diepe slaap (%) in vergelijking met CO_2-niveaus onder 1200 ppm.

De huidige conclusies behoeven verdere validatie, met name wanneer ze in tegenspraak zijn met eerdere studies. Voor toekomstige studies wordt voorgesteld om meer in detail luchtverontreinigende stoffen in slaapkamers te meten om erachter te komen welke rol ventilatie speelt in de relatie tussen die verontreinigende stoffen en de slaapkwaliteit.

1

Introduction & Outline

1.1 Background

1.1.1 Sleep quality

People spend one-third of their life sleeping and sleep is essential for physical and mental health as well as next-day performance [1, 2]. Poor sleep quality was shown to cause cardiovascular disease, cancer, diabetes, worse general physical health, mental health problems, behavioural and emotional dysregulation and cognitive impairments [3].

1.1.1.1 Metrics

Sleep is known to be regulated by circadian and homeostatic processes [4]. Sleep is organized in cycles consisting of two states of being, which are Rapid Eye Movement (REM) and non-REM sleep (NREM). NREM sleep is subdivided into “light” stages (N1 and N2) and “deep” (N3 or slow-wave). Figure 1. 1 shows the sleep architecture of a normal night. One sleep cycle takes around 90 min from the wake, N1, N2, N3 to REM sleep and then starts again.

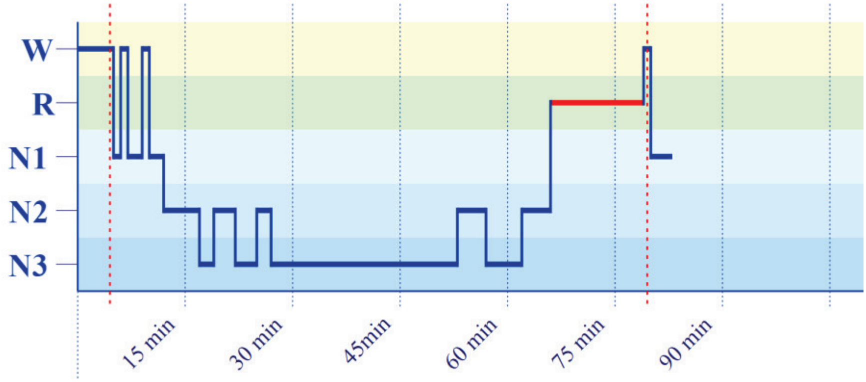

Figure 1. 1 Sleep architecture [5]. W, wake; R, REM.

Other than that, sleep latency, wake after sleep onset (WASO), the number of awakenings, total sleep time and sleep efficiency are also criteria of sleep quality. Sleep latency is the length of time between the time to go to bed and the time to fall asleep; WASO is the time awake after sleep onset; sleep efficiency is defined as the percentage time in bed spent asleep and calculated as the time asleep divided by the time in bed; total sleep time (or time asleep) is the total time a person spends in REM and NREM sleep and is calculated as time in bed minus sleep latency and WASO [6].

The National Sleep Foundation in the United States reviewed 277 sleep studies to summarize the criteria of sleep quality for people of different age groups [7]. The detailed criteria for young adults aged 18-25 years and adults aged 26-64 years are presented in Table 1. 1. Appropriateness was rated from 1 (i.e., extremely inappropriate) to 9 (i.e., extremely appropriate) by an expert panel assembled by the National Sleep Foundation in the United States. ‘Appropriate’ ranges were selected as conditions where 80% of the expert panel votes were 7–9, ‘uncertain’ if 80% of the expert panel votes were 4–6 or 20% fell outside these 3-point ranges, and ’inappropriate’ if 80%

of the expert panel votes were 1–3 [7]. Generally, a higher percentage of deep sleep and sleep efficiency indicates good sleep quality [8].

Table 1. 1 Recommended appropriate, uncertain, and inappropriate ranges of the sleep parameters among people aged 18–25 and 26–64 years by National Sleep Foundation [7, 9] [a].

Items	Appropriate		Uncertain		Inappropriate	
	18–25 years	26–64 years	18–25 years	26–64 years	18–25 years	26–64 years
Sleep latency (min)	≤ 30	≤ 30	31–45	31–45	≥ 46	≥ 46
WASO (min)	≤ 20	≤ 20	21–40	21–40	≥ 41	≥ 41
Sleep efficiency (%)	≥ 85	≥ 85	65–84	75–84	≤ 64	≤ 74
REM activity (%)	-	21–30	≤ 40	≤ 20, 31–40	≥ 41	≥ 41
N1 (%)	≤ 5	≤ 5	6–20	6–20	> 20	> 20
N2 (%)	-	-	≤ 80	≤ 80	> 81	> 81
N3 (%)	-	16–20	≥ 6	6–15, > 20	≤ 5	≤ 5
TST/asleep (h)	7–9	7–9	6, 10–11	6, 10	< 6, > 11	< 6, > 10

WASO, wake after sleep onset; TST, total sleep time.

1.1.1.2 Assessment of sleep quality

Table 1. 2 and Table 1. 3 show common techniques for objective and subjective assessments of sleep quality, respectively. Objective assessments of sleep quality typically use polysomnography (PSG) and actigraphy (sleep tracker). Subjective assessments of sleep quality mostly uses the Pittsburgh Sleep Quality Index (PSQI), the Groningen Sleep Quality Scale (GSQS), and other questionnaires.

Different biologic manifestations, both neurologically and physically, occur in those different sleep stages [10]. Clinical PSG, which contains electromyography (EMG), and electrooculography (EOG), and electroencephalogram (EEG), is the gold standard for objective sleep assessment. Different sleep stages can be distinguished by specific types of brain activities. For example, wave activities and sleep spindles with local or global slow cortical oscillations occur in N3 and N2, respectively, while similar EEG patterns as in waking either with or without eye movement are observed during REM sleep [11]. PSG requires trained sleep technicians and a dedicated PSG acquisition system to record and visually score PSG records [12]. However, two alternative sleep measurements, namely home PSG and actigraphy have been considered and used in literature. Home PSG, such as the Nox A1 from ResMed [13], is a portable and easy-to-use PSG for home sleep testing. The Nox A1 also uses software to distinguish sleep stages in an automated way. Fitbit, a type of sleep tracker combining actigraphy with cardiac signals, was reported to have good agreement with PSG in measuring time asleep (total sleep time) and sleep efficiency, and have gross estimates of sleep stages, although it underestimated sleep latency [14]. There are also other types of sleep trackers, such as Philips Actiwatch 2 and Sensewear Armband [15, 16], but there was little information available regarding their accuracy.

Besides objective assessments of sleep quality, subjective assessments of sleep quality are also widely used. For example, the Pittsburgh Sleep Quality Index (PSQI) and the Groningen Sleep

Quality Scale (GSQS) are broadly utilized in previous sleep studies [17-20]. The PSQI was proposed by Buysse et al. (1989) and suggested to be used in both psychiatric clinical practice and research [21]. The PSQI is a self-rated questionnaire for assessing sleep quality during the past month and the maximum score of 21 indicates poor sleep quality. The GSQS was constructed by Mulder-Hajonides, van der Meulen and van den Hoofdakker (1988) and evaluated by Meijman et al. (1988) [22]. The GSQS is a 15-question questionnaire for daily-monitored sleep quality and the maximum score of 14 points indicates poor sleep quality. There are other questionnaires for assessing sleep quality the previous night, such as the ones listed in Table 1. 3. However, they were not as widely used as the GSQS.

Table 1. 2 Objective assessment of sleep quality.

Items	Concerning parameters	Reference
Polysomnography (PSG)	Sleep latency (SL) Total sleep time (TST) WASO Awakenings Amount and percentage of the sleep stages (N1, N2, slow wave sleep [SWS], and REM)	[23]
Home PSG	Same as PSG	[13]
Actigraphy (sleep tracker)	Time in bed Time asleep Light sleep (min) (N1 + N2) Deep sleep (min) (N3) REM sleep (min) Number of awakening	[15, 24]

Table 1. 3 Subjective assessment of sleep quality.

Items	Concerning parameters	Definition of good sleep quality	Reference
Pittsburgh Sleep Quality Index (PSQI, 21 questions)	PSQI score	A global score of above 5 represents overall poor sleep quality.	[21]
The Groningen Sleep Quality Scale (GSQS, 14 questions)	GSQS score	Maximum score of 14 points indicates poor sleep the night before.	[22]
Questionnaire 1 (5 questions)	Calmness of sleep Ease of falling to sleep Ease of awaking Freshness after awaking Satisfaction about the sleep (5-point Likert scale for each parameter)	A higher score indicates better sleep quality.	[25]
Questionnaire 2 (11 questions)	Global score	A higher score indicates better sleep quality.	[26]

1.1.2 Bedroom ventilation

Carbon dioxide (CO_2) is a marker of ventilation and is used as an indicator of indoor air quality (IAQ) [27-29]. Bedrooms typically have poorer ventilation compared to the living room [30, 31]. CO_2 levels with an average of 428 to 2,585 ppm were measured in previous chamber or field studies involving bedroom ventilation and sleep quality [15, 16, 32, 33]. A Belgian study reported a 6 times higher risk of CO_2 exposure in bedrooms than in the living rooms [31].

Bedroom ventilation types, such as mechanical and natural ventilation, substantially affect the observed ventilation rates. Ai et al. (2016) suggested ventilate the bedroom mechanically for a few times and each time for several min during a normal sleeping period of 8 hours to maintain acceptable IAQ with CO_2 levels below 1000 ppm based on the standard in China [34]. The World Health Organization (WHO) also suggested sleeping with windows open to provide proper ventilation [35]. It relies on bedroom airing behaviours, such as windows or door opening, because these are the main implements for people to ventilate their bedrooms. Approximate 23.5% to 48.0% of bedroom occupants opens windows during sleep, specific fractions depending on seasons, climates, or personal habits [36-40].

1.1.3 Association between bedroom ventilation and sleep quality

A total of 9 studies investigated the association between bedroom ventilation and sleep quality. They reported effects of higher CO_2 levels on objective sleep quality including lower sleep efficiency [15, 16], higher sleep efficiency [41], increased number of awakenings [15], shorter sleep latency [16], reduced next-day performance [16], lower percent of deep sleep [32], increased number of awakenings [41], reduction in the shifting between sleep stages [42], and on subjective sleep quality including lower depth of sleep [15], more sleepy and less able to concentrate on the next day [16], reduced self-reported sleep quality, less rested, lighter sleep, and increased number of awakenings [41]. Non-significant results were found in the remaining 4 studies [33, 41, 43-45].

More information is presented in Chapter 2.

1.1.4 Association between bedroom environment and sleep quality

Besides IAQ, other environmental parameters, such as noise, ambient temperature, relative humidity, and light, are also associated with sleep quality. Two types of noise – intermittent and continuous noise, was researched in previous studies. Exposure to intermittent noises above 35 dB reduced sleep quality and quantity, while the influence of continuous noise requires further study because only few studies were conducted on that. A review concluded that the appropriate range of room temperature and relative humidity for good sleep quality was 17–28 °C and 40–60%. Exposure to light before, during and after sleep influences sleep outcomes. For example, exposure to blue light pre-bedtime is associated with poorer sleep outcomes, while warmer colour temperatures improve sleep quality [46]. EEG, actigraphy, PSQI, and other questionnaires were used in these studies.

1.1.5 Research gap

Research regarding the association between bedroom ventilation and sleep quality is limited, and the results reported in the literature were not consistent. For example, Laverge and Janssens [41] reported higher sleep efficiency when sleeping with windows closed compared to it sleeping with windows open, while two other studies reported lower sleep efficiency [15, 16]. In addition to these consistent results, the studies mentioned above also did not consistently produce the same results for all metrics, and some of the studies found inconclusive results for the association between bedroom ventilation and sleep quality. The mechanism of that association was not clear and thus more physical and physiological parameters are required, such as skin temperature, which is easy to measure and reflects core body temperature that plays a major role in sleep regulation [47]. Besides, previous studies were mainly chamber studies or performed in student dorms. Only one study was conducted in the residential homes but did not find a significant result. The reasons could be a too-small sample size of 24 participants or because the authors did not run a statistical model to adjust for other sleep-related factors, such as exercise, consumption of coffee, alcohol, etc. [33].

In summary, more studies are needed to further explore the association between bedroom ventilation and sleep quality, especially a field study in residential houses among bedroom occupants.

1.2 Research objectives

The topic of the doctoral study was the association between bedroom ventilation and sleep quality.

Specific objectives of the doctoral study were:

- to examine the state-of-the-art of bedroom ventilation and its effects on sleep quality (Chapter 2).
- to investigate the effects of window opening on sleep quality (Chapter 3).
- to explore the bedroom ventilation types in Danish housing, and the associated factors that influence bedroom indoor environmental quality (IEQ) and may disturb sleep quality (Chapter 4).
- to examine the bedroom ventilation and better document the association between CO_2 levels as a marker of ventilation and sleep quality and rank the CO_2 levels and the other reported sleep-related factors (Chapter 5).

1.3 Methods

To realize the objectives of the PhD study, the following investigations were made: (1) performing a literature review of existing evidence and current standards for bedroom ventilation and its impact on sleep quality (Chapter 2); (2) conducting an intervention study for investigating the effects of windows opening, which is a major implement for people to ventilate their bedrooms, on the bedroom environment and resulting sleep quality (Chapter 3); (3) preparing, distributing and analysing an online questionnaire survey in the capital region of Denmark regarding bedroom ventilation types and the subjective sleep quality (Chapter 4); (4) digging into people's daily life to measure bedroom environmental parameters in their bedrooms during sleep, assess their sleep quality both objectively and subjectively, and analyse the association between bedroom ventilation and sleep quality (Chapter 5).

All the statistical analyses were conducted in either SPSS 25.0 (SPSS Ltd., USA), R Studio (version 1.3.1093, Boston, MA, USA), or Spyder (version 5.1.0).

A brief introduction of the methods for each chapter is described as follows. All the details are described in each Chapter.

1.3.1 Literature review and standards (Chapter 2)

Several keywords, such as residential buildings, bedrooms, sleep quality, ventilation, etc., were used for searching the Web of Science. Simulation studies or studies in non-residential buildings were excluded. In addition, only papers published after 2000 were included in the literature review.

Ventilation rates, ACR, and CO_2 concentrations were reported in this literature review. Furthermore, the requirements for these metrics in standards on ventilation and indoor air quality (IAQ) of residential buildings were also reviewed and reported.

1.3.2 Window opening effects on sleep quality (Chapter 3)

An experiment on the effects of window opening on bedroom environment and sleep quality was conducted in four rooms of a university dorm located in Ghent, Belgium, in April 2019. The gathered data included physical measurements in the dorm rooms, Groningen Sleep Quality Scale (GSQS) and home polysomnography (PSG) to assess sleep quality among subjects, sleepiness and next-day performance measured by the Karolinska Sleepiness Scale (KSS) and the attentional network task (ANT), respectively, movements during sleep measured using the Flex Sensor, health symptoms rated using a Likert rating scale (10 points), and mood and stress assessed using the abbreviated Profile of Mood States (POMS) and the Perceived Stress Scale (PSS).

A total of 27 subjects participated in this experimental study. Physical measurements and answers from the subjects are reported. The association between window status (open or closed) and sleep quality is analysed by the paired-samples t-test or the non-parametric Wilcoxon matched-pairs signed-ranks test.

1.3.3 A questionnaire survey in Danish housing (Chapter 4)

An online questionnaire survey was prepared and distributed among people living in the capital region of Denmark. A poster, which was posted in the universities, public libraries, and residential areas in the capital region of Denmark from January to February 2020 (before the first lockdown in Denmark on 11th March due to the COVID-19 pandemic), was made to distribute the questionnaire.

The questions included in the questionnaire were selected and designed according to the objectives of the study, i.e. having an overview of the ventilation types in bedrooms, bedroom airing behaviours, and the associations of them with the subjective sleep quality.

The content of the questionnaire includes background information including personal characteristics; regular sleep pattern during weekdays; smoking habits; bedroom environment, such as building characteristics, building surroundings, bedroom objects, frequency of being disturbed by the environmental factors, such as "stuffy air, too warm, too cool, or noise", etc.; bedroom ventilation, such as bedroom airing behaviours and air terminal devices information; additional questions which may be related to sleep quality, such as having any chronic disease, exercise frequency, etc.; and the Pittsburgh Sleep Quality Index (PSQI).

A total of 517 responses were received. All the results regarding background, bedroom ventilation, etc. are reported. Using the data collected from the online questionnaire survey, the association between bedroom ventilation types and sleep quality was examined by generalized linear models, binary logistic regression models, or univariate linear models.

1.3.4 Field measurement in Danish housing (Chapter 5)

Having done the questionnaire survey, a field measurement study was conducted from September to December 2020, before the second lockdown in Denmark on 9th December 2020. An invitation letter (Annex 1A Invitation letter), instruction (Annex 1A Instruction), sleep diaries, measuring boxes, and posters (Annex 1A poster) were prepared before the measurement. The invitation letter was sent to the respondents who responded to the previous online questionnaire survey mentioned above in the early year of 2020. Background information, such as gender, age, etc., was also collected.

The instruction contains the content of where to put the measuring box, how to use the box, points to be noticed, and how to fill in the sleep diaries. Sleep diaries include both evening and morning versions. The bedroom environment was assessed via continuous visual analogue scales for perceived temperature, humidity, light, air stuffiness, noise and odour; and via another type of continuous scale for thermal comfort, air quality, acoustic comfort, and visual comfort.

A total of 84 subjects joined in this field study, but only 75 of them completed the most important measurements of CO_2 and sleep stages. Descriptive data are reported and the association between bedroom ventilation and sleep quality was analysed using random forest regression models.

1.4 Outline

This doctoral thesis consists of six separate chapters. These chapters have been written as a compilation of four journal publications, three of which have already been published and the fourth is in preparation to be submitted soon. A general outlook of the chapters and the corresponding papers and journals is given below.

- Chapter 1: ‘Introduction’.
- Chapter 2: ‘Bedroom Ventilation: Review of Existing Evidence and Current Standards’ in Building and Environment, published 2020.
- Chapter 3: ‘Effects of Window Opening on The Bedroom Environment and Resulting Sleep Quality’ in Science and Technology for the Built Environment, published 2021.
- Chapter 4: ‘A survey of bedroom ventilation types and the subjective sleep quality associated with them in Danish housing’ in Science of the Total Environment, accepted 2021.
- Chapter 5: ‘Investigating the effects of bedroom ventilation on sleep quality: a field study in the heating season in Danish dwellings’ in preparation.
- Chapter 6: ‘Conclusions and perspectives’.

The content in the following chapters has been revised to improve the readability of the thesis and thus is not completely the same as the publications.

2

Bedroom Ventilation: Review of Existing Evidence and Current Standards

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Building and Environment, published 2020.

The contribution of the thesis' author was to draft the introduction, co-lead the design and making of Tables 2.3 and 2.4, participate in the meetings to discuss the content, and review the paper.

Keywords

Dwellings, Bedrooms, Ventilation, CO_2, Air Exchange Rate, Sleep quality, Standards

Abstract

Sleep is essential for our health and well-being. Some research suggests that air quality influences sleep quality in bedrooms, but the evidence is limited. Research, until now, has focused on how indoor air quality affects health, comfort, and cognitive performance during waking hours. Less information is available on the levels of indoor air quality and ventilation in bedrooms, as well as on their consequences for sleep quality and the next-day performance. This paper addresses the former by reviewing research published in peer-reviewed journals in this millennium. The bedroom ventilation has been chosen as a specific focus of this review paper, which also includes a review of selected international standards for bedroom ventilation. Arising out of this review based on a framework of comparison of field data with CO_2 and ventilation benchmarks from widely adopted international standards, an attempt is made to generalize the level of bedroom ventilation that exists in practice in residential dwellings and apartments across different seasons and different parts of the world. Besides, based on a limited number of studies, published after 2000, dealing with the impact of bedroom ventilation on sleep quality, an attempt is also made to associate the measured field data with a potential impact on sleep quality.

2.1 Introduction

Adequate sleep is essential for physical, cognitive, and emotional health, as well as next-day performance [1, 2]. Sleep can optimize memory consolidation [48-50]. It has been documented that poor sleep cause increased cardiovascular risk [51], altered metabolism, and can increase the risk of obesity and diabetes [52], reduce insulin sensitivity [53], reduce leptin and elevated ghrelin, which might contribute to obesity [54]. Restricting sleep below 7 hours can cause several neurobehavioral deficits, including lapses of attention, slowed working memory, reduced cognitive throughput, depressed mood, and perseveration of thought [55].

Sleep is characterized by different stages, each of them playing an essential role in proper functioning each day. According to the previous sleep research [7], the following sleep continuity variables are considered to be appropriate indicators of sleep quality across the lifespan; sleep latency, number of awakenings longer than 5 minutes, wake after sleep onset, sleep efficiency, and appropriate percentages of different sleep stages. Sleep stages include wakefulness, rapid eye movement (REM) that is associated with dreaming, and non-rapid eye movement (N-REM) [56]. It is reported good sleep for the adults, categorized aged 26–64 years, is less than 30 min of sleep latency, one or fewer number of awakenings, less than 20 min of wake after sleep onset, higher than 85 % sleep efficiency, 21–30 % REM sleep, less than or equal to 5 % N1 (N-REM1) sleep, and 16–20 % N3 (N-REM3) sleep [7].

Most sleep research was done in the laboratories, and the focus was on characterizing sleep, but little research was carried out on the effects of bedroom environmental quality on sleep. Indoor environmental quality (IEQ) research has mainly focused on offices, schools as well as dwellings but still, in the case of the latter, the research has been less abundant and quite modest concerning the conditions in bedrooms and their effects on sleep quality, the focus is mainly on the effects of temperature.

The limited number of studies in bedrooms is surprising, considering that humans spend about one-third of our life in bedrooms. Also, exposure to air in bedrooms is significant. People consume approximately 7.5 [57] and 5.5 L/min [58] of air during awake and sleep, so we consume 9,840 L per day of air if the total sleep time is 8 hours and the time awakened is 16 hours. Consequently, the air inhaled at night accounts for around 26.8% of total air inhaled per day. Over a 70-year lifetime, a person breathes about 66,528 m^3 during the night; this air may contain numerous pollutants of chemical, physical, and microbial origin [57].

Very few studies focused on the role of bedroom air quality and ventilation on the quality of sleep [15, 16, 32, 59]. Although sparse, the results of these studies suggest the poor indoor air quality (IAQ) occurring with low ventilation would disturb proper sleep. For example, increased ventilation with outdoor air indicated by lower CO_2 concentrations was found to correlate with improved actigraphy-measured sleep efficiency [15, 16], higher self-reported sleep quality [16, 32], higher self-assessed sleep depth [15, 59], the fewer number of awakenings [15, 59] and deeper sleep [32]. Additionally, bedroom temperature modified the effect of ventilation (indicated by CO_2 levels) in the case of the percentage of light sleep [32]. There was an interaction effect of temperature and CO_2 on the percentage of light sleep, but the direction of the effect was not presented by the authors [32]. Liao et al. found that higher CO_2 levels with closed windows were associated with higher snore percentages in subjects who otherwise did not report problems with sleep (the Pittsburgh Sleep Quality Index (PSQI) was less than or equal to 5) [60].

The primary objective of this review was to gain a better understanding of what is available as sound scientific knowledge concerning bedroom ventilation characteristics across different climate zones. This knowledge was then connected to the potential effects on sleep quality. Another objective was to gain an insight into the selected major standards for bedroom ventilation and IAQ across different parts of the world. Finally, the thermal environment in bedrooms was considered in case the interaction effect with CO_2 on sleep quality was reported or bedroom ventilation had an effect on the thermal environment. Thermal environment, which was largely studied together with ventilation in the reviewed papers, was an additional part of this Chapter. The other aspects of indoor environmental quality (IEQ), such as light and noise, would be also interesting in regard to sleep quality but are outside the scope of this thesis.

2.2 Methods

The methodology adopted in identifying relevant and high-quality scientific publications involved a search on Web of Science using several keywords, such as residential buildings, bedrooms, sleep quality, ventilation, IAQ, thermal comfort, CO_2, field studies, heating, and cooling. The keywords were discussed and decided by all the co-authors to include as many relevant publications as possible. All publications found were considered to be included but we were not specifically searching publications outside the building-related journals. Publications were also included manually from the reference lists of the original articles identified via a search on the Web of Science. More than 200 papers were collected in this way. They were then shortlisted based on the applicability of their titles and key information provided in their abstracts. Studies that described mainly simulation analysis or ventilation in non-residential buildings were excluded in the process of shortlisting. On the basis that a period of slightly over two decades is a reasonable time frame for advancement in building designs and technologies to have been incorporated in practice, only papers published after 2000 were included in this review. Besides, before 2000, there were rather few studies that investigated indoor air quality or ventilation and sleep. Also, building regulations and lifestyles have been changing, and the papers regarding bedroom ventilation and sleep quality were all published after 2010. Hence, previous publications far before 2010 were not as valuable as the ones published close to 2010 regarding the topic of bedroom ventilation and sleep quality.

A total of 46 papers were included in the final review. These papers were from the peer-reviewed journals that reported ventilation measurements in bedrooms in various climatic zones addressing at least one of the following key attributes: ventilation characteristics, CO_2 measurements, and sleep quality. We report ventilation rates, ACR, and CO_2 concentrations in this review paper. If information was available in the paper, we write that ventilation rate or ACR refers to outdoor air supply rate or air change rate with outdoor air. This will usually be the case for mechanically ventilated bedrooms. If no information about this was given, then the ventilation rate and ACR would likely describe the total airflow including outdoor air and the air from adjacent rooms. With regards to CO_2, if the information was provided that CO_2 represented steady-state, then we report the same. Else, it is usually an average level measured or peak (maximum), if reported. Sometimes, CO_2 (and the number of people in the room) is used to estimate ventilation rates and air change rates. Here, the same limitations will apply regarding interpretation. If CO_2 change was caused only by outdoor air, then it is explicitly written, else ACR or ventilation rate estimated using CO_2 could be the total flow including again outdoor air and air from adjoining rooms.

In addition to collecting papers reporting the measurements in bedrooms, the standards on ventilation and indoor air quality pertaining to residential buildings were also reviewed with a particular focus on the requirements and prescribed conditions that are explicitly dealing with bedroom environments. While no specific criteria for inclusion were considered, an effort was made to cover the main continents and specifically the countries that are known to have such ventilation standards for residential buildings. Furthermore, a lot of countries made their ventilation standards by reference to the authoritative standards, such as the ASHRAE standard. No systematic review was made other than that.

2.3 Ventilation requirements for bedrooms and residential buildings in standards

In the literature, there is a limited number of reviews of some ventilation standards [61, 62]. A broader review of international ventilation standards like ASHRAE and CEN and fifteen country-specific standards in this paper showed that there is general guidance towards the provision of ventilation in the design of residential buildings. In some cases, there is also clear guidance for bedrooms. Table 2. 1 is a summary of these requirements for the number of standards selected for this review. Based on more widespread usage of ASHRAE and CEN standards, the ventilation rates and CO_2 levels specified in them are used as benchmarks for comparison across the various reported studies selected in Table 2. 2 as part of the review analysis in this paper.

ANSI/ASHRAE Standard 62.2 specifies minimum requirements for mechanical and natural ventilation systems and the building envelope intended to provide acceptable IAQ in residential buildings [63]. While not specifically indicating requirements for bedrooms, the standard specifies ventilation requirements for dwelling units, which is based on the floor area and the number of bedrooms. The dwelling ventilation rate increases as the number of bedrooms increases, and the floor area increases, resulting in relatively large ventilation even in case of only one bedroom when the floor area is large.

The European CEN EN 16798-1 standard offers guidance on pre-defined ventilation airflow rates for residential buildings that can comprise one or more of the following components: total air change rate for the dwelling; extract air flows for specific rooms; supply air flows for specific rooms; design opening areas for natural ventilation [64]. The standard specifies total ventilation (including infiltration) of 0.49, 0.42, 0.35, and 0.23 L/s per m^2 floor (corresponding to an air change rate (ACR) of 0.7, 0.6, 0.5 and 0.4 h^{-1}) for Category I, II, III and IV buildings, respectively. These categories represent the level of expectations occupants may have in buildings, ranging from high (Cat. I), medium (Cat. II), moderate (Cat. III), and low (Cat. IV), based on the supply airflow of 10, 7, and 4 L/s per person for the first three categories, respectively. The ventilation rate in Cat. IV is defined using the CO_2 mass balance equation assuming CO_2 emission of 20 L/h per person and 13.6 L/h per person for living rooms and bedrooms, respectively. The design ΔCO_2 levels, in terms of ppm above outdoors, are 380 ppm (Cat I), 550 ppm (Cat II), 950 ppm (Cat III), and > 950 ppm (Cat IV). If the room size is 10 m^2 with a height of 2.5 m, ventilation provision of 4, 7, and 10 L/s per person correspond, with an occupancy of 2 persons, to an air change rate of 1.2, 2.0, and 2.9 h^{-1}. Cat I is for occupants, such as children, elderly, and people with disabilities, with special needs; Cat II is the normal level used for design and operation; Cat III still provides an acceptable environment with some risk of reduced performance for occupants; Cat IV should only be used for a short time of the year or in a space with very short time of occupancy [65].

The CEN EN 16798-1 standard also specifies supply airflow for the three categories of indoor environment in residential buildings, based on perceived air quality, for adapted persons – 3.5, 2.5, and 1.5 L/s per person (0.25, 0.15, and 0.1 L/s per m^2 floor). The extract airflow rates by room and building types, as specified in the CEN standard for the various categories of buildings, are included in Table 2. 1. Finally, for naturally ventilated dwellings, the standard offers a methodology to define default design opening areas such as supply/extract grilles, stack ducts, window grilles, or similar systems. It specifies default design opening areas for dwellings as 100 cm^2 per room (extract from kitchens, bathrooms, and toilets) and 60 cm^2 per room (supply to bedrooms and living rooms).

Among the European countries, ventilation standards from Belgium, Norway, Denmark, Austria, Sweden, France, Germany, Netherlands, and the United Kingdom were reviewed [66-74]. While the provision of supply air ventilation rate in the standards from these nine countries is specified in one or more of the methods described in CEN EN 16798-1, such as L/s, L/s.m^2, L/s.person or h^{-1}, almost every country specifies a provision in terms of local exhaust airflow rate [L/s or h^{-1}].

The ventilation design in residential buildings in China is based on three standards and a design manual as follows:

- GB 50736-2012 Design code for heating ventilation and air conditioning of civil buildings [75]
- GB/T 18883-2002 Indoor air quality standard [76]
- Design manual for heating and air conditioning [77]

GB 50736-2012 stipulates that natural ventilation should be available in residential buildings. When natural ventilation cannot meet the hygiene requirements, mechanical ventilation should be designed. The air change rate should also be no less than 3 h^{-1} in the kitchen and bathroom. For residential buildings that are designed with the mechanical ventilation system, the minimum air change rate is presented as a range between 0.45 and 0.7 h^{-1} based on a range of floor areas, including less than 10 m^2 and more than 50 m^2, and are determined by referring to ASHRAE Standard 62.1 from 2007; the floor area per person, not the total floor area determines the air change rate. Since the occupant density in residential buildings in China is much higher than that in the US, this specification may not be entirely appropriate for Chinese residential buildings.

Table 2. 1 Summary of ventilation requirements for bedrooms and dwellings in the selected standards.

Standard	Mechanical Ventilation[1]													Natural Ventilation	CO_2 level	
	SUPPLY - Air Flow Quantity/Air Change Rate								EXHAUST - Air Flow Quantity/Air Change Rate					Minimum openable area to outdoor (% of floor area being ventilated)	CO_2 level above ambient (ppm)	
	L/s		(L/s.m^2)		(L/s.person)		(h^{-1})		L/s	L/s	h^{-1}	L/s	h^{-1}			
	Whole dwelling	Bedroom	Whole dwelling	Bedroom	Whole dwelling	Bedroom	Whole dwelling	Bedroom	Whole dwelling	Enclosed Kitchen		Bathroom			Whole dwelling	Bedroom
ASHRAE Std 62.2, 2019	-	-	0.17-0.74	-	-		-	-	-	-	5[2]	10[2]	-	-	-	-
EN 16798-1:2019																
Category I	-	-	0.49	-	10		0.7	2.9[3]	-	28-56	-	14-21[4]	-	Supply[5] 60 cm^2/room; Extract[6] 100 cm^2/room	550	380
Category II	-	-	0.42	-	7		0.6	2.0[3]	-	20-40	-	10-15[4]	-		800	550
Category III	-	-	0.35	-	4		0.5	1.2[3]	-	14-28	-	7-10.5[4]	-		1350	950
Category IV	-	-	0.23	-	-		0.4	-	-	10-20	-	5-7.5[4]	-		1350	950
NBN D-50-001 (1991)	20.8-41.7	7-20	1[7]	-	-	-	-	-	-	20.8	-	13.9 - 20.8	-	-	-	-
TEK17 (2017)	-	-	0.33	-	-	7.2	-	-	-	10 -	-	15-30	-	-	-	-
BR18 (2019)	-	-	0.3	0.3	-	-	-	-	-	20	-	10-15		-	-	-

Table 2. 1 to be continued.

	Mechanical Ventilation[1]													Natural Ventilation	CO_2 level	
Standard	SUPPLY - Air Flow Quantity/Air Change Rate								EXHAUST - Air Flow Quantity/Air Change Rate					Minimum openable area to outdoor (% of floor area being ventilated)	CO_2 level above ambient (ppm)	
	L/s		(L/s.m^2)		(L/s.person)		(h^{-1})		L/s	L/s	h^{-1}	L/s	h^{-1}			
ONORM H 6038 (2014)	-	-	-	-	4.17-8.33	5.56	min[8] 0.15	-	-		-		-	-	-	-
Boverket, BFS2014:13-BBR21	-	-	0.35	-	-	-	-	-	-		-		-	-	-	-
Arrete 24.03.82 (1983)	-	-	-	-	-	-	-	-	9.7 -37.5[9]	5.6-12.5[9]	-		-	-	-	-
DIN 1946-6 (2019)	4.17-79.2	-	-	-	-	-	-	-	-	12.5	-	12.5	-	-	-	-
NNI (2006)	7	7	0.9	-	-	-	-	-	-	21	-	14	-			
HM Government (2010)	21.1	-	0.3	-	-	-	-	-	-	30	-		-	-	-	-
GB 50736-2012	-	-	-	-	-		0.45-	-	-		3		3	-	-	-
GB/T 18883-2002	-	-	-	-	8.33	-	-	-	-		-		-	-	<580	-
Design manual for heating and air conditioning, 2008. Lu Yaoqing	-	-	-	-	-	-	1	1	-		3		3	-	-	-
Japan Building Standard Law (1950, 2003)	-	-	-	-	5.56		-	-	-		-		-	5%	-	-
KMOCT 2006-11-512	-	-	-	-	-		0.7	-	-		-		-	-	-	-
IS 3362-1977	-	-	-	-	-		3	3	-		-		-	-	-	-

1- Mechanical ventilation consists of the provision of ventilation rate in terms of SUPPLY Ventilation [air flow quantity (L/s.m^2, L/s.person), Air Change Rate (h^{-1})] or EXHAUST Ventilation [airflow quantity (L/s), Air

Change Rate (h^{-1})].

2- This is the total range of ventilation rate provided in ASHRAE Standard 62.2, obtained from the LOWEST to the HIGHEST across all dwellings. There are subcategories based on dwelling size and number of bedrooms in

each size that would result in different numbers. Total dwelling ventilation rates are specified for different sizes and numbers of bedrooms on the assumption of minimum 2 persons in the smallest sized dwelling (studio or

1-bedroom dwelling) and an additional person for each additional bedroom. For higher occupant densities, an additional 3.5 L/s per person is required.

3- These are continuous local exhaust airflow rates. Kitchen extract is based on kitchen volume. ASHRAE 62.2–2019 also provides separate demand-controlled local ventilation exhaust airflow rates.

4- Corresponding ACR for a 10 m^2 room (ht =2.5 m, Volume =25 m^3) with two persons, and ventilation airflow rates of 4, 7 and 10 L/s.person.

5- Includes bathroom or shower (with or without toilets), toilets and other wet areas.

6- Supply - Bedrooms and living rooms.

7- Extract - Kitchen, bathrooms, toilets.

8- Specific minimum rates for room type provided.

9- During non-occupancy.

10- Range is for the number of main rooms up to 7.

11- Includes a range of floor areas (<10 m^2 and > 50 m^2).

GB/T 18883-2002 is an indoor air quality standard that stipulates a fresh air requirement of 30 m^3/hour/person and the indoor CO_2 equal or below 1,000 ppm. By assuming the ambient CO_2 level to be 420 ppm, the CO_2 level above ambient is equal to or below 580 ppm [76, 78].

The "Design manual for heating and air-conditioning systems" provides guidance on ventilation design for residential buildings and specifies the following air change rates: 1 h^{-1} for bedroom and living room in residential building or dormitory, 3 h^{-1} in kitchen and 1 h^{-1} to 3 h^{-1} in the bathroom [77].

The Japan Building Standard Law states that the minimum requirement for the supply of outdoor air for habitable rooms shall be 20 m^3/h (5.55 l/s) per person in the case when they are mechanically ventilated, and that minimum ratio of the openings shall be 1/20 of the room floor area in case they are naturally ventilated [79].

From 2003, the Building Standard Law also obliges all the buildings to be designed with the mechanical ventilation system to avoid sick building syndrome (SBS) symptoms. For residential buildings, it requires the air change rate of 0.5 h^{-1} with 24-hour ventilation. Additionally, the buildings where the floor is larger than 3,000 m^2 need to comply with the hygiene requirements [80] that require checking the air quality every two months, and the indoor CO_2 level equal to or below 1,000 ppm. Although it applies mainly to non-residential buildings, the other buildings used by many people are expected to make efforts to introduce this indoor air quality standard and keep this condition, including residential buildings.

The Korean ventilation standard stipulates an air change rate of 0.7 h^{-1} for newly built or remodelled apartments and the Indian standard specifies a minimum air change rate of 3 h^{-1} in living rooms and bedrooms [81, 82].

Even though the various ventilation standards use different ways to specify the requirements for ventilation in residential buildings, it appears that they generally result in the air change rate of about 0.5 h^{-1}, unless otherwise directly specified.

2.4 Review of shortlisted papers

An overview of the shortlisted papers for this review is presented in Table 2. 2. The papers in Table 2. 2 are classified into the following six categories:

1. Papers on ventilation in bedrooms showing CO_2 levels
2. Papers on ventilation in bedrooms showing air change rates (ACR)
3. Papers on ventilation in bedrooms showing ACR and CO_2 levels
4. Papers on ventilation and sleep quality
5. Papers on personal ventilation and sleep quality
6. Papers on ventilation in the whole house/dwelling

Personal ventilation (PV) (category 5) is air distribution applying a PV device besides the bed in a bedroom to provide fresh air in the breathing zone of the sleeper, while ventilation (category 4) is ventilating bedrooms from the air outdoors or other space in the dwellings, either by natural ventilation, mechanical ventilation (balanced or unbalanced), or infiltration.

Each paper in Table 2. 2, as identified by its reference number, provides the relevant bibliographic details and an overview of the type of measurements/findings conducted and reported. A short description of each of these papers in the above six categories is given in the following section. Additionally, Table 2. 3 shows all papers (also included in Table 2. 2) which reported measurements of sleep quality.

Table 2. 2 An overview of the papers reviewed.

Author(s)[1]	Year	Journal	CO_2 levels	Air Change Rate	Sleep quality	Ventilation system[2]	Venue	Season	Measurement duration for CO_2 levels	Tracer gas and measurement duration for ACR[3]
Ventilation in bedrooms – CO_2 levels										
Wong and Huang	2004	Build. Environ.	✓	-	-	NV or AC	Apartment	Cooling season	Nighttime	-
Author(s)[1]	Year	Journal	CO_2 levels	Air Change Rate	Sleep quality	Ventilation system[2]	Venue	Season	Measurement duration for CO_2 levels	Tracer gas and measurement duration for ACR[3]

Table 2. 2 to be continued.

Author(s)[1]	Year	Journal	CO_2 levels	Air Change Rate	Sleep quality	Ventilation system[2]	Venue	Season	Measurement duration for CO_2 levels	Tracer gas and measurement duration for ACR[3]
Belmonte et al. *	2019	Journal of Building Engineering	✓	-	-	NV	Apartment	17-month period	Whole day (24 hours)	-
Sekhar and Goh	2011	Build. Environ.	✓	-		NV (with fans for air circulation) or AC(split)	Apartment	Cooling season	Nighttime	-
Liu et al.	2015	Procedia Engineering	✓	-	-	-	-	Whole year	Nighttime	-
Lei et al.	2017	Build. Environ.	✓	-	-	NV	Dormitory	Heating season	Nighttime	-
Fernández-Agüera et al. *	2019	Sustainability-Basel	✓	-	-	NV	Apartment	Whole year	Daytime(living room) & Nighttime (bedroom)	-
Kozielska et al.	2020	Build. Environ.	✓	-	-	NV	Apartment & Detached house	Heating season	Whole day (24 hours)	-
Ventilation in bedrooms – Air Change Rate										
Bornehag et al. **	2005	Indoor Air	-	✓	-	NV, MV(unbalanced), or MV(balanced)	Apartment & Detached	Heating season	-	PFT, 1 week

Table 2. 2 to be continued.

Author(s)[1]	Year	Journal	CO_2 levels	Air Change Rate	Sleep quality	Ventilation system[2]	Venue	Season	Measurement duration for CO_2 levels	Tracer gas and measurement duration for ACR[3]
Shinohara et al. ***	2011	Atmos. Environ.	-	✓	-	NV+MV	Apartment & Detached house	Whole year	-	PFT, 1 week
Du et al. *	2012	Int. J. Environ. Res. Public Health	-	✓	-	NV or MV	-	Whole year	-	PFT, 1 week
Bekö et al. **	2016	Build. Environ.	-	✓	-	NV or MV(unbalanced)	Apartment & Detached	Whole year	-	Occupant generated CO_2, Nighttime Active tracer gas technique, 2-4 days; PFT, 5 days
Ilomets et al. **	2018	J. Building Phys	-	✓	-	NV or MV	Apartment & Detached house	Heating and Cooling season	-	Occupant generated CO_2, Nighttime
Cheng and Li	2018	Energy Build.	-	✓	-	NV+AC	-	Cooling season	-	Occupant generated CO_2, Nighttime
Hou et al. **	2017	Procedia Eng.	-	✓	-	-	-	Whole year	-	Occupant generated CO_2, Nighttime

Table 2. 2 to be continued.

Author(s)[1]	Year	Journal	CO_2 levels	Air Change Rate	Sleep quality	Ventilation system[2]	Venue	Season	Measurement duration for CO_2 levels	Tracer gas and measurement duration for ACR[3]
Ventilation in bedrooms – Air Change Rate and CO_2 levels										
Sekhar	2004	Energy Build.	✓	✓	-	AC(Split) or AC(split)+MV (unbalanced)	Apartment	Cooling season	Daytime & Nighttime	SF_6, Daytime Occupant generated CO_2, Daytime & Nighttime
Lin and Deng	2003	Build. Environ.	✓	✓	-	AC(window) or AC(split)	Apartment	Cooling season	Nighttime	Occupant generated CO_2, Nighttime
Bekö et al.	2010	Build. Environ.	✓	✓	-	-	-	Spring	Nighttime	Occupant generated CO_2, Nighttime
Aubin et al.	2011	Indoor Air	✓	✓	-	-	-	Heating and Cooling season	Whole day (24 hours)	PFT, 6-8 days; SF6, 4-5 hours
Park et al. *	2014	Indoor Air	✓	✓	-	NV, MV(unbalanced), or MV(balanced)	Apartment	Spring	Whole day (24 hours)	Occupant generated CO_2, Whole day Fan flow, Whole day
Ai et al.	2016	Energy Build.	✓	✓	-	NV+AC or MV(unbalanced)+AC	Apartment	Cooling season	Daytime (Short-term measurements) & Nighttime (Long-term measurements)	Occupant generated CO_2, Daytime & Nighttime
Langer et al.	2016	Atmos. Environ.	✓	✓	-	-	Apartment & Detached house	Whole year	Nighttime	Occupant generated CO_2, Nighttime

Table 2. 2 to be continued.

Author(s)[1]	Year	Journal	CO_2 levels	Air Change Rate	Sleep quality	Ventilation system[2]	Venue	Season	Measurement duration for CO_2 levels	Tracer gas and measurement duration for ACR[3]
Canha et al.	2017	Atmos. Pollut. Res.	✓	✓	-	NV	Apartment	Cooling season	Nighttime	Occupant generated CO_2, Nighttime
Hou et al. **	2018	Build. Environ.	✓	✓	-	-	Apartment & Detached house	Whole year	Nighttime	Occupant generated CO_2, Nighttime
Hou et al.	2019	Indoor Air	✓	✓	-	-	Apartment & Detached house	Whole year	Daytime(Short-term measurements) & Nighttime(Long-term measurements)	CO_2 decay method, Daytime Occupant generated CO_2, Nighttime
Canha et al.	2019	Environ. Pollut.	✓	✓	-	NV	Apartment & Detached house	Heating season	Nighttime	Occupant generated CO_2, Nighttime
Canha et al.	2020	Environ. Pollut.	✓	✓	-	NV or MV	Apartment	Heating season	Nighttime	Occupant generated CO_2, Nighttime
Stamatelopoulou et al.	2020	Build. Environ.	✓	✓	-	-	Apartment & Detached	Cooling season	Whole day (24 hours)	Occupant generated CO_2, Nighttime

Table 2. 2 to be continued.

Author(s)[1]	Year	Journal	CO_2 levels	Air Change Rate	Sleep quality	Ventilation system[2]	Venue	Season	Measurement duration for CO_2 levels	Tracer gas and measurement duration for ACR[3]
Ventilation and sleep quality										
Mishra et al.	2018	Indoor Air	✓	-	✓	NV	Apartment	Heating season	Whole day (24 hours)	-
Strøm-Tejsen et al.	2016	Indoor Air	✓	✓	✓	NV or MV(balanced)	Dormitory	Autumn and Heating season	Nighttime	Occupant generated CO_2, Nighttime
Xiong et al.	2020	Sci. Technol. Built Environ.	✓	-	✓	-	-	Cooling season	Whole day (24 hours)	-
Laverge and Janssens	2011	Indoor Air	✓	✓	✓	NV	Dormitory	Autumn	Nighttime	Occupant generated CO_2, Nighttime
Liao et al.	2020	Build. Environ.	✓	-	✓	NV	Dormitory	Spring	Nighttime	-
Lan et al.	2019	Indoor Air	✓	-	✓	Ceiling fan, Task fan, or AC	Chamber	Cooling season	Nighttime	-
Zhang et al.	2018	Build. Environ.	✓	-	✓	No ventilation (window closed and MV is not used.)	Dormitory	Cooling season	Whole day (24 hours)	-
Irshad et al.	2018	Build. Environ.	✓	-	✓	NV or TE-AD system[4]	Chamber	Cooling season	Nighttime	-

Table 2. 2 to be continued.

Author(s)[1]	Year	Journal	CO_2 levels	Air Change Rate	Sleep quality	Ventilation system[2]	Venue	Season	Measurement duration for CO_2 levels	Tracer gas and measurement duration for ACR[3]
Xia et al.	2020	Energy Build.	✓	-	✓	-	Nursing home	Heating season	Nighttime	-
Kim et al.	2010	Indoor Built Environ.	✓	-	✓	-	Apartment	Winter, Spring, and Summer	Nighttime	-
Personal ventilation and sleep quality										
Lan et al.	2013	Build. Environ.	-	-	✓	PV[5]	Apartment	Heating season	-	-
Zhou et al.	2014	Indoor Built Environ.	-	-	✓	MV(unbalanced) + AC + PV[5]	Apartment	Cooling season	-	-
Ventilation in the whole house										
Emenius et al.	2004	Indoor Air	-	✓	-	-	-	Heating season	-	PFT, 4 weeks
Singer et al.	2020	Indoor Air	✓	✓	-	MV	Detached	Whole year	Whole day (24 hours)	Fan flow, Whole day
Yamamoto et al.	2010	Indoor Air	-	✓	-	-	-	Whole year	-	PFT, 2 days
Langer and Bekö	2013	Build. Environ.	-	✓	-	-	-	Heating season	-	PFT, 2 weeks

Table 2. 2 to be continued.

Author(s)[1]	Year	Journal	CO_2 levels	Air Change Rate	Sleep quality	Ventilation system[2]	Venue	Season	Measurement duration for CO_2 levels	Tracer gas and measurement duration for ACR[3]
Stocco et al.	2008	Atmos. Environ.	-	✓	-	-	-	Heating and Cooling season	-	PFT, 5 days
Gilbert et al.	2006	Environ. Res.	-	✓	-	-	-	Heating season	-	PFT, over 1 week
Gilbert et al.	2008	Atmos. Environ.	-	✓	-	-	-	Heating season	-	PFT, over 1 week

1- *: also mentioned ventilation in the living room, **: also mentioned ventilation in the whole house, ***: also mentioned ventilation in the living room and whole house.

2- NV: natural ventilation, MV(unbalanced): supply only or exhaust only mode of ventilation, MV(balanced): both supply and exhaust mode of ventilation, AC: room air-conditioning units.

3- PFT: Passive tracer gas method, utilizing perfluorocarbon tracers, Fan flow: measurement by supply fan flows.

4- TE-AD system: thermoelectric air duct cooling system.

5- PV: Personalized ventilation system.

Table 2. 3 Papers reporting sleep quality data.

Author(s)	Year	Measured IAQ parameters[1]	Objective assessment of sleep quality								Subjective assessment of sleep quality				
			Method	Objective sleep parameters[3]							Subjective sleep parameters				
				TST	SE	SL	Total duration	WASO	NOA	Others	PSQI[4] / Assessed periods		GSQS[5] / Assessed period		Others[3, 6]
Mishra et al.	2018	CO_2, T, RH, noise level	Actigraphy, FlexSensor[2]	✓	✓	✓	-	-	✓	movement	✓	before the experiment, between the 2 test conditions, end of the test period	✓	each morning	depth of sleep and restfulness during the night, time in bed, TST, SE, SL, NOA

Table 2. 3 to be continued.

Author(s)	Year	Measured IAQ parameters[1]	Objective assessment of sleep quality								Subjective assessment of sleep quality				
			Method	Objective sleep parameters[3]							Subjective sleep parameters				
				TST	SE	SL	Total duration	WASO	NOA	Others	PSQI[4] / Assessed periods		GSQS[5] / Assessed period		Others[3,6]
Strøm-Tejsen et al.	2016	CO_2, T, RH	Actigraphy	✓	✓	✓	-	-	-	snooze time	✓	before the experiment	✓	each morning	perceived sleep quality, reasons for any awakenings, NOA, time in bed
Xiong et al.	2020	CO_2, T, RH, T_g, V	Actigraphy	✓	✓	-	✓	✓	✓	time in bed	✓	before the experiment	-	-	Subjective sleep quality assessment
Laverge and Janssens	2011	CO_2, T, RH	Actigraphy	-	✓	✓	-	✓	✓	-	✓	before the experiment, between the 2 test conditions, end of the test period	-	-	perceived sleep quality, reasons for any awakenings, NOA, time in bed
Liao et al.	2020	CO_2, T, RH, $PM_{2.5}$, noise level	Actigraphy, Polysomnography, FlexSensor	✓	✓	✓	✓	✓	✓	snoring percentage, movement, time in bed	✓	before the experiment	✓	each morning	sleepiness (Karolinska Sleepiness Scale), reasons for any awakenings
Lan et al.	2019	CO_2, T, RH, T_g	Polysomnography, Collecting urine sample	✓	✓	✓	✓	✓	✓	Urinary cortisol concentrations	✓	before the experiment	-	-	Subjective sleep quality assessment, NOA, sufficient sleep

Table 2. 3 to be continued.

Author(s)	Year	Measured IAQ parameters[1]	Objective assessment of sleep quality								Subjective assessment of sleep quality				
			Method	Objective sleep parameters[3]							Subjective sleep parameters				
				TST	SE	SL	Total duration of each	WASO	NOA	Others	PSQI[4] / Assessed periods	GSQS[5] / Assessed period	Others[3,6]	TST	SE
Zhang et al.	2018	CO_2, T, RH, T_g, V, noise level, illumination intensity, $PM_{2.5}$	-	-	-	-	-	-	-	-	✓	before the experiment	-	-	Subjective sleep quality assessment, NOA
Irshad et al.	2018	CO_2, T, RH, V, MRT, PMV, PPD, WBGT	Actigraphy	✓	✓	✓	✓	✓	✓	body movement, heart rate (HR)	✓	before the experiment	-	-	Subjective sleep quality assessment, SL, NOA, sufficient sleep
Xia et al.	2020	CO_2, T, RH	Actigraphy	✓	✓	✓	✓	✓	-	-	✓	before the experiment	-	-	Subjective sleep quality assessment
Kim et al.	2010	CO_2, T, MRT, RH, illumination level,	using a nasal cannula connected	-	-	-	-	-	-	Sleep apnea, hypopnea and % FL[7]	-	-	-	-	-

1- CO_2: CO_2 level, T: air temperature, RH: relative humidity, Tg: globe temperature, V: air velocity, MRT: mean radiant temperature, PMV: predicted mean vote, PPD: predicted percentage of dissatisfied, WBGT: wet bulb globe temperature.

2- Flex sensor: movement detection placed under the participants' pillow.

3- TST: total sleep time, SE: sleep efficiency, SL: sleep latency, Sleep stage: stage N1, N2, N3, and REM stage, WASO: wake time after sleep onset, NOA: number of awakenings.

4- PSQI: Pittsburgh sleep quality index (assess the sleep quality of the last month).

5- GSQS: Groningen sleep quality scale (assess the sleep quality of the last day).

6- Subjective sleep quality assessment: which contains Satisfaction with sleep, Calmness of sleep, Ease of falling asleep, Ease of awakening, and Freshness after awakening.

7- % FL: number of flow-limited breaths without snoring.

2.4.1 Papers on ventilation in bedrooms showing CO_2 levels

A few studies that have reported measurements of CO_2 levels in bedrooms during cooling, heating, or whole season where either natural ventilation (NV) or mechanical ventilation (MV) or air-conditioning (AC) [with or without NV/MV] were identified.

Wong and Huang carried out measurements in three residential buildings in Singapore and observed that there was a considerable CO_2 build-up when AC, without MV, was used [83]. The measured CO_2 concentrations under these conditions were substantially higher than in NV bedrooms without AC. While the mean CO_2 levels for NV bedrooms were in the range of 566-670 ppm, they were between 778 and 1,164 ppm in bedrooms with AC. Except for infiltration, whether there was other ventilation means in these cases depends on whether the AC had a fresh air intake. The temperatures in NV bedrooms ranged between 29°C and 30°C and RH between 70% and 80%. The temperatures varied between 23°C and 27°C in bedrooms with AC, and there were more fluctuations observed concerning the measured levels of RH that varied between 47% and 65%. They also found that almost all occupants who used AC during sleep exhibited one or more acute sub-clinical health symptoms (SBS), and these occupants also showed more symptoms when using AC in comparison to using NV.

Belmonte et al. studied an NV residential building in Porto (Portugal) to develop a method for calibrating the IAQ in an ENERGYPLUS building model [84]. A total of eight apartments in the building, consisting of 2-bedroom and 3-bedroom apartments having 65 and 83 m^2 net usable area respectively, were monitored during 17 months between February 2016 and July 2017. Three apartments had occupancy of 1, 2, and 5 respectively; three had 3 occupants each, and two had 4 occupants each. The parameters monitored were mainly air dry-bulb temperatures and CO_2 concentration levels in the living rooms and bedrooms. The average bedroom CO_2 levels over the total measurement period in the 8 apartments ranged between 712 and 1,211 ppm, with an overall average of 1,038 ppm. In the apartment that recorded the highest CO_2 concentration levels in the bedroom, they were higher than the Portuguese regulation-based limit value of 1,250 ppm (not specified though in Table 2. 1) for approximately 40% of the total monitored time. In the same apartment, the minimum and maximum recorded CO_2 levels were 520 and 2,500 ppm, respectively.

Sekhar and Goh studied 12 NV (with fans for air circulation) and 12 AC bedrooms in a hot and humid climate and found that the mean temperatures were around 27-30.5°C and 22.5-25.5°C respectively [85]. While the RH in both types of bedrooms was within 70%, it was much higher in NV bedrooms compared to the AC bedrooms. They reported CO_2 levels around 420-560 ppm in NV bedrooms and twice as high in AC bedrooms. Although they reported that, compared to historical data, the average sleep duration of immediate data increased by 0.8 h and 0.4 h in NV and AC bedrooms, respectively, they stated that there was no clear evidence (statistical support) to support the fact that sleeping duration was lowered with increasing CO_2 levels. Historical data refer to the data on a historical basis of over the past month or so, while immediate data refer to the immediate night before. Based on the observations of CO_2 levels and sleep duration in NV and AC bedrooms, the authors concluded that sleep duration might indeed be affected by the high CO_2 levels.

Liu et al. studied 454 children's bedrooms in Shanghai over one year spanning the whole season and reported a mean CO_2 level of 1,123 ppm [86]. A total of 203 residences had average CO_2 levels higher than 1,000 ppm, and the CO_2 levels in winter were significantly around 300 ppm higher than those recorded in autumn and spring.

Lei et al. studied four bedrooms, two having 4 occupants each and two having 6 occupants each, in an NV dormitory with radiant water heating during the heating season in Beijing and reported CO_2 levels between 1,057 and 5,150 ppm [87]. They reported temperatures around 20.5–24°C and RH around 44-54%. The study did not report sleep quality.

Fernandez-Aguera et al. reported measurements of indoor air quality from three representative case studies with different airtightness conditions, involving NV homes in a mild climate in the South of Spain [88]. They showed large differences in measured CO_2 over time being between 400 and 2,000 ppm; they also reported peak concentrations in bedrooms exceeding 7,500 ppm. The typical median levels of CO_2 in bedrooms ranged between 1,199 and 2,385 ppm. They reported that living room peak CO_2 levels were above 4,500 ppm. As expected, they showed that the lower air tightness resulted in a lower CO_2 level. Another observation made by the authors concerned the CO_2 levels falling below 1,000 ppm in living rooms in mild seasons attributed to the frequent operation of windows in a semi-open position for extended periods. Besides the measurements of CO_2, the authors also reported TVOC and $PM_{2.5}$.

Kozieska et al. measured several indoor contaminants, including CO_2, in two flats and four houses in the Upper Silesia region of Poland during October 2017 and March 2018 [89]. All the houses were insulated and had an NV system; the windows were kept closed during measurements. The 24-h mean, median, and range of CO_2 measurements were 847±251, 803, and 560-1,570 ppm, respectively, for the flats and 790±167, 769 ppm and 543-1,360 ppm, respectively, for the houses. The authors stated that the average CO_2 concentrations in bedrooms studied were comparable to those reported in a Danish study [30]. Using the CEN standard of ΔCO_2 levels in terms of ppm above outdoors [380 ppm (Cat I), 550 ppm (Cat II), 950 ppm (Cat III) and >950 ppm (Cat IV)], the authors found that CO_2 concentrations in bedrooms were characterized by an overall lower air quality. They stated that the IAQ in bedrooms during the night was in Cat I for 50%, Cat II for 24%, Cat III for 18%, and Cat IV for 8% of the time.

2.4.2 Papers on ventilation in bedrooms showing air change rates

In previous papers, the steady-state condition can be used for estimating ventilation rate in L/s.p assuming emission rates of CO_2 from sleeping people. However, it is the decay of CO_2 that was mainly used to estimate ACR. ACR, computed as a reference of outdoor air, would normally be higher than actual ACR, whose reference should be a mix of outdoor air and air from other parts of the dwelling. Papers on ventilation in the whole house/dwelling were also searched using the keywords mentioned in the method section, and they were reported to have a more comprehensive overview of ventilation in residential dwellings and also to compare ventilation between the whole dwelling and bedrooms.

Bornehag et al. investigated 390 bedrooms in Sweden as a case-control study during the heating season to test whether the increased prevalence of asthma and allergic symptoms among children was associated with the low ventilation rate [90]. Using the Perfluorocarbon Tracer (PFT) technique, they measured air change rates and observed that in 80% of single-family houses and 60% of multi-family houses, they were below 0.5 h^{-1}. They reported mean bedroom and the whole building air change rates of 0.35 h^{-1} and 0.36 h^{-1} in single-family houses 74% of which were using NV, 0.37 h^{-1} and 0.35 h^{-1} in row houses, and 0.51 h^{-1} and 0.48 h^{-1} in multi-family houses of which 68% used unbalanced MV, referring to supply only or exhaust only modes of ventilation. While acknowledging that the findings could not corroborate strong associations between home ventilation and health effects due to lack of statistical significance attributable to small sample size, the authors concluded that the hypothesis of low-ventilation rates in homes increasing the risk of allergic symptoms among children could not be rejected.

Shinohara et al. reported measurements in 26 Japanese bedrooms in NV+MV apartments and detached houses [91]. The measurements were carried out across the whole season, and the PFT technique was used to measure ventilation rates. The mean air change rate in bedrooms was 1.3 h^{-1} in summer, 0.49 h^{-1} in autumn, 0.38 h^{-1} in winter, 0.84 h^{-1} in spring, and 1.4 h^{-1} in the following summer. They also reported mean air change rates in the whole dwelling and living rooms which were respectively 1.6 h^{-1} and 1.1 h^{-1} in summer, 0.58 h^{-1} and 0.65 h^{-1} in autumn, 0.61 $h^{-1,}$ and 0.54 h^{-1} in winter, 1.2 h^{-1} and 1.1 h^{-1} in spring and 1.7 h^{-1}, and 1.2 h^{-1} in the following summer.

Du et al. performed air change measurements in 126 bedrooms in the US during the whole season using the PFT technique [92]. They conducted week-long tracer gas measurements during several seasons and reported an average air change rate of 0.73±0.76 h^{-1} (median = 0.57 h^{-1}) in the living rooms and 1.66±1.5 h^{-1} (median = 1.23 h^{-1}) in bedrooms, 27% of which had exhaust fans, 88% of which had forced air heating system and 30% had the central air-conditioning system. While not explicitly stated in the paper, it is inferred that forced-air heating and central air-conditioning systems would include MV as part of the design and operation. Living room air change rates were highest in winter, and those measured in bedrooms were highest in summer. Both were the lowest in spring. They also reported that the bedrooms were ventilated with about 55±18% of air from other parts of the house, while the living rooms only about 26±20% from bedrooms.

Bekö et al. reported measurements in six bedrooms (apartment and detached house) across four seasons, using an active tracer gas and night-time occupant generated CO_2 to measure the ACR in the bedrooms [93]. A median air change rate was 0.49 h^{-1} measured with an active tracer gas technique and 1.20 h^{-1} estimated using the CO_2 technique. The average winter air change rate measured with the PFT technique was 0.63 h^{-1}, which was substantially different from 0.25 h^{-1} obtained when the active tracer gas technique using occupant-generated CO_2 was used.

An Estonian study involving 88 bedrooms during heating and cooling seasons used the night-time occupant-generated CO_2 to report a mean bedroom air change rate of 0.6 h^{-1} and the mean whole building air change rate of 0.32 h^{-1} during winter [94]. When the outdoor temperatures were less than about 12-13 °C, the average indoor temperatures in 190 rooms with central heating were reasonably stable at around 22 °C, while in 66 rooms using a stove or combined heating system, they were 19.5-21.5 °C. As the outdoor temperature fell, so did the indoor temperature. For outdoor temperatures above 13 °C, the indoor temperatures closely tracked the outdoor temperatures.

Cheng and Li studied the air infiltration rates in 202 NV bedrooms with AC in Guangzhou, China, during the 2016 cooling season [95]. They used the occupant-generated CO_2 levels to estimate air change rates. The mean air change rates were 0.41 $h^{-1,}$ and the median was 0.38 h^{-1}. They also reported a mean and median indoor temperature at 26.5 °C.

Hou et al. investigated 410 children's homes in and around Tianjin, China, from September 2013 to January 2016 [96]. They reported the whole house mean air change rates of 0.61±1.05 h^{-1} (median=0.32 h^{-1}) in 340 homes, and the bedroom mean air change rate of 0.81±1.33 h^{-1} (median=0.43 h^{-1}) in 390 bedrooms. The interquartile ranges for the whole house and bedroom air change rates were 0.20 h^{-1} to 0.60 h^{-1} and 0.23 h^{-1} to 0.80 h^{-1}, respectively. They reported whole house median air change rates of 0.28 h^{-1}, 1.11 h^{-1}, 0.29 $h^{-1,}$ and 0.30 h^{-1} during spring, summer, autumn, and winter respectively, and the bedroom mean air change rates of 0.32 h^{-1}, 1.17 h^{-1}, 0.38 h^{-1} and 0.41 h^{-1} for the same four seasons. They reported higher air change rates in smaller homes and much higher air change rates in summer than in the other seasons, which was attributable to the more frequent window opening in summer.

2.4.3 Papers on ventilation in bedrooms showing air change rates and CO_2 levels

It is generally observed from papers reporting bedroom air change rates that they are not explicitly clear if the reference is to only outdoor ACR or ACR computed as a combination of outdoor air and air from other parts of the dwelling. However, if the papers indicate the use of MV, it is reasonable to assume that the reported ACR values are more representative of outdoor ACR if the fresh air towards inlet space. Likewise, the ACR values reported in papers with NV would be typical of a combination of outdoor air and air from other parts of the dwelling. Whether it is a problem for sleep quality to air the bedroom from other parts of the dwelling depends on the air quality of those parts.

In a tropical study by Sekhar involving cooling season only and employing a split-system air-conditioning (AC) unit with no mechanical ventilation, bedroom air change rate with and without a bathroom exhaust ventilation was shown to be 2.68 h^{-1} and 0.40 h^{-1} (SF_6 tracer gas technique) respectively [97]. The supply air was mainly from the bedroom but also depended on if the bedroom door was closed or not. The air change rate calculated using the CO_2 concentration decay technique was found to be 1.96 h^{-1} and 0.32 $h^{-1,}$ respectively, for the cases with and without MV. The bedroom CO_2 reached 2,900 ppm with an occupancy of two adults and a child: This occurred without an exhaust fan in about 8 hours and reduced to 800 ppm with the exhaust fan in less than an hour. The bedroom temperature and RH were within recommended thresholds and were in the range of 23.1-23.9 °C and 51.6-63.4%, respectively.

Lin and Deng reported the findings of field studies that monitored overnight CO_2 levels and ventilation rates in twelve Hong Kong bedrooms where the window and split-type room AC units were installed [98]. To have a better estimate of the outdoor airflow rates in the field, they conducted laboratory experiments with typical window AC units in a simulated wooden enclosure that also had the capability of creating different outdoor wind velocities upstream of the AC units through the use of an axial fan. Using the CO_2 tracer gas decay technique, they obtained the outdoor air change rates, and then subsequently, the total outdoor airflow rates. For window-type AC units equipped with built-in dampers to control a certain amount of indoor air to be exhausted, the average bedroom CO_2 levels were in the range of 456-1,048 ppm (with a mean of 720 ppm). The total outdoor airflow rates were in the range of 2.8-4.4 L/s (the mean was 3.4 L/s) with the damper open and 1.7-4.1 L/s (the mean was 2.7 L/s) with the damper closed. For the split-type AC units, the measured mean CO_2 levels ranged from 1,160 to 1,805 ppm (the mean was 1,500 ppm), and the total outdoor airflow rates ranged from 1.4 to 2.2 L/s (the mean was 1.8 L/s).

Bekö et al. performed measurements in 500 bedrooms during spring in Denmark [30]. Using the night-time occupant-generated CO_2, they showed that Danish bedrooms were poorly ventilated; according to the Danish Building Regulations (Table 2. 1), the minimum ventilation with outdoor air in homes is about 0.5 h^{-1}. They observed a log-normal distribution of the computed air change rates, composed of both outdoor air and air from other parts of the house, having a geometric mean of 0.46 h^{-1}. They stated that 23% of bedrooms exceeded 2,000 ppm, and 6% exceeded 3,000 ppm in 20 minutes. They could not find any relationship between outdoor temperature and ventilation rate during their ten-week long measurements. Finally, they advocated caution in the interpretation of the results given potentially high measurement uncertainty when the ventilation rate is estimated from a single-zone mass balance of CO_2 and stated that relative errors could be as high as 120%.

Aubin et al. reported the results of measurements in 115 Canadian homes, including bedrooms, in Quebec City during a randomized intervention study that investigated how ventilation rates affected IAQ and the respiratory health of asthmatic children [99]. The summer mean air change rate was 0.96 h^{-1} measured using PFT technique in 94 bedrooms, and the winter air change rate was 0.34 h^{-1} (measured using PFT technique in 220 bedrooms) and the fall air change rate was 0.31 h^{-1} measured using SF_6 techniques in 214 bedrooms. The 24-hour average CO_2 concentrations were 884 ppm in 110 bedrooms measured in summer, and 1,024 ppm measured in 203 bedrooms in winter/fall. The temperatures were 22.7 °C and 20.0 °C in summer and winter/fall, respectively, while the RH was 48.7% and 46.3% respectively in summer and winter/fall. The authors concluded that there was a noticeable seasonal dependence of air change rates and some of the IAQ measurements, and most had higher concentrations in winter or fall. During that time, 85% of the homes did not achieve the nominal air change rate of 0.30 h^{-1}.

Park et al. studied the effects of different types of ventilation systems on indoor particle concentrations in 15 single-family apartments in and around Seoul during moderate climate season between April and June 2012 [100]. Their study involved three different ventilation types - unbalanced MV, balanced MV, and NV; balanced MV refers to both supply and exhaust provided ventilation mode. Apart from the outdoor and indoor $PM_{2.5}$ levels, they also measured CO_2, air change rates, temperatures, and relative humidity in both the living/dining room and the master bedroom. They used the CO_2 decay for both MV and NV apartments and additionally flow-hood for the MV apartments. The air change rates determined using the CO_2 decay for unbalanced MV, balanced MV and NV were for the master bedroom 0.6-1.1 h^{-1}, 0.2-0.5 h^{-1} and 0.1-1.0 h^{-1} whereas 0.5-0.9 h^{-1}, 0.7-1.0 h^{-1} and 0.8-1.3 h^{-1} in the living/dining room. The corresponding CO_2 levels were 1,262 ± 318 ppm, 1,256 ± 437 ppm, and 983 ± 272 ppm respectively in the master bedroom, and 775 ± 247 ppm, 577 ± 130 ppm and 566 ± 82 ppm in the living/dining room. The indoor temperatures and relative humidity for the three different ventilation types were 26.4±0.9 °C

(45±5%), 26.3±0.7 °C (52 ± 5%) and 26.7±1.0 °C (40±7%) in the master bedroom and 27.4±1.1 °C (43±5%), 26.9±0.8 °C (48±6%) and 26.9±0.9 °C (36±7%) in the living/dining room.

Ai et al. reported findings from a case study in Hong Kong performed during September, in which they measured indoor and outdoor CO_2 concentrations, air temperature, and relative humidity in a typical residential bedroom [34]. Using occupant generated CO_2, they estimated mean air change rates to be between 1.1 h^{-1} and 2.4 h^{-1} for three different strategies of overnight measurements – overnight NV with a narrow window opening, short-term (20 min) MV with a bathroom exhaust fan and short-term (20 min) NV with large window opening. They also reported mean bedroom CO_2 levels to be 971, 863, and 900 ppm respectively in bedrooms with overnight NV, short-term MV, and short-term NV. The average indoor temperatures and relative humidity in bedrooms with overnight MV were 25.3-24.6 °C and 47-56%, respectively.

Langer et al. reported measurements in bedrooms of 567 residences in mainland France performed between October 2003 and December 2005 [101]. Among the many measured parameters, there were temperature, RH, and CO_2. 70% of the measurements were conducted during the heating season (October – April) and the remaining during the non-heating season (May – September). The authors computed the air exchange rates from a CO_2 mass-balance equation during night-time, assuming a constant outdoor CO_2 concentration and using the CO_2 measurements in the main bedroom and a diary providing information on the occupancy status of each individual in a particular room. They reported a median bedroom air change rate of 0.44 h^{-1}, 0.41 $h^{-1,}$ and 0.49 $h^{-1,}$ respectively, for all dwellings, single-family houses, and apartments. They stated that air change rates in 58% (all dwellings), 61% (single-family houses), and 51% (apartments) were below 0.5 h^{-1}. They also reported a mean bedroom CO_2 level to be 1,266 and 966 ppm during the heating and non-heating season, respectively. The median indoor temperature was 20.7 °C, and the mean indoor relative humidity was 40%.

Canha et al. reported findings of a study from Portugal performed in bedrooms in the summer of 2015 [28]. A computerized tool, based on a novel second-degree solution to single zone mass-balance equation and underpinned by the build-up and steady-state phases of the CO_2, was used to compute the air change rates for the sleeping periods. The build-up phase is associated with CO_2 emission levels higher than the ACRs, and the steady-state being the phase when the CO_2 emission level is balanced with the ACRs. The air change rate was 0.67 h^{-1} with the bedroom door and window closed, 2.20 h^{-1} with the bedroom door closed, but window open, 3.63 h^{-1} with the bedroom door open, but the window closed, and 4.85 h^{-1} with bedroom door and window open. The mean CO_2 levels were respectively 995, 905, 639, and 600 ppm. They observed that only the ventilation setting with the open door and closed window achieved moderate mean temperatures of 24.8±1.1 °C. In contrast, the other three settings resulted in the mean indoor temperatures around 29 °C. The mean relative humidity was around 40-50%.

Hou et al. studied ventilation rates in 399 homes in Tianjin and Cangzhou, China [102]. They reported that the median air change rates in the whole house during the night were 0.27 h^{-1}, 1.11 h^{-1}, 0.29 $h^{-1,}$ and 0.30 h^{-1} for spring, summer, autumn, and winter, respectively. It was 0.25 h^{-1}, 0.25 h^{-1}, 0.30 h^{-1}, and 0.37 $h^{-1,}$ respectively, in the child's bedroom with a closed window and door. 70.8% of homes had air change rates lower than the generally accepted minimum requirement of 0.5 h^{-1} in homes [75]. They were significantly higher when windows were open compared with the levels achieved when the windows were closed. The median bedroom CO_2 levels were 1,146, 575, 1,313, and 1,407 ppm during spring, summer, autumn, and winter, respectively.

In another study in China, Hou et al. found the median infiltration rate of 0.34 h^{-1} in 294 residences estimated from the decay of CO_2 [103]. Furthermore, using occupant-generated CO_2, they determined air change rates in 46 bedrooms using the measurements extending for one year. The median air change rate for residences in cold and severe cold climatic zones, excluding the summer period, was in the range of 0.33-0.52 h^{-1} and 1.44-1.92 h^{-1} during summer. For the bedrooms in hot summer and cold/warm winter climatic zones, the median air change rate was in the range of 0.43 h^{-1} to 1.16 h^{-1} across the four seasons. In the bedrooms located in the mild climate zones, the median air change rate was significantly higher, and in the range of 1.38 h^{-1} to 2.32 h^{-1}. The median bedroom CO_2 levels across all zones and the four seasons were in a range between 549 and 1,296 ppm.

In another study in Portugal, Canha et al. (2019) measured air quality during sleep in twelve NV bedrooms of urban and rural areas for one night [104]. They reported air change rates, computed for the monitored period using a computerized tool that relies on the build-up phase of the CO_2, between 0.39±0.03 h^{-1} and 3.24±0.70 h^{-1}. They found that only 1/3 of the bedrooms had mean CO_2 levels below the limit of 1,250 ppm set by the Portuguese legislation (ordinance) for an indoor environment. The mean CO_2 levels during night-time sleep ranged between 553±24 ppm and 2,671±633 ppm. They also observed that only slightly more than half of bedrooms had temperatures within the comfort range, according to ISO 7730 (2005). The mean temperatures were between 18.4±0.1 °C and 25.5±0.18 ° C, with a median value of 22.8 °C. The mean relative humidity in the 12 bedrooms was in the range between 43.7±1.2% and 61.6±1.1%.

Canha et al. (2020) conducted yet another study in the cold season to obtain a detailed characterization of the IAQ during the sleeping period of ten couples in Lisbon dwellings that had NV in all bedrooms except one that had MV [105]. They measured CO_2, among other indoor pollutants, and their objective was to understand how IAQ compliance was with local legislation and guidelines. CO_2 levels were not always correlated with other pollutants such as volatile organic compounds (VOCs), CO and formaldehyde. CO_2 was more a marker of ventilation than air quality. Bedroom air change rates were obtained for the monitored period using a computerized tool that relies on the build-up phase of the CO_2. They observed that only 30% of bedrooms were below the limit value of 1,250 ppm, defined by the Portuguese legislation. Overall, the mean CO_2 level during sleep in this study was 1,911 ± 895 ppm, ranging from a low level of 667 ± 117 ppm to a high level of 3,783 ± 367 ppm. The bedroom with the lowest CO_2 levels was also the one that had the highest ACRs, and this was the one with mechanical ventilation, showing how important the system was in diluting indoor air contaminants. All bedrooms presented mean ACRs, obtained from occupant-generated night-time CO_2, higher than the minimum value of 0.7 h^{-1} established for bedrooms by the CEN Standard [64]. The global average was 2.15 ± 1.24 h^{-1}, ranging from 0.72 ± 0.19 h^{-1} to 3.75 ± 1.06 h^{-1}. The bedroom with the highest ACR was the only one with mechanical ventilation. The NV bedrooms also had ACRs above 3 h^{-1}. The authors conclude that air change rates are not sufficient to ensure compliance of pollutant levels with legal standards and guidelines.

Stamatelopoulou et al. investigated twenty-five residences located in various areas across the Athens region [106]. The study involved toddlers up to three years of age, and the field campaigns, consisting of 7 days in each residence, took place during the June-October 2015 summer period. The air change rates were obtained from occupant-generated CO_2, using the concentration decay method, after the occupants left the house. CO_2 concentrations varied from 449 to 1,362 ppm in the bedrooms of the children. The highest mean concentration and the highest peak value (3418 ppm) were recorded in one of the residences, where the air conditioning was frequently used during the night along with closed windows and doors. Overall, 7 out of 25 residences were found to exceed the ASHRAE 8-hour CO_2 recommendation of 1,000 ppm [63]. The low air change rates in the range of 0.084-0.636 h^{-1}, calculated using the occupant-generated CO_2 tracer gas concentration-decay method, contributed to the poor ventilation of bedrooms.

2.4.4 Papers on ventilation and sleep quality

Mishra et al. investigated a window/door opening as a means for achieving higher bedroom ventilation and the subsequent impact on sleep quality [15]. Seventeen healthy volunteers from Eindhoven participated. The study was performed during the 2015 heating season in NV bedrooms with radiant heating. Mean measured CO_2 levels were 717 ppm with window or door open, 658 ppm with the window open, 791 ppm with the door open, and 1,150 ppm with window or door closed: it was noted that it could exceed 3,000 ppm when both door and window were closed. Temperatures in bedrooms during conditions with open doors and windows were marginally lower than when windows and doors were closed; they were between 18 and 22 ℃. Relative humidity did not vastly differ between different conditions. Self-evaluated sleep depth and actigraphy measurements indicated differences between the conditions with windows and doors open and closed. Self-evaluated sleep depth and length, objectively measured sleep efficiency, and the number of awakenings measured using actigraphy correlated well with the measured CO_2 levels: the lower CO_2, the better sleep depth, sleep efficiency, and the lesser number of awakenings.

A Danish study examined how bedroom air quality affects sleep and next-day performance [16]. Sleep quality was measured objectively with actigraphy and rated subjectively by people participating in experiments. Two field interventions were conducted in single-occupancy dormitory rooms, one with 14 subjects during autumn to winter in an NV dormitory and the other one with 16 subjects during the heating season after installation of an inaudible fan providing ventilation. The measurement duration was two weeks with a week-long intervention with either window open or closed (the first experiment) or an inaudible fan in operation or disabled (in the second experiment). Occupant-generated CO_2 was used to compute air change rates. In the first experiment, mean bedroom CO_2 was 2,585 ppm (range from 1,730 to 3,900 ppm) with windows closed and 660 ppm (range from 525 to 840 ppm) with windows open. The corresponding mean bedroom air change rates were 0.17 h^{-1} and 1.8 h^{-1}, respectively. The mean bedroom temperature and relative humidity were respectively 23.9 °C and 54% with windows closed and 24.7 °C and 40% with windows open. In the second experiment, the mean bedroom CO_2 was 2,395 ppm (ranging from 1,620 to 3,300 ppm) when the fan was disabled and 835 ppm (range from 795 to 935 ppm) when it was in operation. The mean bedroom air change rates were 0.24 h^{-1} and 1.1 h^{-1}, respectively, while mean bedroom temperature and relative humidity were 21.9 °C and 52% with the fan disabled and 21.8 °C and 40% with the fan running. The lower CO_2 concentration resulted in improved sleep quality, both rated by the subjects and measured by the actigraphy and improved next-day performance.

Xiong et al. conducted a field study during the Australian summer between January and early March 2019 in Sydney that has a humid subtropical climate [32]. Forty-eight subjects (22 males and 26 females) participated in this study, in which online questionnaire surveys and monitoring were carried out over five consecutive days (Monday through Friday) for each subject. The mean bedroom temperature for all subjects was 26.4 °C for those who had opened windows, doors, or operated fans. For those using AC in bedrooms, it was slightly lower at a mean of 25.3 °C. The bedroom CO_2 levels (mean $\pm$ SD) under different scenarios were as follows – fan 955$\pm$721 ppm, AC 889$\pm$521 ppm, open window or door 542$\pm$84 ppm. Thus, it is seen that NV bedrooms recorded the lowest CO_2 levels. Sleep efficiency and REM sleep (%) was estimated by wrist-worn sensors and were found to be negatively correlated with bedroom operative temperature. Wrist-worn sensors were used to estimate deep sleep (NREM) (%) and found to be negatively related to bedroom CO_2 concentration: A 4.3% decrement in deep sleep was observed for every 100-ppm increase in the overnight average CO_2 concentration with adjustments made for the other variables. Inferior bedroom air freshness, gauged by higher CO_2 concentration during the night, was associated with a drop in self-reported sleep quality the next morning. The effect of bedroom CO_2 on the occupants' light sleep percentage also varied significantly depending on the bedroom operative temperature.

Laverge and Janssens reported findings from a Belgian field study examining the influence of ventilation rate on the sleep pattern of eight students in college dormitories during the autumn season [41]. They measured CO_2, temperature, and relative humidity in the students' dorm rooms. They used actigraphy to monitor their sleep patterns, consisting of sleep efficiency, number and duration of awakenings, and a lightness of sleep. They reported peak CO_2 levels between 3,000 and 4,500 ppm in the low ventilation rate scenario (0.2-0.3 h^{-1}) and between 1,000 and 2,500 ppm in the high ventilation rate scenario (0.4-1.0 h^{-1}). The room temperature was maintained at around 20 °C. The results showed only a very small effect of ventilation rate on sleep patterns. The subjects indicated (on questionnaires) that they were less rested and experienced lighter sleep, together with a slight increase in the number of awakenings and had more dreams under low ventilation rates. For the same ventilation conditions, the actigraphy-based sleep efficiency was higher, but the number of awakenings during the night increased slightly. The authors acknowledged that their results should be carefully considered as the study was relatively small, and the effects of ventilation rates on sleep quality may be complex.

Liao et al. studied the effects of two window states (closed or open) on the sleep environment and quality using the wrist-worn sleep tracker and polysomnography (PSG) [60]. Their results suggest that the participants snored significantly less and had a fewer number of awakenings when sleeping with the window open. CO_2 levels remained stable at around 600 ppm with open windows (ACR of 0.4 to 1.0 h^{-1}) while it reached 1,600 ppm with closed windows (ACR of 0.2 to 0.3 h^{-1}). The median CO_2 levels with the window closed were 2.6 times higher than the one with the window open. They also reported 5^{th}–95^{th}percentiles of CO_2, which were 944–2489 ppm and 448–791 ppm with windows closed and open, respectively. Temperatures in bedrooms during conditions with open windows were marginally lower than when windows were closed, where the 5^{th}–95^{th} percentiles of 21–24°C with windows closed and 19–23°C with windows open were observed. Relative humidity was also slightly lower with windows open than when windows were closed, where the 5^{th}–95^{th} percentiles were 33–52% with windows closed and 28–47% with windows open.

Lan et al. studied the effect of elevated airspeed on sleep quality and thermal comfort of 18 elderly in a hot environment in China during July and August of 2018 [43]. The study was conducted in two exactly similar sleep chambers that were converted into rooms simulating bedroom environment. The mean temperatures and relative humidity were 29.8 °C and 56% for the condition with the ceiling fan, 29.7 °C, and 55% for the condition with the task fan, and 26.7 °C and 61% when AC was operated. The corresponding CO_2 levels were 1,405 ppm, 1,399 ppm, and 1,402 ppm, respectively. They evaluated sleep quality objectively by analysing electroencephalogram (ECG) signals that were continuously monitored during the sleeping period. They also analysed urinary cortisol concentrations to measure the activity of the sympathetic nervous system. They reported no significant difference in sleep quality, thermal comfort, or cortisol concentrations between the ceiling fan and the thermally neutral condition (27 °C, 0.2 m/s). They observed, though, a significant difference when a task fan was used: 35 minutes reduction in sleep time, 15-minute reduction in the duration of REM sleep, and an increase of 50 ng/mL in the cortisol concentration in the morning. They attributed these results to lower heat removal with a task fan possibly because of a lower airspeed when the task fan was in operation. The airspeed of 0.8 m/s distributed evenly over the human body was reported to be able to help to maintain sleep quality and thermal comfort in the elderly population at an air temperature that was 3 K higher than thermal neutrality.

Zhang et al. determined the relationship between the indoor environment and sleep quality based on subjective questionnaires and objective measurement methods [44]. The first phase of the study carried out in China involved an extensive online investigation from three different climatic zones in China; 1635 responses were obtained regarding sleep quality and control methods. The authors concluded that there were differences in the individual perceptions of the effects of the environment on sleep quality arising from factors such as age, gender, and salary. In the second phase, the authors did a field study, involving measurements with 24 subjects in university dormitories, to explore quantitative effects of the indoor environment on sleep quality. They used a 5-point sleep quality assessment scale to examine attributes, such as, ease of falling asleep, the calmness of sleep, frequency of night-time awakening, sleep satisfaction, ease of awakening and freshness after awakening. They reported that indoor CO_2 levels increased during the night and reached a steady state of 1,750 ppm. They also reported that the most satisfactory operative temperature was 24.2 °C and that the subjects had a lower neutral temperature and a broader temperature range during sleep. They found indoor relative humidity during sleep to be higher than during other times. Their analysis included the integrated impacts of the different environmental factors on sleep environment satisfaction. They observed a larger positive coefficient for IAQ (subjective assessment), implying IAQ as an attractive factor for overall sleep environment satisfaction.

Irshad et al. conducted a study in the tropical climate in 2017 [42]. They compared the sleeping behaviour of 15 occupants exposed to two different sleeping environments in a university facility – a room with a thermoelectric air duct cooling system (TE-AD) and a normal NV test room. They reported mean CO_2 of 750 and 620 ppm, mean temperatures of 24.6 °C and 25.8 °C and mean relative humidity of 53.1% and 69.6% for TE-AD and the normal test rooms, respectively. In comparison to the NV room, the subjects in the TE-AD room reported better sleep satisfaction, higher overall thermal sensation and comfort rating, shorter sleep onset latency, and a reduction in the shifting of sleep stages from NREM to REM and then to wake stage.

Xia et al., 2020 [45] performed field intervention experiments in bedrooms of 12 elderly subjects (8 males and 4 females, 66.3 ± 3.3 years old), who did not use any heating in daily life and were without sleep disorders, to study the effects of bed heating (covering heating and mattress heating) on their sleep quality and thermal comfort in a cold environment. The experiments were conducted in February in a nursing home in Hubei province in China. Sleep quality was subjectively evaluated using questionnaires in the morning and objectively measured with a wristband, which was continuously monitored throughout the sleep period. Skin temperatures and blood pressure were also measured. Besides a practice night, each subject participated in three conditions over three additional nights: covering heating, mattress heating, and no heating. The mean and SD of the measured CO_2 levels were 718 ± 123 ppm, 733 ± 145 ppm, and 678 ± 146 ppm, respectively, in these three conditions. The subjects felt thermally comfortable in all three conditions. If no heating is the basis of comparison, covering heating and mattress heating enhanced the total sleep time by 35.5 min and 20.3 min respectively. It decreased sleep onset latency by 13.3 min and 18.3 min, respectively. The "wake after sleep onset" indicator with the covering heating decreased by 28.7 min and 12.5 min relative to mattress heating and no heating, respectively, and the corresponding sleep efficiency increased by 2.8% and 5.7%, respectively.

Kim et al. studied 23 bedrooms during winter, spring, and summer in apartments around Seoul and reported seasonal mean CO_2 concentration levels of 1,258, 1,276, and 428 ppm, respectively [33]. They did not observe much difference between the mean radiant temperature (MRT) and the air temperature during a given season and reported temperatures of 22.7°C, 24.4°C and 28.6°C, and relative humidity (RH) of 28.4%, 39.1% and 61.8 % during winter, spring and summer respectively. A key observation made by the authors was that lower RH in winter appeared to have a negative impact on sleep quality, showing a higher apnea-hypopnea index (AHI) in the oldest age group. AHI indicates the average number of sleep-disordered breathing of apneas hypopneas per hour during sleep.

2.4.5 Papers on personal ventilation and sleep quality

Lan et al. studied the potential benefit of applying personal bedside ventilation (PV) in a bedroom; 36 subjects slept in thermally neutral bedrooms with or without bedside PV for an entire night in winter in Shanghai [107]. Bedroom temperature and relative humidity were 22.9±0.8 °C and 52±3% without PV and 22.9±0.8 °C and 43±4% with PV. The PV supplied air was with a temperature of 24.3±0.6°C and an airspeed of 0.14±0.02 m/s. The subjects perceived the air to be cooler, and their skin temperature decreased when they slept with PV even if the PV supply air temperature was slightly higher than that in the immediate environment. Lan et al. did not observe any significant difference in subjectively rated sleep quality or measured with an actigraphy. Still, the power of very low frequency (VLF) component and the low/high frequency (LF/HF) ratio significantly decreased, indicating lower sympathetic nervous activity and a healthier cardiovascular system during sleep when the PV was turned on. CO_2 concentration was not measured, so it was not possible to evaluate the effects of bedside PV on inhaled air quality.

Zhou et al. investigated the effects of bedside PV on children, adults, and the elderly; the sample size was 36 [108]. The authors inferred that the optimal conditions to improve the comfort of sleep and sleep quality require ambient temperature at 22 °C, PV outlet air temperature at 21 °C and airspeed in the breathing zone at 0.1 m/s. It was observed that the PV system had a positive impact (subjective sleep quality evaluation) on children but not adults. No effects were seen for the elderly.

2.4.6 Papers on ventilation in the whole house

Emenius et al. conducted a nested case-control BAMSE (Swedish abbreviation for Children, Allergy, Milieu, Stockholm, Epidemiology) study, which is a world-renowned birth cohort study, between February 1994 and late 1996 in central and north-western Stockholm in Sweden comprising 4,089 children born to investigate the impact of building characteristics and IAQ on recurrent wheezing in infants; measured ventilation rate and indoor humidity [109]. They identified a total of 540 cases and controls, of which 181 were cases in which measurements of different parameters were performed. Even though they stated that measurements of air change rates, temperatures, and humidity were done in all rooms in each home, including the child's bedroom, they did not report the bedroom air change rates but a single air change rate representing ventilation of the whole house. This air change rate was, on average, 0.68 h^{-1}; 31% of all dwellings had the air change rate lower than 0.5 h^{-1}. The air change rate and ventilation type were not associated with the increased risk of wheezing in contrary to poor IAQ caused by certain types of building construction and elevated indoor humidity.

Singer et al. presented the methods and results of the Healthy Efficient New Gas Home (HENGH) field study and compared the findings from 70 detached houses built with mechanical ventilation in 2011-2017 to the California New Home Study (CNHS) homes built in 2002-2005 mostly without mechanical ventilation [110]. Each home in the HENGH study was monitored for a week-long period with windows closed and the central mechanical ventilation system operating. Indoor CO_2 was one of the indoor contaminants measured. Air leakage rates were obtained by blower door method and the ventilation airflows by a calibrated, pressure-controlled, variable-speed fan. The mean, median, and 10th-90th percentiles of the measured CO_2 levels were 620, 608, and 481-770 ppm, respectively, and the authors conclude that these results are not indicative levels that have been reported to affect sleep or next-day alertness. The outdoor air change rates, including both mechanical ventilation and air infiltration, were calculated minute-by-minute in each home following the Enhanced Model described in the 2017 ASHRAE Handbook Fundamentals [111]. All homes met or were close to meeting the ventilation requirements. For the 57 homes that had measured airtightness and mechanical ventilation system airflows and their systems operated throughout the week of monitoring, the mean, median, and 10^{th}-90^{th} percentiles of the estimated infiltration plus mechanical air change rates were 0.33 h^{-1}, 0.30 h^{-1}, and 0.20-0.46 h^{-1} respectively. The authors state that MV provided substantially higher outdoor air exchange rates than would have occurred by infiltration alone.

A few other studies reported the whole dwelling air change rates, though the primary focus in those studies was not related to bedrooms and sleep quality. Yamamoto et al. reported residential air change rates in three major US metropolitan areas (Elizabeth, New Jersey; Houston, Texas; and Los Angeles County, California) [112]. A median air change rate, based on measurements using the PFT tracer gas method in each house, was 0.71 h^{-1} across all urban areas and seasons, and individually, it was 0.87 h^{-1}, 0.88 $h^{-1,}$ and 0.47 h^{-1} in California, New Jersey, and Texas respectively. Langer and Beko reported whole building geometric mean air change rates in the Swedish housing stock (157 single-family houses and 148 apartments) [113]. They were 0.37 h^{-1} in all dwellings, 0.33 h^{-1} in single-family houses, and 0.43 h^{-1} in apartments. They also reported whole building arithmetic mean air change rates of 0.37 h^{-1} in single-family houses and 0.50 h^{-1} in apartments. Stocco et al. reported a Canadian study involving 48 and 45 homes in winter and summer, respectively, with 43 being the same across both seasons [114]. The whole building's mean air change rate in all dwellings was 0.32 h^{-1} in the heating season and 0.19 h^{-1} in the non-heating (cooling) season. Gilbert et al. studied housing characteristics and indoor concentrations of NO_2 and formaldehyde in 96 homes in Quebec City, Canada [115]. The overall mean air change rate was 0.2 h^{-1}; half of the homes had ventilation rates below 7.5 L/s per person. Using the same dataset, Gilbert et al. estimated that the air change rate to ensure a formaldehyde concentration below Health Canada's guideline value of 50 μg/m^3 in 95% of homes were 0.26 h^{-1}, 0.34 h^{-1} and 0.37 h^{-1} for the entire sample, homes with recent off-gassing sources of formaldehyde and homes heated mainly by electrical baseboard heaters [116, 117]. These studies are included in this review based on the assumption that the bedroom air change rates would be more or less similar to the whole dwelling air change rate. It is also necessary to review ACR in the whole dwelling to have an overview that how possible to ventilate the bedroom from the other space inside the dwelling. It must be, however, noted that these studies did not specifically report bedroom air change rates. There could be several factors related not only to the physical design of bedrooms in a house or apartment but also the occupant behaviour such as the window/door opening at night that may considerably alter the bedroom ventilation characteristics from the rest of the building.

2.5 Review analysis

2.5.1 Bedroom CO_2 measurements

The measured CO_2 concentrations in bedrooms across all studies in the literature (Table 2. 2) are presented in Figure 2. 1. In Figure 2. 1, NV is natural ventilation, MV is mechanical ventilation, AC is air-conditioning, crosses are mean value, circles are minimum or maximum of mean value, the symbol (M) below the circles or the cross mark implies that it is a median value rather than a mean, the horizontal bars are the range from the reported minimum to maximum values, red zone indicates the concentrations at which negative effects on sleep quality are to be expected based on previous studies (see section 2.5.3). The studies are arranged in this order: cooling season, heating season, spring, autumn, and the whole year. The review of CO_2 levels in bedrooms is useful to get an overview of reported CO_2 levels in bedrooms in previous studies and further link them to sleep quality once we are clear about the acceptable CO_2 levels or ACR in bedrooms during sleep.

It is observed that the authors reported the measurements for both NV and MV buildings in various formats, such as mean CO_2, including the minimum and maximum of mean values, minimum and maximum of measured CO_2 values and median CO_2 values. Among all international standards, the CEN standard specifies a fairly refined set of CO_2 levels above outdoors for different IAQ in bedrooms [64]; these levels are shown in Figure 2. 1. Although CEN is a European standard, it is used as the basis of a general analysis for all the studies from around the world in this review.

The following observations can be made regarding bedroom CO_2 (Figure 2. 1):

In general, more studies where MV was used report lower CO_2 levels than studies with NV. Almost all the reported mean CO_2 levels in MV bedrooms are within, at least, the CEN Category III, and about half of them are within the CEN Category I level.

Almost 50% of the studies in NV bedrooms report mean CO_2 levels within the CEN Category I.

There is one NV study each during spring, autumn, and the heating season, and three studies (one NV and two other ventilation strategies unknown) during the whole season that report maximum CO_2 levels exceeding 4,000 ppm, including one reporting 7,500 ppm.

It is seen that the reported mean/median CO_2 levels in most cases were generally within the ranges prescribed by the CEN standard.

2.5.2 Bedroom and whole-dwelling air change rate measurements

The air change rate in bedrooms derived from CO_2 measurements, as reported across all studies in the literature (Table 2. 2), are presented in Figure 2. 2. Some studies reported air change rates in dwellings rather than in bedrooms, and these are presented in Figure 2. 3. The various descriptors in Figure 2. 2 and Figure 2. 3 are the same as those described earlier in Figure 2. 1. The studies in Figure 2. 2 are arranged in this order: cooling season, heating season, spring, autumn, and the whole year.

It is observed that authors presented ACR computations from CO_2 measurements in various formats, such as mean ACR, including the minimum and maximum of mean values, minimum and maximum of derived air change rates, and median air changer rates from measured CO_2 concentrations. Again, the symbol M next to the reported mean ACR indicates median rather than a mean value. ACR is another indicator of bedroom ventilation, although it is not as intuitive and straightforward as (steady state) CO_2 levels, that correspond to ventilation rates per person. In addition to the CEN standard that specifies air change rates for different building categories, ASHRAE Standard 62.2 is also used as a basis of comparison for all the studies from around the world [63, 64]. CEN standard specifies total ventilation (including infiltration) of 0.7 h^{-1}, 0.6 h^{-1}, 0.5 h^{-1}, and 0.4 h^{-1}, respectively for Categories I to IV; it is assumed that they are relevant for bedrooms too for this review analysis. However, since CEN standard also specifies bedroom CO_2 thresholds, the corresponding air change rates of 2.9 (Cat I), 2.0 (Cat II) and 1.2 (Cat III) for a typical bedroom of 10 m^2 area and 2.5 m height with two occupants, are also used for benchmarking in Figure 2. 2 and Figure 2. 3. The range of air change rates in ASHRAE 62.2 across

Ref. Number	Ventilation system	
[28]	NV	(door and window closed)
[28]	NV	(door closed but window open)
[83]	NV	
[28]	NV	(door open but window closed)
[28]	NV	(door and window open)
[85]	NV	(with fans for air circulation)
[38]	NV	
[32]	NV	(window or door closed)
[42]	NV	
[32]	NV	(window or door open)
[34]	NV+AC	overnight NV+AC(window)
[34]	NV+AC	short-term NV+AC(window)
[97]	MV+AC	AC (split)
[34]	MV+AC	short-term MV+AC(window)
[42]	TE-AD system[1]	
[97]	AC	AC (split)
[83]	AC	
[85]	AC	AC (split)
[98]	AC	AC (split)
[98]	AC	AC (window)
[43]	AC	
[32]	AC	
[43]	ceiling fan	
[43]	task fan	
[106]	unknown	
[99]	unknown	
[101]	unknown	
[118]	unknown	
[33]	unknown	
[119]	NV	(window closed)
[120]	NV	
[119]	NV	(window open)
[15]	NV	(window or door open)
[89]	NV	(windows were kept closed)
[15]	NV	(window or door closed)
[121]	NV	
[15]	NV	(window closed)
[15]	NV	(door closed)
[15]	NV	(door open)
[15]	NV	(window open)
[16]	MV	(balanced)
[121]	MV	
[16]	without MV	
[99]	unknown	
[118]	unknown	
[101]	unknown	
[33]	unknown	
[45]	unknown	(mattress heating)
[45]	unknown	(covering heating)
[45]	unknown	(no heating)
[30]	NV	mainly NV
[100]	NV	
[100]	MV	(unbalanced)
[100]	MV	(balanced)
[33]	unknown	
[118]	unknown	
[41]	NV[2]	(window closed)
[16]	NV	(window closed)
[41]	NV[2]	(window open)
[16]	NV	(window open)
[118]	unknown	
[122]	NV	
[84]	NV	
[123]	unknown	
[101]	unknown	
[103]	unknown	

1 - TE-AD system: thermoelectric air duct cooling system

2 - Reported peak CO_2 concentration

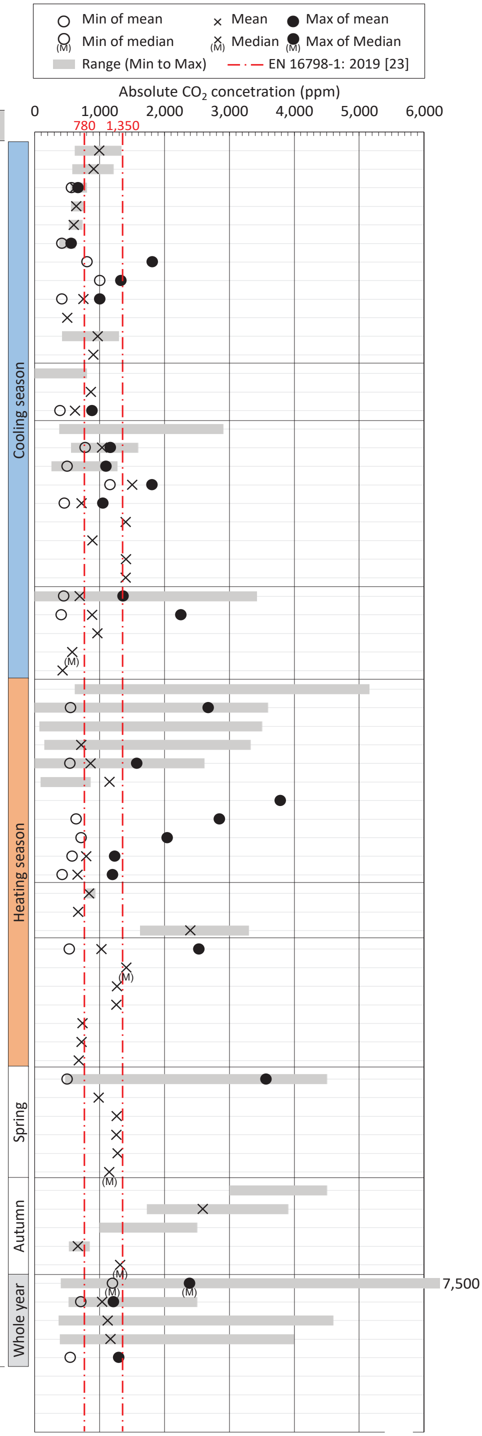


Figure 2. 1 Summary of reported CO_2 measurements in bedrooms.

all floor areas of dwellings and the number of bedrooms in each of the floor areas ranging from 1 to 5 is between 0.2 h^{-1} and 0.7 h^{-1}.

The following observations can be made regarding bedroom air change rates (Figure 2. 2):

If an air change rate of 0.7 h^{-1}, which is the highest total ventilation that is common to both the CEN and ASHRAE standards, is taken as a criterion, a large number of the studies measuring ventilation in NV bedrooms during the cooling season report mean air change rate above this number. But this is not true for the studies measuring ventilation in NV bedrooms in the heating season, most of them being below this number. This result demonstrates that mean air change rates in naturally ventilated dwellings, including bedrooms, are generally much lower during the heating season. While the air change rates reported in spring and autumn are also generally lower than 0.7 h^{-1}, they are slightly better for those studies reporting for the whole season.

If the air change rates of 2.9 h^{-1}, 2.0 h^{-1}, and 1.2 h^{-1} are taken as the criteria, all air change rates reported in NV dwellings paint an even more aggravated picture. All but one of the heating season studies fail to comply even with 1.2 h^{-1}. In the case of mean air change rates during the cooling season, about 50% of the reported values would comply with 1.2 h^{-1}, but only one with 2.9 h^{-1}.

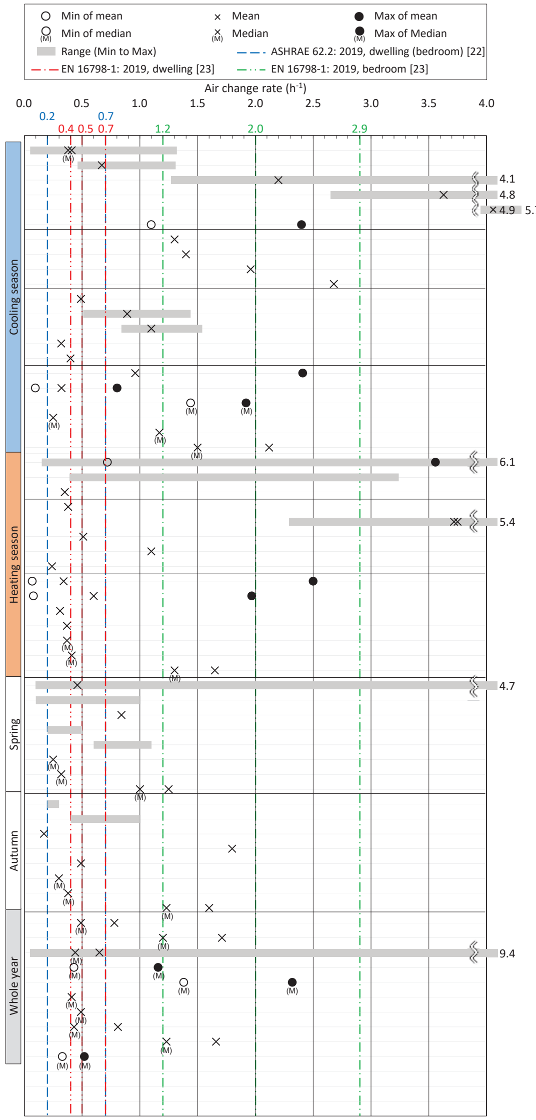
If an air change rate of 0.7 h^{-1} is used as a criterion for bedroom ventilation, a large number of the reported measurements in MV bedrooms performed during the cooling season will comply with this criterion. But this situation is different during the heating season; only one measurement performed in MV bedroom complies with this criterion.

If the air change rates of 2.9 h^{-1}, 2.0 h^{-1} and 1.2 h^{-1} are taken as the criteria, all the air change rate measurements performed in MV bedrooms are not much better than in NV bedrooms.

For most of the studies involving whole dwelling ACRs (Figure 2. 3), it is not clear if the ventilation system is NV or MV, and thus not possible to compare the ACRs between NV and MV. ACRs in the dwellings are considerably lower during the heating season and are of the order of 0.4h^{-1}. The ACR data reported for the whole year is better and is between 0.5 and 0.9 h^{-1}.

Overall, it is possible to make some general inferences based on a closer look at Figure 2. 1, Figure 2. 2, and Figure 2. 3. They suggest that in bedrooms with natural ventilation (NV) during the heating season (especially closed window condition) or when air-conditioning (AC) was operated during the cooling season or hot periods, very low ventilation rates (outdoor air supply rates) were measured and associated with high CO_2 concentration. It can also be observed that the reported mean/median CO_2 levels during the heating season or when air-conditioning (AC) was operated during the cooling season in most cases were below 0.5 h^{-1}. According to the limited evidence, as discussed earlier, such low air change rates and low outdoor air supply rates demonstrated by high CO_2 levels would be expected to affect sleep quality negatively.

Figure 2. 4 shows the temperatures and relative humidity measured in the bedrooms and reported by the studies included in the present review. The results show that the mean temperatures in the cooling season ranged between 25°C and 30°C and in the heating season between 20°C and 25°C depending on different regions or climates. Relative humidity were between 40% and 80% and there were no specific differences between seasons. Wide variations



Ref. Number	Ventilation system
[95]	NV
[28]	NV (door and window closed)
[28]	NV (door closed but window open)
[28]	NV (door open but window closed)
[28]	NV (door and window open)
[34]	NV+AC(window)
[91]	NV+MV
[91]	NV+MV
[97]	MV+AC(split) [1]
[97]	MV+AC(split) [2]
[99]	AC(split)
[99]	AC(window) (ventilation damper closed)
[99]	AC(window) (ventilation damper open)
[97]	AC(split) [1]
[97]	AC(split) [2]
[99]	unknown [3]
[106]	unknown
[103]	unknown
[118]	unknown
[96]	unknown
[124]	unknown
[121]	NV
[120]	NV
[125]	74% using NV [5]
[91]	NV+MV
[121]	MV
[125]	68% using MV [6] (unbalanced)
[16]	MV (balanced)
[16]	without MV
[99]	unknown [3]
[94]	unknown
[99]	unknown [2]
[125]	unknown [7]
[118]	unknown
[96]	unknown
[124]	unknown
[30]	mainly NV
[100]	NV
[91]	NV+MV
[100]	MV (balanced)
[100]	MV (unbalanced)
[118]	unknown
[96]	unknown
[124]	unknown
[41]	NV (window closed)
[41]	NV (window open)
[16]	NV (window closed)
[16]	NV (window open)
[91]	NV+MV
[118]	unknown
[96]	unknown
[124]	unknown
[93]	mainly NV [4]
[93]	mainly NV [1]
[101]	unknown [8]
[103]	unknown
[103]	unknown
[101]	unknown [5]
[101]	unknown [6]
[96]	unknown
[124]	unknown
[103]	unknown [9]

1 - using Occupant-generated CO_2 as a tracer gas
2 - using SF_6 as a tracer gas
3 - using PFT as a tracer gas
4 - using active tracer gas
5 - measured in single-family houses
6 - measured in apartment
7 - measured in row houses
8 - data from all dwellings
9 - excluding the summer period

Figure 2. 2 Summary of reported ACR measurements in bedrooms.

in temperatures were seen in NV bedrooms. In the heating season, the mean temperatures could be as low as 20°C and in the cooling season as high as 30°C.

2.5.3 Effect of bedroom ventilation on sleep quality

Based on the limited evidence on the effects of bedroom ventilation/IAQ on sleep quality, an attempt is made to identify the magnitude of the problems and whether ventilation type, bedroom size or use, and climate and season can explain the observed relationships.

A summary of ten studies examining the effect of bedroom ventilation (IAQ) on sleep quality has been presented earlier. These studies suggest that lower bedroom CO_2 levels indicating higher ventilation rates are correlated with better sleep quality, as seen by different objectively measured indicators and subjective assessment. Table 2. 4 provides a summary of CO_2 levels and ventilation conditions in these studies. It is generally observed that lower ventilation rates (ACR < 0.4 h^{-1}) were typically associated with higher CO_2 levels.

Two papers focused on personal ventilation and some measure of sleep quality, obtained primarily from thermal considerations, and neither of them measured CO_2 levels. It could, however, be indirectly inferred that the use of personal ventilation would have resulted in an improved bedroom air quality by supplying fresh air in the head region of a sleeping person, which could then imply better sleep quality. In the absence of CO_2 or air change rate measurements, this cannot be substantiated and these two papers are not analysed further.

The results presented in Table 2. 4 can be used to develop a tentative relationship between bedroom ventilation and sleep quality. It can be observed that in none of the studies, any effects on sleep quality were measured at CO_2 concentration below 750 ppm and that between 750 ppm and 1,150 ppm, some studies observed effects on sleep quality and some did not. Above 1,150 ppm, the studies are quite consistent. They show that some parameters describing sleep quality, either measured subjectively or objectively, were affected. Additionally, above 2,600 ppm, the next-day performance was observed to be affected as well [16, 59]. It can also be seen that sleep quality is expected to be disturbed when ACR in the bedroom is below 0.24 h^{-1} (2600 ppm from the study of Strøm-Tejsen et al.). Among the frequently observed effects on sleep quality were reduced sleep efficiency, increased sleep onset and number of awakenings. Consequently, the following tentative relationship is proposed, where concentrations refer to the levels of CO_2 that are used as a proxy for ventilation rates with outdoor air:

<750 ppm undisturbed sleep quality range

750-1,150 ppm possibly disturbed sleep quality

1,150-2,600 ppm disturbed sleep quality range

>2,600 ppm disturbed sleep quality range with possible reduced next-day cognitive performance

This tentative relationship requires validation and may be revised based on future studies on ventilation requirements in bedrooms and sleep quality. The CO_2 levels can be converted to an outdoor air supply rate once the emission rates of CO_2 during sleep are known. Some information on these rates exists in the literature [126, 127]. It is interesting to note that the level of CO_2 at 750 ppm is consistent with the recommendation of Petenkoffer for bedrooms, who proposed 1,000 ppm for other spaces to achieve good indoor air quality [128].

Table 2. 4 Summary of CO_2 levels and ventilation conditions in studies examining the effect of bedroom ventilation and IAQ on sleep quality.

Author(s)	Year	Lower ventilation condition		Higher ventilation condition		Observed significant effects on parameters describing sleep quality at lower ventilation conditions measured objectively or rated by occupants	
						Sleep quality parameters measured objectively	Sleep quality rated subjectively
Mishra et al. [15]	2018	average CO_2	1,150 ppm	average CO_2	717 ppm	Lower sleep efficiency Increased number of awakenings	Lower depth of sleep
Strøm-Tejsen et al. [16]	2016	average CO_2	2,585 ppm (1,730 to 3,900 ppm)	average CO_2	660 ppm (525 to 840 ppm)	Shorter sleep onset latency Lower sleep efficiency Reduced next-day performance of a logical thinking task	More sleepy and less able to concentrate on the next day
		ACR	0.17 h^{-1}	ACR	1.8 h^{-1}		
		average CO_2	2,395 ppm (1,620 to 3,300 ppm)	average CO_2	835 ppm (795 to 935 ppm)		
		ACR	0.24 h^{-1}	ACR	1.1 h^{-1}		
Xiong et al. [32]	2020	average CO_2	1,327 ppm (shared occupancy) 1,004 ppm (single occupancy)	average CO_2	around 500 ppm	Lower % of deep sleep	Reduced self-reported sleep quality

Table 2. 4 to be continued.

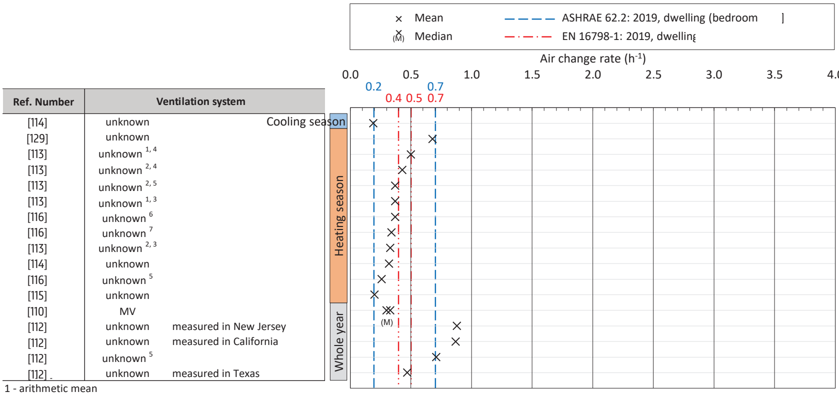
Author(s)	Year	Lower ventilation condition		Higher ventilation condition		Observed significant effects on parameters describing sleep quality at lower ventilation conditions measured objectively or rated by occupants	
						Sleep quality parameters measured objectively	Sleep quality rated subjectively
Laverge and Janssens [41]	2011	Peak CO_2	3,000 to 4,500 ppm	Peak CO_2	1,000 to 2,500 ppm	Higher sleep efficiency Increased number of awakenings	Less rested Lighter sleep Increased number of awakenings
Liao et al. [60]	2020	average CO_2	1,654 ppm	average CO_2	601 ppm	Increased snoring Increased number of awakenings	N/A
		median CO_2	1,550 ppm	median CO_2	585 ppm		
Lan et al. [43]	2019	-	-	average CO_2	around 1,400 ppm	N/A	N/A
Zhang et al. [38]	2018	-	-	steady-state CO_2	around 1,750 ppm	N/A	N/A
Irshad et al. [42]	2018	average CO_2	750 ppm	average CO_2	620 ppm	Shorter sleep onset latency Reduction in the shifting between sleep stages, from NREM to REM, and to wake stage	N/A

Table 2. 4 to be continued.

Author(s)	Year	Lower ventilation condition		Higher ventilation condition		Observed significant effects on parameters describing sleep quality at lower ventilation conditions measured objectively or rated by occupants	
						Sleep quality parameters measured objectively	Sleep quality rated subjectively
Xia et al. [45]	2020	-	-	average CO_2	around 700 ppm	N/A	N/A
Kim et al. [33]	2010	average CO_2	1,258 ppm (winter) 1,276 ppm (spring)	average CO_2	428 ppm (summer)	N/A	N/A

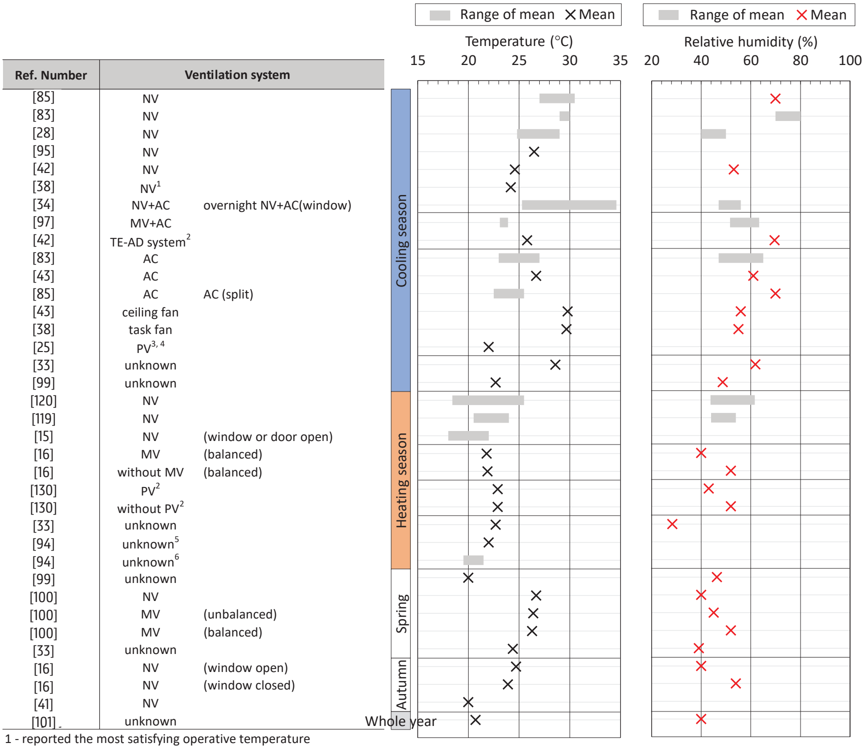
2.5.4 Limitations

It is apparent from the 46 papers reviewed that there were only a few of them that satisfied all three criteria involving CO_2 levels, ACRs and sleep quality attributes. There were only 10 papers in total that involved sleep quality measurements and these typically included just a report of measured CO_2 levels and very few intervention type studies. One of the challenges in reviewing and interpreting the data presented in the various studies is the lack of a standardized measurement protocol including location and duration of measurements. Notwithstanding the difficulty in ventilation measurements, large variations in the quality and specificity of the measured ventilation parameters were quite apparent. Almost all studies reported mean values of CO_2 and ACR measurements in bedrooms and living rooms of dwellings, which only provide a simplistic and limited understanding of the overall ventilation performance, whether the bedroom was with natural or mechanical ventilation. Several papers reporting bedroom air change rates did not explicitly state if the reference was to outdoor air change rates exclusively or ACRs computed as a combination of outdoor air and air from other parts of the dwelling; the same applies to measured CO_2 concentrations especially in naturally ventilated bedrooms. If based on CO_2 decay, ACR, computed as a reference of outdoor air, would normally be higher than actual ACR, which should be computed as a reference of a combination of outdoor air and air from other parts of the dwelling. Based on the review of several ventilation standards, it can be seen that there is no internationally accepted and standardized method of specifying prescriptive ventilation requirements in bedrooms and other parts of a dwelling. Furthermore, a performance-based ventilation criterion, such as prescribed CO_2 levels, in bedrooms and other parts of a dwelling is seen in only two standards. While CO_2 and other performance-based metrics are often seen in ventilation standards for non-residential buildings, its absence in



1 - arithmetic mean
2 - geometric mean
3 - measured in single-family houses
4 - measured in apartment
5 - data from all dwellings
6 - homes heated mainly by electrical baseboard heaters (Health Canada 2005)
7 - homes with recent off-gassing sources of formaldehyde

Figure 2. 3 Summary of reported ACR measurements in whole-dwelling.



1 - reported the most satisfying operative temperature
2 - TE-AD system: thermoelectric air duct cooling system
3 - PV: Personal ventilation
4 - the optimal conditions to improve the comfort of sleep and sleep quality
5 - with central heating
6 - using a stove or combined heating system

Figure 2. 4 Summary of reported temperature and relative humidity measurements in bedrooms.

residential buildings is highlighted as a major limitation in standardization efforts, and thereby, can be seen as an opportunity.

2.6 Conclusions

Forty-six papers presenting measurements of ventilation in bedrooms (or whole-dwelling) and seventeen international standards dealing with ventilation in dwellings were reviewed. With few exceptions, present ventilation standards do not prescribe specific ventilation requirements for bedrooms; ventilation in bedrooms is merely the result of ventilation requirements for the entire dwelling. The reviewed papers indicate a wide range of ventilation rates measured in bedrooms using different methods; mostly carbon dioxide concentration and air change rates were measured. The reported mean CO_2 concentrations ranged from 428 to 2,585 ppm, and the mean air change rates from 0.2 to 4.9 h^{-1}. The measured results suggest that the ventilation rates (indicated by the measured carbon dioxide concentration) are lower during heating seasons, especially in naturally ventilated, as well as in bedrooms when the air conditioning is in operation. It was additionally observed that bedroom temperatures were lower during heating seasons. There is scanty information on whether the reported ventilation rates would disturb sleep quality. Few studies performed to date suggest that sleep quality will not be affected when ventilation rates reduce CO_2 levels below 750 ppm, while CO_2 above 2,600 ppm would not only disturb sleep quality but also can be expected to have a negative effect on the next-day cognitive performance. These results require validation. Therefore, future studies should focus on delineating the relationship between sleep quality and ventilation in bedrooms providing input to ventilation standards, as well as on developing standard methods for measuring and improving ventilation and air quality in bedrooms. All the methods to measure sleep quality and bedroom ventilation used in previous studies can be considered to apply in future studies depending on practical reasons, such as availability, budget, etc. Field measurements, another type of study, in real bedrooms in residential buildings are required.

3

Effects of Window Opening on The Bedroom Environment and Resulting Sleep Quality

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Keywords

Sleep environment; Field study; Sleep quality; Sleep tracker; Home polysomnography

Abstract

The effects of two window states (closed or open) on the bedroom environment and on sleep quality were investigated. Twenty-seven subjects (14 males and 13 females, 20–33 years old) without sleep disorders and chronic diseases participated. The subjects slept for two consecutive nights with windows open and two consecutive nights with windows closed in four dormitory rooms adapted for the purpose of this study, one person at a time. The order of exposure was balanced among participants. Bed temperature, room temperature, relative humidity (RH), carbon dioxide (CO_2), particles ($PM_{2.5}$), and noise were monitored during sleep. Sleep quality was measured using subjective ratings, a wrist-worn sleep tracker, and (for one group of 14 subjects only) polysomnography (PSG) for home use; snoring in this sub-group and awakenings were also registered. Higher $PM_{2.5}$ and noise levels were found with windows open, while higher room temperature, RH, and CO_2 levels were measured with windows closed. There were no differences between conditions in terms of objectively measured sleep stages but the subjects with the PSG attached snored significantly less and woke up significantly less often when sleeping with windows open. Start sleep time, end sleep time, total sleep time (TST) and time in bed (TIB) measured with the sleep tracker were confirmed by the measurements made using PSG, light sleep (N1+N2) and sleep latency were in moderate agreement but there was no significant agreement for REM and deep sleep (N3). When sleeping with windows open, the subjects rated the air as fresher but reported higher noise levels, feeling less rested, a worse mental state and wellbeing, and their replies on the Groningen sleep quality scale indicated poorer sleep quality. There was no clear association between the performance test score and sleep quality. These results suggest that sleeping with windows open can provide some benefits by increasing ventilation with outdoor air, reducing CO_2 concentrations, improving air quality as indicated by the subjectively rated air freshness and some of the parameters defining sleep quality, but it may also result in some discomfort if there are episodic loud noise events outdoors. Further studies are required to clarify the role of open windows in achieving good sleep quality.

3.1 Introduction

Humans spend one-third of each day sleeping. Poor sleep quality has negative effects on health and next-day performance [131-133]. Four sleep continuity variables (sleep latency, awakenings for more than 5 min, wake after sleep onset and sleep efficiency) and five sleep architecture variables (rapid eye movement [REM] sleep, N1 sleep, N2 sleep, N3 sleep, and arousals) have been identified as indicators of sleep quality [7].

A high-quality sleep environment in terms of noise, room temperature, relative humidity (RH), and ventilation rate as indicated by CO_2 is necessary for good sleep quality [46]. Reduced sleep quality and quantity are induced by exposure to intermittent noise above 35 dB(A) [46]. Maintaining room temperatures between 17 and 28 °C with RH between 40 and 60% is considered optimal for bedroom environments [134-136]. However, sleep quality has been found to vary even within this range of optimal room temperatures [137-139]. The CO_2 concentration is regarded as an indicator of ventilation efficiency in the presence of people and thus indirectly a marker of indoor air quality (IAQ). Several studies have shown elevated levels of CO_2 in bedrooms because of insufficient ventilation, usually as a result of energy conservation in either heating or air-conditioning [30, 85, 140]. Very few studies have investigated the relationship between IAQ and sleep quality [15, 59].

Laverge and Janssens (2011) carried out a field intervention experiment to examine the influence of ventilation rate on the sleep pattern among eight subjects, using actigraphy. Peak CO_2 concentration in the low ventilation rate was between 3,000 and 4,500 ppm whereas it was between 1,000 and 2,500 ppm at the high ventilation rate; the ventilation rate was changed by opening or closing windows. They observed only a very small effect of the ventilation rate on the sleep pattern: the number of awakenings was more with the low ventilation rates with windows closed [41]. Strøm-Tejsen et al. (2016) changed bedroom ventilation by opening and closing windows in a pilot experiment ($n = 14$ subjects) and by turning on or idling an inaudible fan in a follow-up experiment ($n=16$ subjects). The average CO_2 level was 2,585 (with windows closed) and 660ppm (with windows open) in the former experiment, and 2,395 (with the fan off) and 835ppm (with the fan on) in the latter experiment. They reported that sleep latency was significantly shorter with windows open ($p<0.05$) and that sleep efficiency was higher with the fan in operation ($p<0.05$). The score obtained on the Groningen Sleep Quality Scale indicating subjectively measured sleep quality improved as did next-day performance of a logical thinking test [16]. Mishra et al. (2018) conducted a field experiment ($n=17$ subjects), in which ventilation was changed by opening or closing the windows. As a result, the average CO_2 levels were 717 and 1,150 ppm, respectively [15]. Higher scores of self-assessed sleep depth, higher actigraphy-measured sleep efficiency, and a lower number of awakenings were found with the lower CO_2 levels. Although previous studies indicated that there might be some benefits with higher ventilation rates (lower CO_2 levels), the results from these studies were not fully consistent and therefore need further confirmation. In addition, some studies performed measurements of other parameters defining bedroom IAQ. For example, in the studies of Lawrence et al. (2018) [141], Shen et al. (2018) [142], and An and Yu (2018) [143], elevated levels of outdoor $PM_{2.5}$ were associated with oversleeping, sleep-disordered breathing, and sleep disorder symptoms. No studies have examined the link between indoor $PM_{2.5}$ and sleep quality.

The purpose of this study was to further examine the effects of window opening on sleep quality. A secondary purpose was to compare the low-cost sleep tracker used to monitor sleep quality with polysomnography. The main hypothesis was that reduced bedroom air quality indicated by the higher CO_2 levels results in poorer sleep quality, reduced next-day performance, and increased next-day sleepiness.

3.2 Method

An intervention study was performed in which participants slept under a window-closed or a window-open condition in a dormitory room adapted for the purpose of the study, the order in which the interventions were implemented being balanced. The resulting sleep environment and its effects on sleep quality were monitored and the quality of the sleep environment was rated by the participants. Sleep quality was measured both objectively and subjectively. Movements (during sleep), next-day sleepiness levels, and next-day performance were also measured.

3.2.1 Study design

The participants slept in a room for two consecutive nights with windows open or closed and then a week later, with the other window setting; the first night served to familiarize the subjects with the sleeping environment and only measurements that were performed during the second night were used in the analysis. The participants were exposed in two groups. One group slept in the first block of two rooms and the other group slept in another block of two rooms. In the first group, sleep quality was measured using polysomnography (PSG) and a sleep tracker (a PSG group), while in the other group only a sleep tracker was used (a non-PSG group). Four participants were exposed per night – two of them in the PSG group and two in the non-PSG group. The participants were randomly assigned to the groups and to the order in which they encountered the two sleeping conditions; each participant always slept in the same room throughout the experiment.

The participants arrived either 1–2 hours (PSG group) or half an hour (non-PSG group) before their bedtime. They completed the evening questionnaire, performed the Attentional Network Task (ANT), put on the sleep tracker and PSG (if relevant), recorded their bedtime, and went to sleep. In the morning after waking up, they recorded their rising time, completed the morning questionnaires and performed the ANT test. After that, they proceeded with their normal daily activities and also rated their sleepiness four times during the daytime. During the first night (adaptation night), they did not complete the questionnaire or perform the ANT test. Instead, they practiced a 2-min trial (practice) before the ANT test each time. Not to fill out the questionnaire during the first night was just to catch the first impression of subjects to the questions during the test nights.

3.2.2 Participants and location

The experiment was carried out in April 2019 in Ghent, Belgium with an oceanic climate according to Worldwide Köppen climate classifications [144]. During the month of experiment the daily average minimum and maximum temperatures were respectively 6.3 and 15.9 °C, and the daily average relative humidity was 66% [145]. Students who were living in the university dormitory housing the experiment were recruited after completing an online questionnaire, including the Pittsburgh Sleep Quality Index (PSQI) and a few selection questions. Fourteen males and fourteen females were recruited based on three selection criteria – good sleep quality with the PSQI score less than or equal to 5, non-smokers, no sleep disorder, or chronic disease. Participants were asked to avoid intensive physical activities for at least 6 hours prior to their bedtime on the test nights. No alcohol, caffeinated drinks, tea or tobacco was allowed for at least 6 hours before bed or before 17:00 on the day after the test night. They wore the same pyjamas during the experiment. The participants were also encouraged to operate the thermostat-controlled heater to select their preferred temperature. They were paid €75 if they wore the PSG at night, or €50 if they did not, which they received after the experiment.

All the participants in this study gave their written informed consent to take part in the experiments. In the consent form, they declared that they participated in the experiment out of their own free will. They gave permission to the experimenter to save, analyse, and report their results in an anonymous way. They were aware of the possibility to stop the experiment at every possible moment and that they do not need to state any reason for stopping their participation. Also, they were aware of the possibility to obtain a summary of the study results by request.

Figure 3. 1 Experiment location.

The experiment took place in the same dormitory in four rented rooms labelled from A to D on the ground floor; the rooms were all adjacent to each other. Figure 3. 1 shows the experiment location, where a major road and river nearby are indicated. The four rooms were uniformly furnished and a schematic diagram of the interior is shown in Figure 3. 2. During the first week of the experiments, the windows were open in rooms A and C but closed in rooms B and D and the other way round in the second week. The rooms were similar to the participants' own rooms in the dormitory but had been adapted for the experiments by blocking the vents using tape, placing air monitors on the chest of drawers, and opening/closing windows. The bathroom door remained closed toward the bed during sleep. The indoor air monitors were placed on top of the chest of drawers (0.53 m), which was slightly lower than the bed and located at the foot end of the bed. This location according to the newly published results by Sekhar, Wargocki et al. (2020) should well depict the local microenvironment [146]. The vents were blocked so the only ventilation in the rooms was airing through windows and infiltration. The only ventilation method was opening the window (with a small angle tilt, see Figure 3. 3). The curtains (closed) were taped on the window frame so they did not move. The airing was obtained from the two sides of the windows. Rooms A and B were used for the participants from the PSG group, and Rooms C and D were used for those from the non-PSG group. The rooms were similar to the ones the participants used to sleep and the building surroundings were the same as well. The bed and bedding were the same as a standard dorm package they were provided when moving to the dormitory. They consisted of a duvet and pillow, but not their own.

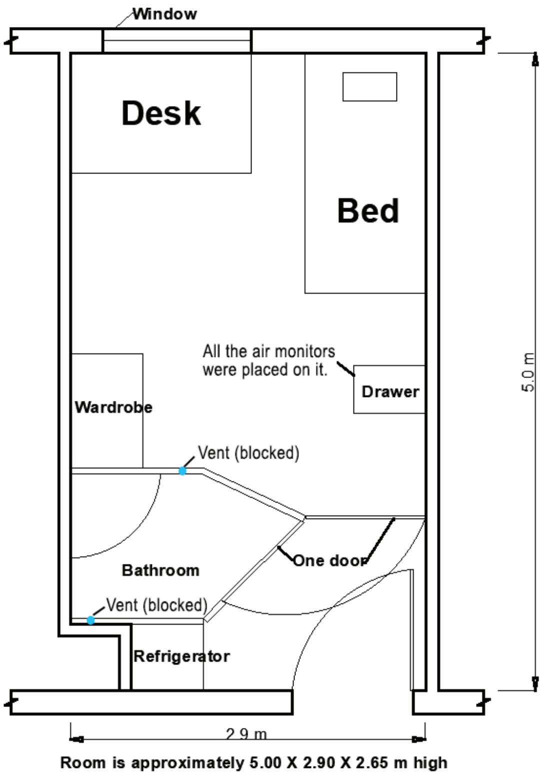

Figure 3. 2 Schematic diagram of the room in the dormitory.

Figure 3. 3 Opening (on the left) or closing (on the right) the window (curtains were kept closed during sleep).

3.2.3 Measurements of the environmental quality in bedrooms

Room temperature, RH, CO_2, noise, $PM_{2.5}$, bed temperature and bed relative humidity were logged every 5 min throughout the experimental period; the bed temperature refers to the temperature under the cover and above the chest. Table 3. 1 shows the brand, type, accuracy, and measuring range of the calibrated devices used. The adjustable chest band with the temperature data logger inside it is shown in Figure 3. 4. The participants wore the chest bands above the chest, with a miniature temperature data logger attached to the front of the chest for the purpose of measuring the bed temperature and relative humidity. Different "bed temperature or relative humidity" would be recorded if they slept on their side or on their stomachs since they were not constrained or instructed to sleep on their backs.

The participants also rated how they perceived their sleeping environment. The rating was made using the online questionnaires the following morning. They rated temperature, humidity, air freshness, noise, and odour. A Likert rating scale (10 points) was used to assess each factor. The endpoint labels of each scale are shown in Table 3. 2, the 8 other equally-spaced points on each scale being unlabelled.

Figure 3. 4 Adjustable chest band with the temperature data logger (HOBO U12-012) inside.

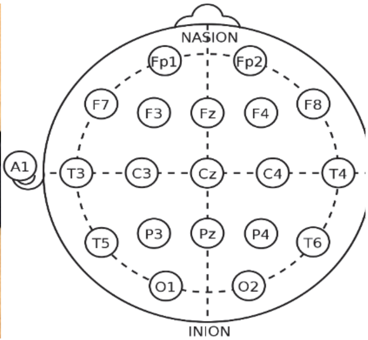

Figure 3. 5 Electrode locations of the international 10–20 system for EEG (Wikipedia, 2019).

Table 3. 1 The details of the devices used.

Parameter	Device/Sensor	Accuracy	Measuring range
Room temperature	Netatmo	± 0.3 °C	0–50 °C
Relative humidity		± 3 %	0–100 %
CO_2		± 50 ppm (from 0 to 1000 ppm) ± 5% (from 1000 to 5000 ppm)	0–5000 ppm
Noise		-	35–120 dB(A)
$PM_{2.5}$	PMSA003I-A	±10 % (from 100 to 500 μg/m^3) ±10 μg/m^3 (from 0 to 100 μg/m^3)	0–500 μg/m^3
Bed temperature	HOBO U12-012 (put in adjustable chest band)	± 0.35 °C	-20–70 °C
Bed relative humidity		± 2.5 %	5–95 %

Table 3. 2 A Likert rating scale (10 points) for a self-assessed sleep environment [16].

Items	Left scale endpoints	Right scale endpoints
Bed temperature	Too cold	Too warm
Room temperature	Too cold	Too warm
Air humidity	Too dry	Too humid
Air freshness	Stuffy air	Fresh air
Noise	Quiet	Noisy
Odour intensity	Strong odour	No odour

3.2.4 Measurements of sleep quality

Both subjective and objective measurements of sleep quality were made: the Groningen Sleep Quality Scale (GSQS) in the case of the former, and a sleep tracker and home polysomnography (PSG) in the case of the latter.

3.2.4.1 Objective assessments of sleep quality

Two sets of the home polysomnography (PSG) – the Nox A1 from Resmed company and four wrist-worn sleep trackers were available; because of this limitation, PSG was used only for half of the participants (n=14 subjects).

The Nox A1 is a portable and easy-to-use polysomnography (PSG) for home sleep testing; it can also be used for lab experiments. The Nox A1 contains electroencephalography (EEG), electrooculography (EOG), and chin electromyography (EMG). The EEG of the Nox A1 includes 8 channels (electrodes). Each electrode placement site has a letter to identify the lobe, or area of the brain it is reading from prefrontal (Fp), frontal (F), temporal (T), parietal (P), occipital (O), and central (C). Figure 3. 5 shows the electrode locations of the international 10–20 system for EEG. The main locations of C3, C4, F3, F4, A1 (M1), A2 (M2), O1 and O2, cover the recommended EEG derivations of F4, C4, and O2 from the American Academy of Sleep Medicine (AASM) [147], and were used for the Nox A1. The Nox A1 was set up via the Noxturnal software system. The electrodes were applied 2 hours before bedtime, as were the oximeter. The Noxturnal tablet app was used to set up recorders, perform bio-calibration, and impedance checks to ensure the electrodes, and attached electrodes were running well. For example, the signal curve of the respiratory monitor would change as the participants breathe, and the signals of electrodes would be shown green, orange, or red to indicate good, moderate, or bad signals, respectively. The sleep results were analysed automatically by the Noxturnal software system. The participants were asked to wash their hair, take a shower, and shave their beard (if any) before the Nox A1 was attached to ensure good connection signals to the home PSG.

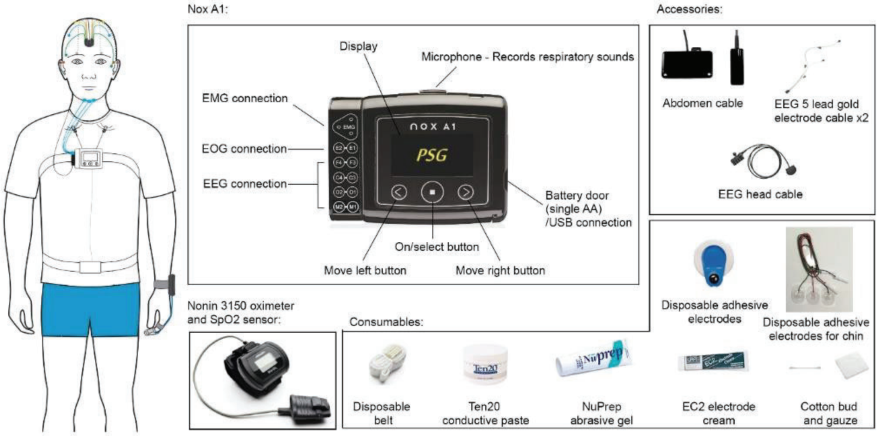

Figure 3. 6 The Nox A1, Nonin 3150 oximeter and oxygen saturation (SpO_2) sensor, accessories, and consumables (revised from the Nox A1 handbook from the Resmed company). EMG, electromyography; EOG, electrooculography; EEG, electroencephalography.

Figure 3. 6 shows the devices of the Nox A1, Nonin 3150 oximeter and oxygen saturation (SpO_2) sensor, accessories, and consumables. The device of the Nox A1 contained display, 3 buttons, microphone, battery door, USB connection port, and EMG, EOG and EEG connections. Accessories include abdomen cable, EEG head cable, and EEG 5 lead gold electrode cable. EEG 5 lead gold

electrode cable was used for the electrode placement locations of C3, C4, F3, F4, A1 (M1), A2 (M2), O1 and O2, as well as E1 and E2, the locations of EOG connection (Figure 3. 7). Among consumables, Ten 20 was applied for connecting the EEG 5 lead gold electrodes to skin, and NuPrep abrasive gel was used for cleaning skin. EC2 electrode cream was placed on gauze and then was used above the EEG 5 lead gold electrodes for stabilizing them on the head. Disposable adhesive electrodes were used with the EEG head cable.

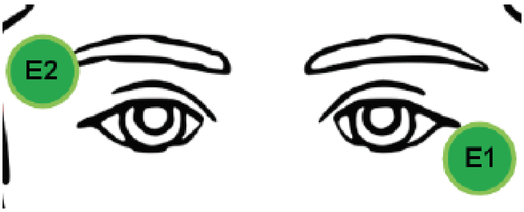

Figure 3. 7 The locations of E1 and E2 (from the Nox A1 handbook).

The results were clustered in four groups showing the overview parameters, sleep scoring parameters, sleep stages, and arousal. Overview parameters included the oxygen desaturation index (ODI), and the snore percentage. Sleep scoring included analysis start time, analysis stop time, total sleep time (TST), analysis duration (TRT), wake after sleep onset (WASO) (time awake after sleep onset) and sleep efficiency (TST/TRT × 100). Sleep stages included N1, N2, N3, REM, and wake stages. Interruptions of sleep lasting 3 to 15 seconds are defined as arousal interruptions, and the arousal would become an awakening if it lasted more than 15 seconds (ASAA 2019). Arousals are scored as interruptions of sleep of 3–30 seconds by the Nox A1. Arousal index (AI; the average number of arousals per hour in TST), number of arousals (in TST; the number of interruptions of sleep lasting 3–30 seconds), and number of arousal awakenings (the number of interruptions of sleep lasting 15–30 seconds) were recorded.

ODI is defined as the average number of desaturation episodes per hour. Desaturation episodes are generally described as a decrease in the mean oxygen saturation of 4% (over the last 120 seconds) that lasts for at least 10 seconds [148].

The snore percentage is defined as the total duration of snore train events as a percentage of TST. A snore train is a minimum of 3 consecutive snores. The automatic analysis in Noxturnal uses the Nox A1's internal microphone to detect snores. This algorithm also checks for inhalation overlap as any sound higher than 65dB(C) coming from another source would probably not coincide with the user's inhalation and can, therefore, be excluded. This audio-based record of snoring has been found to be the most valid approach among microphone, cannula and piezoelectric sensor methods [149].

The Fitbit Charge 2 was used as a wrist-worn sleep tracker [12]. It shows sleep quality based on the four sleep stages: wake, light, deep, and REM. These stages are estimated based on the heart rate and limb movements. Sleep start time and end time, the time asleep and awake, the time in bed (TIB), REM, light sleep, deep sleep, the number of awakenings, and sleep latency were obtained using the measurements obtained with the sleep tracker. Light sleep contains sleep stages N1 and N2, whereas deep sleep corresponds to N3 [12]. All the parameters obtained using

Fitbit Charge 2 could also be obtained from the measurements made using PSG (Nox A1). Time asleep and TIB measured by the sleep tracker correspond to TST and TRT in the case of PSG. However, interruptions of sleep lasting more than 30 seconds are defined as awakenings by the Fitbit Charge 2, which is different from the number of arousal awakenings recorded by the PSG.

3.2.4.2 Subjective assessments of sleep quality

The Groningen Sleep Quality Scale (GSQS) was used to assess subjectively rated sleep quality (Meijman, Thunnissen, and de Vries-Griever 1990). It includes 15 true or false questions and the answers are summed into a single number indicator. The score is from 0 to 14 and the maximum score indicates poor sleep quality the preceding night.

3.2.5 Other measurements

Movements during sleep (using a flex sensor), daytime sleepiness (using the Karolinska Sleepiness Scale), cognitive performance before bed and after waking (using the Attentional Network Test), and health symptoms were measured or rated as indirect indicators of sleep quality.

3.2.5.1 Flex sensor

Movements during sleep were monitored using flex sensors [15]. A flex sensor can be used to measure bending. Its resistance increases when the degree of bending increases. The flat resistance range is from 7000 to 13,000 Ohms, and the 180 pinch bend would be at least twice the flat resistance value (Flex sensor data sheet 2014). We used tape to paste the flex sensor on the back of the pillow and connected it to an OMEGA Om-daqpro-5300 data logger which recorded the voltage every second. The voltage changed as the resistance of the flex sensor changed when the participants moved. We counted the number of movements by calculating the differences of the data from the next second to the previous one, and the participants were considered to move if the differences were larger than ± 0.001 Volt, which was not exceeded when the participants remained still. The number of movements per hour was also calculated and defined as the movement index.

3.2.5.2 Karolinska sleepiness scale (KSS)

The Karolinska Sleepiness Scale (KSS) is a tool for evaluating subjective sleepiness. The KSS has been shown to be closely related to EEG alpha and theta power [150]. The score of the KSS was positively linked to alpha and theta power in the condition with eyes open and negatively linked to alpha power in the condition with eyes closed [150]. Sleepiness is evaluated by a 9-point scale from 1 (extremely alert) to 9 (extremely sleepy). The KSS was used immediately after the subjects left the bed and at 9:30, 12:00, 14:30, and 17:00 the day following the test night, in order to monitor the daytime sleepiness of the participants [151].

3.2.5.3 Attentional network task (ANT)

Attention is a major cognitive function [152] that is commonly connected to feeling of being sleepy or rested. The Attention Network Theory was proposed by Posner and Petersen [153] as an effective method to measure attention. They stated that there are at least three types of attention networks: alerting, orienting and executive. The aim of the alerting network is achieving and maintaining an internal state while the incoming stimuli are prepared to be perceived. The orienting network is for selecting information and shifting the attentional focus from one area or object to another using sensory input in the visual field. The executive network aims to monitor and solve conflict-related tasks computed in different neural areas [154].

The Attentional Network Task (ANT) is a method to that can be used to test the attentional networks that were mentioned above [155]; it was used in the present study as a cognitive performance test. The online ANT from Science Of Behavior Change was applied [156]. The test lasts 17min including three experimental blocks of 5min each with a break between two blocks, and a 2-min practice block before the experimental blocks. Each experimental block includes 144 trials, 4 cue conditions (no cue, centre cue, double cue or spatial cue), 2 central arrow directions (left- or right-pointing), 3 flanker conditions (neutral, congruent or incongruent), 2 target locations (upper or lower part of the screen), and 3 repetitions. These trials were randomly presented.

A cue is to alert the participants to the possible location of an array of 5 arrows, which consist of a middle arrow and flanker arrows that are either congruent, incongruent or neutral. Congruent means the other 4 arrows are in the same directions as the middle one, incongruent means opposite directions, and neutral means the 4 lines have no arrowheads. Participants were asked to press the arrow key corresponding to the direction of the middle arrow as quickly and correctly as possible. Middle arrows were always left or right. Reaction time (RT, ms) and error rate (ER, %) were recorded in an Excel document at the end of the test. The ANT was used to test the participants' cognitive performance the evening before their exposure and the morning after. The same laptops were used for the two phases when performing the ANT.

The median RT was calculated from the correct trials for each participant. The effect of the alerting cue was calculated by subtracting the median RT of the double cue conditions from the median RT of the no cue conditions [155, 156]. Those two cue conditions would not provide information about the location where the arrow array would appear, which led to diffused attention. The effect of the orienting was calculated by subtracting the median RT of the spatial cue conditions from the median RT of the centre cue conditions. The spatial cue could encourage people's attention to one place where the arrow array would appear, while the centre cue was regarded as a control. The effect of executive control was calculated by subtracting the median RT of congruent flanker conditions from the median RT of incongruent flanker conditions. Usually, the RT of the incongruent flanker condition, which is the most complex condition, is longer than the other flanker conditions. There were only small differences between the congruent and neutral flanker conditions [155]. More details regarding ANT can be found in [155].

3.2.5.4 Health symptoms

In addition to the GSQS and the KSS, 12 SBS symptoms were rated in the morning using a Likert rating scale (10 points) of equal distance from severe to no symptoms (Table 3. 3), which indicated their intensity [16], the 8 other points on each scale being unlabelled.

The morning questionnaire included questions about indoor environmental parameters, health symptoms, the Groningen Sleep Quality Scale (GSQS), and the Karolinska Sleepiness Scale (KSS).

Table 3. 3 A Likert rating scale (10 points) for the self-assessed sleep environment.

Items	Left scale endpoints	Right scale endpoints
Nose blocked	Nose blocked	Nose clear
Nasal dryness	Nose dry	Nose running
Thirst	Very thirsty	Not thirsty at all
Mouth dryness	Mouth dry	Mouth not dry
Lips dryness	Lips dry	Lips not dry
Eye dryness	Eyes dry	Eyes not dry
Eye clearness	Eyes gummed up	Eye clear
Skin dryness	Skin dry	Skin not dry
Headache	Severe headache	No headache
Rested	Tired out	Well rested
Mental state	Uptight, irritated	Relaxed, content
Well-being	Bad	Good

3.2.5.5 Logbooks

The participants were asked to record their bedtime and rising time on the logbooks, to which the analysis start time and stop time of PSG were adjusted. They also recorded how many times and why they woke up during the night.

3.2.5.6 Evening questionnaire

Because mood [157] and stress [158] influence sleep quality, the abbreviated Profile of Mood States (POMS) and the Perceived Stress Scale (PSS) were used to assess them. The two parts were combined in the evening questionnaire. The POMS questionnaire contains 40 items where five negative subscales and two positive subscales including anger, fatigue, depression, confusion, esteem-related affect, and vigour [159]. Total Mood Disturbance (TMD) is calculated by summing the totals for the negative subscales and then subtracting the totals for the positive subscales. The higher the score of TMD, the worse the mood. The PSS contains 10 questions to assess the stress experienced during the last month. Scores ranging from 0–13, 14–26, and 27–40 respectively indicate low, moderate, and high perceived stress [160].

The morning and evening questionnaires were filled out on the test days of sleep.

3.3 Statistical analyses

SPSS 25.0 (SPSS Ltd., USA) was used in all statistical analyses. The Kolmogorov-Smirnov test and the Shapiro-Wilk test were used to assess whether the data were normally distributed. The independent sample t-test and the Mann- Whitney U test were used to examine the difference in environmental variables depending on whether the data were normally or non-normally distributed. The paired-samples t-test and the non-parametric Wilcoxon matched-pairs signed-ranks test were used to examine other outcomes. Intraclass correlation coefficients (ICC), a widely-used measure of agreement for continuous variables [161], were calculated for the sleep parameters from both the sleep tracker and PSG to examine whether their indications agree.

All analyses were considered statistically significant when the *p*-value was less than 0.05 (2-tailed). The null hypothesis was that there is no difference between two window states for the parameters defining the bedroom environment or the parameters defining sleep quality.

3.4 Results

Twenty-seven participants, of which thirteen were females, completed all experiments. Two participants had a BMI below 18.5 and four above 25. Their PSQI scores were less than or equal to 5. The detailed information about the subjects is shown in Annex 3A Table A3. 1.

3.4.1 Environmental parameters

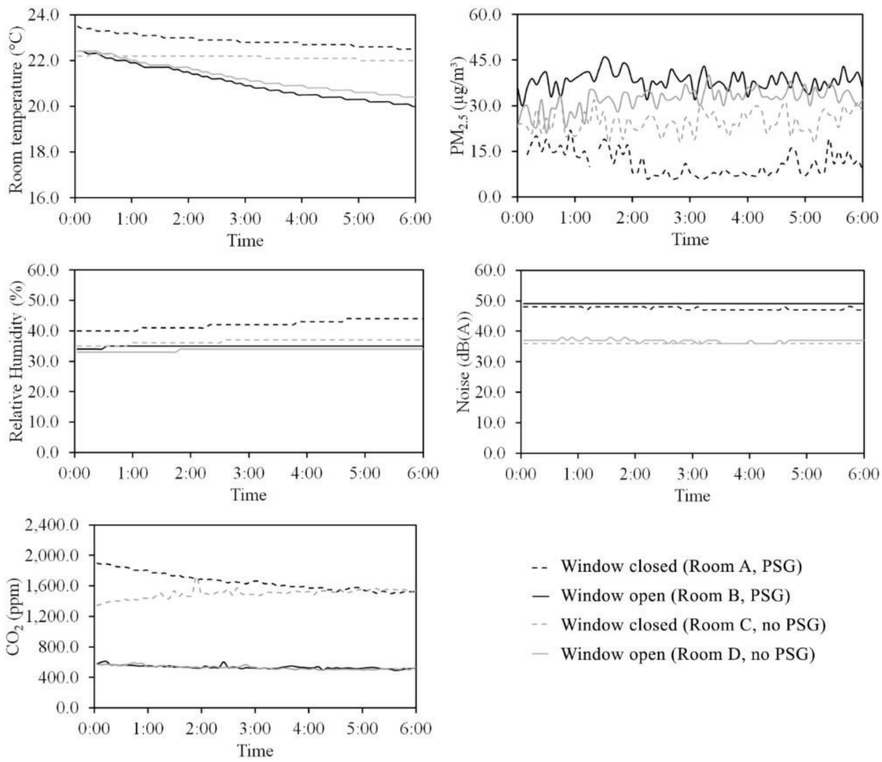

Figure 3. 8 Room temperature, relative humidity, CO_2, $PM_{2.5}$, and noise from 0:00 to 6:00 during a typical night (Rooms A and C with windows closed; Rooms B and D with windows open; In rooms A and B PSG was used; in rooms C and D PSG was not used).

Figure 3. 8 shows the measured room temperature, RH, CO_2, $PM_{2.5}$, and noise from 0:00 to 6:00 during a typical night. The indoor environmental parameters were different in all four rooms at the onset of sleep. Temperatures in the rooms with windows open decreased from 0:00 to 6:00 compared with the rooms with windows closed. RH increased gradually from 0:00 to 6:00. CO_2 levels remained stable at about 600 ppm in rooms with windows open and at about 1,600 ppm in rooms with windows closed in the latter part of the night. However, the CO_2 levels of the two rooms with windows closed showed different trends – the levels in the rooms where subjects did not wear PSG increased whereas they decreased in the rooms where the PSG was used. Usually, there were two persons present (the participant and the researcher) in the rooms where the participants wore PSG for more than one hour before the participants' bedtime, mainly setting up PSG. Thus, the CO_2 level at the onset of sleep was higher in the rooms where participants wore the PSG but only when windows were closed. $PM_{2.5}$ levels fluctuated during the night but in general the levels were higher in the rooms with windows open. The difference in noise levels between the rooms where PSG was used and not used was due to the presence of an aspirated and thus noisy sensor box in each room where PSG was used. It was used to monitor temperature, RH, CO_2, and $PM_{2.5}$ to compare with the data monitored by the other air monitors listed in Table 1, but the data from the noisy sensor boxes were lost. There were no noisy sensor boxes in the rooms where PSG was not used because only two boxes were available.

Figure 3. 9 shows the box plots of night-average room temperature, relative humidity (RH), CO_2, $PM_{2.5}$, and noise when windows were open or closed, in no PSG or PSG rooms. The night-average parameters were calculated from the data between bedtime and rising time (room temperature, RH, CO_2, and noise in the following text express night-averaged parameters). All the parameters shown in Figure 3. 9 were significantly different between the two window states ($p<0.05$). The median room temperature with windows closed was 1.5 °C higher and the RH was 5% higher. Absolute humidity (AH) was calculated to be 8.7 with windows closed and 7.0 g/m3 with windows open (Annex 3A Table A3. 2). The median CO_2 levels with windows closed were ca. 2.6 times higher than they were with windows open. The median $PM_{2.5}$ was significantly higher in the rooms with windows open ($p<0.05$). It is worth noting that although objectively measured average noise levels were unaffected by opening a window, the median level was significantly lower. Taken together, this indicates that occasional loud noises must have occurred outdoors. The median noise levels were 12 dB(A) higher in the PSG rooms than those in the no PSG rooms. The specific values of the environmental parameters are listed in Annex 3A Table A3. 2. The median bed temperature and RH during the nights were respectively 33.2 °C (interquartile range: 32.2–33.9 °C) and 38.1% (34.5–45.7%) during sleep and did not differ significantly between the two window states (Annex 3A Table A3. 2).

Annex 3A Table A3. 3 compares the sleep parameters measured during the first (adaption) and the second (experiment) nights. No significant differences were observed and therefore the sleep parameters from the adaptation nights were included in the following analyses.

As the indoor environmental parameters in the no-PSG rooms and in the PSG rooms were different, we also compared all the parameters between the two window states in these rooms separately. Table 3. 4 shows the medians with interquartile ranges (IQR) of the parameters from the morning questionnaire, daytime sleepiness, and evening questionnaire for the groups with and without PSG and for all participants, under conditions with windows open and closed. The participants reported lower room temperature, fresher air, higher GSQS scores (poorer sleep quality) and higher noise levels with windows open, and they felt less rested and were in a worse mental state, indicating perhaps that they had been more often disturbed by external noises or by drafts. The average outdoor temperature was 11 °C (min. – max., 6.3 - 15.9 °C) [145]. They experienced higher levels of mouth dryness and better wellbeing with windows closed, the effect being close to significant (p-value < 0.10). The participants from the group using PSG rated higher well-being and lower KSS scores and their eyes were less "gummed up" with windows open, the effect being close to significant (p-value < 0.10). Although some results that were significant for all participants did not show significance in both non-PSG and PSG groups separately because of not enough samples, the differences were in the same direction.

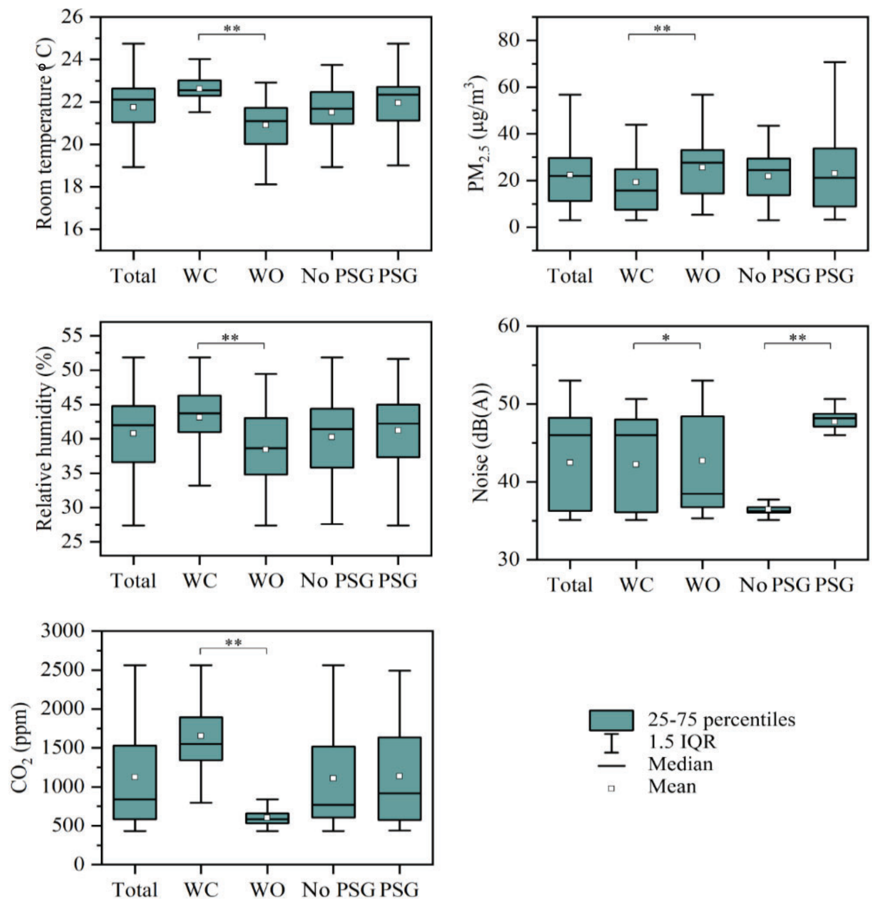

*Figure 3. 9 Box plots of night-average room temperature, relative humidity, CO_2, $PM_{2.5}$, and noise. The total represents all experimental nights; WC, windows closed, represents the nights with windows closed; and WO, windows open, represents the nights with windows open; no PSG represents the rooms where the participants did not wear PSG; PSG represents the rooms where the participants wear PSG. IQR, interquartile range. *, p-value < 0.05; **, p-value < 0.01.*

Table 3. 4 Medians (interquartile range, IQR) of the parameters from the morning questionnaire, daytime sleepiness, and evening questionnaire for both the groups that used PSG and did not used and for all participants, under conditions with windows open and closed.

Items	N	Median (IQR)					
		All		No PSG		PSG	
		WO	WC	WO	WC	WO	WC
Morning questionnaire							
Room temperature (cold (1)–warm (10))	27	5.0 (4.0 – 6.0)	5.0 (5.0 – 6.0)*	5.0 (4.0 – 6.0)	5.0 (5.0 – 6.0)	5.0 (4.0 – 6.0)	5.0 (5.0 – 5.3)
Bed temperature (cold (1)–warm (10))	27	5.0 (5.0 – 7.0)	6.0 (5.0 – 6.0)	5.0 (5.0 – 7.0)	6.0 (5.0 – 6.5)	5.5 (5.0 – 7.0)	6.0 (5.0 – 6.0)
Air humidity (dry (1)–humid (10))	27	5.0 (5.0 – 5.0)	5.0 (4.0 – 5.0)	5.0 (4.5 – 5.0)	5.0 (4.5 – 5.0)	5.0 (4.8 – 5.0)	5.0 (4.0 – 5.0)
Air freshness (stuffy (1)–fresh air (10))	27	7.0 (5.0 – 8.0)	5.0 (4.0 – 7.0)**	7.0 (5.5 – 8.0)	5.0 (4.0 – 6.5)*	7.5 (5.0 – 9.0)	5.0 (3.8 – 7.0)**
Noise (quiet (1)–noisy (10))	27	6.0 (4.0 – 8.0)	3.0 (1.0 – 6.0)**	6.0 (5.5 – 8.0)	2.0 (1.0 – 3.0)**	6.5 (3.5 – 8.0)	5.0 (2.8 – 6.3)
Odour intensity (strong (1)–no odour (10))	27	9.0 (7.0 – 10.0)	9.0 (6.0 – 10.0)	9.0 (8.0 – 10.0)	9.0 (8.0 – 10.0)	8.0 (5.0 – 10.0)	8.5 (4.0 – 9.3)
Nose blocked (blocked (1)–clear (10))	27	6.0 (4.0 – 10.0)	8.0 (3.0 – 9.0)	6.0 (4.0 – 10.0)	9.0 (3.5 – 9.5)	6.5 (4.0 – 9.3)	6.5 (3.0 – 9.0)
Nasal dryness (dry (1)–running (10))	27	5.0 (3.0 – 6.0)	5.0 (2.0 – 6.0)	5.0 (3.5 – 6.0)	5.0 (1.5 – 5.5)	5.0 (2.8 – 7.0)	4.5 (3.0 – 6.3)
Thirst (very thirsty (1)–not thirsty (10))	27	4.0 (3.0 – 7.0)	4.0 (3.0 – 7.0)	4.0 (3.0 – 7.5)	4.0 (3.0 – 7.5)	3.5 (2.8 – 7.3)	4.0 (2.8 – 5.8)
Mouth dryness (dry (1)– not dry (10))	27	5.0 (3.0 – 8.0)	3.0 (3.0 – 8.0)#	6.0 (3.0 – 8.0)	4.0 (2.0 – 8.5)#	3.5 (2.8 – 8.0)	3.0 (3.0 – 6.5)
Lips dryness (dry (1)–not dry (10))	27	4.0 (3.0 – 7.0)	4.0 (3.0 – 8.0)	5.0 (3.0 – 6.5)	4.0 (3.0 – 8.5)	4.0 (2.8 – 8.0)	4.0 (3.0 – 5.8)
Eye dryness (dry (1)–not dry (10))	27	5.0 (4.0 – 8.0)	5.0 (4.0 – 9.0)	4.0 (4.0 – 7.5)	7.0 (4.0 – 9.0)	5.5 (4.0 – 8.3)	5.0 (3.0 – 8.5)
Eye clearness (gummed up (1)–clear (10))	27	8.0 (5.0 – 9.0)	7.0 (4.0 – 9.0)	7.0 (3.0 – 9.0)	8.0 (4.0 – 9.0)	8.5 (5.0 – 9.3)	5.5 (3.8 – 9.0)#
Skin dryness (dry (1)–not dry (10))	27	6.0 (4.0 – 9.0)	5.0 (4.0 – 9.0)	5.0 (4.0 – 6.0)	5.0 (3.5 – 8.5)	9.0 (5.0 – 9.3)	6.5 (4.0 – 9.3)
Headache (severe (1)–no headache (10))	27	10.0 (7.0 – 10.0)	9.0 (9.0 – 10.0)	10.0 (8.5 – 10.0)	9.0 (7.0 – 10.0)	10.0 (6.5 – 10.0)	9.5 (8.8 – 10.0)
Rested (tired out (1)–well rested (10))	27	7.0 (5.0 – 9.0)	8.0 (7.0 – 9.0)**	8.0 (5.5 – 9.0)	9.0 (6.5 – 9.0)	6.5 (4.0 – 8.3)	8.0 (7.8 – 8.3)*
Mental state (uptight (1)–relaxed (10))	27	7.0 (5.0 – 8.0)	8.0 (7.0 – 9.0)*	7.0 (7.0 – 9.0)	7.0 (6.5 – 9.5)	6.0 (4.0 – 8.0)	8.5 (7.0 – 9.0)**
Well-being (bad (1)–good (10))	27	8.0 (7.0 – 9.0)	9.0 (8.0 – 9.0)#	8.0 (7.0 – 10.0)	9.0 (8.0 – 9.5)	7.0 (6.3 – 8.3)	9.0 (7.8 – 9.0)*
GSQS (good (0)–bad sleep quality (14))	27	2.0 (0.0 – 4.0)	1.0 (1.0 – 1.0)**	2.0 (0.0 – 3.0)	1.0 (1.0 – 1.5)	2.0 (0.8 – 7.0)	1.0 (0.0 – 1.3)*

Table 3. 4 to be continued.

Items	N	Median (IQR)					
		All		No PSG		PSG	
		WO	WC	WO	WC	WO	WC
KSS (alert (1)–sleepy (9))	27	5.0 (3.0 – 7.0)	5.0 (3.0 – 6.0)	5.0 (3.0 – 6.5)	5.0 (3.0 – 6.0)	5.0 (3.0 – 7.0)	4.5 (3.0 – 6.0)
Woke up times	27	1.0 (0.0 – 2.0)	1.0 (0.0 – 2.0)	1.0 (0.0 – 2.5)	1.0 (0.5 – 1.0)	1.5 (0.0 – 2.5)	1.5 (0.0 – 2.3)
Evening questionnaire							
Mood (good (56)– bad mood (216))	27	91.0 (85.0 – 109.0)	89.0 (84.0 – 103.0)	91.0 (87.0 – 110.5)	92.0 (84.0 – 104.0)	90.5 (83.8 – 100.0)	86.5 (83.0 – 100.0)
Stress (low (0)– high stress (40))	27	15.0 (11.0 – 20.0)	14.0 (11.0 – 20.0)	18.0 (12.0 – 23.0)	15.0 (12.0 – 22.5)	15.0 (9.8 – 16.5)	13.0 (10.5 – 18.0)
Daytime sleepiness							
KSS, 9:00 a.m. (alert (1)–sleepy (9))	27	3.0 (3.0 – 5.0)	3.0 (2.0 – 5.0)	4.0 (3.0 – 4.5)	4.0 (2.0 – 5.0)	3.0 (2.0 – 5.0)	3.0 (2.0 – 5.0)
KSS, 12:00 a.m. (alert (1)–sleepy (9))	27	3.0 (2.0 – 4.0)	3.0 (2.0 – 5.0)	3.0 (2.0 – 5.0)	4.0 (2.5 – 5.0)	3.5 (2.0 – 4.3)	2.5 (1.8 – 5.0)
KSS, 14:30 p.m. (alert (1)–sleepy (9))	26	4.0 (3.0 – 6.0)	3.0 (2.8 – 5.3)	3.0 (3.0 – 5.0)	3.5 (3.0 – 5.8)	4.0 (3.0 – 6.3)	3.0 (2.0 – 5.3)*
KSS, 17:00 p.m. (alert (1)–sleepy (9))	27	3.0 (3.0 – 4.0)	3.0 (3.0 – 4.0)	4.0 (3.0 – 5.0)	4.0 (3.0 – 5.0)	3.0 (2.0 – 4.0)	3.0 (2.0 – 4.0)

GSQS, Groningen sleep quality scale; KSS, Karolinska sleepiness scale. WO, windows open; WC, windows closed.
Bold indicates significant results. * p-value < 0.05, ** p-value < 0.01, # p-value < 0.1.

3.4.2 Attentional network task (ANT)

Table 3. 5 shows the reaction time (RT) and error rates (ERs) of the attentional network task (ANT) the next morning and recovery from the preceding night to the next morning. In the congruent condition, the participants tended to have a shorter RT when sleeping with windows open compared to sleeping with windows closed (p-value < 0.06). However, they made significantly more errors in the double cue condition when sleeping with windows open compared to sleeping with windows closed. In the neutral condition, their RT after sleep was significantly shorter with windows closed than with windows open. No differences between the two window states were found for the alerting, orienting or executive functions. Thus in general, no consistent effects of sleeping with different window status on the results obtained with the ANT test could be shown.

3.4.3 Sleep and other parameters

Table 3. 6 shows the means (medians) of the sleep parameters from PSG and sleep tracker for the groups with and without PSG and for all participants, under conditions with windows open and closed. The participants with PSG snored more (p-value < 0.02) and woke up more often (p-

value < 0.02) with windows closed although they tended to have a shorter sleep latency (*p*-value < 0.10), i.e. they tended to fall asleep more quickly.

Table 3. 5 Medians (interquartile range, IQR) of the reaction time and error rates of the attentional network task on the next-day morning and recovery from the preceding night to the next morning.

Items	The next morning (n=26)				Recovery from the preceding night to the next morning (night minus morning) (n=22)			
	Reaction time (ms)		Error rate (%)		Reaction time difference (ms)		Error rate difference (%)	
	WO	WC	WO	WC	WO	WC	WO	WC
Four cue and three flanker conditions								
No cue	629.8 (611.3 – 751.1)	648.5 (621.9 – 702.6)	0 (0 – 2.8)	0 (0 – 2.8)	-15.5 (-49 – 7.5)	0.8 (-18.6 – 55)	0 (0 – 2.8)	0 (0 – 2.8)
Centre cue	593.5 (569.4 – 675.1)	625.0 (569.4 – 671.8)	0 (0 – 0.7)	0 (0 – 2.8)	-5.3 (-34.1 – 21.0)	4 (-12.8 – 31.5)	0 (0 – 0)	0 (0 – 2.8)
Double cue	605.3 (572.8 – 649.8)	615.3 (588.0 – 639.9)	0 (0 – 2.8)	0 (0 – 0)*	9.0 (-36.6 – 32.6)	14 (-16.1 – 34.5)	0 (-0.7 – 2.8)	0 (0 – 0)
Spatial cue	548.3 (462.3 – 580.0)	532.5 (496.8 – 598.3)	0 (0 – 0)	0 (0 – 0)	11.5 (-10.8 – 39.0)	19.3 (-16.9 – 37.5)	0 (0 – 0.7)	0 (0 – 0)
Congruent	584.8 (538.4 – 635.5)	590.3 (558.8 – 643.5)#	0 (0 – 0)	0 (0 – 0)	0.8 (-25.6 – 16.9)	-4.8 (-23.9 – 15.9)	0 (0 – 0.1)	0 (0 – 0)
Incongruent	620.8 (596.9 – 731.3)	644.8 (614.4 – 698.6)	1.1 (0 – 2.1)	0 (0 – 4.2)	11.3 (-36.8 – 44.5)	14.5 (-13.9 – 43)	0 (-2.1 – 2.6)	0 (0 – 2.1)
Neutral	574.5 (561.8 – 636.3)	578.0 (556.6 – 625.1)	0 (0 – 0.5)	0 (0 – 0)	-17.8 (-44.3 – 16.5)	10.5 (-9.6 – 34.5)*	0 (0 – 2.1)	0 (0 – 0)
The function of cue or flanker conditions								
Alerting [a]	46.0 (18.0 – 81.5)	33.0 (22.1 – 71.8)	-	-	-12.5 (-54.9 – 25.6)	1.0 (-34.3 – 40.0)	-	-
Orienting [b]	66.5 (50.0 – 121.1)	85.8 (64.3 – 102.6)	-	-	-19.8 (-51.6 – 24.1)	-11.8 (-18.6 – 15.9)	-	-
Executive [c]	57.8 (32.9 – 76.8)	52.5 (31.9 – 70.9)	-	-	15.0 (-30.4 – 31.8)	23.0 (-12.1 – 40.6)	-	-

[a] Alerting, the effect of an alerting cue on response time; [b] Orienting, orienting effect; [c] executive, executive function effect.
WO, the window open; WC, the window closed.
Bold indicates significant results. * *p*-value < 0.05, # *p*-value < 0.1.

The participants recorded the reason they thought they had woken up during the night (Table 3. 7). The reason is listed according to the rank of reported times. Waking up naturally or no reason was reported 16 times, a too warm bed nine times, annoyance caused by the PSG cable eight times, noise six times, a dream or nightmare six times, a bathroom visit three times, turning around three times; other reasons were blamed once or twice including bad position, pain in the stomach, thirsty, or felt nervous and uneasy. The reason for the other 14 was not mentioned. Only during a total of 18 nights, ten nights with windows open and eight nights closed, out of 54 nights was no waking up recorded. The major reason that caused the difference of the self-reported wake up times was noise and a too warm bed – both of them had five more wake up times with windows open compared to them with windows closed. From the perspective of the number of wake up nights, noise was the major reason for waking up when sleeping with windows open. These subjective responses indicate that noise was the major reason but not the only reason for waking up at night.

Table 3. 8 shows the Intraclass Correlation Coefficients (ICC) of the sleep parameters from the sleep tracker and PSG. The ICC indicated significant agreement between the sleep tracker and the PSG values for sleep start time, sleep end time, TST, TIB (analysis duration), light sleep (N1+N2) and sleep latency. ICC values of less than 0.5, 0.50-0.75, 0.75-0.90, and above 0.90 indicate poor, moderate, good, and excellent agreements, respectively [162]. Sleep start time was in excellent agreement; sleep end time, TST, and TIB (analysis duration) were in good agreement; and light (N1+N2) sleep and sleep latency were in moderate agreement. Sleep efficiency tended to be in poor agreement (*p*-value < 0.10). Time awake, time REM, time deep (N3), REM in percent, light sleep (N1+N2) in percent and deep sleep (N3) in percent were not in significant agreement. The number of awakenings from the sleep tracker and the number of arousal awakenings from PSG were not comparable because their definitions were different - the number of awakenings recorded by the Fitbit tracker was defined as interruptions of sleep lasting more than 30 seconds, whereas the number of arousal awakenings recorded by PSG was defined as interruptions of sleep lasting 15-30 seconds.

Table 3. 6 Medians (interquartile range, IQR) of the sleep parameters from PSG and sleep tracker for the groups with and without PSG and for all participants, under conditions with windows open and closed.

Items	N	Median (IQR)		Median (IQR) (non-PSG)		Median (IQR) (PSG)	
		WO	WC	WO	WC	WO	WC
Sleep parameters from the sleep tracker							
Sleep latency (min)	18	9.0 (4.8 – 13.5)	8.0 (3.3 – 11.0)	9.0 (3.9 – 15.5)	10.0 (6.1 – 11.0)	10.0 (4.8 – 13.0)	4.0 (1.8 – 7.8)[#]
Asleep (min)	18	423.0 (361.0 – 454.5)	433.5 (400.3 – 463.3)	423.5 (355.5 – 454.5)	424.5 (400.3 – 472.5)	422.0 (413.3 – 461.8)	444.5 (395.5 – 458.5)
Awake (min)	18	49.0 (40.0 – 60.0)	53.5 (46.3 – 68.8)	52.0 (41.5 – 60.0)	54.5 (49.3 – 75.0)	47.0 (38.0 – 58.3)	52.0 (41.0 – 64.0)
Number of awakenings	18	24.0 (20.8 – 31.8)	28.5 (24.8 – 31.3)	25.5 (23.8 – 37.5)	29.0 (27.0 – 32.3)	21.5 (17.5 – 23.8)	25.5 (23.5 – 29.0)*
TIB (min)	18	466.0 (420.0 – 507.3)	484.5 (457.3 – 517.3)	472.0 (405.8 – 503.3)	482.0 (457.3 – 524.3)	466.0 (454.8 – 511.0)	492.5 (447.5 – 513)
REM sleep (min)	18	85.5 (66.5 – 108.0)	86 (69.5 – 106.0)	74.5 (52.5 – 90.5)	90.0 (68.3 – 103.0)	103.5 (81.8 – 120.8)	77.5 (68.5 – 115.0)
Light sleep, N1 + N2 (min)	18	258.0 (232.0 – 312.0)	272.5 (235.5 – 324.0)	273.5 (208.3 – 332.8)	279.5 (228.0 – 341.5)	246.5 (235.3 – 278.5)	272.5 (237.3 – 313.5)
Deep sleep, N3 (min)	18	64.0 (51.3 – 78.5)	59.0 (46.0 – 84.3)	65.5 (42.3 – 78.5)	57.5 (44.3 – 86.8)	62.0 (57.0 – 95.0)	60.0 (47.5 – 82.3)
Sleep efficiency (%)	18	90.3 (85.6 – 91.3)	89.2 (86.7 – 90.2)	90.0 (85.6 – 91.3)	88.6 (86.0 – 90.2)	90.5 (86.1 – 92.4)	89.4 (87.0 – 90.8)
Awake (%)	18	9.7 (8.7 – 14.4)	10.8 (9.8 – 13.3)	10.0 (8.7 – 14.4)	11.4 (9.8 – 14.0)	9.5 (7.6 – 14.0)	10.6 (9.2 – 13.0)

Table 3. 6 to be continued.

Items	N	Median (IQR)		Median (IQR) (non-PSG)		Median (IQR) (PSG)	
		WO	WC	WO	WC	WO	WC
REM sleep (%)	18	18.7 (14.3 – 22.7)	18.6 (14.0 – 22.4)	16.2 (12.7 – 18.9)	18.6 (13.8 – 22.5)	22.3 (17.5 – 23.4)	18.5 (13.4 – 22.6)
Light sleep (%)	18	56.6 (49.7 – 63.1)	56.4 (54.1 – 62.7)	61.8 (49.9 – 64.5)	59.4 (50.0 – 67.4)	54.6 (48.9 – 57.8)	56.3 (54.8 – 62.1)
Deep sleep (%)	18	14.0 (10.5 – 17.0)	12.2 (9.9 – 16.1)	15.6 (9.3 – 17.0)	11.2 (9.3 – 16.7)	13.5 (11.3 – 19.0)	13.3 (10.4 – 16.6)
Sleep parameters from PSG							
TST (min)	15	-	-	-	-	431.5 (387.3 – 453.0)	446 (378.7 – 477.0)
Analysis duration (min)	15	-	-	-	-	453.6 (430.2 – 495.7)	482.2 (420.6 – 502.2)
Sleep latency (min)	15	-	-	-	-	7.7 (3.9 – 26.9)	7.0 (4.4 – 17.2)
WASO (min)	15	-	-	-	-	18.4 (10.0 – 29.0)	15.9 (11.3 – 29.8)
Sleep efficiency (%)	15	-	-	-	-	93.4 (88.9 – 96.6)	95.2 (90.0 – 96.5)
N1 (min)	15	-	-	-	-	7.0 (3.0 – 11.0)	7.0 (4.5 – 14.0)
N2 (min)	15	-	-	-	-	244.0 (180.5 – 275.0)	236.0 (213.0 – 294.0)
N1 + N2 (min)	15	-	-	-	-	250.5 (194.0 – 290.0)	249.5 (229 – 298.5)
N3 (min)	15	-	-	-	-	84.0 (68.5 – 94.5)	84.5 (73.0 – 103.0)
REM (min)	15	-	-	-	-	99.5 (77.5 – 109.3)	91.0 (51.0 – 114.0)
Wake (min)	15	-	-	-	-	30.1 (15.9 – 54.5)	23.5 (17.2 – 42.0)
N1 (%)	15	-	-	-	-	1.5 (0.7 – 2.4)	1.7 (0.9 – 2.9)
N2 (%)	15	-	-	-	-	51.9 (43.3 – 57.3)	52.5 (47.1 – 58.6)
N1 + N2 (%)	15	-	-	-	-	53.8 (44.0 – 58.8)	54.1 (49.9 – 62.7)
N3 (%)	15	-	-	-	-	18.8 (13.0 – 23.7)	19.8 (14.7 – 21.7)
REM (%)	15	-	-	-	-	20.5 (14.5 – 23.3)	17.9 (13.1 – 23.0)
Wake (%)	15	-	-	-	-	6.6 (3.4 – 11.1)	4.8 (3.5 – 10.0)
AI (times/h)	15	-	-	-	-	10.1 (4.6 – 12.0)	7.3 (6.0 – 9.5)
Number of arousals	15	-	-	-	-	75.0 (27.0 – 88.0)	55.0 (42.0 – 61.0)

Table 3. 6 to be continued.

Items	N	Median (IQR)		Median (IQR) (non-PSG)		Median (IQR) (PSG)	
		WO	WC	WO	WC	WO	WC
Number of awakenings	15	-	-	-	-	16.0 (11.0 – 40.0)	14.0 (9.0 – 25.0)
Snore percentage (%)	10	-	-	-	-	3.0 (0.4 – 9.1)	5.9 (0.4 – 16.9)*
ODI (/h)	11	-	-	-	-	2.8 (1.4 – 3.6)	1.7 (1.0 – 7.3)
Flex sensor							
Movement (times)	28	811.5 (519.3 – 1080.8)	753.0 (506.8 – 1205.3)	798.0 (442.0 – 881.0)	740.0 (361.0 – 1005.0)	822.0 (527.5 – 1269.0)	766.0 (558.0 – 1368.0)
Movement index (times/h)	28	101.2 (60.3 – 131.2)	98.1 (58.6 – 134.9)	97.6 (55.1 – 110.1)	103.3 (45.1 – 106.9)	104.8 (70.1 – 157.0)	92.9 (62.6 – 139.8)

PSG, polysomnography; TST, total sleep time; WASO, wake after sleep onset; AI, arousal index; ODI, oxygen desaturation index; TIB, time in bed. WO, windows open; WC, windows closed.
Bold indicates significant results. * p-value < 0.05, # p-value < 0.1.

Table 3. 7 The reason and its reported times for self-reported woke up and the number of woke up nights in total, under two window states, and the different times from windows open to closed.

Items	Woke up times				The number of woke up nights			
	In total	WO	WC	WO-WC	In total	WO	WC	WO-WC
Reason for waking up								
Wake up naturally or no reason	16	7	9	-2	6	2	4	-2
Not mentioned	14	8	6	2	8	3	5	-2
A too warm bed	9	7	2	5	4	2	2	0
PSG cable	8	2	6	-4	5	1	4	-3
Noise	7	6	1	5	5	4	1	3
Dream or nightmare	6	3	3	0	4	1	3	-2
Bathroom visit	3	2	1	1	3	2	1	1
Turn around	3	0	3	-3	1	0	1	-1
Pain in the stomach	2	2	0	2	1	1	0	1
Bad position	2	2	0	2	1	1	0	1
Nervous and uneasy	2	2	0	2	1	1	0	1
Thirsty	1	0	1	-1	1	0	1	-1
In total	73	41	32	9	40	18	22	-4

PSG, polysomnography; WO, windows open; WC, windows closed.

Table 3. 8 Intraclass correlation coefficients (ICC) of the sleep parameters from the sleep tracker and PSG (n=22[a]).

Items (from the sleep tracker/PSG)	Median (IQR)		ICC (95% CI)	*p*-value
	The sleep tracker	PSG		
Sleep start time/Analysis start time	23:41 (22:54 – 00:22)	23:44 (22:48 – 00:14)	**0.989 (0.974-0.995)**	**< 0.001**
Sleep end time/Analysis stop time	7:31 (6:42 – 8:18)	7:22 (6:42 – 7:45)	**0.866 (0.665-0.945)**	**< 0.001**
Asleep/TST (min)	428.5 (402.0 – 468.0)	441.0 (403.3 – 466.1)	**0.858 (0.663-0.940)**	**< 0.001**
Awake/Wake (min)	47.0 (40.5 – 57.8)	26.2 (14.4 – 42.7)	0.144 (-0.299-0.530)	0.253
TIB/Analysis duration (min)	484.0 (444.0 – 512.5)	469.0 (437.4 – 497.3)	**0.823 (0.580-0.926)**	**< 0.001**
REM (min)	97.0 (70.8 – 118.5)	100.9 (59.6 – 114.5)	0.042 (-1.398-0.608)	0.463
Light/N1+N2 (min)	259.5 (233.8 – 286.5)	251.8 (228.8 – 298.7)	**0.531 (-0.143-0.806)**	**0.048**
Deep/N3 (min)	63.5 (55.0 – 95.3)	77.5 (63.9 – 91.0)	-0.209 (-1.966-0.502)	0.665
Sleep efficiency (%)	90.2 (87.7 – 91.2)	94.4 (90.0 – 96.8)	*0.327 (-0.242-0.684)*	*0.055*
REM (%)	20.0 (15.2 – 23.0)	21.8 (15.4 – 23.8)	-0.215 (-2.153-0.510)	0.663
Light (%)	56.3 (49.4 – 61.0)	55.2 (50.2 – 60.5)	-0.334 (-2.249-0.449)	0.743
Deep (%)	13.6 (11.3 – 19.6)	16.8 (14.3 – 20.5)	0.230 (-0.755-0.673)	0.270
Sleep latency (min)	7.5 (2.5 – 13.5)	9.3 (4.1 – 26.8)	**0.669 (0.221-0.861)**	**0.007**

[a] 22 pairs of data obtained from 14 people. PSG, polysomnography; TST: total sleep time; TIB: time in bed.

Bold indicates significant results. Italic indicates *p*-value < 0.1.

3.5 Discussion

The effects of window opening on the bedroom environment and on sleep quality were investigated. More awakenings were recorded by the sleep tracker and higher snore percentages were recorded by the PSG when windows were closed and CO_2 concentrations were therefore higher, indicating lower ventilation rates. In previous studies sleep efficiency was lower with higher CO_2 levels [15, 16], and the self-reported sleep quality obtained with the GSQS was better at lower CO_2 concentrations [15]. No effects on sleep efficiency were found in the present experiment and the GSQS score increased with the window open, indicating that self-reported sleep quality was worse when the window was open. On contrary, Zhang, Cao, and Zhu showed that when satisfaction of air quality increased the self-assessed sleep quality satisfaction was higher as well (2018) [38]. The participants were more easily disturbed by episodic external noise events with windows open and this may be why they rated their sleep quality as low on the GSQS in the present study, as discussed below.

The snore percentage was 5.1% higher when windows were closed. An additional analysis was made examining the correlation between snore percentage, personal characteristics, and indoor environmental parameters (Annex 3A Table A3. 5). Snore percentage was significantly correlated only with CO_2 (ρ=0.430, *p*-value < 0.016): the higher the CO_2 level, indicating lower ventilation, higher concentrations of other contaminants in the rooms and increase levels of bio-effluents emitted by people, the higher the snore percentage. Snoring is one of the symptoms that indicate sleep-disordered breathing (SDB) [163], but no significant difference in blood oxygenation (as indicated by ODI) was found between the two window states. We did not perform any other measurements that might provide an explanation for increased snoring. One plausible explanation could be an increased end-tidal CO_2 ($ETCO_2$) during reduced ventilation as indicated by increased CO_2 levels. Zhang, Wargocki, and Lian (2017) reported that $ETCO_2$ increased during increased exposure to bio effluents as indicated by CO_2 levels above 600 ppm [164]. An increase in $ETCO_2$ suggests insufficient elimination of CO_2 from the blood, which may affect respiration and result in snoring. Future studies should investigate this possible mechanism and examine other possible reasons for increased snoring caused by poor ventilation.

Although a higher number of awakenings were recorded by the sleep tracker when windows were closed, this was only significant among the participants with PSG, although the tendency was in the same direction for all the participants. Twenty-two to twenty-nine awakenings were recorded by the sleep tracker on average but only from 0 to 5 awakenings were reported by the participants. A similar difference in reported numbers of awakenings was earlier reported by Slightam et al. (2018) [165]. The increased number of awakenings at higher CO_2 when the window was closed confirms the results reported by Mishra et al. (2018) [15], and by Laverge and Janssens (2011) [41]. An additional correlation analysis (Annex 3A Table A3. 5) showed that both higher RH and CO_2 levels were related to an increased number of awakenings as recorded by the sleep tracker. As hypothesized above, reduced ventilation as indicated by increased CO_2 can affect respiration, which could explain increased snoring. The changes in respiration are expected to result in shallow breathing [166]. Shallow breathing [167] and snoring could also affect sleep quality by increasing the number of awakenings during the night. Additionally, the number of awakenings increased at the higher RH levels caused by the reduced ventilation rate indicated by higher CO_2 levels. Previous studies have found that higher temperatures and RH induced more awakenings from temperature/RH of 26/50 to 32/80 [135, 168]. Humid heat during sleep increases the thermal load and increases awakening [169]. However, as the increases in room temperature were only about 1.6 °C higher with windows closed in the present study, and bed temperature was not affected, the difference in room temperature was considered unlikely to affect sleep quality. As the participants were reminded to adjust the thermostat-controlled heater the temperature difference between the two window states must be assumed to have been acceptable. However, more studies are required to examine the association between RH, CO_2, and sleep quality. Another parameter affecting awakening could be $PM_{2.5}$. Chuang et al. (2018) found that exposure to higher $PM_{2.5}$ levels was associated with an increased number of awakenings [170]. Significantly higher $PM_{2.5}$ levels were observed in the present experiment when windows were open (Figure 3. 9), so it may be that increased $PM_{2.5}$ offset the positive effect of reduced CO_2.

In the ANT performance task, the mean ER in the double cue condition was lower, the RT difference from the preceding night to the next morning was longer, but the RT in the congruent condition was longer when sleeping with windows closed compared to sleeping with windows open. No significant RT difference between two window states was found under the condition with neutral flankers the next morning, meaning that the improvement with windows closed was due to worse performance on the experimental night (Table 3. 5). Also, the median ER under the condition of double cue were zero with both windows closed and open, which also means there was no measurable effect of window condition on the majority of the participants - only six out of 27 subjects had higher ER with windows closed. They usually performed the ANT test under the window condition under which they had been sleeping. This means that they might have been more easily interrupted by external noises when the windows were open, as there will have been higher levels of outdoor noise in the morning (especially in the dorm where many people lived), when performing the ANT test. On the other hand, the participants tended to have a shorter RT after sleeping with windows open. This might reflect better sleep quality with windows open, but another possible reason might be that they conducted the ANT test with higher ventilation rates (lower CO_2 levels) because the windows were still open when the test was conducted in the morning. Previous studies reported that the performance of other tasks was improved by higher ventilation rates as indicated by lower CO_2 concentrations [171, 172], so in future studies of the effects of sleep on performance the ANT performance test should be performed under standardized IAQ conditions, such as under the same room temperature and CO_2 levels, to diminish the effects of different IAQ conditions on performance.

Self-rated sleep quality as indicated by GSQS was better but the number of awakenings recorded by the sleep tracker was higher when windows closed for the participants who wore the PSG. Strøm-Tejsen et al. (2016) found the opposite result for GSQS, next-day performance and air quality [16]. The composite answers used to determine the GSQS score in the present study were consequently analysed. They indicated that the main reason for the higher GSQS score was fewer reports of sleeping poorly, less rest, and feeling less well (Annex 3A Table A3. 4). Also, higher GSQS ratings were correlated with a few health symptoms in term of less rested (ρ = -0.541, p-value < 0.01), worse well-being (ρ = -0.342, p-value < 0.02) and mental state (ρ = -0.484, p-value < 0.01). Mental state (ρ = -0.484, p-value < 0.01) was also highly correlated to less rested (ρ = 0.728, p-value < 0.01) and worse well-being (ρ = -0.750, p-value < 0.01). The reasons for higher GSQS scores and a lower number of awakenings with windows open were different. Higher GSQS scores were related to more self-reported waking up and self-rated noise levels, whereas the number of awakenings recorded by the sleep tracker was related to higher levels of CO_2 and RH (Annex 3A Table A3. 5). These findings imply that higher levels of CO_2 (i.e. lower ventilation rates) and RH could induce more short awakenings, which might not be perceived or remembered the next morning. Snoring too is often not perceived or self-reported. What they will have remembered is any longer periods awake and they will then have rated poorer sleep quality on the basis of their self-reported awakenings. Although there was little difference on average in the noise levels recorded by the sensors in the two windows states, the participants reported subjectively higher levels of noise when the windows were open. The reason was such episodic external noise events as people shouting or laughing loudly, as specifically reported by some participants. Such episodic external noise events may have been what offset the beneficial effect of improved air quality on sleep, as they will have caused the participants to report poorer sleep quality. Opening windows to improve indoor air quality is one method of improving sleep quality, but only if other factors such as episodic external noise events are absent. Future studies of open window effects on sleep should ensure that there is no external noise. Previous studies [15, 16, 59] reported better sleep quality with windows open compared to with windows closed, but a direct comparison between study outcomes is not appropriate due to different outdoor experimental conditions, in this case, the noise events, but high levels of outdoor air pollution might also lead to apparently contradictory results.

In previous studies, the average CO_2 level with windows open was 660 ppm [16], which is similar to the levels in this study; also, Mishra et al. (2018) showed CO_2 levels largely below 1,000 ppm when either windows or doors to bedrooms were opened. This suggests that window and door opening is an effective method to improve ventilation in bedrooms. When windows were closed different average levels of CO_2 were reported from under 1,500 ppm [15] to ca. 2,500 ppm [16]. With respect to peak CO_2 concentrations, Laverge and Janssens reported them as high as 3,000-4,500 ppm with windows closed [41, 59]. Such high levels have also been reported in other studies [140]. Fernandez-Aguera et al. (2019) and Stamatelopoulou et al. (2020) reported peak levels in bedrooms exceeding 7,500 and 3,400 ppm, respectively [122, 173]. However, the peak CO_2 level in the present study was only 2,820 ppm. Different building characteristics, in such factors as bedroom floor area, extract ventilation flow and building airtightness, seem likely to be the major reason for the different results obtained in these studies.

Sleep start time, sleep end time, time asleep, TIB, light sleep, and sleep latency as recorded by the sleep tracker showed significant agreement with those parameters as monitored by the PSG. The sleep tracker (Fitbit Charge 2) could reliably differentiate awake from sleep. This conclusion supports those of a review study of 22 publications that examined different Fitbit models in comparison with PSG, actigraphy, home electroencephalogram (EEG), sleep diary, or survey methods [14]. It was expected that the EMG electrodes used for the PSG and attached to the participants' chins could show poor signals during sleep as the participants moved; this could be the case especially for men who still had some beard growth after shaving. A relatively high amplitude of chin EMG usually indicates a waking state [174, 175]. "Stage wake" is characterized by the same rapid eye movement signals as stage REM but also has elevated chin EMG signals, so reliable chin EMG signals are the only way to distinguish stage wake and REM sleep [175]. Hence, the PSG could indicate wake stages at the beginning of the night (sleep latency) but might not be as accurate during sleep if the EMG electrodes started to provide poor signals during sleep due to beard growth. This could lead to the conclusion that REM sleep and sleep efficiency were higher and time awake lower than they actually were. The observed differences between PSG and sleep trackers might be caused by such errors of measurement.

In the present experiments, one night was used for adaptation similarly as by Hu et al. (2010) [176]. No significant differences in the sleep parameters were observed between the first night and the second night. Hasegawa et al. (2013) did not observe the effect of the first night either and concluded that one-night sleep recording would be sufficient in the sleep laboratories [177]. No significant differences in sleep parameters between the first and the second night could be because the participants slept in the same building and the room similar to their own during present experiments; additional rooms in their dorm were adapted to perform present study. Consequently, we decided to use the first night results to increase the power of statistical analyses. Hasegawa et al. also reported that most previous sleep studies in the laboratory used only the first night as adaptation [177]. Hence, we used one night for adaptation as well. Also, the subjects were their own control and we put one-week wash-out period to keep the potential slightly first-night effect almost the same for the two cases.

During the experiments, the windows were kept ajar when opened and they were not fully open to minimize the risk of draught. Although air velocity was not measured, our results did not suggest significant differences in bed temperature, thus we did not expect that air velocity could largely impact the findings. Future studies should consider this measurement and its lack was certainly a limitation. We did expect that the participants were used to sleep with the windows open or at least were aware that windows could be open if needed during the night because they could do it in their rooms as well. Thus, it was not very unusual for them to sleep with window open. However, we did not collect information whether the participants normally sleep with windows open or closed, or how frequent and when they opened the windows. This was another limitation of the present work and in future studies this information should be collected.

A home PSG was used for the first time in a field experiment. However, the ventilation was controlled crudely (by opening the windows) and the participants slept only two nights under each experimental condition. Window opening led to increased awakening due to episodic external noise events and higher noise levels as rated by participants, and to slightly but significantly lower room temperature and RH, although this did not result in a lower bed temperature and bed RH and therefore can be dismissed as confounding factors. Using an inaudible fan would be a better field intervention that improved the IAQ than opening windows [16]. We limited bedroom air quality by the indicator of CO_2 because again, CO_2 is a marker of ventilation and indoor air quality. Other than CO_2, only $PM_{2.5}$ was measured. It would be interesting to include more pollutants in the future, such as volatile organic compounds, which are typical pollutants indoors. The present study recruited only participants who did not report problems with sleep, and they all had PSQI lower than or equal to 5. Future research should investigate whether poor ventilation exacerbates sleep problems for people who already have such problems.

3.6 Conclusions

Higher $PM_{2.5}$ and noise levels were measured with windows open, and higher room temperature, relative humidity (RH), and CO_2 levels with windows closed. Fresher air but higher noise levels, feeling less rested, having worse mental state and well-being, and higher scores on the Groningen sleep quality scale (suggesting worse sleep quality) were reported by the participants while sleeping with windows open. Start sleep time, end sleep time, total sleep time (TST) and time in bed (TIB) measured with the sleep tracker agreed with the measurements made by PSG, light sleep (N1+N2) and sleep latency agreed moderately, while there was no agreement for REM, deep sleep (N3), and the number of awakenings. There were no differences between conditions in terms of objectively measured sleep stages, but the participants snored significantly less and woke up less often, as recorded by the sleep tracker, when sleeping with windows open. There was no clear association between sleep quality and the results obtained with the performance test. The results suggest that poorer bedroom ventilation, as indicated by higher CO_2 levels, gave rise to increased snoring. Additionally, in conditions with higher RH and CO_2 levels, more awakenings were observed. Sleeping with windows open can provide some benefits by increasing ventilation with outdoor air as indicated by lower CO_2 levels, improving indoor air quality, and some parameters defining sleep quality, yet it may also result in some discomfort because of episodic external noise events and the admission of outdoor air pollution. Further studies are required to clarify the role of open windows in achieving good sleep quality. Several points, in addition to the ones mentioned in the discussion, should be considered for future studies. The first window status should be the same as their usual sleep patterns. Starting CO_2 levels for sleeping should be at a similar level for all subjects. Also, the surroundings of the location should be quiet.

4

A SURVEY OF BEDROOM VENTILATION TYPES AND THE SUBJECTIVE SLEEP QUALITY ASSOCIATED WITH THEM IN DANISH HOUSING

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PSQI, Sleep disturbance, Stuffy air, Noise, Thermal comfort, Occupant behaviour

Abstract

We performed a survey of the types of bedroom ventilation in Danish dwellings (January–February 2020) and the associated subjective sleep quality. Five hundred and seventeen people responded. Their median age was 33 years old and 55.4% of them were males. We used an online questionnaire and collected information on the type of bedroom ventilation, bedroom airing behaviour by the respondents, the bedroom environment, building surroundings and location, and sleep disturbance caused by stuffy air, noise, and the thermal environment. Subjective sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI); its median among respondents was >5 indicating reduced sleep quality. 35.4% of the bedrooms had mechanical (balanced mechanical), 24.6% exhaust (unbalanced mechanical), and 40.0% natural ventilation. Sleeping in a bedroom with mechanical ventilation tended to reduce sleep disturbance. The absence of mechanical ventilation and the presence of carpet in the bedroom were all associated with stuffy air causing sleep disturbance, which was the second most sleep-disturbing factor. PSQI increased significantly with increased sleep disturbance. People who reported that their sleep was disturbed by stuffy air or "too warm" conditions opened windows frequently during the day or night, but no association was found between PSQI and bedroom airing behaviours. Our results are valid for the heating season and the survey would have to be repeated in the non-heating season to permit generalization of the findings. The results present associations and are qualitative, so field measurements are necessary to validate the present observations and provide further explanations.

4.1 Introduction

Sleep environment plays an important role in maintaining the good sleep quality that is vital for human health [2, 9]. Light and noise are known to affect sleep quality [178, 179]. An increasing number of studies have also documented the importance of the thermal environment [37, 119, 180, 181] for sleep quality. In addition to these bedroom environmental conditions that have a direct impact on sleep disturbance, other factors such as building characteristics, building surroundings and objects present in bedrooms are likely to be associated with satisfaction with the sleep environment. For example, individuals living in apartments have lower overall satisfaction levels for thermal and acoustic comfort and for ventilation compared to those who live in detached or row houses [182].

Recent studies have found that indoor air quality (IAQ) can also affect sleep quality [15, 16, 32, 60, 183]. IAQ in bedrooms is often quantified in terms of the ventilation rate: the higher the ventilation rate the better the bedroom air quality [146]. Ventilation in bedrooms can be provided by several different types of ventilation systems. In a new review performed by Sekhar et al. (2020) [146], improved air quality in bedrooms, as indicated by lower CO_2 concentration, was associated with the presence of mechanical ventilation. It should however be acknowledged that bedrooms with other systems also in some cases had a low CO_2 concentration suggesting that the air quality was good.

Window opening can improve bedroom ventilation [184-186]. The World Health Organization (WHO) has recommended that bedroom windows should be open during sleep to provide proper ventilation [35]. A few studies have investigated bedroom window opening behaviour [36-39]. Zhang et al. (2016) found that 67% of respondents in China closed bedroom windows at night in winter: these respondents preferred to maintain thermal comfort with bedroom windows closed instead of opening them to maintain good IAQ [39]. Another study reported that nearly half of the respondents aged 45 or older in Norway slept with open bedroom windows over the whole year [36]. Opening or closing windows was the main strategy to adjust thermal comfort. Lee and Shaman (2017) reported that 23.5% of the respondents selected “opening bedroom windows” as their most commonly used strategy for reducing excessive bedroom temperatures in summer in New York City [37]. Zhang et al. (2018) found that respondents from the severely cold climate regions in China preferred to open bedroom windows to control temperature during sleep in summer [38].

A few studies examined the effect of window opening on sleep quality. Strøm-Tejsen et al. (2016) reported that subjects rated the air in their student room to be stuffier when the windows were closed and under this condition, that subjective sleep quality was lower and next-day cognitive performance was worse [16]. Mishra et al. (2018) reported that subjectively rated depth of sleep improved with windows open [15]. Liao et al. (2021) [60] found that open windows reduced snoring during sleep, while Laverge and Janssens (2011) observed a small effect of ventilation achieved by opening windows on the objectively measured sleep pattern [41].

Bedroom ventilation can also be improved by keeping internal doors to the bedroom open during sleep [187-189]. One study reported that the CO_2 concentration decreased by 55% to 64% without reducing thermal comfort when the bedroom door was open during sleep, compared to conditions in which the door was closed [188]. Another recent study showed a clear reduction in CO_2 concentration in a naturally ventilated bedroom when the bedroom door was kept open [189].

In this paper, our main focus was on the type of bedroom ventilation and the associated factors that influence the quality of the bedroom environment and may disturb sleep quality. We were not able to find papers specifically focusing on this topic. The other motivation for the present work was to identify bedrooms in dwellings with different types of ventilation so that they could be used in a planned series of cross-sectional and intervention studies whose purpose was to provide a basis for stipulating the ventilation requirements in bedrooms that will ensure optimal sleep quality. Besides collecting information on bedroom ventilation type, we also collected information on other parameters associated with bedroom ventilation, occupant bedroom airing behaviours, factors disturbing sleep quality and subjectively rated sleep quality, and how they relate to each other. The online survey was performed in the Capital Region of Denmark in January and February 2020 i.e., during the heating season and before the first lockdown was implemented in Denmark on March 11, 2020, in response to the COVID-19 pandemic. Using the data collected, we specifically wanted to answer the following research questions (RQs):

RQ1: Do people whose bedroom is mechanically ventilated report different sleep quality compared with people whose bedrooms are not mechanically ventilated?

RQ2: Do people who regularly air their bedrooms by opening windows during the day or night report different sleep quality compared with people who do not air their bedrooms regularly, and does this depend on the type of bedroom ventilation?

RQ3: Do people who sleep with the bedroom door open report different sleep quality compared with people who do not sleep with the bedroom door open, and does this depend on the type of bedroom ventilation?

As no measurements of CO_2 were made, we used the perception of stuffy air as a marker of poor air quality so that the following question could be answered:

RQ4: Are there differences in reporting of sleep disturbance caused by stuffy air between people whose bedrooms are mechanically ventilated and those whose bedrooms are not?

4.2 Methods

4.2.1 Online questionnaire

The questionnaire was developed by the study team by adapting the questions used in other studies [15, 16] and adding new questions. It included the Pittsburgh Sleep Quality Index (PSQI), a standard method for measuring subjective sleep quality [21]. The final version of the questionnaire was tested on a group of people, and final adjustments were then made. No other validation was made before its deployment. The questionnaire consisted of seven parts and took about 10 min to complete; the full questionnaire is shown in Annex 4A. People could choose to either scan the QR code or send 'sleep' to the official email address shown on the poster. The poster is shown in Annex 4B Figure A4. 1. The respondents provided the answers to the following questions:

1. Background questions on age, gender, height, weight, postal code, and the number of years the respondent had lived in Denmark. Using the postal code, we categorized the location of each respondents' dwellings as urban, suburban, or rural.

2. Questions concerning sleep during weekdays (excluding holidays) including information on whether the respondents slept alone, with bedroom windows or doors open.

3. Questions concerning the environment in the bedroom including building characteristics such as building type, year of building construction, bedroom floor number and floor area, building surroundings, such as highways, active airports, presence in the bedroom of air terminal devices or trickle vents for ventilation, and of objects such as house plants, printers, TV sets or fish tanks.

4. Questions regarding bedroom airing behaviour and particularly whether and when windows and doors were left open.

5. Questions on sleep disturbance caused by the parameters defining indoor environmental quality in bedrooms such as noise, stuffy air, or thermal discomfort (feeling “too warm” or “too cool”).

6. Questions on any other aspects relevant for sleep such as information on chronic diseases, the age of the youngest child at home, pet(s) at home, exercise frequency, use of sleep aids such as essential oils, use of earplugs, and eye masks during sleep, daytime nap-taking behaviour, work/study patterns, especially whether they worked in the evening or on night shift, smoking including e-cigarettes and whether their dwelling was a smoke-free environment.

7. Questions allowing calculation of the Pittsburgh Sleep Quality Index (PSQI) providing information on subjective sleep quality during the past month [21]. The PSQI consists of seven components assessing sleep quality, sleep latency, sleep duration, habitual sleep quality, sleep disturbance, use of sleep medication and daytime dysfunction. The questions used to determine PSQI are shown in Annex 4A.

The questionnaire was posted online. It was advertised on posters placed on the notice boards of universities; the leaflets were delivered directly to the mailboxes of randomly selected dwellings. It was also announced through professional networks and social media on the Internet. The respondents could access the questionnaire by contacting the researchers and then using a link or a QR code they provided. As an incentive, the respondents participated in a lottery for a 30-kroner voucher to a coffee shop.

All questions were answered by choosing one or more of the options that appeared under the question or by typing a short text; the respondents could omit the answer to any question if they felt it was too sensitive or if they did not know the answer. They were not forced to reply to all the questions, i.e., they could advance in the survey without answering all the questions.

The responses on the questionnaire could be made in Danish or English. The first page contained information about the project and a consent form, to comply with the General Data Protection Regulation (GDPR). Permission to perform the survey was obtained from the Technical University of Denmark and archived under DOCX 19/1002413; there was no need for ethical review board (ERB) approval. As required by GDPR, the responses were anonymized and saved on a university server. The respondents could at any time withdraw their consent by contacting the study team.

4.2.2 Statistical analyses

Statistical analyses were performed using SPSS 25.0 (SPSS Ltd., USA) and R Studio (version 1.3.1093, Boston, MA, USA). "stats" package in R Studio was used. All analyses were considered statistically significant when the *p*-value was less than 0.05 (2-tailed); a 2-tailed test was used as the direction of the effects could not be anticipated using previously reported results.

The PSQI of different subgroups of respondents were analysed using the Mann-Whitney *U* test or the Kolmogorov-Smirnov test. The Chi-square test or Fisher's exact test was used to test differences in sleep disturbance caused by indoor environmental quality (IEQ) in the bedroom based on personal characteristics, bedroom airing behaviour, and bedroom environment. Spearman's correlation coefficients were used to analyse the correlations between PSQI and disturbance to sleep caused by bedroom IEQ and any additional factors. Significant factors related to PSQI or sleep disturbances caused by bedroom IEQ were included in the subsequent models while other factors were added as adjustments. Generalized linear models were used to test the associations between PSQI and sleep disturbances caused by bedroom IEQ and bedroom environment because the distribution of PSQI was close to a Poisson distribution based on the one-sample Kolmogorov-Smirnov test. PSQI was also analysed as a binary variable: PSQI>5 indicating poor sleep quality and PSQI ≤5 indicating good sleep quality [21]. Binary logistic regression models were used to estimate the risk of having PSQI>5 and disturbance to sleep caused by bedroom IEQ or by characteristics or features of the sleep environment. Finally, univariate linear models were used to estimate the effects of the co-exposure of disturbance to sleep caused by bedroom IEQ and the effects of bedroom environment on PSQI. The estimated adjusted marginal means of PSQI were calculated from the univariate linear models. The potential covariates used in the models were the age of the youngest child living at home, essential oil, earplugs, consumption of meat, napping behaviour, shift work, smoking, sleeping habits, chronic disease, gender, inter-quartile range of age, and BMI. The actual factors used for model adjustments are noted in the subsequent sections.

4.3 Results

4.3.1 Responses

We received 517 responses to the survey; Annex 4A Table A4. 1 provides basic descriptive statistics on the responses to all questions in the survey. We retained all responses in the analyses although there were missing answers to some questions because, as indicated in the Methods section, the respondents were not obliged to answer all questions. We obtained at least 465 answers to each question.

To examine whether our respondents represent a subset of the population where the survey was distributed, we compared them with the population of the Capital Region of Denmark where the study was performed (Table 4. 1 and Table 4. 2): 55.4% of respondents were male, which was slightly higher than the proportion of males in the population of the Capital Region of Denmark (49.1%) [190] (Table 4. 1). The median (interquartile range, IQR) age of respondents was 33 (24–40) years old. The respondents were generally younger compared to the typical age distribution in the Danish population [190] (Table 4. 1). A nearly equal number of responses was obtained in the following age subgroups 14–24, 25–28, 29–40, and 41–78 years old, but the age group below 28 years old was overrepresented and the age group above 40 years old underrepresented (Table 4. 1). The age subgroups were divided based on median and IQR.

Table 4. 1 Comparison between the demographic data of the survey respondents and the population in the Capital Region of Denmark where the survey was made (Statistics Denmark, 2020).

Items	Number (fraction)	
	Online survey	Statistics Denmark (2020)[b]
Sex		
Male	282 (55.4%)	906,304 (49.1%)
Female	227 (44.6%)	939,719 (50.9%)
Total	509 (100%) [a]	1,846,023 (100%)
Age		
14–24	151 (29.6%)	249,527 (16.9%)
25–28	122 (23.9%)	124,745 (8.5%)
29–40	111 (21.8%)	309,352 (21.0%)
41–78	126 (24.7%)	788,587 (53.6%)
Total	510 (100%) [a]	1,472,211 (100%)

[a] Only 509 and 510 answers to these questions were obtained. b data from the 1st quarter of 2020.

Table 4. 2 Comparison of the housing type between the survey respondents and the general population of the Capital Region of Denmark in the 1st quarter of 2020 (Statistics Denmark, 2020).

Items	Number (fraction, %)	
	Online survey	Statistics Denmark (2020)
Detached houses	121 (24.3%)	188,907 (22.0%)
Row houses	50 (10.1%)	111,251 (13.0%)
Multi-dwelling apartment	305 (61.4%)	532,016 (62.0%)
Others [a]	21 (4.2%)	26,019 (3.0%)
Total	497 (100.0%) [b]	858,193 (100.0%)

[a] Others include residential buildings for communities, cottages, etc.
[b] not all respondents answered the question.

Table 4. 2 shows the information on the housing of the respondents. More than half of the respondents lived in multi-dwelling apartments and nearly a quarter in detached houses. These

proportions were according to Statistics Denmark (2020) [190] quite similar to those of the housing in the Capital Region of Denmark (Table 4. 2).

38.4% of respondents lived near a “highway or major road with heavy traffic”. 16.9% of respondents lived near a railway and 12.0% near commercial zones or shopping centres. 2.9% lived close to the airport and 5.5% lived close to a large industrial chimney. 53% of respondents had a house plant in their bedroom, 39.5% a fish tank, 49.4% a carpet, 41.2% a printer, and 42.2% a TV set. These and all other data are shown in Annex 4A Table A4. 1.

4.3.2 Bedroom ventilation

4.3.2.1 Ventilation system type

Using the information about air terminal devices and vents, we estimated the type of ventilation in bedrooms. We considered that respondents might not know the ventilation systems in their bedrooms, and thus pictures of air terminal devices and vents were used. No other assessments whether the approach chosen was correct were conducted. Bedrooms with air terminals were considered to have a fully balanced mechanical ventilation system. Bedrooms with trickle vents and exhaust fans in the bathroom or kitchen were considered to have mechanical ventilation with exhaust only (defined as exhaust ventilation). In all other cases, the bedrooms were considered to be naturally ventilated. Following this analysis, 40.0% of bedrooms were naturally ventilated, 24.6% had exhaust ventilation, and 35.4% had fully balanced mechanical ventilation (Table 4. 3).

According to a review of the Danish Building Regulations (Annex 4C Table A4. 2), air extraction from so-called wet rooms has been mandatory in new dwellings since the first regulations were published in 1961 but it could be obtained using natural or mechanical means. From 1961 to 1995, mechanical extraction was optional, while from 1995 it was compulsory in multi-dwelling apartments. Since 2010, a fully balanced mechanical ventilation system with heat recovery has been compulsory in new Danish housing. We were not able to verify the analyses presented in Table 4. 3 with the information presented in Annex 4C Table A4. 2 regarding the construction year of a building and its type.

Table 4. 3 The numbers and proportions of three categories of ventilation systems in the bedrooms.

Ventilation systems	Air terminal in the bedroom	Air terminal in the bathroom	Trickle vents in the bedroom	Number (fraction)
Natural ventilation	No	-	No	190 (40.0%)
Exhaust ventilation (air extraction)	No	Yes	Yes	117 (24.6%)
Mechanical ventilation (fully balanced with supply and exhaust)	Yes	-	-	168 (35.4%)
In total				475 (100.0%) [a]

[a] not all respondents answered the questions.

4.3.2.2 Bedroom airing behaviour

Bedroom airing behaviour was characterized by collecting information on whether the bedroom window or door was open during the day or night. The majority of respondents opened windows for less than 15 min in the morning (39.9%) or evening (43.4%); 23.5% usually did not open windows. 70.4% of respondents slept with bedroom windows closed and 48.3% of respondents slept with the bedroom door closed (Annex 4A Table A4. 1); 33.9% of respondents slept with both bedroom windows and bedroom door closed. A total of 29.6% of respondents slept with windows open regularly or occasionally. This proportion was higher than observed in another Danish study where only 19.2% of respondents reported that their bedroom windows were open during the night [191] and much lower than the 39.2% respondents living in Norway in the study of Bjorvatn et al. (2017) [36]. A total of 48.3% of respondents closed the door while sleeping. This proportion was much higher than observed in the study of Bekö et al. (2011) [191], where only 9.6% of respondents kept the bedroom door closed during the night. It should be mentioned that the sample of the population studied by Bekö et al. (2011) [191] numbered 495 and that of Bjorvatn et al. (2017) numbered 1001 [36]; the study of Bekö et al. [191] was carried out from March to May 2008 and that of Bjorvatn et al. was in winter. Table 4. 4 shows the association between bedroom airing behaviour and bedroom ventilation systems. A lower proportion of respondents who had mechanical ventilation systems in their bedrooms opened windows in the morning or during sleep compared to those who had other types of ventilation systems. A higher proportion of respondents who had exhaust ventilation systems in their bedrooms opened windows in the evening or during sleep compared to those who had the other ventilation systems. A higher proportion of those who had natural ventilation systems in their bedrooms kept their windows open during sleep than with the other ventilation systems.

Table 4. 4 Association between bedroom airing behaviour and bedroom ventilation systems; the number of respondents (and fraction in %) are presented.

Items	Mechanical ventilation		Exhaust ventilation		Natural ventilation	
	No	Yes	No	Yes	No	Yes
1. Windows open in the morning						
Never	**63 (54.3)**	**53 (45.7)****	93 (80.2)	23 (19.8)	**81 (69.8)**	**35 (30.2)***
Open for some time	**267 (70.6)**	**111 (29.4)**	285 (75.8)	91 (24.2)	**224 (59.4)**	**153 (40.6)**
2. Windows open in the evening						
Never	72 (62.6)	43 (37.4)	**97 (84.3)**	**18 (15.7)***	71 (61.7)	44 (38.3)
Open for some time	255 (67.5)	123 (32.5)	**279 (74.2)**	**97 (25.8)**	236 (62.6)	141 (37.4)
3. Windows open during sleep						
Never	**225 (63.7)**	**128 (36.3)***	**282 (80.1)**	**70 (19.9)****	217 (61.5)	136 (38.5)
Regularly or occasionally	**109 (73.6)**	**39 (26.4)**	**101 (68.7)**	**46 (31.3)**	94 (63.5)	54 (36.5)
4. The door open during sleep						
Never	158 (64.5)	87 (35.5)	193 (78.8)	52 (21.2)	152 (61.8)	94 (38.2)
Regularly or occasionally	176 (68.5)	81 (31.5)	191 (74.9)	64 (25.1)	160 (62.5)	96 (37.5)

* p-value < 0.05; ** p-value < 0.01. Bold indicates statistically significant results. p-value was from the Chi-square test; the comparison is made between those who had and not had a certain type of ventilation system.

4.3.3 Sleep quality

4.3.3.1 PSQI (subjective sleep quality)

Table 4. 5 An overview of the Pittsburgh Sleep Quality Index (PSQI) and scores for each PSQI component.

Component score [a]	Number of responses (fraction)	Component score [a]	Number of responses (fraction)
PSQI	482 (100%) [b]	Sleep disturbance [e]	
≤ 5 (good sleep quality)	209 (43.4%)	0	16 (3.3%) [b]
> 5 (poor sleep quality)	273 (56.6%)	1	354 (73.0%)
Subjective sleep quality		2	108 (22.3%)
0 (very good)	65 (13.4%) [b]	3	7 (1.4%)
1 (fairly good)	285 (58.6%)	Use of sleep medication	
2 (fairly bad)	125 (25.7%)	0 (not during the past month)	437 (89.9%) [b]
3 (very bad)	11 (2.3%)	1 (< 1/week)	29 (6.0%)
Sleep latency [c]		2 (1 – 2/week)	6 (1.2%)
0	105 (21.7%) [b]	3 (≥ 3/week)	14 (2.9%)
1	88 (18.2%)	Daytime dysfunction [f]	
2	195 (40.3%)	0	98 (20.2%) [b]
3	96 (19.8%)	1	246 (50.6%)
Sleep duration (hrs.)		2	123 (25.3%)
0 (> 7 hrs.)	191 (39.4%) [b]	3	19 (3.9%)
1 (6–7 hrs.)	264 (54.4%)		
2 (5–6 hrs.)	26 (5.4%)		
3 (< 5 hrs.)	4 (0.8%)		
Sleep efficiency [d]			
0 (> 85%)	339 (69.9%) [b]		
1 (75 – 84%)	102 (21.0%)		
2 (65 – 74%)	28 (5.8%)		
3 (< 65%)	16 (3.3%)		

[a] Component score was calculated from one or more items and rescaled to 0 to 3. More information can be found in Buysse et al. (1989) [21].

[b] Not all respondents answered this question.

[c] The "sleep latency" score was calculated by two questions in PSQI. They are "time to take to transition from wake to sleep" and "during the past month, how often have you had trouble sleeping because you cannot get to sleep within 30 minutes".

[d] (Number of hours slept / number of hours spent in bed) × 100.

[e] Sum of questions 5b – 5j in the PSQI from 0, 1 – 9, 10 – 18, and 19 – 27 to 0, 1, 2, and 3 for the component "sleep disturbance".

[f] Sum of questions 8 and 9 in the PSQI from 0, 1 – 2, 3 – 4, and 5 – 6 to 0, 1, 2, and 3 for the component "daytime dysfunction".

The median (IQR) of subjectively rated sleep duration was 7.0 (6.5–8.0) hours. A total sleep time of 7–9 h is regarded as good [36]; only 39.4% of respondents indicated sleeping on average more than 7 h. The median (IQR) of subjectively rated sleep latency was 15 (10–30)min. Sleep latency lower than 30min is defined as an indicator of good sleep quality [36]; only 39.9% of respondents reported having sleep latency below 30 min. A total of 69.9% of respondents had sleep efficiency higher than 85%, which was defined as indicating good sleep quality [36]. While the PSQI global score has a range of 0–21 points, it ranged between 0 and 18 in the present study because no one had scores of 19–21. According to Buysse et al. (1989) [21], PSQI scores between zero and five correspond to good sleep quality and scores above five correspond to poor sleep quality. The median (IQR) PSQI score for the respondents in the present survey was 6.0 (4.0–8.0) (Table 4. 5), indicating that >50% of respondents would be classified as having poor sleep quality. The difference of PSQI among personal characteristics and sleep habits is shown in Annex 4D Figure A4. 2.

The fraction of respondents with PSQI > 5 was 56.6% in the present study. This is higher than the 41.9% among 93 participants aged 28.0 ± 7.4 years old in a study in Thailand [192], 35.4% among 243 daytime workers aged 49.4 ± 10.7 years old in Japan [193], 21–31% among 1635 Chinese undergraduate students aged 19.5 ± 0.8 years old [38], 40.2% among the 2197 Chinese residents with the average age of 37.5 years [194], but lower than in a study in China where 66.3% among the 1979 Chinese undergraduate students aged 20.3 ± 1.3 years old [195] obtained a PSQI > 5. On the whole, the respondents in the present study had poorer sleep quality compared to most previous studies.

4.3.3.2 Sleep disturbance caused by bedroom environmental conditions

37.5–56.3% of the respondents were disturbed by noise, stuffy air or thermal discomfort "regularly or occasionally" during sleep; "too warm" was the most prevalent type of sleep disturbance experienced occasionally in bedrooms; a similar number of respondents experienced regular disturbance to sleep caused by too warm or too cool conditions, stuffy air or noise (Figure 4. 1). The correlations between any of those sleep disturbances were weak ($\rho < 0.3$, see Annex 4E Table A4. 3).

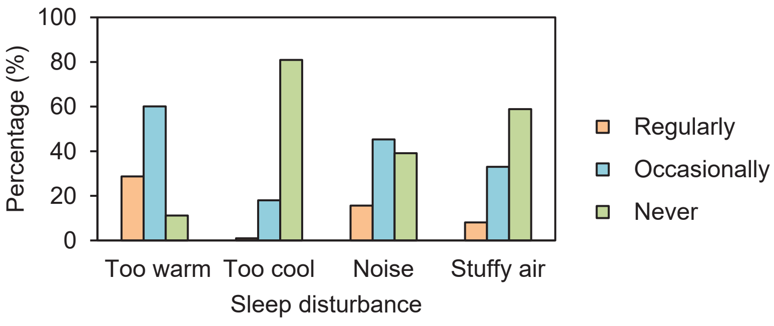

Figure 4. 1 Incidence of sleep disturbance caused by noise, stuffy air, and thermal discomfort experienced in bedrooms.

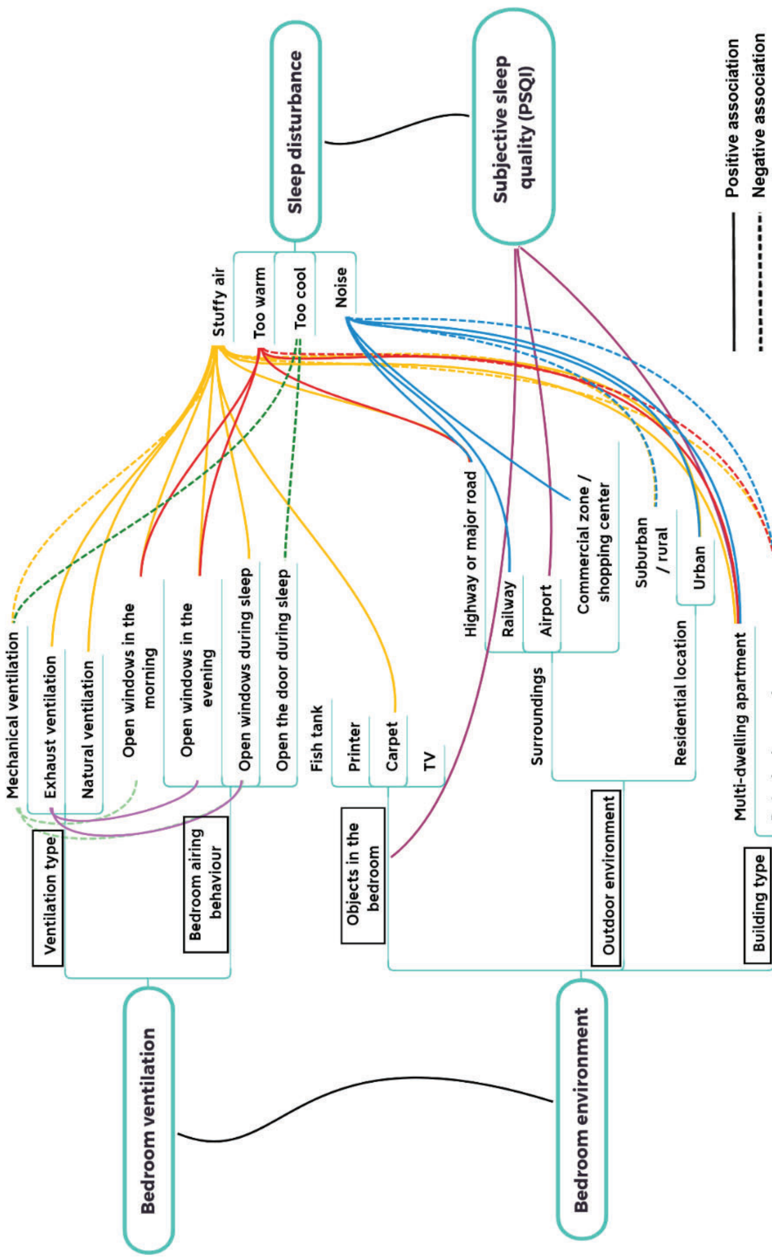

Figure 4. 2 A mind map describing associations between bedroom environment and ventilation and the conditions for sleep expressed as sleep disturbances and sleep quality expressed as PSQI (Pittsburgh Sleep Quality Index); significant effects are described by splines where the continuous line shows positive and dashed line shows negative associations. Annex 4E Table A4. 4 shows detailed results supporting the relationships presented in this figure.

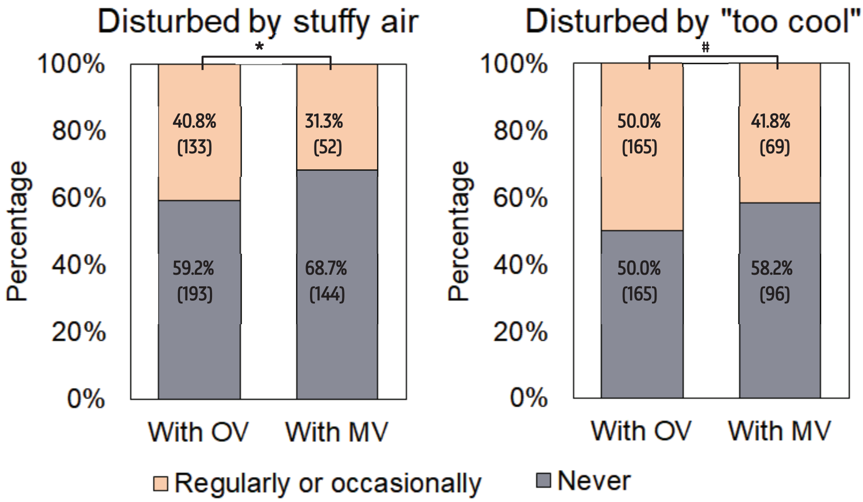

Figure 4. 3 Mechanical ventilation in bedrooms reduced responses of being disturbed by stuffy air or "too cool" conditions during sleep. Sample sizes are shown in the brackets. MV, mechanical ventilation; OV, other ventilation including exhaust ventilation and natural ventilation. * *p*-value < 0.05, $^{\#}$ *p*-value < 0.01 (Chi-square test).

4.3.4 Associations between sleep quality and bedroom ventilation

Figure 4. 2 shows all associations between parameters characterizing the bedroom environment and the sleep disturbance and sleep quality that were found to be significant; the full table with all the results of these analyses is shown in Annex 4E Table A4. 4. It shows that bedroom ventilation affected disturbance to sleep caused by stuffy air, too cool and too warm conditions in bedrooms. The detailed analysis presented in Figure 4. 3 shows that those whose bedrooms were mechanically ventilated reported less disturbance to sleep due to stuffy air or "too cool" conditions. Sleep disturbance caused by noise was mainly associated with the outdoor environment and building types, and sleep disturbance caused by stuffy air was additionally associated with objects present in bedrooms; very few associations were observed for sleep disturbance caused by thermal discomfort. PSQI was only affected by the objects in bedroom, surroundings and location of the building. No association between airport and sleep disturbance of noise was shown because of insufficient data on this point. Moreover, no association between opening windows and noise indicates that noise was not the main reason for the respondents to open or close windows.

Multivariate linear regression was conducted to examine the risk of experiencing sleep disturbance depending on the bedroom conditions; the risk was expressed as an odds ratio (OR). Table 4. 6 shows that sleeping in bedrooms without mechanical ventilation systems, living in a multi-dwelling apartment, and living close to a "highway or major road" or commercial zones/shopping centres significantly increased the risk for reporting sleep disturbance caused by stuffy air, too cool thermal conditions and noise. No associations were found with the sleep

Table 4. 6 Sleep disturbance and bedroom environment; the results of multivariate analyses. Only significant associations are shown.

	OR (95% CI) for experienced disturbance (OR>1 means increased risk)	*p*-value [a]
1. Sleep disturbed by stuffy air in a bedroom [b]		
Bedroom close to highway or major road with heavy traffic compared with other bedrooms	1.74 (1.12 – 2.72)	0.020
Bedroom without mechanical ventilation compared with the bedroom with mechanical ventilation	1.67 (1.03 – 2.73)	0.039
2. Sleep disturbed by feeling "too cool" in a bedroom [d]		
Bedroom without mechanical ventilation compared with the bedroom with mechanical ventilation	1.64 (1.03 – 2.63)	0.048
3. Sleep disturbed by noise in a bedroom [e]		
Bedroom close to commercial zones/shopping centres compared with other bedrooms	2.18 (1.11 – 4.39)	0.032
Bedroom in an apartment in a multi-dwelling building compared with bedroom in detached or row houses	1.77 (1.11 – 2.83)	0.029

[a] adjusted by the False Discovery Rate (FDR) method.

[b] adjusted for meat consumption and chronic disease.

[c] adjusted by sex, age interquartile range (IQR), BMI and essential oil.

[d] adjusted by chronic disease, the youngest child age at home and earplugs.

OR, odds ratio; CI, confidence interval. All models included mechanical ventilation, building surroundings (highway or major road, railway, and commercial zones/shopping centre), carpet and house type, adjusted by age of the youngest child living at home, essential oil, earplugs, meat consumption, nap, shift work, smoking, chronic disease, gender, age IQR and BMI. Only significant factors were included in the final models. Adjusted factors were selected by significant Spearman's correlation coefficients shown in Annex 4E Table A4. 5.

Table 4. 7 The percent increase in PSQI and odds ratio (OR) for PSQI higher than five and sleep disturbance.

Sleep disturbance	The percent increase in PSQI (95% CI) [a]	*p*-value [b]	OR [a] (95% CI) for PSQI >5	*p*-value [b]
Reporting stuffy air vs. non stuffy air	19.1 (10.1 – 28.9)	< 0.001	1.89 (1.21 – 2.97)	0.009
Reporting noise vs. no noise	15.0 (6.3 – 24.3)	0.002	2.62 (1.68 – 4.10)	0.001

[a] adjusted by chronic disease, exercise, the youngest child's age at home, sleep habits and BMI.

[b] adjusted by the False Discovery Rate (FDR) method.

[c] adjusted by chronic disease, exercise, the youngest child's age at home and sleep habits.

CI: confidence interval. The models included stuffy air, too warm, too cool and noise, adjusted by chronic disease, age of the youngest child living at home, exercise, essential oil, shift work, sleeping with another, sex, age IQR and BMI. Only significant factors were included in the final models. Adjusted factors were selected by significant Spearman's correlation coefficients shown in Annex 4E Table A4. 6.

disturbance caused by "too warm" conditions. We modelled also the risk of reduced sleep quality as indicated by PSQI >5 when reporting disturbance to sleep (Table 4. 6). Reporting disturbance to sleep caused by stuffy air and noise significantly increased PSQI by more than 15% suggesting that sleep quality could be reduced when these disturbances are reported; both disturbances were also significant risk factors for PSQI being higher than 5 indicating that sleep quality is poor.

PSQI was positively correlated with the number of disturbances to sleep reported by the respondents (Figure 4. 4). PSQI with no disturbances was only marginally lower than 5 suggesting that there were also other factors influencing sleep quality.

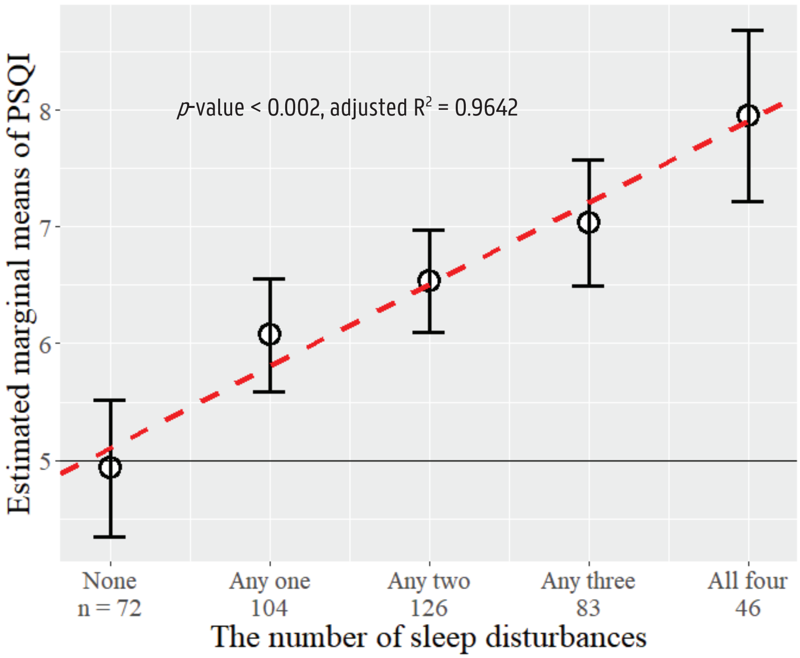

Figure 4. 4 PSQI increased with an increased number of sleep disturbances. Sleep disturbances include stuffy air, noise, too warm, and too cool (max four min zero). The results were adjusted by chronic disease, exercise, age of the youngest child living at home, sleep habits and BMI. Error bars represent 95% confidence intervals of the estimated marginal means of the PSQI scores. Details are shown in Annex 4G Table A4. 7.

4.4 Discussion

Bedroom ventilation type and sleep quality were expected to be associated, but no direct association was found in the present study, although mechanically ventilated bedrooms protected occupants against disturbance caused by stuffy air or "too cool" conditions, compared to those whose bedrooms were not mechanically ventilated. Since the questions used to derive

PSQI do not refer specifically to the type of ventilation, bedroom airing behaviour, or location of the bedroom and mainly collect information on sleeping habits (see Annex 4A), this is probably why no associations with PSQI were obtained, or the associations were not as significant as the other factors. In this Chapter, sleep quality was assessed by PSQI.

Stuffy air, indicating poor bedroom air quality, was among the most significant causes of sleep disturbances in the present study, the other one being noise. As the survey was made in the heating season when respondents could effectively control bedroom temperatures only a few associations were observed for disturbances caused by the thermal environment. This does not mean that thermal problems would not occur during summer so a second survey in summer is required, as bedroom temperatures have previously been found to influence sleep quality [32, 138]. Another reason was that the survey was not designed specifically for figuring out the association between thermal environment and sleep quality, and thus only a few associations were observed. The effects of stuffy air on sleep quality would be different in summer as thermal environment, which is related to ventilation, is different. The results for disturbance to sleep caused by stuffy air are consistent with previously reported associations between bedroom air quality and sleep quality [183]. Poor perceived air quality was associated with poor self-reported sleep quality in the study of Xiong et al. (2020) [32]. Several studies showed that poor IAQ resulted in a higher snoring percentage, lower sleep efficiency, less deep non-rapid eye movement (NREM) sleep and an increased number of awakenings [8, 15, 16, 32, 38, 60, 183].

Table 4. 8 The percent increase in PSQI and odds ratios (OR) for PSQI higher than five and sleep environment.

	The percent increase in PSQI (95% CI) [a]	*p*-value [b]	OR (95% CI) for PSQI >5 [c]	*p*-value [b]
One or more bedroom objects: fish tank, carpet, printer, or TV vs. bedroom with none	8.8 (5.3 – 12.4)	< 0.001	1.44 (1.20 – 1.74)	0.001
One or more noise-related factors of a highway, railway, commercial zone, airport, apartment, and living in urban areas vs. bedroom with none of these	10.1 (-0.3 – 21.8)	0.071	1.51 (0.91 – 2.53)	0.113

[a] adjusted by chronic disease, exercise, the youngest child's age at home, sleep habit and BMI.

[b] adjusted by the False Discovery Rate (FDR) method.

[c] adjusted by chronic diseases, exercise and sleep habits.

CI: confidence interval.

Both of the models included bedroom objects, noise factors and mechanical ventilation, adjusted by chronic disease, the youngest child's age at home, exercise, essential oil, having a shift job, sleep habit, sex, age IQR and BMI. Adjusted factors were selected by significant Spearman's correlation coefficients shown in Annex 4E Table A4. 6. Not all those factors were included in each model, and the final models are shown above.

Poor bedroom IAQ can be caused by sources of pollution in the bedroom and by insufficient ventilation. Sekhar et al. (2020) [140] reviewed literature presenting measurements of ventilation in bedrooms and ventilation standards for bedrooms and found that bedrooms with mechanical ventilation had better IAQ compared to those with natural ventilation, and that insufficient ventilation in bedrooms reduced sleep quality. To examine the effect of pollution sources in bedroom we used multivariate modelling to find any associations between the risk of poor sleep quality (PSQI>5) and the bedroom environment, as in the analyses presented in Section 4.3.4. A significant risk was found only for the presence of any of the following objects in the bedroom: fish tank, carpet, printer, or TV (Table 4. 8); the presence of any of these objects increased PSQI by 8.8%. Figure A4. 3 in Annex 4F also shows PSQI increased with an increased number of those bedroom objects. This means that the more sources disturbing sleep in the bedroom, the poorer sleep quality. Carpets have been shown to increase levels of fungal concentration, and the concentration of volatile organic compounds (VOCs) and formaldehyde [106, 196, 197]. Printers have been shown to be the source of numerous air pollutants, such as VOCs and particulate matter [198]. The relative humidity could be higher in bedrooms with uncovered fish tanks. High humidity increases the concentration of airborne contaminants [199] and promotes house dust mites [200]. Those sources were not only the pollution sources, but also the sources affecting lifestyles. For example, Green et al. (2018) [201] showed that a TV in the bedroom can prolong sleep latency. The associations in Table 4. 8 were not all shown in Figure 4. 2 because they were from a different statistical method and also the factors listed in Table 4. 8 were combined as the two factors.

Stuffy air disturbing sleep was associated with the type of ventilation and bedroom airing behaviour. It was observed that bedrooms were aired more frequently when they were not mechanically ventilated. Improved bedroom air quality can be achieved through windows, by infiltration through building envelope air leakage and by window opening by occupants in bedrooms without mechanical ventilation [84]. Stuffy air was also associated with bedroom location: Urban bedrooms, in a multi-dwelling apartment, and close to major roads were associated with a higher incidence of stuffy air disturbing sleep. This is consistent with the results of Gasana et al. (2012) [202] who showed that people living close to major roads had greater exposure to vehicular emissions, leading to worse indoor air quality. Also, Branco et al. (2019) [203] showed that CO_2 levels in bedrooms located in urban areas were slightly higher compared to those located in rural areas. Using our data, we found that multi-dwelling apartments were more likely to be located in urban areas ($\rho = 0.518$, p-value <0.001), so sleep disturbance caused by stuffy air could be due to the reasons given above. We also found that sleep disturbance caused by noise was associated with the location of the bedroom and the building type though not with ventilation type, the results being consistent with the study of Kayaba et al. (2014) [204] who reported that noise, of which 21% was related to traffic such as cars, motorcycles, and trains, was associated with PSQI >5 and the adjusted OR was 2.1 (95% CI, 1.1–4.1). The World Health Organization (WHO) has recommended that bedroom windows should be open during sleep to provide proper ventilation as mentioned in the introduction. However, people prefer to close their windows if outdoor noise levels are high since bedroom sound levels can be reduced by 30–35 dB and 10–15 dB respectively with windows closed and only slightly open for most of the types of windows used in central Europe [205], making possible a trade-off between sleep disturbance caused by stuffy air and noise. Too warm bedrooms disturbing sleep were associated with airing behaviour and resulted in more frequent airing. This has been found in previous studies where opening windows was one of the major strategies for occupants to reduce bedroom temperatures [37, 206]. Airing could also be caused by stuffy air that was correlated with too warm bedrooms. Such a correlation was observed in a study by de Oliveira et al. (2021) [27] where satisfaction with air quality tended to be lower with increased temperature in winter. Sleep disturbance caused by too warm bedrooms was also associated with the building type: it was more prevalent in multi-dwelling apartments than in detached and row houses. Location close to a major road was also associated with a higher incidence of disturbance to sleep caused by too warm bedrooms. The reason could be the increased noise levels caused by open windows and the need for a trade-off between noise and warmth.

Too cool bedrooms disturbing sleep were associated with closing the door to the bedroom during sleep and bedrooms without a mechanical ventilation system. A plausible explanation is that people avoid cold drafts and keep the bedroom warm by closing the door and air the bedroom more when there is no mechanical ventilation to avoid discomfort caused by poor air quality. Also, bedrooms with extract ventilation can have trickle vents open allowing outdoor (colder) air to enter the dwelling. Moreover, dwellings with balanced ventilation systems being most probably often more recent and thus better insulated and thus warmer. Studies to validate or refute these speculations are required.

The associations between bedroom airing behaviour and sleep disturbance are somewhat similar to the results obtained in the study by Sharpe et al. (2015) [207] and Heide et al. (2021) [208]. They reported that "too warm" conditions and odour (poor indoor air quality) were the major drivers for opening windows, with 72% and 36% occupant responses, respectively. Moreover, Sharpe et al. (2015) [207] reported that the reasons for not opening windows included "heat loss" (59%), noise (17%), security (11%), and outdoor air pollution (5%). Heide et al. (2021) [208] reported additionally that the opening of windows at night was governed by habit or simply forgetting to do so. Besides window-opening behaviours, bedroom door-opening behaviours during sleep were mainly associated with thermal discomfort in the present study.

4.4.1 Limitations

The present survey is cross-sectional and is prone to the limitations typical for this type of design. For example, we could not control all sources of bias and had to reduce the length of the questionnaire so that its length would not limit the number of responses. To this end, we did not collect information on sleeping mattresses that may have a new ergonomic design conducive to good sleep. Furthermore, the information regarding the period for the respondents living in the dwelling, which might affect the results of sleep quality if they just moved, was not collected. Our results consequently show potential associations and should not be interpreted as proving causation. Since the survey was posted online we could not determine the response rate.

The two most important limitations of the present survey are the sample size and the age distribution of the respondents. Although we made efforts to encourage as many people as possible to respond to our survey, we received only about 500 responses. In comparison with previous surveys of this type, the number of responses is moderate to high; in other studies, the size was 229, 495, 554, 1001 [36, 187, 191, 209]. We attempted to obtain responses from people with different types of ventilation in bedrooms and living in buildings representative for the area where the survey was performed. We succeeded on this point (Table 4. 2) but the mean age of our respondents was lower than in the population so the information on sleep quality may be biased towards younger people. If sleep quality decreases after the age of 50 years old [210], we may expect that our results could be biased towards better sleep quality. Also, the associations with the analysed parameters might be different, either weaker or stronger.

We characterized bedroom ventilation type using responses to our questions and pictures embedded in the survey. However, although we were not able to validate these results, we believe that the error associated with this analysis is rather small as we have not seen associations in our results that could be considered spurious or uncommon. As our focus was on ventilation type and the resulting indoor environment in bedrooms, we did not ask questions about disturbance to sleep caused by bedroom light conditions or many other potential causes of disturbed sleep. One aspect that we omitted was air humidity – air dryness, but we consider that responses to the question regarding air stuffiness will have included the influence of moisture since high relative humidity leads to poor perceived air quality [211, 212]. The perceived air quality decreases with increasing humidity at the same level of pollutants and temperature. The respondents could indicate which other factors disturbed their sleep when responding to the questions that are used to derive PSQI. Only one respondent mentioned that winter darkness reduced sleep quality. Other sleep-disturbing reasons included stress, pets (cat/dog), children, snoring spouse, chronic disease (migraine, stomach-ache, etc.), flu, bad position, odour, examinations, and a rooster crowing at 2 a.m.

We did not ask about activities before sleep that could also affect sleep quality such as watching TV in bed, use of smartphone and computer in bed, etc. Other studies have shown that they could also influence sleep quality [213]. We observed that the presence of different objects in the bedroom including a TV may have a negative effect on sleep quality. This is consistent with the results showing that some lifestyles can lead to poorer sleep quality [214]. Another limitation was that we did not measure sleep quality objectively - we used PSQI. The accuracy of PSQI was tested by polysomnography when the PSQI was formulated and the global PSQI score was significantly but weakly (or moderately) correlated with sleep latency (ρ=0.20), REM% (ρ=0.34), and the number of arousals (ρ=0.47) depending on different subject groups (either in control or depressive patient groups) [21]. It may thus be inferred that in our survey no associations between bedroom environment and PSQI does not indicate an association between bedroom environmental factors and sleep latency, REM sleep or the number of arousals, but this should be examined in future field experiments.

PSQI includes questions on thermal discomfort and breathing discomfort which can probably be used to characterize the effects of the bedroom environment. We correlated them with the responses in the survey indicating disturbance to sleep caused by too warm and too cool conditions in bedrooms and stuffy air in the bedroom. They were moderately but significantly correlated: ρ=0.526 and ρ=0.555 for the correlations with too warm and too cool conditions and ρ=0.219 for the correlations with stuffy air. However, it should be noted that these questions yield only 1 point out of the total of 21 points that can be scored in PSQI. Consequently, it is possible that the global PSQI score is not sufficiently sensitive in its response to bedroom environmental conditions that may disturb sleep. This may explain the few associations between PSQI and bedroom environment that were found in the present study. However, PSQI was correlated with sleep disturbance and this is consistent with the above correlations.

Figure A4. 3 in Annex 4F show reduced sleep quality with an increased number of objects in the bedroom and with increased sleep disturbance, respectively. An alternative explanation for these results is that sleep disturbance and objects in the bedroom are markers of the type of person who sleeps badly for unknown reasons and is either ignorant of why this might be or unwilling to do anything about it. The results shown in these figures therefore do not prove causation or truly additive effects as they were not obtained in an intervention study. This is a general limitation of the present survey of associations - it does not prove causation. Studies capable of proving causation are required to validate the observed associations.

Table 4. 9 The frequency and percentage of respondents to be disturbed by sleep disturbances in winter and summer.

Sleep disturbances	Winter, n (%)	Summer, n (%)	*p*-value [a]
1. Sleep disturbed by stuffy air			
Regularly or occasionally	185 (37.5)	202 (41.1)	0.081
Never	309 (62.5)	289 (58.9)	
2. Sleep disturbed by too warm/hot			
Regularly or occasionally	283 (56.3)	443 (88.8)	< 0.001
Never	220 (43.7)	56 (11.2)	
3. Sleep disturbed by too cool/cold			
Regularly or occasionally	234 (47.2)	93 (19.1)	< 0.001
Never	262 (52.8)	395 (80.9)	
4. Sleep disturbed by noise			
Regularly or occasionally	213 (42.7)	304 (60.9)	< 0.001
Never	286 (57.3)	195 (39.1)	

[a] *p*-values were calculated by non-parametric Wilcoxon matched-pairs signed-ranks test.

The present results are valid for the heating season because the survey was performed in January and February, the winter months in Denmark. We asked respondents to provide information on bedroom IEQ parameters disturbing sleep both during winter and summer. The answers regarding the summer situation were still valued for comparison with the winter situation to some extent, although they were based on the recall of the respondents and the quality of the answers were not uncertain. We used the former in the analyses as the survey was performed in winter. We could not use the latter in our models as PSQI refers only to sleep during the last month. Furthermore, we did not ask the respondents whether they slept in the same bedroom the preceding summer. Nevertheless, we compared sleep disturbances caused by bedroom IEQ in winter and in summer and the results are presented in Table 4. 9. It shows that these responses differ. In particular, more respondents reported being disturbed by too warm conditions and noise in summer than in winter. Which parameters characterizing the sleep environment and bedroom ventilation can explain these differences and how these responses affect sleep quality would have to be investigated in a survey performed in summer for the reasons given above. It is worth noting that the frequency of responses indicating the disturbance to sleep caused by stuffy air did not differ significantly between the two seasons.

4.5 Conclusions

We carried out a questionnaire survey among residents of the Greater Copenhagen Area in Denmark in early 2020, before the COVID-19 pandemic restrictions were introduced. We received 517 responses characterizing bedroom ventilation type, airing behaviour, sleep environment, sleep disturbance, and sleep quality; sleep quality and indoor environment quality were assessed by the respondents and not measured objectively. The study provides information on the associations among subjective sleep quality, sleep disturbance caused by the quality of bedroom environment, bedroom ventilation and the bedroom environment. We focused on bedroom ventilation type as well as other factors that are related to bedroom ventilation.

People who slept in bedrooms with mechanical ventilation were less disturbed by stuffy air and "too cool" conditions during sleep compared to those who slept in bedrooms with other types of a ventilation system. However, no association was found between the type of bedroom ventilation and subjective sleep quality.

Sleep disturbance caused by stuffy air, noise, and thermal discomfort was found to be associated with reduced subjective sleep quality. Sleep disturbance caused by stuffy air and thermal discomfort were the main reasons of occupant bedroom airing behaviour during the morning/ evening or night. However, no associations were observed between occupant bedroom airing behaviour and subjective sleep quality. PSQI may not be an unambiguous indicator of how sleep quality is affected by environmental parameters.

Field measurements in bedrooms are necessary to validate the results obtained in the present work, and a survey would have to be performed in the summer to permit generalization of the present results obtained during the heating season to other periods of the year.

5

Investigating the effects of bedroom ventilation on sleep quality: a field study in the heating season in Danish dwellings

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Keywords

Perceived air quality; CO_2; GSQS; Sleep tracker; Deep sleep; Wrist skin temperature

Abstract

A field study on bedroom ventilation and sleep quality in Danish housing was conducted in the heating season between September and December 2020. A total of 75 bedroom occupants completed the experiment. The median age was 26 years (interquartile range (IQR), 24-32 years) and 54.7% of them were males. Bedroom air quality was rated by the occupants before and after sleep, and the levels of CO_2, a marker of ventilation, were measured in their bedrooms during sleep. Sleep quality was assessed by the Groningen Sleep Quality Scale (GSQS) the next morning and measured by sleep trackers during sleep. The median GSQS was 4.0 (IQR, 1.0 – 6.0). Medians of the objective sleep parameters of sleep efficiency, light sleep, deep sleep and REM sleep were 88.1% (86.1-89.5%), 59.4% (54.9-64.5%), 18.3% (15.0-21.7%) and 23.0% (18.4-26.4%), respectively. Random forest regression models were built to predict GSQS and deep sleep (%). The predicted GSQS increased from 3.23 (95%CI, 3.19-3.25) to 4.09 (4.04-4.14) when the unacceptable rating of perceived air quality increased from 4 to 60. The deep sleep (%), which was predicted by a machine learning model, increased from 18.6% (95%CI, 18.3-19.0%) to 20.6% (20.1-21.1%) when mean CO_2 increased from 450 to 1200 ppm. Previous studies reported adverse impacts on sleep quality when the average CO_2 levels were higher than 1200 ppm, while we could not confirm those findings because of data limitations. Bedroom ventilation is required after sleep, and a lower ventilation rate, compared to after sleep, may be necessary during sleep. Additional studies are needed to confirm this.

5.1 Introduction

Sleep quality is vital for our mental and physical health, as well as next-day performance. Insufficient sleep quality and quantity can cause mental diseases and cardiovascular illnesses [215-218]. Metrics using for defining sleep quality comprise sleep efficiency, sleep latency, number of awakenings, and sleep architecture. The American National Foundation reported the appropriate sleep quality for adults aged 26-64 years is sleep latency less than 30 min, less number of awakenings, sleep efficiency higher than 85%, rapid eye movement (REM) sleep 21-30%, N1 (N-REM1) sleep less than or equal to 5%, and N3 (N-REM3) sleep 16-25% [7].

Sleep quality can be affected by numerous aspects including the quality of the sleep environment, which contains four main aspects, namely the thermal, acoustic, visual environment, and air quality in bedrooms [46]. Previous studies widely investigated thermal, acoustic, and visual environments, while few of them investigated the effects of air quality on sleep quality. Ventilation is the most crucial implement to improve indoor air quality, and carbon dioxide (CO_2) is a marker of ventilation and was extensively used in previous studies for indoor air quality [8, 15, 16, 60, 219, 220]. Akimoto et al. (2021) [183] reviewed 10 studies regarding the association between ventilation and sleep quality, and reported that poor ventilation in bedrooms negatively affected sleep quality, which would become poorer and poorer when average CO_2 levels during sleep were higher than 1004 ppm. However, almost all of the 10 studies were chamber or intervention studies, field studies were rare.

High CO_2 levels were reported in bedrooms in previous field studies, which proved that plenty of bedrooms were poorly ventilated during sleep. Liu et al. (2015) [123] reported that average CO_2 levels of 45.6% of 445 children's bedrooms during sleep in winter exceed the Indoor Air Quality Standard in China, which is 1000 ppm, and 1000 ppm is also Category II (a normal level for design and operation) of bedrooms proposed by the European Committee for Standardization (CEN, Chapter 2). The average CO_2 levels of 54.0% of 104 bedrooms were above 1000 ppm in transition seasons in China [8]. Bekö et al. (2010) [30] reported the average CO_2 levels in 68% of 500 children's bedrooms exceeded 1000 ppm in the heating season in Denmark. Kotol et al. (2014) [221] reported CO_2 levels of 66% of 79 bedrooms in Greenland were above 1000 ppm in winter. Kim et al. (2010) [33] reported that 79.3% of 29 bedrooms exceed 1000 ppm in winter in Korea. Laverge et al. (2015) reported CO_2 levels of 30.0% of 114 bedrooms in Belgium were above 1000 ppm.

Bedroom ventilation is also related to occupants' window- or door- opening behaviours and ventilation types. Sleeping with the window open was recommended by the World Health Organization (WHO) to supply proper ventilation [35]. However, whether to sleep with the window open depends on personal habits. 67% of 1339 surveyed Chinese slept with windows closed to main thermal comfort instead of better indoor air quality, while more than 44.8% of surveyed Norwegian aged 45 years or older slept with the window open during the whole year [36, 39, 40]. Mechanical ventilation improves indoor air quality. Liao et al. (2021) [222] found that occupants were less frequently disturbed by stuffy air during sleep in their bedrooms with mechanical ventilation, compared to them with other types of ventilation.

Zhang et al. (2021) [8] investigated ventilation and sleep quality among 104 healthy bedroom occupants in Beijing, China, and concluded that higher CO_2 levels reduced both subjective and objective sleep quality indicating decreased sleep efficiency, ease of awakening, and sleep satisfaction. Xiong et al. (2020) [32] measured CO_2 levels among 48 subjects in a student dorm in Sydney, Australia during a summer season, and reported that deep sleep time (in percent) decreased with higher CO_2 levels. Kim et al. (2010) [33], Laverge and Janssens (2010) [41] and Laverge et al. (2012) [223] also performed a field study of a similar topic, but both of them were inconclusive. Most of the previous field studies concluded that higher CO_2 levels were associated with sleep quality, and this was consistent with previous chamber or intervention studies [15, 16, 220]. However, the mechanism or the reason why poor ventilation (higher CO_2 levels) decreased sleep quality was not clear.

One key sign for people to have better sleep quality (more deep sleep) is the decline in core body temperature during sleep [224]. Nevertheless, core body temperature is tough to measure. Skin temperature was reported to be highly correlated with core body temperature [47] and would be a feasible replacement.

The present study aimed to evaluate the effects of bedroom ventilation on sleep quality in the heating season based on a field study in the capital region of Denmark. Bedroom ventilation is characterised by occupants' window- or door- opening behaviours, ventilation types in bedrooms, and CO_2 levels.

5.2 Methods

5.2.1 Study subjects

A field study was conducted from September to December 2020 in the capital region of Denmark before the second lockdown on 9 December in Denmark. The monthly average outdoor temperature in the capital region of Denmark during the experiment period was 15.1 °C (3.5 – 26.9 °C) September, 11.2 °C (1.6 – 18.6 °C) October, 8.1 °C (-1.4 – 17.2 °C) November, and 4.8 °C (-4.5 – 9.4 °C) December [225].

Bedroom environment and sleep quality were rated by using online sleep diaries and measured via instruments (and sleep tracker). Personal characteristics and other information that might be related to sleep quality were collected by an online questionnaire. An instrument box and an envelope with instructions, a consent form, and a sheet of QR codes to sleep diaries webpages were delivered to the subjects on Sundays during the experiment period.

The subjects were recruited by sending an invitation e-mail to all the respondents from our previous online survey study or by posting a poster on social media [222]. Those interested in the present study replied to the invitation e-mail or fill out their contact information by scanning the QR code on the poster. A total of 84 subjects participated in the present study. Detailed demographic information will present in the results.

Our proposal was approved by the Technical University of Denmark and archived under DOCX 19/1002413. The subjects signed the consent form and the replies to sleep diaries or other questionnaires were anonymized and saved on a university server, to comply with the General Data Protection Regulation (GDPR).

5.2.2 Sleep diary

Online sleep diaries contained both evening and morning versions, namely evening sleep diary (ESD) and morning sleep diary (MSD) (see Annex 5A). The subjects were asked to reply to the ESD and MSD for at least two continuous nights of sleep within ten minutes before and after sleep, respectively, from Monday evening to Friday morning during the experiment week.

Perceived bedroom environment was assessed via a continuous visual analogue scale ranging from 0 to 100 for temperature, humidity, light, air stuffiness, noise, and odour. The scales of the perception of temperature, humidity, and light were equally divided into seven parts, and the corresponding labels were marked on the nodes. Besides, the acceptable levels of the thermal comfort, air quality, and acoustic comfort were rated by another continuous visual analogue scale, where 0 – 49.9 and 50.1 – 100 refer to “acceptable” and “unacceptable”, respectively. “clearly acceptable”, “just acceptable”, “just unacceptable”, and “clearly unacceptable” were labelled on the four nodes. Subjects could not remember what they rated last time, thus the ratings were only based on their feelings at that time. The example of all the scale formats can be found in Annex 5A.

In addition, other factors which may have an impact on sleep quality were included in the ESD. They were nap length, sleepiness before sleep, exercise time, dinner time, had heavy dinner or not, coffee/tea/caffeinated beverages/alcohol/cigarette consumption, any use of pills/herbal tea/essential oil, screen time before sleep, and health status. In the MSD, the information included the number of adults and children, sleepiness level, reasons for waking up during sleep last night, window/door status during sleep last night, and sleep quality. Sleep quality was assessed by the Groningen Sleep Quality Scale (GSQS), which is one of the standard questionnaires assessing sleep quality for the previous night. The replies on the sleep diaries could be made by clicking the link icon displayed on the tablet we delivered or by scanning the QR codes via their phone and were available in English or Danish.

5.2.3 Measurements

5.2.3.1 Physical environment

Measured bedroom environmental parameters included CO_2 levels, temperature, relative humidity and light intensity. The specification of the instruments is listed in Table 5. 1. All the instruments were put in an instrument box and the subjects were asked to place the box around one meter away from the head and the same height as the bed during sleep. They were also asked to keep the box plugged in for the entire measuring period.

The subjects were asked not to enter the bedroom for at least half an hour the next morning after leave and keep the windows and door the same status as they were sleeping since air change rates (ACRs) would be calculated by the CO_2 decay of the morning.

Table 5. 1 Specification of the instruments.

Parameter	Device	Range (unit)	Accuracy	Interval
CO_2		0 - 5000 ppm	± (2 % of range ± 2% of reading)	
Temperature	Vaisala GMW22	0 - 50 °C	± 0.5 °C – ± 0.6 °C	5 min
Relative humidity		0 - 95%	± 0.25% – ± 4.0%	
Light intensity	HOBO U12	1-3000 lumens/ft^2	-	

5.2.3.2 Sleep quality

Subjective sleep quality was assessed by the GSQS in the MSD as mentioned above. GSQS score ranges from 0 to 14 and a higher score indicates poorer sleep quality the previous night. A score higher than 5 indicates a disturbed sleep quality, and a score of 0-2 refers to undisturbed sleep [20, 22]. However, the GSQS score of 3-5 is an undefined range.

Two types of Fitbit - Charge 2 and Alta HR, were used as sleep trackers to measure objective sleep quality. Fitbit, which determines awakenings and sleep stages based on movement and cardiac sensors [226], was reported to have good agreement with polysomnography in measuring time asleep (total sleep time) and sleep efficiency, and have gross estimates of sleep stages, although it underestimated sleep latency [14]. Fitbit or other similar actigraphy was used in previous similar studies [8, 15, 16, 60].

Sleep start time, sleep end time, time in bed (TIB), number of awakenings, minutes asleep, minutes light sleep (N1 ± N2), minutes deep sleep (N3), minutes rapid eye movement (REM) sleep, and sleep latency can be obtained by the sleep tracker. Sleep efficiency and percentages of light, deep, and REM sleep were calculated by "(minutes asleep ÷ TIB) × 100" and "(minutes light/deep/REM sleep ÷ minutes asleep) × 100", respectively. Higher percentages of deep/REM sleep (lower percentage of light sleep) and sleep efficiency indicate better sleep quality.

The subjects were asked to wear the sleep tracker on the non-dominant wrist during sleep and synchronize it via the Fitbit App on the tablet in the mornings of all the weekdays during the experiment week.

5.2.3.3 Wrist skin temperature

The wrist skin temperature was measured by the I-Button DS1922L, where the measuring range was -40 – 85 °C with ± 0.5 °C resolution and 5-min intervals. The I-Button was attached on a Velcro wristband and worn by the subjects during sleep of all the weekdays during the experiment week.

5.2.4 Statistical analyses

The first step was to sort out sleep start time (SST) and sleep end time (SET) based on the recordings from the sleep trackers and sleep diaries. Given that the sleep trackers record sleep start and end time accurately, and sleep stages were not always being tracked, the process to select SST and SET is shown in Figure 5. 1. All the mean, median, quartiles, etc. of physical parameters were calculated during sleep time based on the ranges of the SST and SET selected by this process.

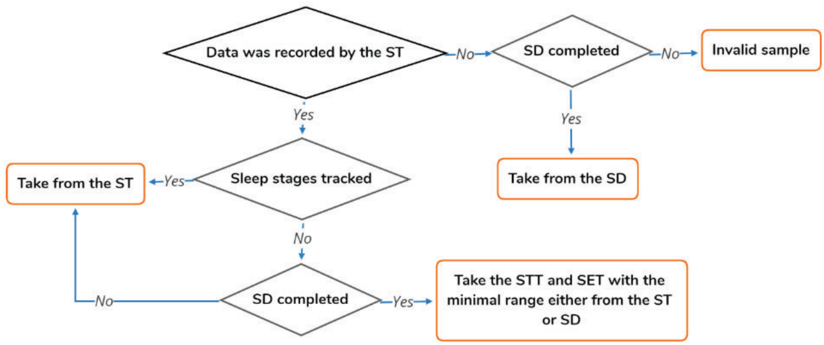


Figure 5. 1 Selection of sleep start time (SST) and sleep end time (SET).
The orange square indicates the decision. The diamond indicates the decision question.
ST, sleep tracker. SD, sleep diaries (incl. ESD and MSD).

Only 75 participants completed the measurements of CO_2 levels and sleep parameters from the sleep tracker, which were regarded as the key parameters. Among the 75 subjects, 14 of them replied to the SD for only one night's sleep. For the remaining 61 subjects, the data of the sleep parameters and CO_2 levels of either the 1st or 2nd night were from the same distribution (see Annex 5B). Therefore, the data was picked for either the 1st or 2nd night randomly for those 61 subjects. Afterward, 70 subjects had no missing values, while 3 subjects had missed ESD, and 2 subjects missed both ESD and MSD. The final sample size was 75 after the missing values of ESD and MSD had been handled. Besides, 2 other subjects missed skin temperature in the final dataset.

Within the dataset, the missing values accounted for 2.7 - 6.7% and were filled in using model-based imputation between the variable to be filled and the most correlated variable in the dataset. Mean, median, or mode imputation was easy to manipulate, while model-base imputation is an improvement over them and suitable for missing data at random [227]. Hence, model-based imputation was chosen.

The two-sample Kolmogorov–Smirnov test was used to analyse if the data from the first and second nights were from the same distribution. The Mann-Whitney *U* test was used to analyse the difference of CO_2 levels between ventilation types or window and door status. Spearman's correlation coefficients were used to analyse the correlations between any two of the variables. All the variables significantly correlated to the sleep parameters were included in the subsequent models as either main variables or adjustments.

After the descriptive and crude analyses as mentioned above, we adopted random forest (RF) regression models to further explore the association between perceived air quality/CO_2 levels and sleep parameters. RF is one of the most powerful machine learning (ML) algorithms. It is a completely non-parametric method, and can handle large numbers of variables and cope with collinearity and outliers [228]. A 10-fold cross-validation was used in the grid search to tune the optimal hyper-parameters including the number of trees, the depth of the tree, minimum number of splits, and minimum number of leaf samples for the RF regression models [228].

For regression challenges, there are also other ML algorithms – Ridge regression, Lasso regression, artificial neural network (ANN), and support vector regression (SVR). Ridge or Lasso regression belongs to linear regression so we have to assume that output and input are linear correlated. However, this may not be the case. For example, we cannot assume that the higher the temperature, the better the sleep quality. The ANN is also inappropriate since it is data hungry, whereas we only have a small sample size. The SVR is also possible to be used, but a lot of pre-processing is needed before analyses. However, we can use the data as it is for RF, which is also a very flexible, non-linear algorithm, and it handles outliers and collinearity problems. Besides, RF was performed well during previous regression analyses [229, 230].

Although the RF regression is very robust, it is not easy to interpret the results. Therefore, Shapley additive explanation (SHAP) values, which were introduced by Lundberg and Lee [231], were used to understand the associations between features and model outputs, and mean absolute SHAP values were used to rank feature importance [232]. SHAP values can give us an insight into the extent and directions that the inputs influence the output.

Root mean square error (RMSE), (equation (1)) and adjusted R^2 (equation (2)) were utilized for evaluating the model performance.

$$RMSE = \sqrt{\frac{1}{n}\sum_i^n (y - \hat{y})^2} \tag{1}$$

where y and $\hat{y}$ are actual and predicted values of the model output, respectively; n is the number of cases.

$$Adjusted\ R^2 = 1 - \frac{(1-R^2)(n-1)}{n-m-1} \tag{2}$$

where R^2 is the original multiple correlation coefficient; n is the number of cases; m is the number of variables.

Statistical analyses and plots were performed by using “scikit-learn”, “statsmodels”, “matplotlib”, “seaborn”, and “forestci” packages in Python (version 3.8.11). All analyses were considered statistically significant when the p-value was less than 0.05 (2-tailed).

5.3 Results

5.3.1 Subjects

Table 5. 2 shows the demographics information of the subjects. In general, the subjects were healthy and young adults and non-smokers with normal body mass index (BMI). However, there were 15 subjects either working at night or shift, but no significant differences in the sleep parameters were found between those working during daytime and at night/shift. The median

number of awakenings for two adults in the bedroom during sleep was 29 (interquartile range (IQR), 24-35.5), which was slightly higher than that for one adult – 25.5 (21-34.5), the effect close to significance (*p*-value < 0.1). Besides, females had a significantly higher percent of REM sleep than males (median, IQR; 24.1, 18.7-27.6% vs. 20.6, 17.4-25.1%). The 9 subjects, whose BMI were not in the range of 18.5-29.9, had significantly longer sleep latency (13.0, 9.3-15.8 min vs. 8.3, 4.9-12.6 min), but a higher percent of REM sleep (27.2, 25.1-27.9% vs. 21.7, 17.8-26.1%) and fewer number of awakenings (24, 15-26 times vs. 27, 23.5-36 times). Age, within the narrow range in which the subjects fell, and smoke frequency was not correlated with any of the sleep parameters.

Table 5. 2 Demographics information of the subjects.

Item		Result
1. Gender, n (%)		
	Male	41 (54.7)
	Female	34 (45.3)
2. Age, median (25^{th} – 75^{th}), years		26 (24 - 32)
3. BMI [a], median (25^{th} – 75^{th}), kg/m^2		22.2 (20.7 – 24.1)
4. Number of adults in the room during sleep, n (%)		
	One	50 (66.7)
	Two [b]	25 (33.3)
5. Chronic disease [c], n (%)		
	No	69 (92.0)
	Yes	6 (8.0)
6. Smoke, n (%)		
	Never	68 (90.7)
	Regularly	1 (1.3)
	Occasionally	6 (8.0)
7. Shift work/study, n (%)		
	Daytime	60 (80.0)
	Night-time	3 (4.0)
	Day and night (on shift)	12 (16.0)
8. Window and door status during sleep, n (%)		
	Both closed	33 (44.0)
	Only the door open	17 (22.7)
	Only windows open	14 (18.7)
	Both open	11 (14.7)

[a] calculated by "weight (kg) / [height (m)]^2". [b] "two adults in the room during sleep" includes two samples of "two adults + one child" and "two adults + two children".

[c] asthma, rhinitis, hay fever, eczema, migraine headaches/recurring headaches, diabetes, or other.

BMI: body mass index.

44.0% of the subjects slept with the window and door closed, while the remaining slept with either window or door open. The fractions of “window or door open” is shown in Table 5. 2. “Either window or door open”, the situation used for the following analyses, contains the scenarios of “only window open”, “only door open”, and “both window and door open”. No significant differences in the sleep parameters were found among the subgroups of those open status. All the other responses are shown in Annex 5C Table A5. 1.

5.3.2 Bedroom environment

5.3.2.1 Perceived environment

Table 5. 3 and Table 5. 4 show the distribution of bedroom environment perception and the difference of bedroom environment perception between window and door status. Overall, the subjects rated the bedroom environment before or during sleep as slightly cool, not dry nor humid, slightly dark, the air slightly fresh, quiet, and a slight odour. They rated the bedroom environment after sleep as slightly cool, not dry nor humid, slightly dark, the air slightly stuffy, quiet, and a slight odour.

Perceptions of thermal comfort and air quality during sleep might not be accurate as people would not have clear sensations during sleep. However, people can be easily disturbed by noise during sleep and four subjects found the acoustic comfort during sleep unacceptable. All the subjects found the visual comfort during sleep acceptable.

Perceived air quality before, during, and after sleep were significantly different between “window and door closed” and “either window or door open”. Perceptions of thermal comfort before sleep and humidity after sleep tended to be slightly more acceptable and dryer with window and door open, respectively, compared to with either window or door open. Overall indoor environmental quality (IEQ) was deduced by averaging thermal comfort, air quality, and acoustic comfort, which can be related to ventilation. Ventilation causes noise, influences thermal comfort depending on the outdoor temperature, and improves air quality. The subjects found IEQ more acceptable with either window or door open, compared to it with both closed.

Figure 5. 2 shows the distribution of bedroom environment perception before, during and after sleep. All the subjects found IEQ acceptable before and during sleep, but some of them found it to be unacceptable after sleep, mainly because of poor perceived air quality, which can be seen in Figure 5. 2. All significant results of the differences of bedroom environment perception before and after sleep are displayed in this Figure. The thermal sensation was rated slightly warmer after sleep compared to before sleep, although it did not reach statistical significance. However, air quality and thermal comfort were rated significantly less acceptable after sleep than before sleep, and air stuffiness and odour show similar trends, especially air stuffiness. Overall, IEQ was rated less acceptable after sleep compared to before sleep. Detailed data are shown in Annex 5E Table A5. 3.

Table 5. 3 Distribution of bedroom environment perception.

Item	Mean ± std.	Min	25%	50%	75%	Max
1. Bedroom environment perception before sleep						
(1) Cold (0) – Hot (100)	45.4 ± 14.9	15.0	34.0	43.0	53.0	83.0
(2) Too dry (0) - Too humid (100)	47.1 ± 10.3	17.0	44.0	49.0	51.0	72.0
(3) Too dark (0) - Too bright (100)	31.8 ± 17.9	5.0	18.0	27.0	40.5	83.0
(4) Fresh (0) - Stuffy air (100)	34.6 ± 20.3	2.0	16.5	34.0	47.0	83.0
(5) Quiet (0) - Noisy (100)	23.3 ± 19.7	1.0	8.0	17.0	33.0	77.0
(6) No (0) - Strong odour (100)	20.2 ± 18.8	1.0	6.5	16.0	27.0	99.0
(7) Thermal comfort [b]	21.8 ± 14.3	1.1	10.0	20.0	30.6	56.7
(8) Air quality [b]	22.2 ± 15.1	0.0	10.0	21.1	30.6	55.6
(9) Acoustic comfort [b]	21.5 ± 17.3	1.1	7.8	16.7	29.4	91.1
(10) IEQ [c]	21.8 ± 11.6	1.1	15.0	19.6	27.0	50.0
2. Bedroom environment perception during sleep						
(1) Cold (0) – Hot (100)	46.6 ± 16.3	6.0	34.0	48.0	57.5	83.0
(2) Too dry (0) - Too humid (100)	46.2 ± 13.0	13.0	38.0	48.0	51.0	83.0
(3) Too dark (0) - Too bright (100)	26.2 ± 14.7	6.0	17.0	20.0	34.5	69.0
(4) Fresh (0) - Stuffy air (100)	37.0 ± 21.2	3.0	17.0	36.0	54.5	88.0
(5) Quiet (0) - Noisy (100)	17.6 ± 16.6	0.0	6.5	12.0	21.5	81.0
(6) No (0) - Strong odour (100)	20.0 ± 18.2	1.0	7.0	16.0	25.7	98.0
(7) Thermal comfort [b]	24.7 ± 15.5	0.0	12.2	23.3	35.6	60.0
(8) Air quality [b]	24.7 ± 14.4	2.2	11.1	24.4	37.2	62.2
(9) Acoustic comfort [b]	17.3 ± 14.2	1.1	6.1	13.3	23.9	65.6
(10) IEQ [c]	22.2 ± 11.8	1.5	13.0	20.7	30.9	48.1
(11) Visual comfort [b]	14.9 ± 12.3	2.2	6.1	11.1	20.0	46.7
3. Bedroom environment perception after sleep						
(1) Cold (0) – Hot (100)	47.6 ± 15.8	12.0	35.0	48.0	58.5	83.0
(2) Too dry (0) - Too humid (100)	47.7 ± 14.2	18.0	39.5	49.0	53.5	90.0
(3) Too dark (0) - Too bright (100)	38.2 ± 22.1	4.0	21.0	33.0	53.0	82.0
(4) Fresh (0) - Stuffy air (100)	46.3 ± 24.2	3.0	26.0	52.0	65.5	89.0
(5) Quiet (0) - Noisy (100)	24.5 ± 19.1	1.0	10.5	19.0	32.5	90.0
(6) No (0) - Strong odour (100)	24.3 ± 20.3	0.0	9.0	20.0	32.0	99.0
(7) Thermal comfort [b]	26.6 ± 16.5	4.4	12.8	25.6	41.1	76.7
(8) Air quality [b]	30.4 ± 16.9	3.3	13.3	32.8	44.4	71.1
(9) Acoustic comfort [b]	20.1 ± 16.7	2.2	7.2	15.6	27.8	91.1
(10) IEQ [c]	25.7 ± 12.7	3.7	16.7	25.2	33.9	63.8

[a] calculated by the Mann-Whitney *U* test.

[b] 0, clearly acceptable; 49.9, just acceptable; 50.1, just unacceptable; 100, clearly unacceptable.

[c] defined as "(thermal comfort ± air quality ± acoustic comfort)/3".

IEQ, indoor environmental quality.

Table 5. 4 The difference of bedroom environment perception between window and door status.

Item	Quartiles						*p*-value [a]
	Mean ± std.	Min	25%	50%	75%	Max	
1. Bedroom environment perception before sleep							
(1) Thermal comfort [b]							
Window and door closed	19.5 ± 14.7	1.1	6.7	15.6	29.2	56.7	*0.063*
Either window or door open	21.8 ± 17.4	1.1	7.8	15.6	39.4	63.3	
(2) Air quality [b]							
Window and door closed	26.2 ± 16.2	4.4	11.1	25.6	44.4	54.4	**0.041**
Either window or door open	19.0 ± 13.6	0.0	7.5	18.9	24.7	55.6	
2. Bedroom environment perception during sleep							
(1) Fresh (0) - Stuffy air (100)							
Window and door closed	42.3 ± 19.6	6.0	31.0	46.0	56.0	78.0	**0.045**
Either window or door open	32.9 ± 21.7	3.0	13.0	31.0	49.0	88.0	
3. Bedroom environment perception after sleep							
(1) Too dry (0) - Too humid (100)							
Window and door closed	45.2 ± 17.5	18.0	31.5	47.0	52.5	90.0	*0.058*
Either window or door open	49.7 ± 10.7	18.0	45.8	50.0	56.0	69.0	
(2) Fresh (0) - Stuffy air (100)							
Window and door closed	55.6 ± 22.4	4.0	41.5	61.0	68.5	89.0	**0.002**
Either window or door open	39.0 ± 23.3	3.0	13.8	40.5	61.3	86.0	
(3) No (0) - Strong odour (100)							
Window and door closed	28.9 ± 20.4	0.0	12.0	25.0	45.0	69.0	**0.046**
Either window or door open	20.7 ± 19.7	2.0	7.8	13.5	28.3	99.0	
(4) Air quality [b]							
Window and door closed	35.9 ± 16.5	8.9	22.2	41.1	46.7	71.1	**0.009**
Either window or door open	26.1 ± 16.2	3.3	9.7	27.2	38.9	57.8	
(5) IEQ [c]							
Window and door closed	29.4 ± 13.3	7.0	23.0	26.3	40.7	63.8	**0.038**
Either window or door open	22.8 ± 11.5	3.7	14.8	23.1	30.4	46.3	

[a] calculated by the Mann-Whitney *U* test.

[b] 0, clearly acceptable; 49.9, just acceptable; 50.1, just unacceptable; 100, clearly unacceptable.

[c] defined as "(thermal comfort ± air quality ± acoustic comfort)/3".

IEQ, indoor environmental quality.

Bold indicates significant results.

Italic indicates 0.05< *p*-value < 0.1.

Only significant results are shown in this table. Full data are in Annex 5D Table A5. 2.

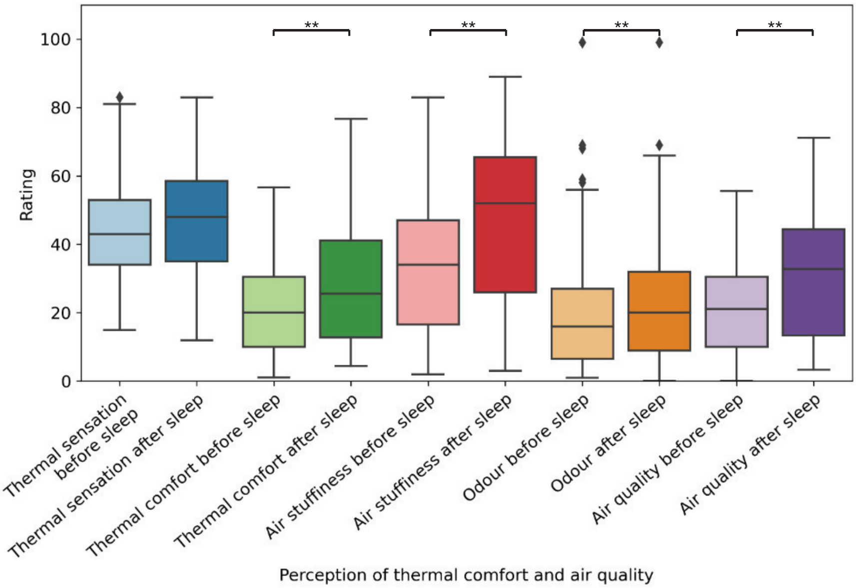


Figure 5. 2 Distribution of the perception of thermal comfort and air quality before and after sleep.
IEQ, indoor environmental quality. The diamond indicates outliers.
*** p-value < 0.01. p-values were calculated by the non-parametric Wilcoxon matched-pairs signed-ranks test.*

5.3.2.2 Physical environment

Figure 5. 3 shows the mean CO_2 level, mean temperature, and relative humidity before, during, and after sleep. The CO_2 levels before and after sleep were mean CO_2 concentrations within "10 min before and after sleep start time" and "10 min after sleep end time", respectively. The CO_2 level was significantly increasing from before sleep, during sleep, to after sleep. The mean room temperature was not significantly different between before, during, and after sleep. Relative humidity slightly but significantly increased after sleep compared to before/during sleep. Detailed data of CO_2, temperature and relative humidity are shown in Annex 5F Table A5. 4, as well as light intensity. Besides, mean CO_2 was the only physical environmental parameter showing a difference between two window and door status. The median ACR was 0.44 h^{-1} (0.25 – 0.88 h^{-1}) (4 samples missed).

Figure 5. 4 shows the regression line between perceived air quality and mean CO2 levels during sleep. An increase of 10 points in perceived air quality was significantly associated with an increase of 167 ppm for mean CO_2 levels.

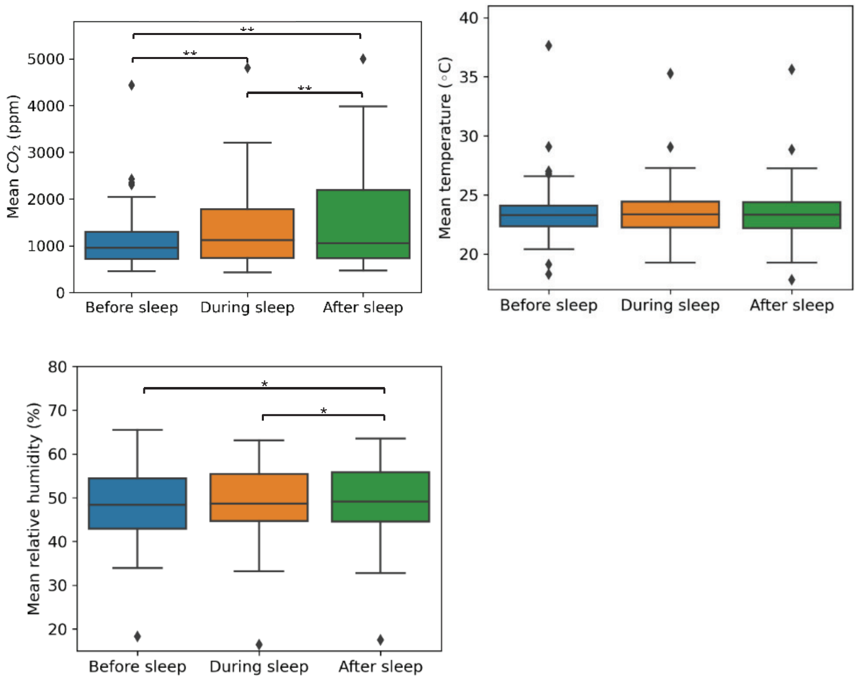


Figure 5. 3 Distribution of CO_2 level, mean temperature, and relative humidity before, during, and after sleep. The diamond indicates outliers.

** p-value < 0.05, ** p-value < 0.01. p-values were calculated by the non-parametric Wilcoxon matched-pairs signed ranks test.*

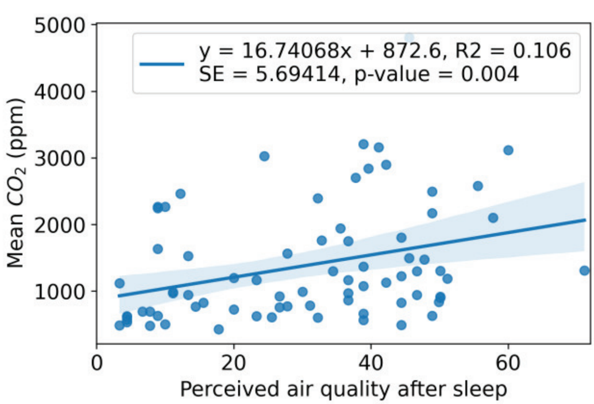


Figure 5. 4 The regression line between perceived air quality and mean CO_2 levels during sleep.

5.3.3 Bedroom ventilation

Figure 5. 5 shows that mean CO_2 levels (CO_2 levels below) during sleep were significantly lower with "either window or door open" or mechanical ventilation (MV), compared to nights with "window and door closed" or other types of ventilation, respectively. The mean CO_2 levels during sleep were 1631.9 (IQR, 942.5-2535.3) and 888.0 (624.2-1222.4) ppm with "window and door closed" and "either window or door open", respectively, while they were 782.6 (630.0-971.6) and 1210.3 (785.8-2062.4) ppm with MV and other types of ventilation, respectively. Two outliers shown in the group of MV indicate that the two bedrooms might have air terminals but the terminals were kept shut during sleep or the system was malfunctioning. Three outliers in the group of "either window or door open" had the window closed but door open during sleep, indicating inadequate ventilation of the space towards which the bedroom door opens.

Figure 5. 6 shows that the mean CO_2 level was significantly lower with either window or door open, compared to with window and door closed, when other types of ventilation (OV) are considered. However, different window and door status did not result in significant differences in the CO_2 levels for mechanical ventilation (MV). The distributions of CO_2 levels could be very similar without the outliers shown in Figure 5. 5(B). On the other hand, the CO_2 levels were not significantly different between window and door status probably due to limited sample size and outliers in the subgroup of MV.

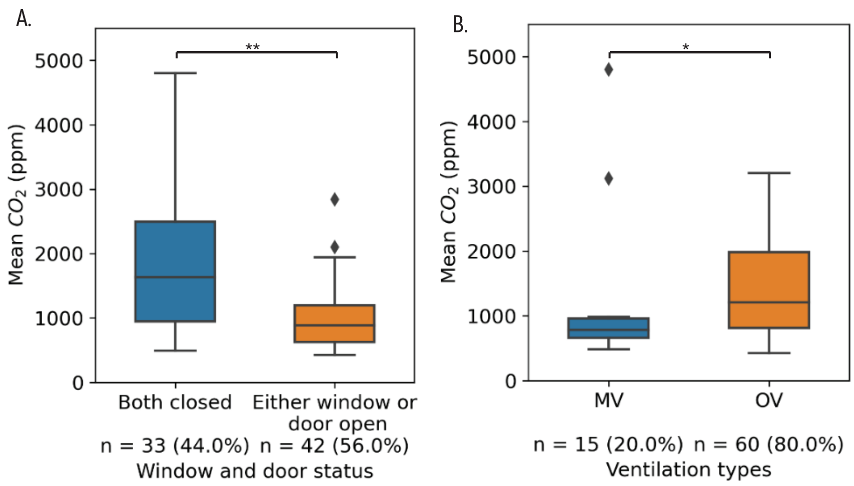


Figure 5. 5 Mean CO_2 of different window and door status (A) and ventilation types (B) during sleep.
MV, mechanical ventilation; OV, other ventilation types.
The diamond indicates outliers.
** p-value < 0.05, ** p-value < 0.01. p-values were calculated by the Mann-Whitney U test.*

Figure 5. 7 shows that the mean CO_2 level was substantially and significantly higher with two adults in the room during sleep compared to with one adult when window and door were closed, whereas the CO_2 levels were not much different between the number of adults in the room during sleep when sleeping with either window or door open.

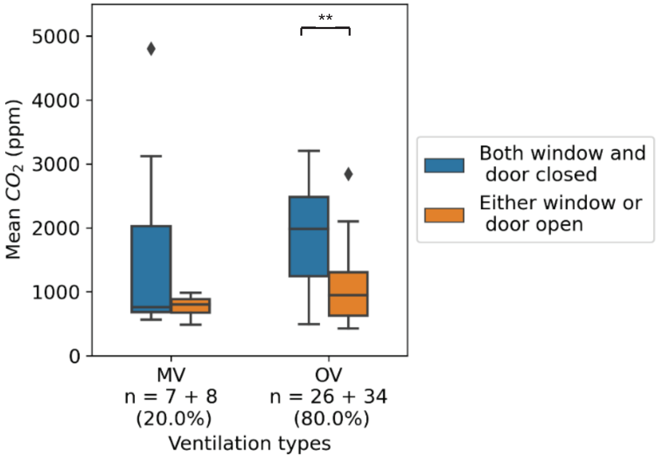


Figure 5. 6 Mean CO_2 between two "window and door status" for different ventilation types during sleep.
MV, mechanical ventilation; OV, other types of ventilation.
The diamond indicates outliers.
*** p-value < 0.01. p-values were calculated by the Mann-Whitney U test.*

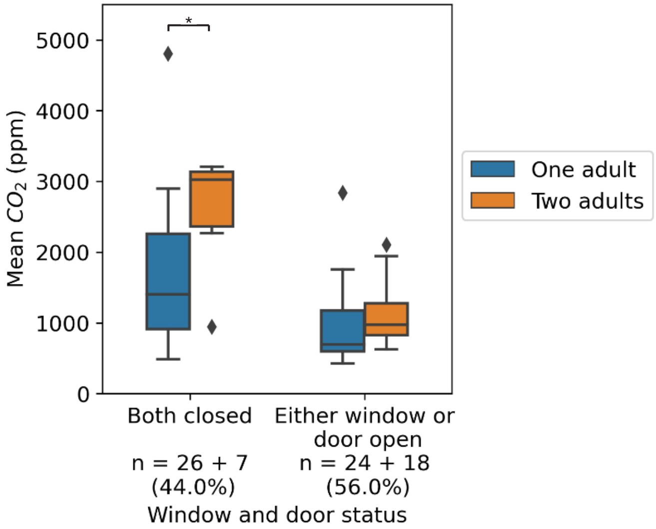


Figure 5. 7 Mean CO_2 between one and two adults for different window and door status during sleep.
"Two adults" includes two samples of "two adults + one child" and "two adults + two children".
The diamond indicates outliers.
** p-value < 0.05. p-values were calculated by the Mann-Whitney U test.*

5.3.4 Sleep quality

Table 5. 5 shows the distribution of GSQS and sleepy levels after sleep. In general, the subjects rated GSQS between 1.0 and 6.0, and as typically sleepy (1.0) to somewhat awake (3.0). 33.3% of the occupants had undisturbed sleep quality with GSQS below or equal to 2, while 30.7% of the occupants had poor sleep quality with GSQS above 5. The remaining 36.0% of subjects had a GSQS of 3-5, which is an uncertain range.

Figure 5. 8 shows the GSQS and sleepiness levels after sleep between window and door status. The subjects who slept with window and door closed, rated the median GSQS two points higher compared to those who slept with either window or door open. In addition, the subjects who slept with the window and door closed were sleepier after sleep compared to those who slept with the window or door open. In addition, GSQS was weakly correlated with noise condition during sleep (ρ = 0.267, p-value < 0.05) and visual comfort during sleep (ρ = 0.255, p-value < 0.05).

Table 5. 5 Distribution of GSQS and sleepy levels after sleep.

Item		Quartiles				
	Mean ± std.	Min	25%	50%	75%	Max
1. GSQS (0-14, good to poor sleep quality)	4.1 ± 3.2	0	1.0	4.0	6.0	14.0
2. Sleepy levels after sleep (0, very sleepy; 5, widely awake)	2.0 ± 1.2	0	1.0	2.0	3.0	4.0

GSQS, Groningen Sleep Quality Index.

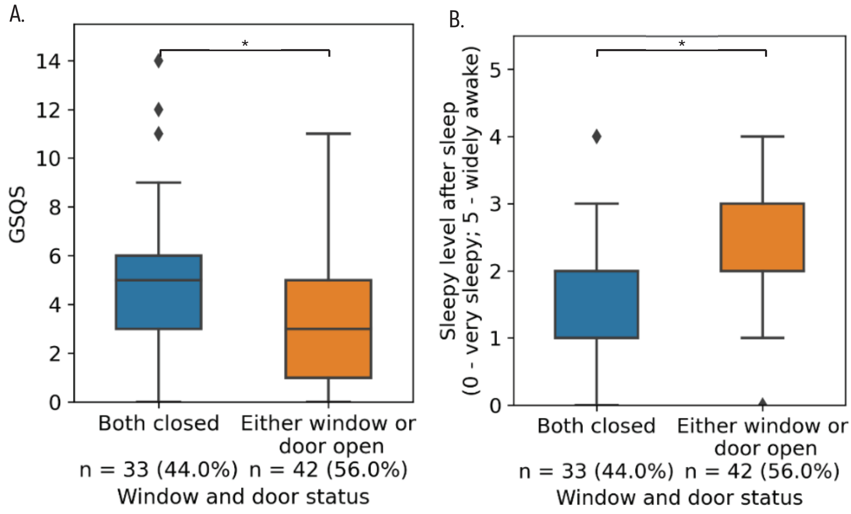


Figure 5. 8 GSQS (A) and sleepy levels (B) after sleep between the different window and door status. Data shows in Annex 5G Table A5. 5.
The median of the sleepy level after sleep was 2.0 – somewhat sleepy for both window and door status.
GSQS, Groningen Sleep Quality Scale.
* p-value < 0.05. p-values were calculated by the Mann-Whitney U test.

Table 5. 6 shows the distribution of the objective sleep parameters, and Table 5. 7 shows the number and fraction of the subjects in the recommended appropriate, uncertain, and inappropriate ranges of the sleep parameters among people aged 26–64 years by the American National Sleep Foundation (see Table 1. 1). Only 41.3% of the subjects slept for appropriate 7-9 hours, whereas 27 subjects slept for 6-7 hours and 1 subject 9.7 hours (> 9 hours), which were defined as uncertain ranges. More than half of the subjects did not have enough sleep time compared to what is recommended. 81.3% of the subjects had sleep efficiency within an appropriate range (> 85%), and the remaining subjects had it within the uncertain range of 75-85%. The appropriate range of "N1 + N2 (light)" is 50–63%. 57.3% of the subjects had appropriate light sleep of 50-63%, whereas 7 and 24 subjects had it "less than 50%" and "between 63-83%", respectively. Only 33.3% of the subjects had appropriate deep sleep (N3) of 16–20%, while 23 (30.7%) and 26 subjects (34.7%) had it in the uncertain ranges between 6-15% and more than 20%, respectively. 53.3% of the subjects had appropriate REM sleep of 21-30%, and 31 (41.3%) and 4 subjects (5.3%) had it within uncertain ranges of less than or equal to 20% and 31-40%, respectively. All the subjects had appropriate sleep latency, which is below 30 min. A total of 16, 1, and 1 subjects had inappropriate ranges of time asleep (< 6 hours), light sleep (> 80%), and deep sleep (≤ 5%), respectively. No subject was in the inappropriate ranges for the other sleep parameters. In general, the variation of each objective sleep parameter was considerable, and the sleep quality of the subjects was not good due to either insufficient time asleep or sleep stages in percent.

The objective sleep parameters were not correlated with the GSQS.

Table 5. 6 Distribution of the objective sleep parameters.

Item	Quantiles					
	Mean ± std.	Min	25%	50%	75%	Max
Sleep start time	23:45 ± 1:27	20:17	23:04	23:38	0:34	3:56
Sleep end time	7:26 ± 1:25	1:50	6:36	7:18	8:18	10:54
Time in bed (min)	461.4 ± 77.0	201.0	416.5	470.0	505.5	650.0
Number of awakenings (NOA)	27.8 ± 8.5	8.0	22.0	27.0	35.0	44.0
NOA/hour asleep	4.1 ± 1.0	1.6	3.4	4.1	4.8	6.4
Sleep latency (min)	9.4 ± 6.2	0.5	5.0	9.0	13.0	25.0
Minutes asleep	404.8 ± 67.4	179.0	363.5	408.0	448.0	580.0
Hours asleep	6.7 ± 1.1	3.0	6.1	6.8	7.5	9.7
Minutes light sleep	244.4 ± 52.2	117.0	213.0	241.0	286.5	338.0
Minutes deep sleep	72.2 ± 23.4	13.0	55.5	72.0	89.5	139.0
Minutes REM sleep	88.2 ± 28.8	4.0	72.0	90.0	106.5	162.0
Sleep efficiency (%)	87.8 ± 2.7	81.4	86.1	88.1	89.5	94.6
Light sleep (%)	60.4 ± 8.5	42.5	54.9	59.4	64.5	88.4
Deep sleep (%)	17.9 ± 5.0	3.7	15.0	18.3	21.7	29.8
REM sleep (%)	21.8 ± 5.9	1.0	18.4	23.0	26.4	32.5

Table 5. 7 The number and fraction of the subjects in the appropriate, uncertain, and inappropriate ranges for the sleep parameters.

Item	Appropriate, n (%)	Uncertain, n (%)	Inappropriate, n (%)
Time asleep (h)	31 (41.3)	28 (37.4)	16 (21.3)
Sleep latency (min)	75 (100)	0 (0)	0 (0)
Sleep efficiency (%)	61 (81.3)	14 (18.7)	0 (0)
Light sleep (%)	43 (57.3)	31 (41.4)	1 (1.3)
Deep sleep (%)	25 (33.3)	49 (65.4)	1 (1.3)
REM sleep (%)	40 (53.3)	35 (46.7)	0 (0)

Table 5. 8 shows the self-reported wake-up times and reasons for them during sleep. More than half of the subjects woke up one or more times during sleep, with seven the highest number of reported awakenings. A total of 14 subjects (18.7%) reported waking up because of the sleep environment. Besides, more subjects woke up because of other reasons than physical discomfort, stress and sleep environment. Those reasons consisted of partner/roomie got up while the subject was sleeping, went to the toilet, dreams/nightmares, the phone rang, woke up naturally, cats, noise neighbours, children woke up, own movements, not being able to sleep (no reason), and simply no reasons.

Table 5. 8 Self-reported wake-up times and the reasons to wake up during sleep.

Item	n (%)
1. Number of self-reported wake-up times	
0	29 (38.7)
1	20 (26.7)
2	9 (12.0)
3	10 (13.3)
4	3 (4.0)
5	3 (4.0)
6	0 (0)
7	1 (1.3)
2. Woke up reasons during last night because of	
Stress	4 (5.3)
Sleep environment (bed temperature, humidity, noise, light, and air quality)	14 (18.7)
Physical discomfort (e.g. muscle pain, headache, etc.)	4 (5.3)
Other	24 (32.0)
Did not wake up	29 (38.7)

5.3.5 Wrist skin temperature

Figure 5. 9 shows the wrist skin temperature during sleep on a typical night from 23:17 10 November 2020 to 7:01 11 November 2020. The temperature was 32.2 °C on average and fluctuated during the night of sleep. The maximum drop of the wrist skin temperature during sleep was 2.5 °C.

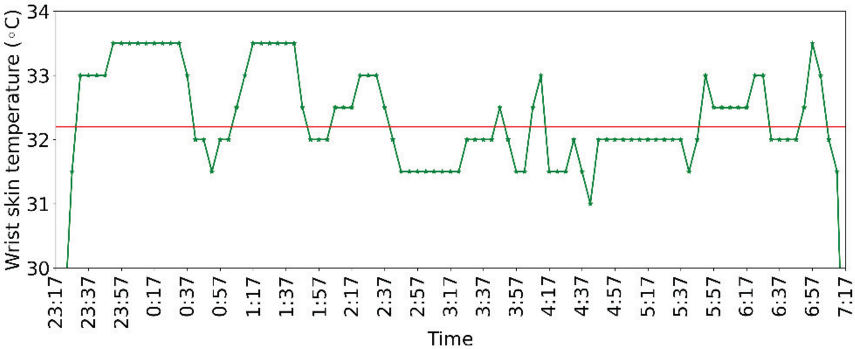


Figure 5. 9 Wrist skin temperature during sleep on a typical night. The Red line indicates the mean skin temperature (32.2 °C) during sleep. Sleep start time and end time were 23:17 and 7:01, respectively.

Table 5. 9 Distribution of the wrist skin temperature (◦C), the drop of it, and the differences between genders.

Item		Quartiles						
		Mean ± std.	Min	25%	50%	75%	Max	*p*-value [a]
Wrist skin temperature								
	Overall	33.9 ± 1.0	31.9	33.1	34.0	34.7	35.6	
	Male	33.4 ± 0.9	31.9	32.7	33.4	34.2	35.1	**< 0.001**
	Female	34.4 ± 0.8	32.4	33.6	34.7	34.9	35.6	
Drop in wrist skin temperature during sleep								
	Overall	2.3 ± 0.8	0.5	2.0	2.5	2.7	4.5	
	Male	2.4 ± 0.8	1.0	2.0	2.5	3.0	4.0	0.310
	Female	2.3 ± 0.8	0.5	2.0	2.4	2.5	4.5	

[a] calculated by the Mann-Whitney *U* test.

Bold indicates significant results.

Table 5. 9 shows the distribution of the wrist skin temperature and the drop of it during sleep, and the differences between genders. The drop of wrist skin temperature was calculated by "max – 25th percentile", and the 25th percentile was used instead of the min value to avoid taking the bedroom temperature as the lowest measured point. Females had an average 1 ◦C higher wrist skin temperature than males. Table 5. 10 shows the thermal sensation and thermal comfort by gender before and after sleep. The 7-point scale of thermal sensation, which was converted from the continuous scale and the standard scale for it, is also shown. We did not use the 7-point scale from the start because it is only a standard scale for thermal sensation, and the continuous scales

were used to uniformly catch more detailed changes in all the ratings. Females felt warmer after sleep than males based on thermal sensation, consistent with the fact that females had higher skin temperature than males and also consistent with a previous study indicating that people felt warmer when their wrist skin temperature was higher [233]. However, no significant difference in thermal comfort was found between genders, nor for the thermal sensation and thermal comfort before sleep between genders.

Table 5. 10 Thermal sensation and thermal comfort between gender before and after sleep.

Item	Quartiles						*p*-value [a]
	Mean ± std.	Min	25%	50%	75%	Max	
1. Before sleep							
(1) Cold (0) – Hot (100) [b]							
Male	44.7 ± 14.5	18.0	33.5	41.0	53.0	81.0	0.554
Female	46.3 ± 15.5	15.0	34.8	44.7	60.5	83.0	
Convert to the 7-point scale:							
Male	0.1 ± 1.0	-1.7	-0.6	-0.1	0.7	2.7	0.554
Female	0.2 ± 1.1	-1.9	-0.5	0.1	1.1	2.8	
(2) Thermal comfort							
Male	21.6 ± 14.4	1.1	10.6	18.9	33.9	49.9	0.877
Female	22.0 ± 14.4	3.3	8.9	21.4	31.7	56.7	
2. After sleep							
(1) Cold (0) – Hot (100) [b]							
Male	42.8 ± 14.9	12.0	32.0	43.0	51.0	80.0	**0.003**
Female	53.4 ± 15.1	21.0	39.8	52.0	66.0	83.0	
Convert to the 7-point scale:							
Male	0 ± 1.0	-2.2	-0.8	0	0.6	2.6	**0.003**
Female	0.7 ± 1.1	-1.5	-0.1	0.6	1.6	2.8	
(2) Thermal comfort							
Male	26.2 ± 15.7	4.4	14.4	24.4	34.4	76.7	0.852
Female	27.2 ± 17.5	4.4	8.6	26.7	43.9	56.7	

[a] calculated by the Mann-Whitney *U* test.
[b] thermal sensation.
Bold indicates significant results.

5.3.6 Air quality and sleep quality

Figure 5. 10 shows the regression lines between perceived air quality after sleep and GSQS, and mean CO_2 and deep sleep (%). An increase of 10 points in perceived air quality was significantly associated with an increase of 0.46 (95% CI, 0.04 – 0.09) in GSQS. Higher points indicate a higher unacceptable level of perceived air quality, and 50 is the threshold between acceptability and unacceptability to perceived air quality. Taking the mean GSQS and perceived air quality of 4.1

and 30.4, respectively, as an example, GSQS would change to 5.5, which was defined as disturbed sleep quality, as the perceived air quality increases to 60. Even GSQS was 0, the increase of 60 in perceived air quality would shift GSQS to around 3. The linear regression line also suggests that GSQS could increase by 2.8 as the perceived air quality would increase by 60. Hence, it would be easy for GSQS to fall into the uncertain range of 3-5, or even disturbed range of " > 5" when bedroom occupants rated unacceptability to the air quality.

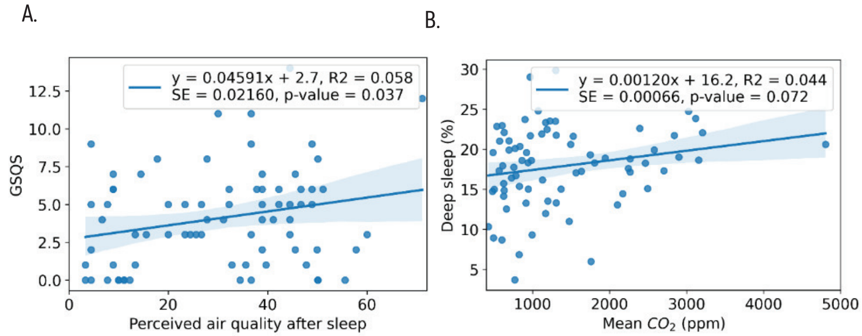


Figure 5. 10 The regression line between (A) perceived air quality after sleep and GSQS, and (B) mean CO_2 and deep sleep (%).

An increase of 500 ppm of mean CO_2 increased deep sleep (%) by 0.60% (95% CI, -0.05 – 1.25%), the effect being close to significance, which means an increase of 3.0% deep sleep from 500 to 3000 ppm. The linear regression line indicates that deep sleep (%) could be outside the recommended range but only by a margin. The appropriate window of deep sleep (16-20%) is only 4%. Therefore, an appropriate ventilation rate would be important for people to have appropriate deep sleep (%). For the two effects of sleep quality parameters above, the one for GSQS was much stronger than the one for deep sleep (%).

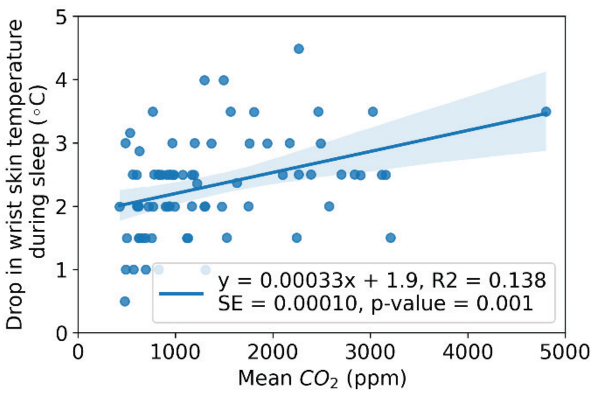


Figure 5. 11 The regression line between mean CO_2 and the drop in wrist skin temperature.

The correlations between perceived air quality/mean CO_2 and the other sleep parameters, including deep sleep (%) (for perceived air quality) or GSQS (for mean CO_2), time asleep, sleep latency, NOA/hour asleep, sleep efficiency, light sleep (%), and REM sleep (%), are not (close to) significant, shown in Annex 5H Figure A5. 1 and Figure A5. 2. However, no significant association was found between window and door status and objective sleep quality (see the boxplot in Annex 5I Figure A5. 3).

Figure 5. 11 shows the regression line between the drop in wrist skin temperature and mean CO_2. An elevation of 1000 ppm of mean CO_2 levels was significantly associated with an increase of 0.33 °C (95% CI, 0.134 – 0.526) drop in wrist skin temperature. In addition, an increased drop in wrist skin temperature was associated with a higher percentage of deep sleep (Figure 5. 12).

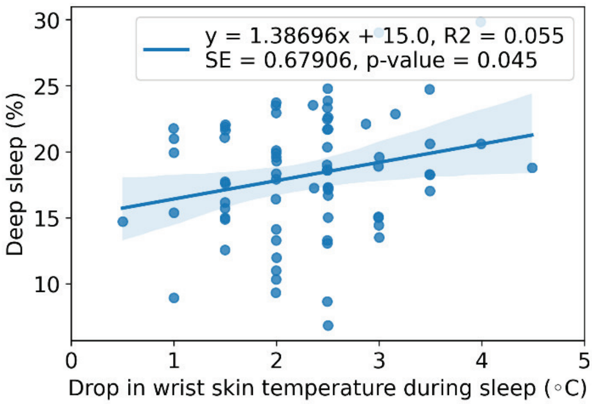


Figure 5. 12 The regression line between the drop in wrist skin temperature and deep sleep (%). Two outliers were removed in this figure (see Annex 5J Figure A5. 4).

Given these correlations, we proceeded by using random forest regression models between the perceived air quality after sleep and GSQS, and between mean CO_2 and deep sleep (%) to further investigate their importance among all the potentially important variables that affect sleep quality and to show a more clear association between air quality and sleep quality after the other variables in the models having been controlled.

5.3.6.1 Variables screening

Four bedroom environmental aspects, namely perceived air quality after sleep, thermal comfort before sleep, noise condition during sleep and visual comfort during sleep were included in the model for predicting GSQS for the following reasons. Significant higher levels of unacceptable air quality were found after sleep compared to before sleep. Thermal comfort before sleep was reported to be associated with sleep quality [234], and it was moderately correlated with thermal comfort during (ρ = 0.461, p-value < 0.01) and after sleep (ρ = 0.659, p-value < 0.01). Noise condition and visual comfort during sleep were correlated with GSQS as mentioned in Section 5.3.4.

Physical measurements of mean CO_2 during sleep, mean temperature during sleep and maximum light intensity before sleep, instead of perceived air quality, thermal comfort and visual comfort because the subjective assessment for the bedroom environment was not correlated with deep sleep (%), were included in the model for predicting % deep sleep. Noise levels were not measured and thus noise condition during sleep rated by the subjects was included in the model.

Other variables in both models involve the drop in wrist skin temperature during sleep; gender; sleepiness level before bed; consumption of coffee, tea, etc.; heavy dinner; an exercise in the morning/afternoon/evening; take something to help sleep; 2 adults in the room during sleep; sleep disturbed by other reasons; did not wake up during sleep; window and door status during sleep. All of those variables were significantly correlated with one or more sleep parameters. We included all of them even though some of them were not directly and significantly correlated to GSQS or % deep sleep. A total of 17 inputs were ended up starting the models.

5.3.6.2 Model performance

The scatter plots between the predicted and actual GSQS/deep sleep (%) are shown in Annex 5K Figure A5. 5 and Figure A5. 6. The adjusted R^2 and RMSE for GSQS were 0.745 and 2.115, respectively; and 0.720 and 3.586 for deep sleep (%). A previous study used five ML algorithms and ended up with the RMSE between 1.75 and 4.59 for the prediction of the students' grades ranged from 0 to 20 (the numbers of variables and sample size were 31 and 395, respectively) [230]. Therefore, we assessed that the models performed well. Besides, the minimum number of leaf samples was set to 3 to avoid overfitting problems (Table 5. 11).

Table 5. 11 shows the optimal hyper-parameters and the test range of the random forest regression model.

Table 5. 11 Optimal hyper-parameters and the test ranges of the random forest regression model.

Hyper-parameter	Optimal hyper-parameter		
	Test range	The model for GSQS	The model for deep sleep (%)
Number of trees	100-2000	500	100
Depth of the tree	2-22	11	22
Minimum number of splits	6-20	6	7
Minimum number of leaf samples	3-15	3	3

5.3.6.3 Model interpretation

Perceived air quality and GSQS

Figure 5. 13 shows the rank of the feature importance (A) and the SHAP values among all the features in the model to predict GSQS (B). "Either window or door open during sleep" was ranked as one of the most important features of GSQS. Perceived air quality after sleep was ranked as the third important feature among all the four aspects of bedroom environment perception. The mean absolute SHAP values of "either window or door open during sleep" and "air quality after sleep" were 0.306 and 0.217, respectively. Other variables, such as did not wake up during sleep, sleep not disturbed by other reasons, a high drop in wrist skin temperature, consumed none of the coffee, tea, etc. after 4 p.m., etc. can be also critical to ensure good sleep quality.

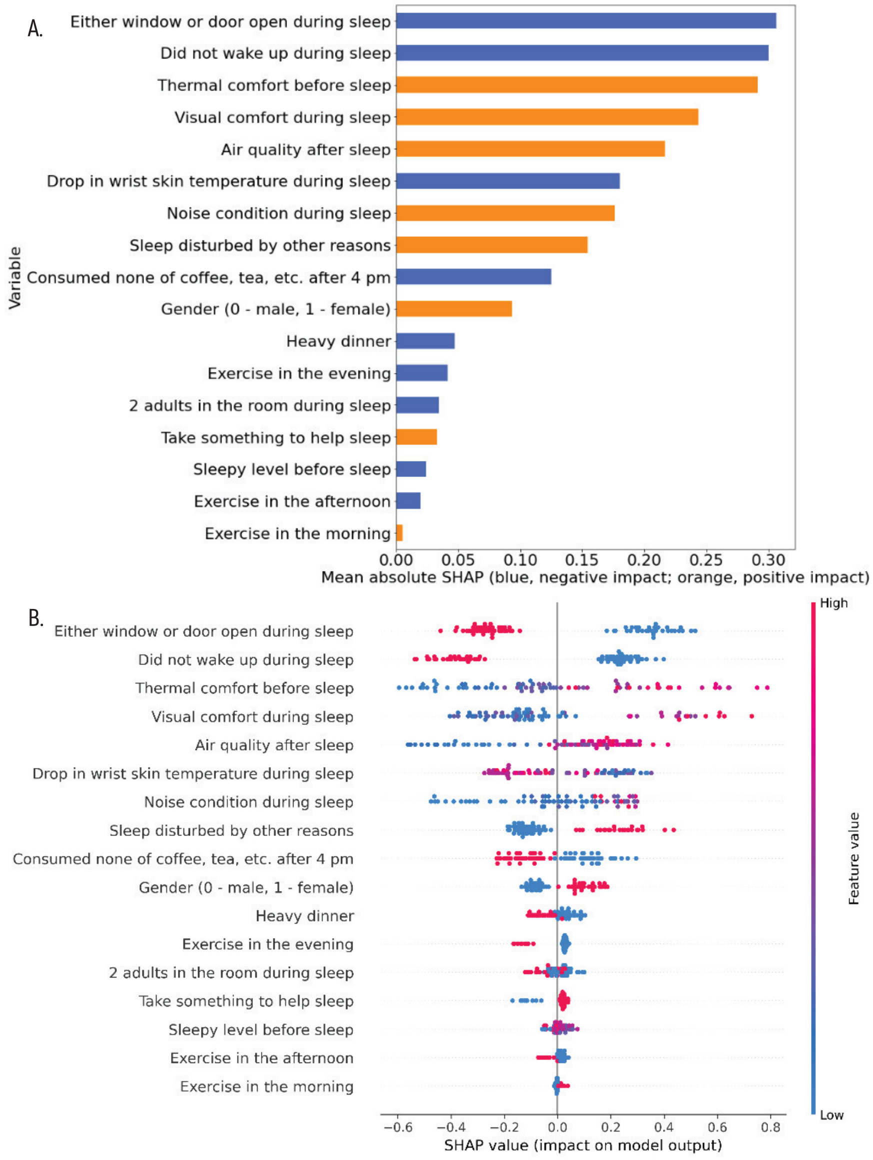


Figure 5. 13 The rank of the feature importance (A) and the SHAP values among all the features in the model to predict GSQS (B). Features are ranked based on the mean absolute SHAP values. High value: either window or door open during sleep, did not wake up during sleep, unacceptable to thermal comfort before sleep; unacceptable to visual comfort during sleep; unacceptable to air quality after sleep; noise condition of noisy during sleep; sleep disturbed by other reasons; consumed none of the coffee, tea, etc. after 4 pm; gender of female; heavy dinner; an exercise in the evening; an exercise in the morning; an exercise in the afternoon; 2 adults in the room during sleep; and take something to help sleep. SHAP, Shapley additive explanation; GSQS, Groningen Sleep Quality Scale.

In Figure 5. 13(B), blue and red indicate low and high values, respectively. Taking "either window or door open during sleep" as an example, red points (value "1") were within the range of negative SHAP values, which means "either window or door open during sleep" pushed the output to the lower GSQS – better sleep quality, while "window and door closed" (value "0") pushed the output to the higher GSQS – poorer sleep quality.

Figure 5. 14 shows the change of the predicted GSQS based on perceived air quality after sleep. The predicted GSQS increased from 3.23 (95%CI, 3.19-3.25) to 4.09 (4.04-4.14) when the unacceptable level of perceived air quality after sleep increased from 4 to 60. The increasing trend of GSQS was rapid within the rating of perceived air quality between 10 to 40 and tended to be more gradual after 40.

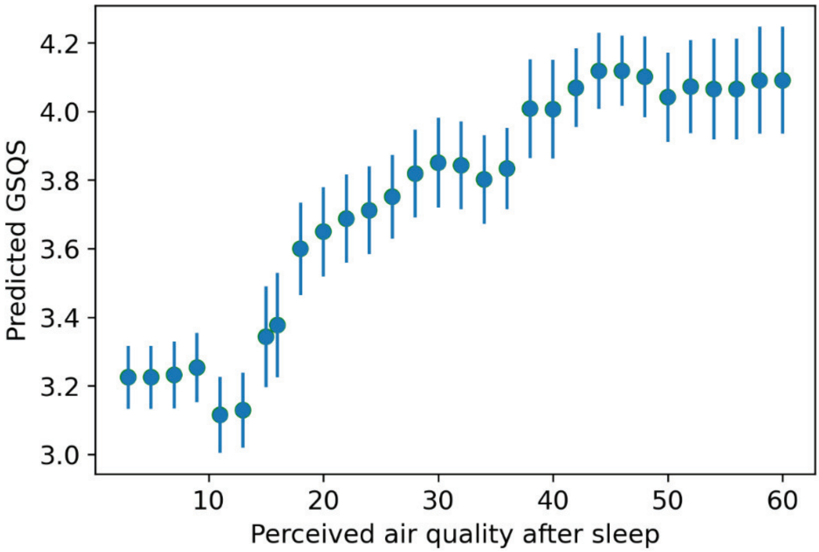


Figure 5. 14 Predicted GSQS and perceived air quality after sleep. GSQS, Groningen Sleep Quality Scale. Error bar indicates standard error.
Note: the prediction of GSQS would be different if the set-up of the artificial person changed, while the predicted trend would be similar.

The artificial person for the prediction in Figure 5. 14 was set to "male; no heavy dinner; 1 adult in the room during sleep; did not exercise during the morning, afternoon, and evening; did not take anything to help sleep; consumed none of the coffee, tea, etc.; was not disturbed by other reasons during sleep; did not wake up during sleep; window and door closed during sleep". Thermal comfort before sleep, noise condition during sleep, visual comfort during sleep, the sleepy level before sleep, and the drop in wrist skin temperature were respectively set to 21.8, 17.6, 14.9, 1.9, and 2.3 ◦C, the mean of all the samples in this study.

CO_2 levels and deep sleep

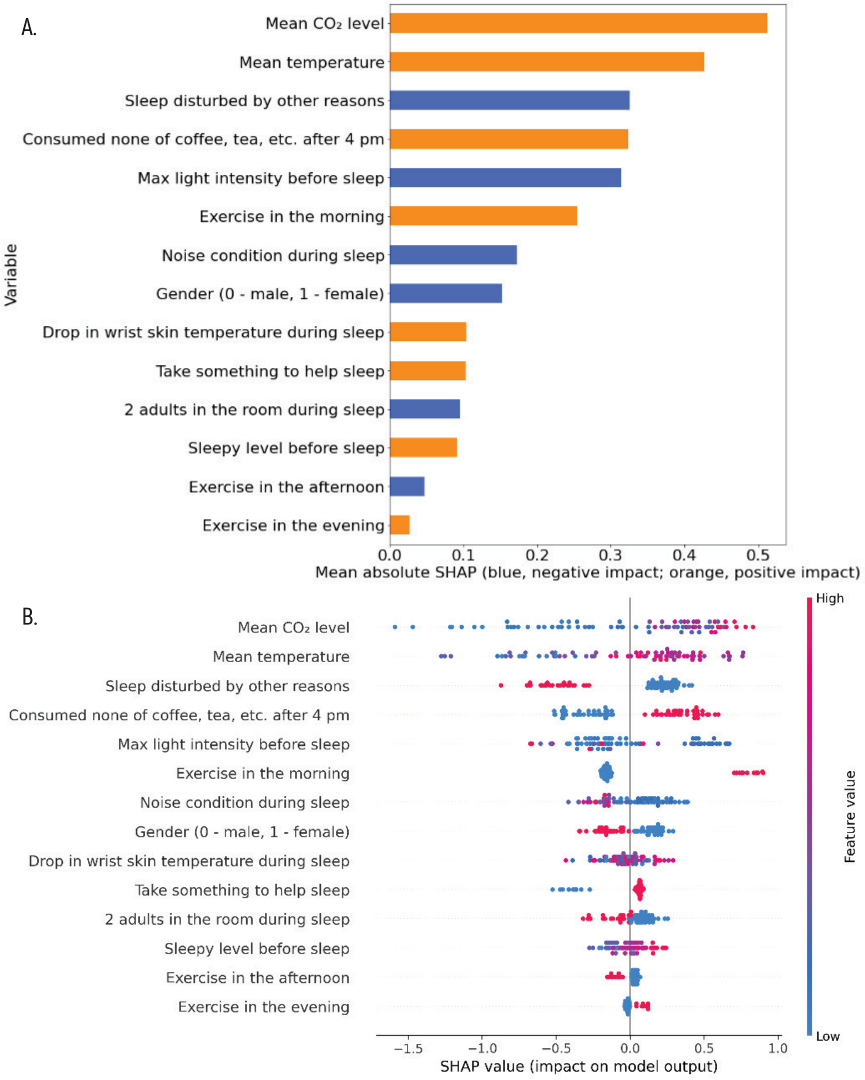


Figure 5. 15 The rank of the feature importance (A) and the SHAP values among all the features in the model to predict deep sleep (%) (B). Features are ranked based on their importance to deep sleep (%). High value: consumed none of the coffee, tea, etc. after 4 pm; sleep disturbed by other reasons; an exercise in the evening; an exercise in the morning; an exercise in the afternoon; gender of female; take something to help sleep; 2 adults in the room during sleep; and sleepy level of widely awake before sleep. SHAP, Shapley additive explanation.

The model of deep sleep (%) includes 14 inputs after 3 unimportant variables (SHAP values less than 0.001) were excluded. The unimportant variables were either window or door open during sleep, did not wake up during sleep, and heavy dinner. Figure 5. 15 shows the rank of the feature importance (A) and the SHAP values among all the features in the model to predict deep sleep (%) (B). Different variables were included in the model from the model of GSQS because subjective ratings of environment and window and door status were not significantly correlated with deep sleep (%). Other than that, the variables in small weights lower than 0.01 were also excluded in the model of deep sleep (%). Mean CO_2 was ranked as the most important variable to deep sleep (%), whose mean absolute SHAP value was 0.513. Other variables on the figure also affected deep sleep. In Figure 5. 16(B), 58.7% of the samples had positive SHAP on the line of "mean CO_2" and all of them are in red, which again indicates that higher CO_2 levels increased deep sleep (%).

Figure 5. 16 shows the change of the predicted deep sleep (%) based on mean CO_2. The predicted deep sleep (%) increased from 18.6% (95%CI, 18.3-19.0%) to 20.6% (20.1-21.1%) when mean CO_2 increased from 450 to 1200 ppm. However, deep sleep (%) tended to be stable afterward.

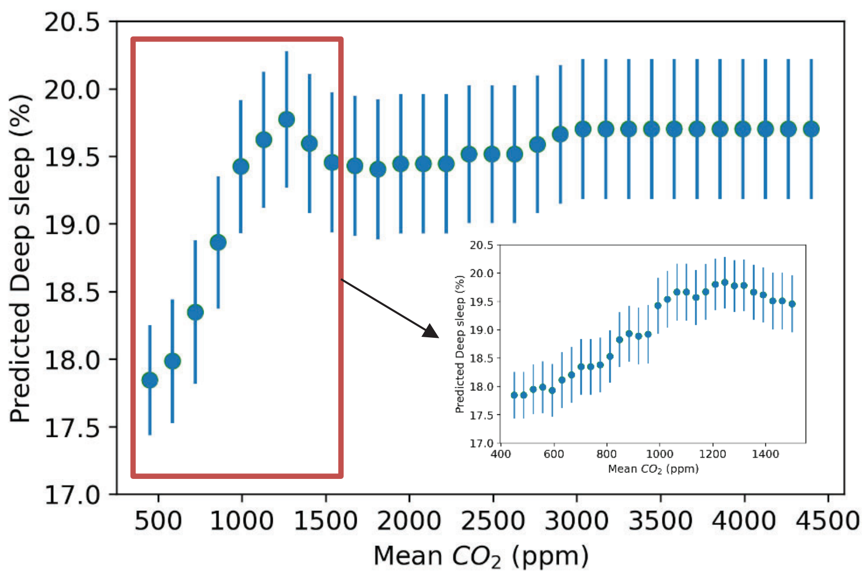


Figure 5. 16 Predicted deep sleep (%) and mean CO_2. Error bar indicates standard error.
Note: the prediction of deep sleep (%) would be different if the set-up of the artificial person changed, while the predicted trend would be similar.

The artificial person for the prediction in Figure 5. 16 was set to "male; 1 adult in the room during sleep; did not exercise during the morning, afternoon, and evening; did not take anything to help sleep; consumed none of the coffee, tea, etc. after 4 pm; and was not disturbed by other reasons during sleep. Mean temperature, max light intensity before sleep, noise condition during sleep, and the drop in wrist skin temperature were respectively set to 23.5, 47.9, 14.9, and 2.3 ◦C, the mean of all the samples in this study.

In summary, "either window or door open" and "higher acceptable levels of perceived air quality after sleep" were associated with lower GSQS, referring to better sleep quality. However, an opposite result was found between the mean CO_2 levels and deep sleep in percent - the higher the mean CO_2 levels within the range of 450-1200 ppm were associated with higher percent in deep sleep. No other associations were found between air quality-related variables and sleep quality.

5.4 Discussion

The present study investigated the association between bedroom air quality and sleep quality. Bedroom air quality was rated by the subjects before and after sleep. CO_2 levels in the bedrooms were measured during sleep. Window and door status during sleep was reported by the subjects. Subjective sleep quality was assessed by the GSQS and objective sleep quality was measured by sleep trackers.

The mean CO_2 levels of 52.0% of 75 bedrooms were above 1000 ppm in the present study. The percentage was lower than most previous studies where this was the case in 45.6%, 54.0%, 66%, 68%, and 79.3% of bedrooms in winter or transition seasons [8, 30, 33, 123, 221]. Window or door open during sleep and mechanical ventilation in bedrooms decreased CO_2 levels, and increased ventilation rates and bedroom air quality.

Room temperature was not significantly different before, during and after sleep, but thermal comfort was less acceptable after sleep than before sleep. A previous study reported that higher temperatures would lead people to rate the air stuffier [235]. Perceived air quality and thermal comfort after sleep were moderately correlated ($\rho = 0.534$, p-value < 0.001).

People rated the bedroom environment as slightly drier with window and door closed after sleep compared to with either of them open, although relative humidity was measured higher with window and door closed compared to it with either of them open. The feeling of dryness is an indication of air pollution, irritation, and pungency, stipulating slightly poor air quality with window and door closed [236]. This was consistent with a significantly lower acceptable level of air quality after sleep.

The subjects, who slept with either window or door open, had better subjective sleep quality, in comparison with those who slept with window and door closed. The subjects also had better subjective sleep quality when they perceived air quality as more acceptable. The subjects rated the IEQ after sleep, especially air quality, more acceptable when either window or door open compared to when window and door were closed. This could be the main reason that the subjects reported lower GSQS with either window or door open compared with window and door closed. Similar results, that stuffy air induced poorer subjective sleep quality, were found in previous studies [8, 15, 16, 32, 222, 237]. Nevertheless, this was not consistent with the results of Chapter 3, where opening windows made people have a worse mental state and well-being and poorer subjective sleep quality. The reason could be that the subjects in Chapter 3 were asked to sleep with windows open or closed instead of their preferences, and the surroundings of the experiment location were not quiet, while bedroom occupants in the present study slept with their usual window or door status. The bedroom surroundings of the occupants would typically be quiet if they chose to sleep with the window or door open. Also, the questionnaire survey study in Chapter 4 found that people who were disturbed by stuffy air opened windows more frequently during sleep, and this initiative seems not enough for them to be less disturbed by stuffy air if the outdoor air quality was also poor (stuffy), which was normally found in urban areas (Chapter 3), while the majority of the subjects (78.7%) lived in rural or suburban areas. Therefore, outdoor air quality is suggested to be measured or surveyed in future studies.

However, we found an opposite result when it comes to objective sleep quality. Higher CO_2 levels within the range of average 450-1200 ppm had a positive impact on deep sleep in percent. This phenomenon could be explained in two directions. One is that higher CO_2 levels were associated with a higher drop in wrist skin temperature (Figure 5. 11), which indicates higher declines in core body temperature [47]. Declines in core body temperature were associated with increases in deep sleep after sleep onset [224]. Therefore, a higher drop in wrist skin temperature is a sign of an increase in deep sleep, and CO_2 levels were associated with that sign. A drop in skin temperature was also positively correlated with deep sleep (%) (Figure 5. 12). The other explanation could be that rising CO_2 levels increased end-tidal CO_2 ($ETCO_2$) [164]. Increased $ETCO_2$ was associated with a lower heart rate [238]. Heart rate fell slightly from wakefulness to deep sleep, and reached the lowest rate during deep sleep (N3) [239]. Hence, lower heart rates caused by higher CO_2 levels between the average ranges of 450-1200 ppm may help people stay in deep sleep during sleep.

Nevertheless, Duarte et al. (2020) [124] reported that the increase of CO_2 from 280 to 5000 ppm resulted in a decrease of 0.3-0.4 pH units in blood. Decreasing pH in blood would cause numerous health issues [124]. Previous studies reported that CO_2 levels higher than 600 ppm, along with rises of CO_2 in blood, would lead to sleep apnea [240], and irrigation, fatigue, headaches when awake [241, 242]. Besides, emotional responses of fear, anxiety and escape actions were reported [124]. Furthermore, elevated CO_2 levels caused a series of responses to abiogenesis and obesity, although such experiments for chronic exposure to indoor CO_2 levels under 5000 ppm were absent [124, 243]. In addition, deep sleep (%) almost stopped rising when CO_2 levels were above 1200 ppm in the present study (Figure 5. 16). The threshold of the CO_2 level of improving deep sleep and reducing health symptoms should be explored in further studies.

On the other hand, that appropriate CO_2 levels increased deep sleep (%) was opposite with previous similar studies. For example, both studies of Xiong et al. (2020) [32] and Xu et al. (2021) [220] reported lower deep sleep (%) with CO_2 levels of 1004 and 3000 ppm, compared to the CO_2 levels of 500 and 800 ppm, respectively. The reason could be that the experiment was performed in a different season, which was summer in the study of Xiong et al. (2020) [32]. Also, whether temperature and CO_2 levels correlated was not reported in that study. The temperature might influence the results. Xu et al. conducted the experiment in a chamber, which is different from the present field study observing occupants' bedrooms. The result was observed when comparing to the CO_2 levels of 800, 1900, and 3000 ppm. The model showed a slight decrease in deep sleep (%) after CO_2 levels of 1200 ppm in Figure 5. 16, while whether deep sleep (%) would further decrease at the points of 1900 and 3000 ppm was difficult to clarify in the present study because the data after around 1900 ppm were limited (see Figure 5. 10(B)).

However, people were indeed disturbed by stuffy air (poor air quality) for subjective sleep quality either based on the results in the present or previous similar studies [8, 15, 16, 32, 222, 237]. Lack of ventilation not only causes elevated CO_2 levels, but also an increased level of pollutants in bedrooms, such as carbon monoxide (CO) and volatile organic compounds (VOCs) [28]. However, pollutants were not measured during those previous studies of ventilation and sleep quality. pollutants were associated with either sleep quality or sleep-disordered breathing [3]. Particle matters (PM) with a diameter of 10 micrometres or less (PM_{10}) were negatively associated with sleep efficiency [244]. Poor air quality due to PM_{10}, sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), and CO induced snoring [245]. PM_1 and $PM_{2.5}$ were strongly associated with all sleep disorder symptoms [246]. Besides, O_3 was related to sleep-disordered breathing [247]. Cooking oil fumes exposure was associated with poor sleep quality [248]. Indoor exposure to biomass fuel decreased sleep quality and more snoring (Chapter 3) [60, 249, 250]. Bedroom pollution sources including carpet, printers, fish tanks, and television were also associated with poorer subjective sleep quality [222]. The pollutions mentioned above can be sourced either from indoors or outdoors. Reduced ventilation is a surrogate for increased exposure to bedroom pollutants. However, increased ventilation with either window or door open would not be helpful to dilute pollutions from outdoors or from the home space towards which the bedroom door opens. Future studies concerning bedroom ventilation and sleep quality are suggested not only to measure CO_2 levels, but also pollutions, and to investigate the pollution sources in bedrooms, such as supply air, carpet, printer, fish tank, etc.

We did not find an association between deep sleep (%) and window and door status, although CO_2 levels were significantly lower with either window or door open. It might be because the same range of CO_2 levels existed between the different window and door status, and pollutions levels in the bedrooms were not considered. Moreover, GSQS was not correlated with any of the objective sleep parameters.

5.4.1 Limitations

Exposure to air pollutants in the bedroom was not adequately captured by measuring only CO_2, although it is still an indication and worth analysing in relation to what reported in this thesis. CO_2 is a marker of ventilation, but it could not show ventilation rates accurately in bedrooms, and especially is not a marker for indoor air quality. Indoor pollutions should be measured to have a more comprehensive perspective on indoor air quality in bedrooms in future studies.

Furthermore, the variation of deep sleep (%) and other objective sleep parameters was considerable and therefore, it is not straightforward to figure out the association between ventilation and those parameters. GSQS would be more accurate for people to assess their sleep quality. Besides, other metrics for sleep quality are suggested, such as heart rate, skin temperature in different parts of the body, etc.

Unfortunately, the hypnogram was not saved during the experiment, otherwise, it could be used to compare with the skin temperature during sleep and calculate the skin temperature for each sleep stage. Therefore, the drop in wrist skin temperature can be more accurately calculated. The subjects were only told to wear the sleep tracker during all the measuring nights instead of all days. This would be the reason why sleep stages could not be tracked for some nights of sleep due to inadequate background data in it. Moreover, we asked the occupants to wear the iButton to measure skin temperature only during sleep. Skin temperature before and after sleep was suggested to be measured for a while to catch the changes during sleep from awake. In this way, the change of wrist skin temperature would be more clear from awake to sleep and during sleep.

Sample size has always been a limitation for many field studies including the present one, and accordingly, subjects recruitment should be more careful. Sleep quality should be assessed before the experiment to select those who have relatively better sleep quality because there would be many reasons for bedroom occupants to have poor sleep quality and those with poor sleep quality may have sleep disorders. However, that would not be a problem with big data. Besides, we used the outlier (5,000 ppm of the average CO_2 levels in MV bedroom, and 4804 ppm was also close to the upper limit of the measuring range) because random forest handles those. We also checked (calibrated) all CO_2 monitors before the experiment, so we were not sure why so high levels were measured.

The CO_2 levels around 1200 ppm were concluded to be the most appropriate levels for deep sleep (%), and the CO_2 levels higher than 1200 ppm did not further improve the proportion of deep sleep. First, humans cannot have a high proportion of deep sleep as they want, such as 50%. Therefore, the effects of high CO_2 levels on improving deep sleep (%) would be limited. Second, the amount of data when CO_2 levels above 2000 ppm was limited and if there would be other health symptoms occur when CO_2 levels were high during sleep was not sure.

In future studies, pollutions related to sleep quality or sleep-disordered breathing should be measured together with ventilation rates, and two main questions regarding the association between bedroom ventilation and sleep quality are expected to be tackled. The first one is how ventilation affects air pollutions exposure during sleep and further influences sleep quality, and the second one is what is the threshold level of CO_2 to benefit deep sleep the most and meanwhile avoid health symptoms related to chronic exposure to increased CO_2 levels during sleep?

5.5 Conclusions

Perceived air quality after sleep was significantly better with either window or door open, compared with both closed. The subjects had better subjective sleep quality (lower GSQS) when they slept with either window or door open and perceived better air quality after sleep, in comparison to those who slept with window and door closed and perceived poorer air quality after sleep. Higher CO_2 levels in bedrooms within the range of 450 – 1200 ppm increased deep sleep (%). Future studies are needed to measure all kinds of sleep-related pollutions in bedrooms and figure out how ventilation affects bedroom occupants' exposure to them, as well as the most appropriate range of CO_2 levels for sleep.

6

Conclusions & Perspectives

6.1 Conclusions

The present study investigated the association between bedroom ventilation and sleep quality. The literature review (Chapter 2) showed that mean CO_2 levels reported in previous studies ranged from 428 to 2,585 ppm. CO_2 is higher during heating seasons comparing to the other seasons, in particular in bedrooms with natural ventilation. Limited studies suggest that sleep quality would not be disturbed when CO_2 levels were below 750 ppm, whereas sleep quality and next-day performance were disturbed when CO_2 levels were above 2,600 ppm.

Mechanical ventilation and window or door opening can be used to ventilate their bedrooms during sleep. Nevertheless, opening windows caused some side effects, such as higher $PM_{2.5}$ and noise levels, although it was beneficial to decrease snoring and the number of awakenings (Chapter 3). Mechanical ventilation may therefore be more amenable for good bedroom ventilation.

The questionnaire survey study (Chapter 4) in the heating season concluded that sleep disturbance caused by stuffy air, noise, and thermal discomfort was associated with reduced subjective sleep quality. Stuffy air and thermal discomfort were the main drivers for occupants to air their bedrooms by changing bedroom window or door status. Bedroom objects (carpet, printer, fish tank, and a TV set) were associated with poorer sleep quality.

The field study (Chapter 5) in occupants' bedrooms indicated that occupants had better subjective sleep quality when sleeping with either window or door open, compared to those who slept with both closed. This indicated that opening windows or door would be beneficial to sleep quality if the bedroom occupants prefer to sleep in that way, while the survey (chapter 4) showed that this depends on bedroom surroundings, such as acoustic, light, and air quality conditions. On the other hand, sleeping with appropriate CO_2 levels of 1200 ppm increased deep sleep (%), compared to sleeping with CO_2 levels below 1200 ppm. Previous studies found that higher CO_2 levels above 1200 ppm had an adverse impact on sleep quality, which could be determined by exposure to both indoor and outdoor pollutions. The effects of ventilation on general air quality in bedrooms need further studies.

To summarize, Figure 6. 1 shows a mind map for the conclusion of the association between bedroom ventilation and sleep quality. Bedroom ventilation was investigated using four methods – ventilation type in bedrooms was surveyed; bedroom airing behaviours during sleep was surveyed or recorded during the measurement period; perceived air quality after sleep and CO_2 levels were measured. Sleep quality was assessed both subjectively and objectively. The subjective methods, PSQI and GSQS, assessed occupants' sleep quality during the past month and previous night, respectively. Sleep tracker and polysomnography were used to measure sleep stages, number of awakenings, snoring percentage, etc. Furthermore, sleep disturbance caused by stuffy air, too warm, too cool or noise was surveyed.

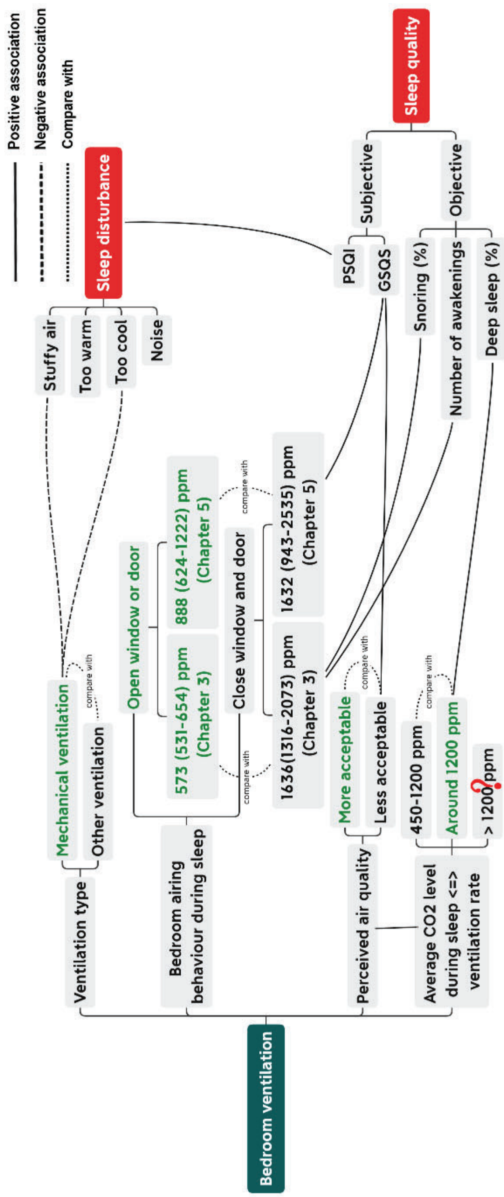


Figure 6. 1 A mind map for the conclusion of the association between bedroom ventilation and sleep quality. ppm is the unit of CO_2 levels. The CO_2 levels indicated in Chapter 3 were the levels in the PSG group. The CO_2 levels in Chapters 3 & 5 are shown in median (interquartile range). Snoring (%) was measured by polysomnography; the number of awakenings and deep sleep (%) were measured by the sleep tracker. PSQI & GSQS, Pittsburg Sleep Quality Index & Groningen Sleep Quality Scale (a higher score refers to poorer sleep quality). Green text indicates positive items for good sleep quality.

In Figure 6. 1, mechanical ventilation was negatively associated with sleep disturbance caused by stuffy air and feeling too cool. It meant that mechanical ventilation improved indoor air quality, reduced sleep disturbance and lower PSQI, compared to the other types of ventilation, mainly the type of natural ventilation. The two reasons, stuffy air and feeling too cool, as well as too warm and noise, were positively associated with the PSQI (poorer sleep quality during the past month). Sleeping with both window and door closed, as well as higher unacceptable levels of perceived air quality, was positively associated with the GSQS (poorer sleep quality the previous night). When it comes to CO_2 levels, the association between bedroom ventilation and sleep quality seems to be more complicated. The average CO_2 levels during sleep were positively associated with deep sleep (%) within the range of 450-1200 ppm. Deep sleep (%) decreased below 1,200 ppm of average CO_2. Higher CO_2 levels were also correlated with lower ventilation rates.

6.2 Strengths & Limitations

The studies of Chapters 4 and 5 were performed in occupants' bedrooms, and although Chapter 3 was conducted in the university dorm, all the subjects were recruited in the dorm and they were sleeping in a similar environment as usual during the experiment. This point was different from most of the similar previous studies.

There are also limitations. We only used average CO_2 levels to assess bedroom ventilation and air change rate (ACR) was not calculated in Chapter 3 since CO_2 is a marker of ventilation and, in addition to ACR, also provides CO_2 exposure levels which have been shown to have physiological effects. Nevertheless, it is not a good marker of general indoor air quality. As a matter of fact, neither is ACR. Bedroom ventilation standards were reviewed, and threshold values for 'good sleep quality ventilation' were suggested, while these were not applied in the following studies in the thesis since the association between general bedroom indoor air quality and sleep quality still required validation. All the findings were only based on observations or intervention, and they lack a clear mechanism that explains them. Another major limitation was subjects recruitment, which was not given enough attention during the field study since it was difficult to recruit subjects and should be handled more carefully in future studies as sleep quality varies from person to person. The ideal subjects for studying the association between ventilation and sleep quality to avoid the issue of noise in the data are those who do not consume coffee or consume it at most 300-400 mg per day but only in the morning [251]; do not or seldom consume alcohol or black tea; non-smokers; do not sleep with child(ren); are not usually stressed; and have a stable lifestyle, such as regular/no exercise, go to bed and wake up at the same time every day, have dinner at the same time every day, and do not have heavy dinner; do not have shift work/study or work/study at night; and never or occasionally being disturbed by thermal, acoustic and light comfort during sleep.

6.3 Possible implications

What does all this mean to ventilation policy and practise? According to the conclusion of the thesis, bedroom ventilation requirements should distinguish between during and after sleep in the future design. A low ventilation rate during sleep to maintain CO_2 levels around 1200 ppm and a higher ventilation rate after sleep to reduce CO_2 levels for bedroom occupants for faster waking (and better-subjective sleep quality) are advocated.

The implementation can be ventilating bedrooms from outdoors. During sleep, passive ventilation windows can be used. After sleep, passive ventilation windows, trickle vents, opening of windows, or mechanical ventilation can be implemented. The premise of ventilating the bedroom from outdoors is that the bedroom is not close to a highway or main traffic road since nitrogen dioxide is negatively associated with sleep quality and is mainly related car emissions [3]. When ventilation from outdoors, penetration of noise should also be mitigated.

We can also ventilate bedrooms from the other spaces inside the dwelling. Probably we can install something like a passive ventilation door and reorganize the airflow inside the dwelling for ventilation during sleep. For ventilation after sleep, we can use negative pressure ventilation if the passive ventilation door is not enough, although noise would be a problem.

6.4 Perspectives

The conclusions obtained in this PhD study are just the tip of the iceberg of the association between bedroom ventilation and sleep quality. My recommendations for future studies are:

Future studies should focus on a more general indoor air quality in bedrooms instead of only considering CO_2. Air pollutants suggested for being measured both indoors and outdoors include CO, VOCs, PM_{10}, $PM_{2.5}$, PM_1, SO_2, NO_2, and O_3. Most of these pollutants were all found to be associated with sleep quality but there is a lack of studies conducting the typical indoor pollutants - VOCs. What kind of role ventilation plays in those pollutants and further influences sleep quality should be figured out. Besides, exposure to those air pollutants during daytime and their effects on night-time sleep quality would also be interesting to consider to be added for thorough research on the topic.

Chamber and field studies were conducted previously and more types of studies on this topic are needed, such as intervention studies in occupants' own bedrooms other than the intervention study in a chamber. A study is suggested that investigates the effects of changing the status of windows or door in occupants' bedrooms on the sleep quality. Also, a study is proposed to investigate the effect of low, medium and high ventilation rates in occupants' bedrooms on their sleep quality. Sleep quality in different CO_2 levels in previous intervention studies including the one in Chapter 3 was only tested for 2-3 days as many sleep studies in laboratories. However, an 11-day cruise study indicated that submariners required some time to adapt to high CO_2 levels, and during the first two days, respiratory disturbances were caused during sleep [252]. This may be why the subjects had poorer sleep quality in previous intervention studies [15, 16, 220]. Hence, a longer period of time for intervention studies instead of intermittent exposure (less than 3 days) to high CO_2 levels is needed to confirm this point.

All the indoor climate parameters – temperature, relative humidity, and ventilation rate (fresh air volume) are suggested to be considered together to explore the effects on sleep quality and provide more information for HVAC (Heating, Ventilation, and Air Conditioning) designers for designing an air conditioning or ventilation system specifically for bedrooms. Future studies can also investigate the optimal indoor climate for different groups of people, such as different gender, age, etc.

Meanwhile, physiological parameters are recommended to be measured to examine the physical mechanism explaining the observed results, such as core body temperature, heart rate, breathing rate, heart rate variability, etc. [253, 254]. Also, cooperation with the experts from the medical field is highly recommended.

In addition, biomarkers, such as urinary cortisol concentrations [43], may be interesting to measure. A systematic review regarding this field should be conducted to decide which biomarker would be necessary to measure for assessing sleep quality or exposure to certain pollutants.

ANNEX

Annex 1A

Invitation letter*

Dear Participants of the Online Survey carried out early this year,

Hope all is well with you and your loved ones.

Thank you for participating in our survey regarding the bedroom environment and its consequence on sleep quality carried out before Denmark was locked down because of COVID-19. We apologize for our late feedback about your response because our work was also disrupted and all the planned works have been postponed due to the current pandemic crisis. Thank you very much for your contribution to our research work. We are glad to inform you that we are now ready to resume based on the outcomes of the survey.

As promised for the survey, we are ready to reward the lucky participants with the **30 kr. voucher** to Lagkagehuset. And guess what – **YOU ARE ONE OF THEM**. Unfortunately, there is no e-voucher available in Lagkagehuset. Therefore we propose that you reply to this email if you want to pick it up. The pickup point is *Nils Koppels Alle, Building 402, International Centre for Indoor Environment and Energy at DTU Lyngby Campus, Room 231.*

With this email, we also would like to investigate whether you want to win a bigger prize, at least a voucher of 1,000 kr. up to 2,000 kr. To be able to win this voucher we invite you to participate in another field measurements in which we will ask you to measure your bedroom environment for two nights (chance to win 1 voucher) or four nights (chance to win 2 vouchers) and your sleep quality on weekdays, as well as answer a few times the 6-minute online diary. The measurements will be performed using an INSTRUMENT BOX provided by us that you just need to plug into the electrical outlet in your bedroom. **Your anonymity will be highly preserved**, and after the measurements, you will receive a sleeping/bedroom passport with the results of the measurements.

As we only invite a limited number of people to participate in these measurements, the odds of winning are very high; you will get the passport no matter what. Acceptance to participate in these measurements is on the first-come, first-serve principle so hurry up and make the decision now. Note that we are flexible and can perform the measurements on the weeks that suit you best but no later than mid-December 2020. We will of course secure good hygiene and sanitize the box before you receive it.

If you are interested, please reply to this email. We will then provide you with detailed instructions, consent declaration, and discuss the dates. The time for this study is flexible, which can be selected based on your own preference, as mentioned above. The 30 kr. voucher to Lagkagehuset will also be delivered to you with the INSTRUMENT BOX.

We are looking forward to hearing from you soon and once again thanks for your participation in the survey.

SleepVent Group

International Centre for Indoor Environment and Energy

Department of Civil Engineering

Technical University of Denmark

*The invitation letter was drafted by Xiaojun Fan, and reviewed and modified by the other members including the thesis' author in the SleepVent Group.

Instruction*

This document briefly describes what is going to happen during the measurements and what is expected that you should do.

First, we will deliver the instrument BOX in-person to your place (post is also feasible if you prefer), which contains all the instruments used to perform the measurements (**Figure 1**). We will collect the BOX and INSTRUCTION once the measurements end.

The BOX contains instruments for measuring carbon dioxide (VAISALA sensor), temperature, relative humidity, light level (HOBO sensor) and other air contaminants (FLOW sensor). You do not have to do anything with these instruments, except placing the BOX at one location in the bedroom recommended by us and plugging the BOX into an electrical outlet once you are home and ready to start the measurements. The BOX shall be remained plugged for the entire measuring period.

The BOX contains also the watch that can track your sleep quality (FITBIT), a battery-like sensor on a Velcro wrist band to measure your skin temperature (IBUTTON), and a tablet with a few apps (DIARY) hooked on 4G (TABLET, or ROUTER); you do not have to hook on your Internet. How to use these instruments is described below.

There is also a Memo-list/Log-book (MEMO-LIST/LOG-BOOK) for indicating special events and checking if you have completed all the necessary procedures each day.

The BOX shall be plugged into the electrical outlet in your bedroom using the white cord and placed in the head region of your bed, around 1 meter away to your head, ideally at the same height (such as on a night table), see **Figure 2**. The power consumption for the entire measurement is minimal and comparable to one-time heating water in a kettle.

FITBIT and IBUTTON shall be worn on your wrist when sleeping as instructed below. FITBIT should be placed on the **NON-DOMINANT** wrist (left if you are right-handed and vice-versa) as shown in **Figure 3** and IBUTTON on the **OPPOSITE** wrist as shown in **Figure 4**.

The measurements with FITBIT and IBUTTON shall be performed on all weekdays during the entire measuring period. We ask you to wear the FITBIT and IBUTTON on all nights during the week starting on Monday night and finishing on Friday morning. They have to be put on before you go to bed and removed when you wake up the following morning. After removal, FITBIT should be placed on the charger and synchronized with its App on the TABLET. How to synchronize is shown in **Figure 5**.

The FLOW should also be synchronized with its App on the TABLET. It can be done at the same time as synchronizing FITBIT, again see **Figure 5**.

On two nights and two following mornings, any two from Monday to Thursday, such as Monday-Tuesday, Tuesday-Wednesday, or Wednesday-Thursday, you will be asked to fill in a short DIARY on the TABLET (**Figure 6**) within 10 min before sleep at night and after waking up the following morning. Details regarding how to vote/answer the diaries are explained below. A total of twice the evening diary and twice the morning diary should be filled. A reminder email will be sent before you need to fill in the diary on that day. Some measurements will be based on your judgments. Therefore, please try to be as honest as possible in your judgments. The DIARY includes also a simple 3-min cognitive task, which requires to be done as quickly and accurately as you can. You should also fill in a MEMO-LIST/LOG-BOOK (paper version) enclosed together with the BOX after all the preparations done in both evening and morning.

Every morning when leaving the bedroom, we ask you to keep the windows/doors in the same state as the previous night and do not go into the bedroom again in the morning after you leave.

Finally, we ask you to sketch and measure your bedroom dimensions anytime during the week. Indicate the location of the window(s), bed, and door(s) and provide approximate length, breadth and height in **Figure 7 (A)** (see **Figure 7 (B)** for example). If possible, please take a picture of your bedroom and send it to us (via the email below), indicating your SleepVent ID. Also note whether you have any of the following in your bedroom: trickle vents and terminals for supplying air (see **Figure 8**). Please mark directly in **Figure 8** by circling what you have.

We do not have any other requests or restrictions except perhaps avoiding all-night partying.

<u>Note that all information below will be anonymized</u> and will only be used for scientific analysing purposes.

Your SleepVent ID combined with the group number is indicated on the BOX (**Figure 1**).

In case you have any questions or problems during the experiments, please do not hesitate to connect with us using your sleepVent ID. Our 24/7 hotline is open for any questions and queries you may have. Send email to <u>sleepvent@byg.dtu.dk</u> or call **<u>+45 5020 9866</u>** or **<u>+32 483514579.</u>**

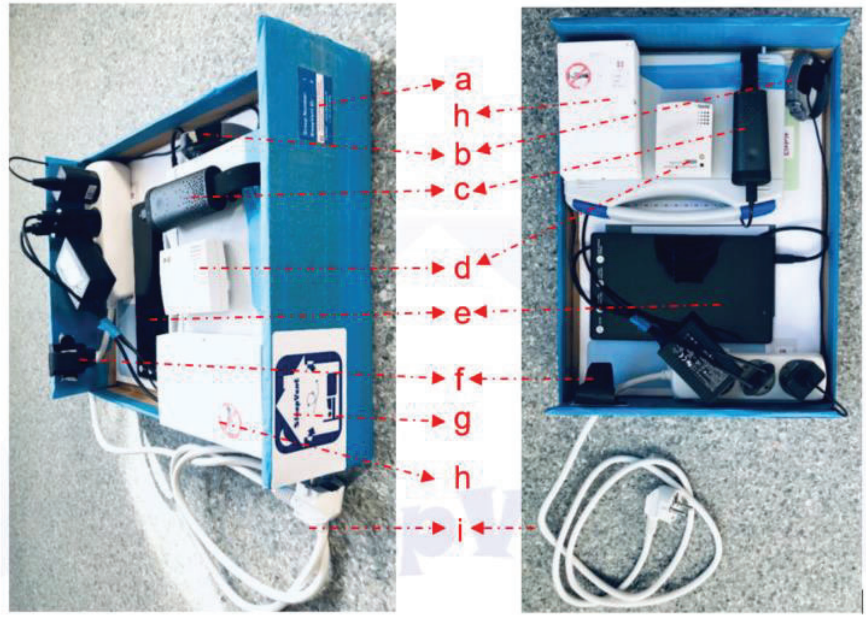


Figure 1. The layout of the BOX. (a) Your SleepVent ID and Group Number; (b) Fitbit; (c) Flow; (d) HOBO; (e) Tablet; (f) I-button; (g) Logo; (h) Vaisala; (i) The plug to charge the box.

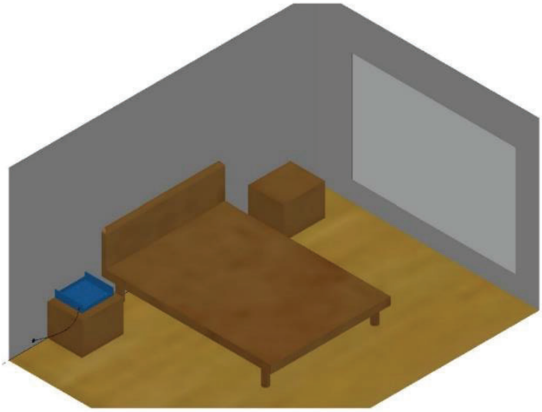


Figure 2. Proposed location of the Box coloured by blue in the bedroom.

Figure 3. Wearing Fitbit

Note: please keep the Fitbit on your NON-DOMINANT hand with 2-3 finger-widths to your wrist bone. Should be tightly attached to the skin.

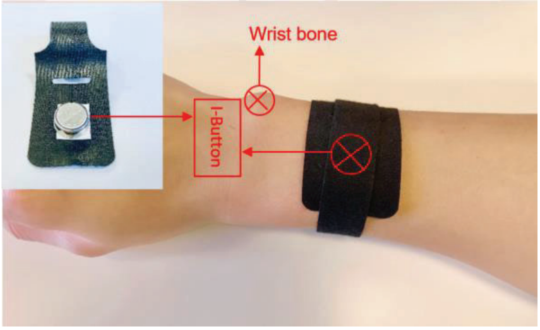


Figure 4. Wearing I-button

Note: Please place the IBUTTON on your DOMINANT hand. Also, place it before filling in the evening diary and take it off after completing the morning diary. Should be tightly attached to the skin.

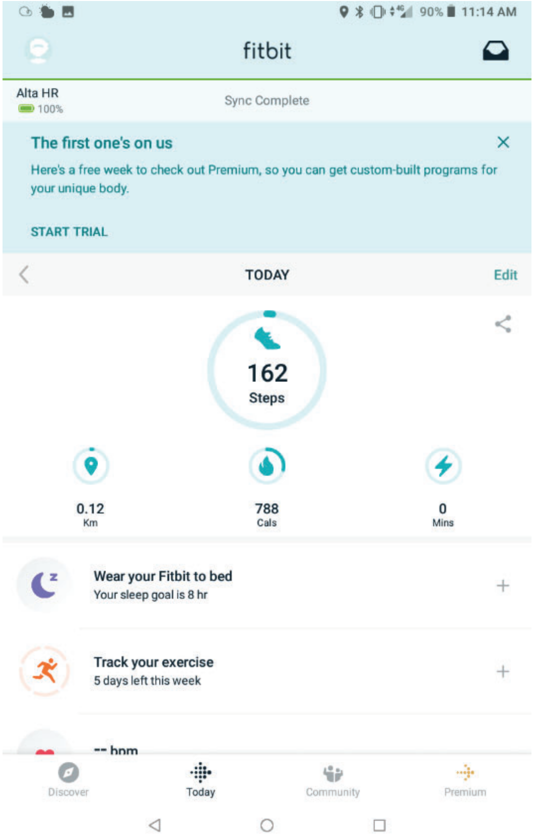


Figure 5. Synchronizing Fitbit. Open the Fitbit App, press and swipe down the main screen until **'Sync Complete'** appears.

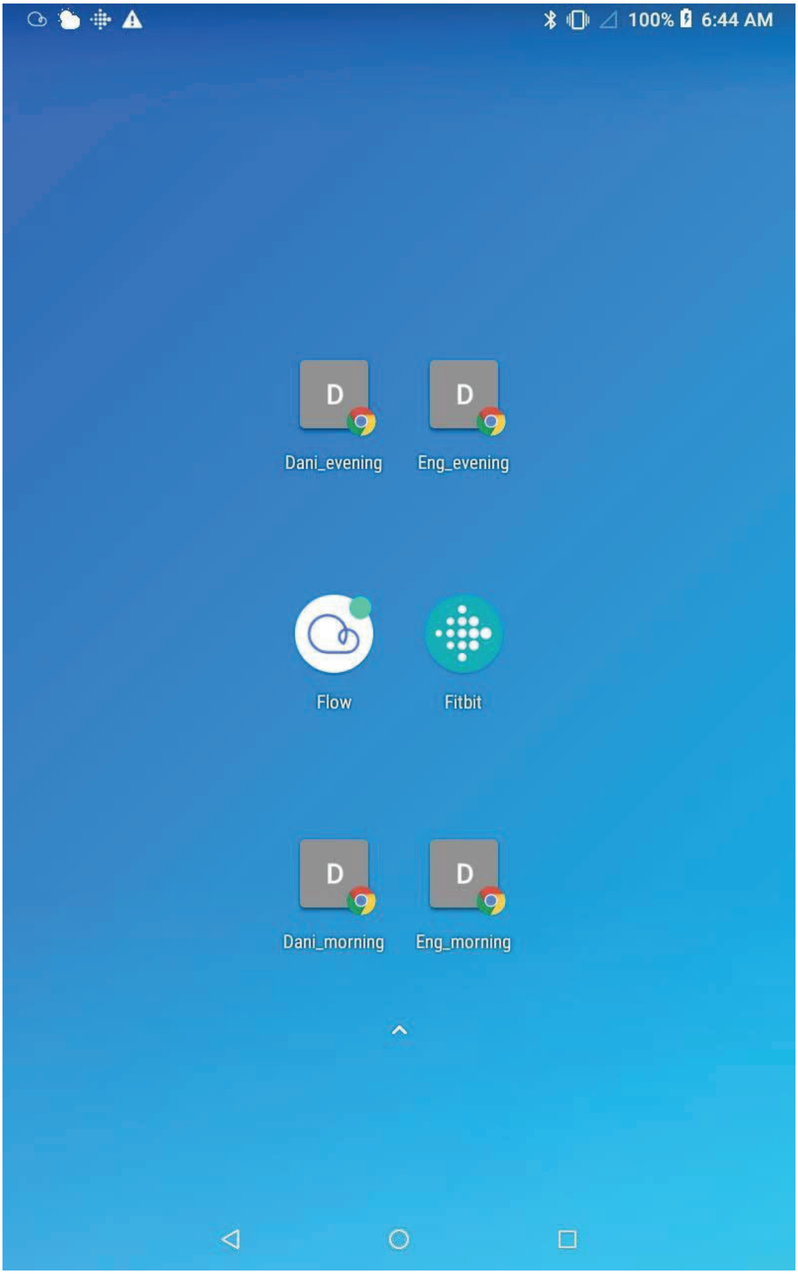
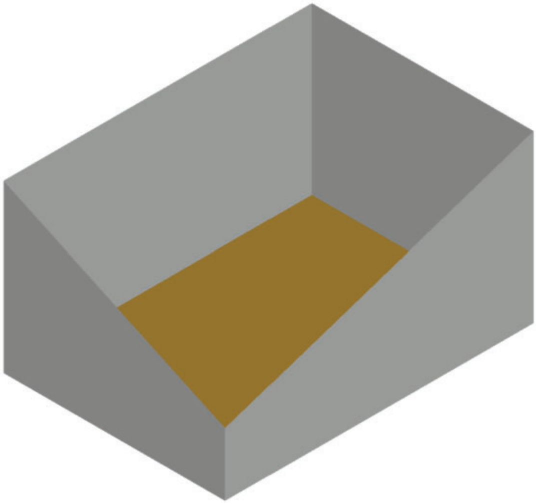
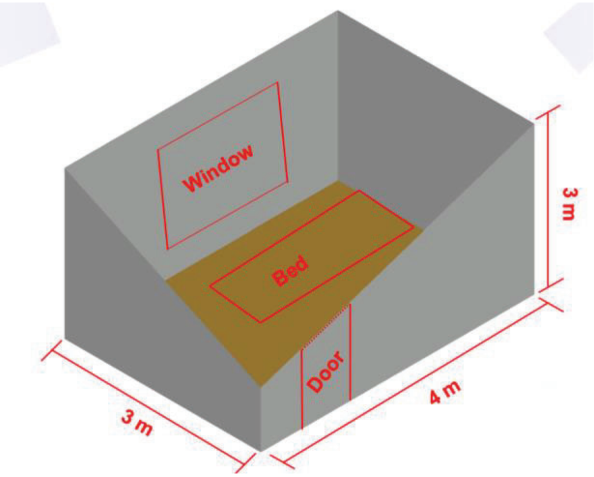


Figure 6. The layout of the default screen of the tablet. The diaries are linked by different shortcuts. Each diary has two shortcuts drafted in English and Danish respectively. You can fill in one of them in your preferred language. A reminder will be sent via email. Also, you may prefer to fill in the diary via your own smartphone, then please scan the QR code of your preferred language enclosed with the BOX.



(A)



(B)

Figure 7. (A) Schematic diagram of a bedroom; **(B)** An example of how to sketch your bedroom. Note: Please indicate the location of the window(s), bed, and door(s) and provide approximate width, breadth and height in (A).

(A)

(B)

Figure 8 (A). Terminals for supplying air; **(B)** Trickle vents.

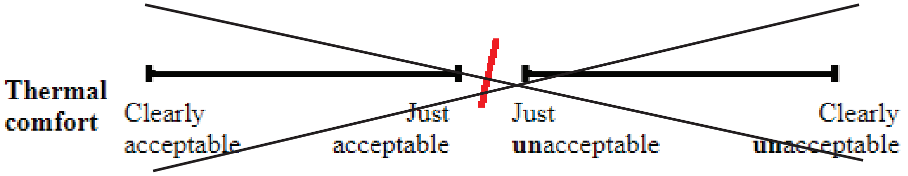
<u>Information about the sleep diaries.</u>

In the sleep diaries, except for the common information, you will be asked to vote on the perception of the indoor environment in the bedroom room and your status. You will have to answer how you feel at that moment. The vote using several kinds of scales is exemplified below. Generally, the intersection of the line you drew and the scale indicate your vote. Please mark in the short line if your vote is in the intersection in the scale.

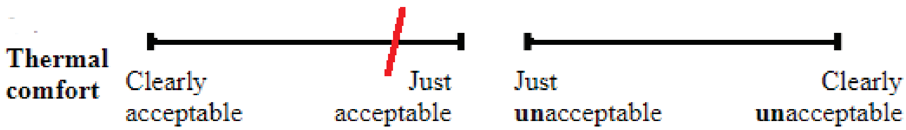
The acceptability scale is a scale that is divided into two parts, the upper and the lower part. At first, you have to decide whether the parameter under evaluation is acceptable or unacceptable. If the parameter is acceptable you should use the left part of the scale and whether it is **un**acceptable you should use the right part of the scale. Then, you should indicate on the scale to which extent you evaluate the parameter to be acceptable or unacceptable. You can mark anywhere on the scale except placing it in the gap between "Just acceptable" and "Just unacceptable" (Example 1-1). In the examples below, the parameter is assessed to be slightly acceptable (Example 1-2), middle **un**acceptable (Example 1-3), and clearly **un**acceptable (Example 1-4).

Q: Please rate your overall thermal comfort:

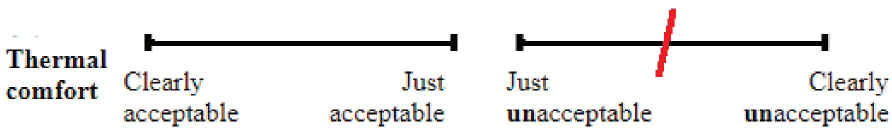
Notice the distinction between acceptable and unacceptabale



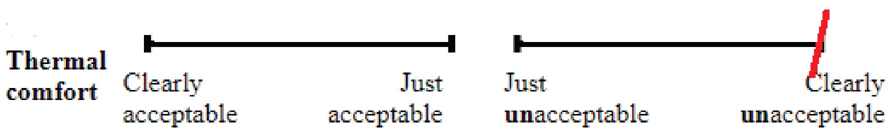
Example 1-1



Example 1-2



Example 1-3

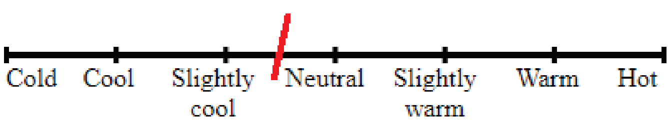


Example 1-4

The linear scale has several grades with descriptions with which you indicate the magnitude of your perceptions. You can mark anywhere on the scale, such as "Example 2".

Continuous scales with two endpoints are applied in the diaries. Please indicate the appropriate magnitude of perception anywhere on the scale, such as "Example 3".

Example 2: your thermal sensation in the **bedroom/bed** is a little bit cool:



Example 3: you perceive the indoor air too stuffy:

*The **<u>Information about the sleep diaries</u>** was drafted by the thesis' author, the rest of the instruction was drafted by Xiaojun Fan, and reviewed and modified by all the members in the SleepVent Group.

Annex 3A

Table A3. 1 Demographic characteristics and study information of the participants (N=27).

No.	Room No.	Sex	Age (years old)	Height (cm)	Weight (kg)	BMI	PSQI	Windows first condition	PSG used
1	A	Male	25	185	80	23.4	3	Open	Yes
2	A	Male	27	175	58	18.9	4	Open	Yes
3	A	Male	22	193	82	22.0	3	Open	Yes
4	A	Male	27	178	65	20.5	2	Open	Yes
5	A	Male	26	173	93	31.1	2	Open	Yes
6	A	Male	27	163	62	23.3	5	Open	Yes
7	A	Female	21	167	61	21.9	4	Open	Yes
8	B	Female	27	163	50	18.8	5	Closed	Yes
9	B	Male	23	178	65	20.5	5	Closed	Yes
10	B	Male	23	164	56	20.8	5	Closed	Yes
11	B	Male	26	168	74	26.2	3	Closed	Yes
12	B	Male	24	183	72	21.5	4	Closed	Yes
13	B	Female	25	160	52	20.3	5	Closed	Yes
14	B	Female	28	165	50	18.4	3	Closed	Yes
15	C	Male	28	169	67	23.5	4	Open	No
16	C	Female	31	160	61	23.8	0	Open	No
17	C	Female	28	159	62	24.5	5	Open	No
18	C	Female	22	166	67	24.3	4	Open	No
19	C	Female	21	166	60	21.8	3	Open	No
20	C	Male	33	172	67	22.6	4	Open	No
21	C	Male	20	180	95	29.3	4	Open	No
22	D	Female	24	157	68	27.6	3	Closed	No
23	D	Female	33	162	50	19.1	3	Closed	No
24	D	Female	22	167	53	19.0	4	Closed	No
25	D	Female	25	172	58	19.6	5	Closed	No
26	D	Female	25	162	48	18.3	3	Closed	No
27	D	Male	26	178	75	23.7	5	Closed	No

BMI, body mass index; PSQI, Pittsburgh sleep quality index; PSG, polysomnography.

Table A3. 2 Means and 5 percentiles concentrations of night-average sleep environment parameters between two window states or different rooms during sleep.

Items	*N* [a] (%)	Mean ± Std.	5th	25th	50th	75th	95th	*p*-value [b]
Average bed temperature (°C)								
Total	99 (100)	33.0 ± 1.3	30.7	32.2	33.2	33.9	34.7	
Window closed	51 (51.5)	32.9 ± 1.3	30.2	32.2	33.0	33.8	34.7	0.506
Window open	48 (48.5)	33.0 ± 1.3	30.8	32.3	33.3	33.9	34.5	
Rooms C&D (Non-PSG)	51 (51.5)	32.9 ± 1.2	30.8	32.2	33.1	33.7	34.5	0.493
Rooms A&B (PSG)	48 (48.5)	33.0 ± 1.4	30.1	32.3	33.3	34.0	34.7	
Average bed relative humidity (°C)								
Total	99 (100)	41.0 ± 10.5	10.5	27.3	34.5	38.1	45.7	
Window closed	51 (51.5)	42.4 ± 10.8	27.3	34.9	39.2	51.6	64.1	0.136
Window open	48 (48.5)	39.6 ± 10.2	25.8	33.1	37.2	43.6	65.1	
Rooms C&D (Non-PSG)	51 (51.5)	42.8 ± 11.1	26.3	35.5	39.8	49.9	64.8	0.052
Rooms A&B (PSG)	48 (48.5)	39.1 ± 9.7	27.3	33.2	36.5	42.4	63.1	
Average room temperature (°C)								
Total	105 (100)	21.8 ± 1.4	19.2	21.0	22.1	22.7	23.8	
Window closed	52 (49.5)	22.6 ± 0.8	20.9	22.3	22.6	23.0	24.2	**< 0.001**
Window open	53 (50.5)	20.9 ± 1.3	18.7	20.0	21.1	21.8	22.7	
Rooms C&D (Non-PSG)	49 (46.7)	21.5 ± 1.4	18.5	20.9	21.7	22.5	23.5	0.092
Rooms A&B (PSG)	56 (53.3)	22.0 ± 1.3	19.2	21.1	22.3	22.7	24.1	
Average relative humidity (%)								
Total	105 (100)	40.8 ± 5.8	29.5	36.3	42.0	44.9	49.4	
Window closed	52 (49.5)	43.1 ± 5.1	32.6	40.7	43.7	46.4	51.7	**< 0.001**
Window open	53 (50.5)	38.5 ± 5.6	28.4	34.7	38.7	43.6	46.8	
Rooms C&D (Non-PSG)	49 (46.7)	40.2 ± 6.0	29.3	35.7	41.4	44.5	50.6	0.407
Rooms A&B (PSG)	56 (53.3)	41.2 ± 5.7	29.2	37.2	42.2	45.0	49.5	
Average CO_2 (ppm)								
Total	105 (100)	1122.6 ± 618.6	468.0	584.4	840.7	1550.4	2451.5	
Window closed	52 (49.5)	1654.3 ± 440.9	943.7	1334.8	1550.4	1919.1	2488.9	**< 0.001**
Window open	53 (50.5)	600.9 ± 121.2	447.9	531.1	585.4	658.5	790.9	
Rooms C&D (Non-PSG)	49 (46.7)	1107.0 ± 600.1	462.0	604.1	769.6	1524.1	2450.2	0.842
Rooms A&B (PSG)	56 (53.3)	1136.2 ± 639.5	473.0	568.2	917.1	1637.9	2461.2	
Average $PM_{2.5}$ ($\mu g/m^3$)								
Total	77 (100)	22.4 ± 13.3	5.0	11.2	22.0	30.0	44.6	
Window closed	39 (50.6)	19.3 ± 14.3	3.2	7.5	15.7	24.8	51.2	**0.007**
Window open	38 (49.4)	25.6 ± 11.7	5.7	14.2	27.7	33.1	44.1	

Table A3. 2 to be continued.

Items	N [a] (%)	Mean ± Std.	5th	25th	50th	75th	95th	p-value [b]
Average $PM_{2.5}$ ($\mu g/m^3$)								
Rooms C&D (Non-PSG)	38 (49.4)	21.7 ± 10.2	4.1	13.4	24.5	29.5	37.3	0.887
Rooms A&B (PSG)	39 (50.6)	23.0 ± 15.9	5.2	8.9	21.2	33.8	56.8	
Average noise (dB(A))								
Total	105 (100)	42.5 ± 6.1	35.6	36.3	46.0	48.2	50.1	
Window closed	52 (49.5)	42.2 ± 6.0	35.4	36.1	46.0	48.0	50.2	**0.028**
Window open	53 (50.5)	42.7 ± 6.2	35.8	36.7	38.5	48.4	50.7	
Rooms C&D (Non-PSG)	49 (46.7)	36.4 ± 0.7	35.3	36.1	36.2	36.8	37.9	**< 0.001**
Rooms A&B (PSG)	56 (53.3)	47.7 ± 3.0	37.6	47.1	48.2	48.7	51.0	

[a] some samples are missed if the total sample size is less than 108.

[b] calculated by the Mann-Whitney U test.

Bold indicates p-value < 0.05.

Table A3. 3 Medians of the sleep parameters between adaptive and test nights.

Items	Median (25th – 75th)		p-value
	Adaption nights	Test nights	
Sleep parameters from PSG			
Analysis start time	23:35 (23:06 - 24:05)	23:58 (23:02 - 24:20)	0.234
Analysis stop time	7:22 (6:41 - 8:15)	7:27 (6:49 - 7:47)	0.157
TST (min)	449.5 (403.3 - 474.7)	436.5 (385.2 - 459.2)	0.163
Analysis duration (min)	477.8 (443.9 - 504.1)	460.6 (421.1 - 487.4)	0.145
Sleep latency (min)	6.8 (4.2 - 24.9)	13.0 (3.8 - 29.8)	0.528
REM latency (min)	73.3 (31.1 - 121)	86.5 (60.5 - 178.2)	0.339
WASO (min)	17.9 (10.8 - 31.2)	14.1 (6 - 19)	0.058
Sleep efficiency (%)	94.1 (89.7 - 96.5)	95.3 (91.7 - 97.6)	0.112
N1 (min)	7.0 (4.3 - 14.3)	5.3 (3 - 8.8)	0.492
N2 (min)	256.0 (224.1 - 289.5)	240 (200.3 - 301.1)	0.349
N1 + N2 (min)	257.5 (238.8 - 298.6)	246 (202.3 - 305.4)	0.316
N3 (min)	86 (76 - 102.3)	81.8 (63.9 - 98.9)	0.117
REM (min)	88.5 (50.8 - 102.7)	103.2 (58.8 - 125.8)	0.420
Wake (min)	27.5 (16.9 - 43.8)	22.2 (10.3 - 35.2)	0.089
N1 (%)	1.6 (0.9 - 2.8)	1.3 (0.6 - 2)	0.522
N2 (%)	53.5 (46.6 - 58.5)	52.9 (45 - 65.6)	0.913
N1 + N2 (%)	54.1 (49.7 - 60.2)	55.2 (46.8 - 66.6)	0.845
N3 (%)	19 (14.6 - 22.5)	19.4 (13.5 - 21.4)	0.396
REM (%)	17.5 (12.4 - 21.6)	22.6 (14.2 - 27)	0.286
Wake (%)	5.9 (3.5 - 10.3)	4.7 (2.4 - 8.3)	0.112

Table A3. 3 to be continued.

Items	Median (25th – 75th)		p-value
	Adaption nights	Test nights	
AI (times/h)	9.5 (6.3 - 11.9)	7.7 (5.6 - 12)	0.670
Arousal count (times)	63.5 (47.3 - 94)	60 (39.5 - 85)	0.102
Arousal count in wake (times)	13.5 (9 - 29.5)	12.5 (5.8 - 20)	0.184
AHI (/h)	0.6 (0.5 - 4.5)	4 (2.4 - 6.5)	0.087
Snore percentage (%)	0.7 (0.4 - 4.5)	0.8 (0.3 - 10.9)	0.115
ODI (/h)	1.7 (1.2 - 2.7)	1.5 (0.9 - 3.7)	0.249
PLMS index (/h)	5.4 (4.5 - 129.5)	6 (4.8 - 47.2)	0.767
Sleep parameters from the smartwatch			
Sleep Start Time	23:28 (22:29 - 24:00)	23:31 (23:06 - 23:56)	0.308
Sleep End Time	7:41 (7:03 - 8:05)	7:13 (6:56 - 7:40)	0.254
Sleep latency (min)	8 (4 - 13)	8.5 (4.3 - 12.8)	0.999
Asleep (min)	442 (408 - 460)	426.5 (398.3 - 465)	0.520
Awake (min)	52.5 (43.3 - 65.3)	51 (41.3 - 62.3)	0.165
Number of awakenings	26 (23.3 - 31)	25 (20.3 - 30.8)	0.193
TIB (min)	490.5 (462.5 - 507)	479.5 (452.5 - 510.8)	0.153
REM sleep (min)	88 (78 - 114.8)	91 (70.3 - 112)	0.775
Light sleep, N1 + N2 (min)	270.5 (242.3 - 312.5)	264.5 (239.3 - 297.8)	0.383
Deep sleep, N3 (min)	66 (55.3 - 91.3)	65 (52.3 - 79.5)	0.198
Sleep efficiency (%)	89.7 (87.1 - 91.2)	89.9 (86.7 - 91.3)	0.458
Awake (%)	10.3 (8.8 - 12.9)	10.1 (8.7 - 13.3)	0.466
REM sleep (%)	18.9 (14.3 - 23.4)	18.9 (16 - 22.5)	0.648
Light sleep (%)	55.7 (49.4 - 62.2)	55.4 (52.5 - 61.9)	0.710
Deep sleep (%)	14.7 (10.7 - 17.8)	14.3 (11.1 - 17)	0.274

TST, total sleep time; WASO, wake after sleep onset; AI, arousal index; AHI, apnea-hypopnea index; ODI, oxygen desaturation index; PLMS, periodic limb movement of sleep; TIB, time in bed.

Table A3. 4 The number (%) of the answer of False in the Groningen Sleep Quality Scale between two window states (N=27).

Questions	Window states	n (%)	p-value [a]
I had a deep sleep last night	WC	2 (7.4)	0.250
	WO	5 (18.5)	
I feel like I slept poorly last night	WC	27 (100)	**0.031**
	WO	21 (77.8)	
It took me more than half an hour to fall asleep last night	WC	27 (100)	0.250
	WO	24 (88.9)	

Table A3. 4 to be continued.

Questions	Window states	n (%)	*p*-value [a]
I felt tired after waking up this morning	WC	25 (92.6)	0.375
	WO	22 (81.5)	
I woke up several times last night	WC	18 (66.7)	0.227
	WO	13 (48.1)	
I feel like I didn't get enough sleep last night	WC	26 (96.3)	0.125
	WO	21 (77.8)	
I got up in the middle of the night	WC	19 (70.4)	< 0.999
	WO	19 (70.4)	
I felt rested after waking up this morning	WC	1 (3.7)	**0.039**
	WO	8 (29.6)	
I feel like I only had a couple hours of sleep last night	WC	27 (100)	0.063
	WO	22 (81.5)	
I feel I slept well last night	WC	0 (0)	**0.016**
	WO	7 (25.9)	
I didn't sleep a wink last night	WC	26 (96.3)	< 0.999
	WO	25 (92.6)	
I didn't have any trouble falling asleep last night	WC	4 (14.8)	< 0.999
	WO	4 (14.8)	
After I woke up last night, I had trouble falling asleep again	WC	27 (100)	0.500
	WO	25 (92.6)	
I tossed and turned all night last night	WC	23 (85.2)	0.625
	WO	21 (77.8)	
I didn't get more than 5 hours sleep last night	WC	27 (100)	< 0.999
	WC	26 (96.3)	

[a] from the McNemar test.

Table A3. 5 Spearman's correlation coefficients (ρ) of the number of awakenings, GSQS, snore percentage, wake-up times, sleep environmental parameters from both the air monitors and subjective assessments, age, sex, and BMI in the PSG group.

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	-0.107	-0.046	0.327	**0.451****	**0.354***	0.005	-0.091	0.188	0.206	0.113	-0.219	-0.119	**-0.459***	-0.085	0.051	0.186	0.099	-0.016
2		0.412	-0.058	-0.039	-0.230	0.089	0.059	-0.068	0.100	0.111	0.265	-0.305	**0.527****	-0.182	**0.753****	-0.055	0.003	0.242
3			0.256	0.104	**0.433***	-0.092	-0.083	-0.009	-0.059	0.165	-0.253	-0.068	0.341	-0.032	-0.094	0.333	-0.175	0.334
4				**0.414****	**0.824****	**-0.324***	-0.1	0.268	0.35	-0.112	-0.023	-0.344	-0.178	-0.033	0.134	-0.152	0.158	0.065
5					**0.403****	-0.112	-0.065	0.054	-0.132	0.199	-0.188	-0.132	-0.017	0.192	0.094	0.042	0.114	**0.279***
6						-0.254	**-0.307***	0.274	0.203	-0.004	-0.114	**-0.384***	-0.213	-0.029	-0.043	0.083	0.006	0.026
7							-0.015	-0.24	0.000	0.242	0.018	0.278	0.300	-0.029	-0.017	0.071	-0.043	0.208
8								0.17	0.27	0.042	0.034	0.223	0.042	0.158	-0.157	-0.227	0.159	-0.059
9									**0.557****	0.078	0.059	0.336	0.06	**0.411***	-0.166	-0.055	**0.393***	-0.352
10										-0.17	0.084	0.051	-0.019	0.055	-0.065	-0.316	**0.408***	-0.324
11											0.006	0.164	0.151	-0.186	-0.099	0.372	0.281	0.113
12												0.09	0.115	-0.154	0.140	-0.072	0.243	-0.084
13													-0.063	**0.409***	**-0.500****	0.049	0.339	-0.161
14														0.197	**0.456***	-0.099	-0.01	0.347
15															-0.179	0.01	0.127	0.200
16																-0.061	-0.038	0.287
17																	-0.119	0.257
18																		0.102

1, number of awakenings; 2, GSQS (Groningen Sleep Quality Scale); 3, snore percentage; Indoor parameters measured from the air monitors: 4, room temperature; 5, relative humidity; 6, CO_2; 7, $PM_{2.5}$; 8, noise; Subjective assessments of indoor parameters: 9, room temperature; 10, bed temperature; 11, air humidity; 12, illumination; 13, air freshness; 14, noise; 15, odour; 16, wake up times; 17, sex; 18, age; 19, BMI.

[a] BMI, body mass index, BMI was divided into 3 groups: group 0, normal BMI (18.0-25.9); group 1, overweight (25.0-29.9); group 2, obese (> 30.0). * *p*-value < 0.05; ** *p*-value < 0.01. Bold indicates *p*-value < 0.05.

Annex 4A

SleepVent Survey

Welcome to this SleepVent survey

The questionnaire consists of six parts that will be used to recruit subjects for the sleep project.

It would take about 10 minutes to fill the questionnaire.

Your cooperation would be highly appreciated.

CONSENT FORM

This questionnaire seeks to identify potential volunteers for a comprehensive study called SleepVent, related to the Indoor Environmental Quality (IEQ) in their sleeping environments and their sleep quality. The study is carried out by researchers at the Technical University of Denmark (DTU).

The questionnaire collects information on age, absence of any medically diagnosed sleep disorder, type of residential dwelling (detached/semi-detached house, apartment, dormitory, etc.), type of ventilation system, neighbourhood characteristics (such as proximity to busy roads, commercial zones, airports, etc.), subjectively measured sleep quality, and sleeping habits (about sleeping time, duration of sleep, operation of natural/mechanical ventilation system and heating/cooling system in bedrooms). You can choose not to answer some questions in the questionnaire if you prefer not to.

The information collected through the questionnaire will be used in selecting volunteers who will be asked to participate in a study during which two-week measurements of their bedroom IEQ and sleep quality will be performed. For this study, additional approval will be sought upon recruitment of volunteers.

The information collected through the questionnaire will additionally be used for analysis to investigate how bedroom IEQ affects sleep quality in the general population. For those respondents that will not be recruited for the follow-up study, the information in the questionnaire will be COMPLETELY anonymized, and we will save no information that can lead to the identification of a specific person.

In order to proceed with the questionnaire, we need your consent to collect and save the information included in it. By giving your consent, you agree to the following:

□ I hereby give my consent to DTU to collect and save the information I give in the questionnaire.

□ I hereby declare that I am fully aware of my rights and that I, at any time, can withdraw my consent by contacting the following e-mail address: sleepvent@byg.dtu.dk

Background

1. Name (Full name):

____

2a. Email address:

____

2b. Please retype Email address:

____

3. Postal/zip code of your home:

____

4. You are?

○ Male

○ Female

○ I prefer not to disclose this information.

○ Other: ______________

5. Age:

____

6. Weight [kg]:

____

7. Height [cm]:

____

8. How long have you been living in Denmark?

○ Less than 1 year

○ 1 to 2 years

○ Over 2 years

Smoking habit (cigarettes, e-cigarettes etc.)

1. Do you smoke?

○ Regularly.

○ Occasionally.

○ No, I don't.

2. Is your home a non-smoking place?

○ Yes, it is a non-smoking place.

○ No, it is a smoking place.

Regular sleep pattern during weekdays, excluding holidays

1. Do you sleep alone during weekdays, excluding holidays?

○ Yes, I sleep alone.

○ No, I sleep with spouse or partner.

○ No, I sleep with child(ren).

○ I prefer not to disclose this information.

○ Other: ______________

2. Do you sleep with window(s) open? (e.g. Any means of airing by outside such as windows, terrace doors, garden doors, balcony doors, etc.)

○ Regularly.

○ Occasionally.

○ No, I don't.

3. Do you sleep with door(s) to the bedroom open?

○ Regularly.

○ Occasionally.

○ No, I don't.

Bedroom environment

In this section, the term 'your bedroom' means the bedroom you sleep in.

1. In which type of building do you live?

○ Detached house (not joined to another house on either side)

○ Row-house (joined to another house)

○ Multistory apartment building

○ Other: ________

2. On which floor is your bedroom? (Ground floor is '0' floor. If your bedroom is on the 1st floor, please write '1')

____

3. Which year was the building built?

○ Before 1960

○ 1961 to 1995

○ 1996 to 2009

○ After 2010

○ I don't know.

4. What is the approximate area of your bedroom?

○ Less than 10 m^2

○ 10 to 15 m^2

○ 15 to 20 m^2

○ More than 20 m^2

○ I prefer not to disclose this information.

5. How long do you keep the window(s) open in your bedroom during the daytime? (e.g. Any means of airing by outside such as windows, terrace doors, garden doors, balcony doors, etc.) Mark only one circle per row.

	< 15 min	≥ 15 min	I don't open the window(s).

a. in the morning	○	○	○
b. in the evening	○	○	○

6. These are examples of air terminal devices for mechanical ventilation systems.

6-1. Do you have any of the above or similar air terminal devices in your bedroom?

○ Yes

○ No

6-2. Do you have any of the above or similar air terminal devices in your bathroom(s)?

○ Yes

○ No

7. These are vents for trickle ventilation, and they are attached to a window, an external door, or on the wall.

Do you have any of the above or similar vents in your bedroom and open them during sleep at night?

○ Yes, I do have and open regularly.

○ Yes, I do have and open occasionally.

○ Yes, I do have and do nothing with them.

○ I don't have any of them.

8. Do you have any of the following nearby your home? *Mark all that is applicable. If not, go to the next question.*

□ Highway or major road with heavy traffic

□ Railway where trains move by several times/day

□ Active airport

□ Large industrial chimneys

□ Commercial zone/shopping centre

9. Do you have any of these in your bedroom? (Some of these may be a source of indoor pollutants and may also affect sleep quality.) *Mark all that is applicable.*

□ House plant

□ Fish tank

□ Carpet

□ Printer

□ TV

10. How often are you disturbed by any of the following during sleep at night in winter? Mark only one circle per row.

	Regularly.	Occasionally.	No, I don't.
a. Noise	○	○	○
b. Stuffy air	○	○	○
c. Too warm/hot	○	○	○
d. Too cool/cold	○	○	○

11. How often are you disturbed by any of the following during sleep at night in summer? Mark only one circle per row.

	Regularly.	Occasionally.	No, I don't.
a. Noise	○	○	○
b. Stuffy air	○	○	○

c. Too warm/hot	○	○	○
d. Too cool/cold	○	○	○

Additional questions

1. Do you have any of these chronic diseases? (Asthma, Rhinitis, Hay fever, Eczema, Migraine headaches/Recurring headaches, Diabetes)

○ No, I don't have any.

○ Yes.

○ I prefer not to disclose this information.

2. How old is the youngest child at home? (Write zero (0) if you live without children.)

____

3. Do you have pet(s)?

○ No, I don't have any.

○ Yes (dog, cat, or other)

4. Mark only one circle per row.

	Yes, regularly.	Yes, occasionally.	No, I don't.
a. Do you exercise?	○	○	○
b. Do you use essential oil to help you sleep?	○	○	○
c. Do you sleep with earplugs?	○	○	○
d. Do you sleep with an eye mask?	○	○	○

5. Are you a meat-eater?

○ Yes, I eat meat.

○ No, I do not eat meat but I do eat fish.

○ No, I do not eat meat and fish either.

○ I prefer not to disclose this information.

○ Other: ________________

6. Do you regularly take naps during the day?

○ Yes, I do for less than 15 minutes.

○ Yes, I do for 15 to 30 minutes.

○ Yes, I do for more than 30 minutes.

○ No, I do not.

7. When do you usually work / study?

○ Daytime

○ Night-time

○ Daytime and night-time (on shift)

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 the majority of days and nights in the past month. Please answer all questions.

1. During the past month, at what time have you usually gone to bed? (Example: 22:30)

____

2. During the past month, how long (in minutes) has it taken you to fall asleep each night?

______________minutes

3. During the past month, at what time have you usually gotten up in the morning? (Example: 8:30)

____

4. During the past month, 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… (Mark only one circle per row.)

	Not during the past month	Less than once a week	Once or twice a week	Three or more times week
a. Cannot get to sleep within 30 minutes	○	○	○	○

b. Wake up in the middle of the night or early morning	○	○	○	○
c. Have to get up to use the bathroom	○	○	○	○
d. Cannot breathe comfortably	○	○	○	○
e. Cough or snore loudly	○	○	○	○
f. Feel too cold	○	○	○	○
g. Feel too hot	○	○	○	○
h. Have bad dreams	○	○	○	○
i. Have pain	○	○	○	○
j. 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?

○ Not during the past month

○ Less than once a week

○ Once or twice a week

○ Three or more times week

7. During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity?

○ Not during the past month

○ Less than once a week

○ Once or twice a week

○ Three or more times week

8. During the past month, how much of a problem has it been for you to keep up enthusiasm to get things done?

○ Not during the past month

○ Less than once a week

○ Once or twice a week

○ Three or more times week

9. During the past month, how would you rate your sleep quality overall?

○ Very good

○ Fairly good

○ Fairly bad

○ Very bad

Thanks for your answers!

Now, you have a chance to win a Philips wake up light, a 30 kr. voucher to Lagkagehuset or free testing of your bedroom environment and sleep quality. Lucky winners will be notified by email.

Table A4. 1 Sample sizes and proportions for all the questions in the survey (N ≤ 517).

Items	N (%) [a]
Background	
1. Gender	
Male	282 (55.4)
Female	227 (44.6)
2. Age	
14–24	151 (29.6)
25–28	122 (23.9)
29–40	111 (21.8)
41–78	126 (24.7)
3. BMI (kg/m^2)	
<18.5	14 (2.8)
18.5—24.9	315 (62.5)
25.0—29.9	141 (28.0)
> 29.9	34 (6.7)
4. Residential location [b]	
Urban	185 (36.3)
Suburban	282 (55.4)
Rural	42 (8.3)
5. Years living in Denmark	
Less than 1 year	55 (10.7)
1 to 2 years	35 (6.8)
Over 2 years	424 (82.5)

Table A4. 1 to be continued.

Items	N (%) [a]
Sleep habits	
1. Sleep alone or with other(s)	
Yes, I sleep alone	208 (40.2)
No, I sleep habits a spouse or partner	253 (49.0)
No, I sleep habits children	13 (2.5)
I prefer not to disclose this information.	12 (2.3)
Others [c]	31 (6.0)
2. Sleep with window(s) open (e.g. Any means of airing by outside such as windows, terrace doors, garden doors, balcony doors, etc.)	
Regularly	66 (12.9)
Occasionally	85 (16.7)
No, I don't.	359 (70.4)
3. Sleep with the bedroom door open	
Regularly	215 (42.1)
Occasionally	49 (9.6)
No, I don't.	247 (48.3)
Bedroom airing behaviour	
3. Time to keep the window(s) open in your bedroom during the daytime *(e.g., Any means of airing by outside air, such as windows, terrace doors, garden doors, balcony doors, etc.)*	
a. in the morning	
I don't open the window(s)	116 (23.5)
< 15 min	197 (39.9)
≥ 15 min	181 (36.6)
b. in the evening	
I don't open the window(s)	115 (23.3)
< 15 min	214 (43.4)
≥ 15 min	164 (33.3)
Bedroom environment	
1. Building characteristics	
(1) Building type	
Detached house (not joined to another house on either side)	121 (24.3)
Row-house (joined to another house)	50 (10.1)
Multi-dwelling apartment	305 (61.4)
Others [d]	21 (4.2)

Table A4. 1 to be continued.

Items	N (%) [a]
(2) Your bedroom floor number (ground floor is '0' floor)	
-1	4 (0.8)
0	159 (33.8)
1	142 (30.1)
2	62 (13.2)
≥ 3	104 (22.1)
(3) Year the building was built	
Before 1960	153 (30.4)
1961 to 1995	139 (27.5)
1996 to 2009	47 (9.3)
After 2010	92 (18.3)
I don't know.	73 (14.5)
(4) Bedroom area	
Less than 10 m^2	56 (11.1)
10 to 15 m^2	257 (51.0)
15 to 20 m^2	132 (26.2)
More than 20 m^2	57 (11.3)
I prefer not to disclose this information	2 (0.4)
(5) Air terminal devices	
a. in your bedroom	
Yes, I have.	168 (33.4)
No, I don't have	335 (66.6)
b. in your bathroom(s)	
Yes, I have.	415 (82.8)
No, I don't have	86 (17.2)
(6) Vents in the bedroom and open them during sleep at night	
Yes, I have and open regularly	109 (21.7)
Yes, I have and open occasionally	39 (7.7)
Yes, I have but do nothing with them	34 (6.8)
I don't have any of them	321 (63.8)
2. Building surroundings	
(1) Highway or major road with heavy traffic	
Yes	196 (38.4)
No	314 (61.6)

Table A4. 1 to be continued.

Items	N (%) [a]
(2) Railway where trains move by several times/day	
Yes	86 (16.9)
No	424 (83.1)
(3) Active airport	
Yes	15 (2.9)
No	495 (97.1)
(4) Large industrial chimneys	
Yes	28 (5.5)
No	482 (94.5)
(5) Commercial zone/shopping centre	
Yes	61 (12.0)
No	449 (88.0)
3. The objects in the bedrooms	
(1) House plant	
Yes	274 (53.0)
No	243 (47.0)
(2) Fish tank	
Yes	204 (39.5)
No	313 (60.5)
(3) Carpet	
Yes	254 (49.1)
No	263 (50.9)
(4) Printer	
Yes	213 (41.2)
No	304 (58.8)
(5) TV	
Yes	218 (42.2)
No	299 (57.8)
Sleep disturbances	
1. The frequency of disturbance by any of the following during sleep at night in winter	
(1) Noise	
Regularly	32 (6.4)
Occasionally	181 (36.3)
Never	286 (57.3)

Table A4. 1 to be continued.

Items	N (%) [a]
(2) Stuffy air	
Regularly	36 (7.3)
Occasionally	149 (30.2)
Never	309 (62.5)
(3) Too warm/hot	
Regularly	34 (6.8)
Occasionally	249 (49.5)
Never	220 (43.7)
(4) Too cool/cold	
Regularly	31 (6.3)
Occasionally	203 (40.9)
Never	262 (52.8)
2. The frequency of disturbance by any of the following during sleep at night in winter	
(1) Noise	
Regularly	78 (15.6)
Occasionally	226 (45.3)
Never	195 (39.1)
(2) Stuffy air	
Regularly	40 (8.1)
Occasionally	162 (33.0)
Never	289 (58.9)
(3) Too warm/hot	
Regularly	143 (28.7)
Occasionally	300 (60.1)
Never	56 (11.2)
(4) Too cool/cold	
Regularly	5 (1.0)
Occasionally	88 (18.0)
Never	395 (80.9)
Additional questions	
1. Any chronic diseases? (e.g., asthma, rhinitis, hay fever, eczema, migraine headaches/recurring headaches, diabetes, etc.)	
No	319 (64.3)
Yes	173 (34.9)
I prefer not to disclose this information.	4 (0.8)

Table A4. 1 to be continued.

Items	N (%) [a]
2. Age of the youngest child living at home	
No child at home	349 (73.9)
< 5	43 (9.2)
≥ 5	80 (16.9)
3. Pet(s)	
No, I don't have any.	394 (79.3)
Yes (dog, cat, or other)	103 (20.7)
4. Exercise habit	
Yes, regularly	262 (53.0)
Yes, occasionally	172 (34.8)
No, I don't	60 (12.2)
5. Essential oil used to help sleep better	
Yes, regularly	8 (1.6)
Yes, occasionally	15 (3.0)
No, I don't	471 (95.4)
6. Sleep habits earplugs	
Yes, regularly	14 (2.8)
Yes, occasionally	51 (10.4)
No, I don't	429 (86.8)
7. Sleep habits an eye mask	
Yes, regularly	11 (2.2)
Yes, occasionally	33 (6.7)
No, I don't	450 (91.1)
8. Meat consumption	
Yes, I eat meat.	426 (91.6)
No, I do not eat meat, but I do eat fish	6 (1.3)
No, I do not eat meat and fish either	18 (3.9)
I prefer not to disclose this information	1 (0.2)
Others [e]	14 (3.0)
9. Take regular naps during the day	
Yes, I do for less than 15 min	23 (4.6)
Yes, I do for 15 to 30 min	49 (9.9)
Yes, I do for more than 30 min	23 (4.6)
No, I don't	401 (80.9)

Table A4. 1 to be continued.

Items	N (%) [a]
10. Time for usual work/study	
Daytime	428 (86.8)
Night-time	10 (2.0)
Daytime and night-time (on shift)	55 (11.2)
11. Smoking frequency (cigarettes, e-cigarettes, etc.)	
Regularly	23 (4.5)
Occasionally	43 (8.3)
No, I don't	448 (87.2)
12. Your home is a non-smoking place	
Yes, it is a non-smoking place	484 (94.2)
No, it is a smoking place	30 (5.8)

[a] Some sample sums were lower than 517 since some of the respondents did not answer the corresponding questions.

[b] Residential locations were deduced from postcodes. Urban regions refer to the areas with the first two numbers of postcodes 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] Others indicate sleeping alone sometimes, with dogs present, sharing bedrooms, etc.

[d] Others: not specified.

[e] Others indicate “only eat meat once a week”, “seldom eat meat”, etc.

BMI: body mass index.

Annex 4B

Figure A4. 1 Poster to distribute the online questionnaire survey.

Annex 4C

In Denmark, the ventilation requirements of bedrooms and the type of ventilation depending on the age of the building. From 1961, mechanical ventilation was optional; from 1995, newly-built dwellings had to be ventilated mechanically, either via an extraction system combined with air vents or a supply and extraction system; and from 2010, mechanical ventilation with heat recovery was required in the heating season. In naturally ventilated dwellings, from 1961 ventilation guidelines required that outdoor air was supplied either by opening windows or doors to the outside and/or via adjustable vents in external walls or windows. We divided the dwellings we surveyed into four periods, defined by the ventilation requirements that were in force when they were built: before 1960, 1961 – 1995, 1996 – 2009, and after 2010.

Table A4. 2 Building regulation (BR) of mechanical and natural ventilation requirements.

	Mechanical ventilation	Natural ventilation
BR61	optional	Dry rooms are supplied either via opening windows or doors to the outside or an adjustable vent in external walls, windows or doors.
BR95	Should be ventilated either via an extraction system combined with air vents or a supply and extraction system.	Dry rooms and wet rooms are supplied via opening windows, hatches or external doors and one or more adjustable air vents.

Table A4. 2 to be continued.

	Mechanical ventilation	Natural ventilation
BR10	The basic air exchange must be carried out via mechanical ventilation with heat recovery by supplying outdoor air to the dry rooms and extracting air from the wet rooms.	Outside the heating season, the air supply may come through windows, vents, etc.

Annex 4D

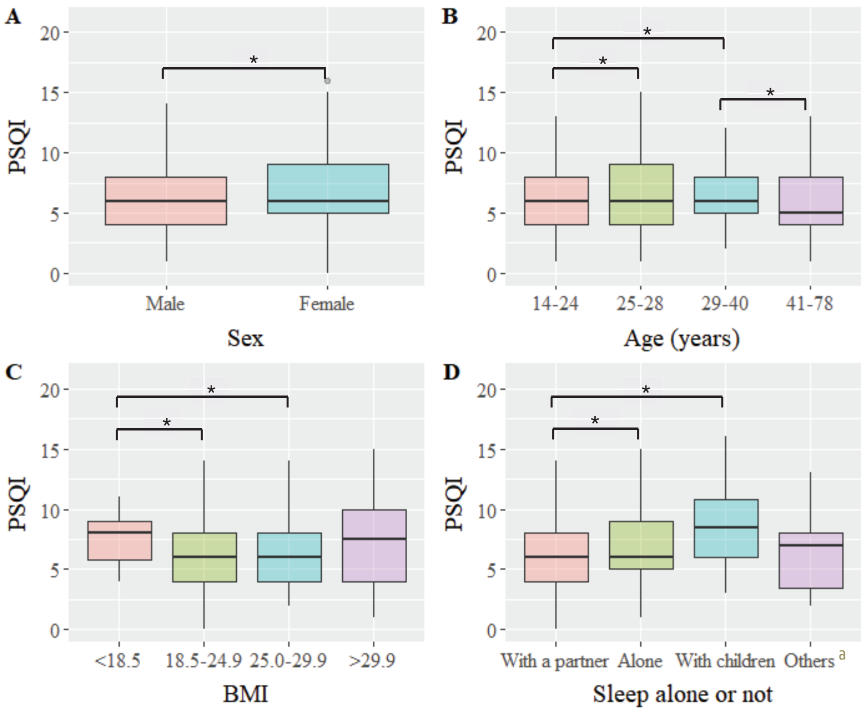


Figure A4. 2 The PSQI as a function of different personal characteristics and sleep habits. IQR, interquartile range; the maximum PSQI was 18 in the present study. Box range is between 25th and 75th percentiles, vertical lines above and below boxes are ranges within 1.5 IQR, horizontal line indicates median.
[a] Others indicate sleeping alone sometimes, sleeping with dogs in the bedroom, sharing bedrooms, etc.
[**] p-value < 0.01, [*] p-value < 0.05 (Chi-square test).

Figure A4. 2 shows the PSQI as a function of personal characteristics and sleeping alone or not. Females obtained a PSQI that was slightly higher compared to males (p-value < 0.035). Respondents who slept with children rated PSQI the highest thus had the worst sleep quality compared to those sleeping with a partner or sleeping alone. Those who had a BMI below 18.5, compared to those who had a BMI between 18.5 and 29.9, rated PSQI higher thus had reduced sleep quality. The respondents with a BMI higher than 29.9 also rated PSQI to be higher but the difference did not reach statistical significance. The BMI groups of <18.5, 18.5 – 24.9, 25.0 – 29.9, and >29.9 were categorized as underweight, normal, overweight, and obese, respectively (WHO, 2019).

Annex 4E

Table A4. 3 Spearman's correlation coefficients (ρ) of sleep disturbance.

Items	Too warm	Too cool	Noise
Stuffy air	0.253**	0.165**	0.232**
Too warm		0.173**	0.136**
Too cool			0.151**

** p-value < 0.01.

Table A4. 4 Association between sleep disturbance, PSQI and "personal characteristics, bedroom airing behaviour and the environment in the bedroom".

Items	Sleep disturbance: Stuffy air in the bedroom number (%) No	Stuffy air in the bedroom number (%) Yes	Too warm bedroom number (%) No	Too warm bedroom number (%) Yes	Too cool bedroom number (%) No	Too cool bedroom number (%) Yes	Noise in the bedroom number (%) No	Noise in the bedroom number (%) Yes	Subjective sleep quality: PSQI score Mean (SD)	PSQI score Median (IQR)
Personal characteristics										
1. Gender										
Male	174 (63.7)	99 (36.3)	**136 (49.3)**	**140 (50.7)****	**166 (60.8)**	**107 (39.2)****	160 (58.2)	115 (41.8)	**6.0 (2.6)**	**6.0 (4.0 – 8.0)***
Female	131 (61.5)	82 (38.5)	**82 (37.4)**	**137 (62.6)**	**94 (43.7)**	**121 (56.3)**	121 (56.0)	95 (44.0)	**6.7 (3.0)**	**6.0 (4.0 – 9.0)**
2. Age interquartile range (IQR)										
14–24	**90 (62.5)**	**54 (37.5)***	**60 (40.8)**	**87 (59.2)***	**67 (45.9)**	**79 (54.1)***	**83 (56.5)**	**64 (43.5)****	6.4 (2.6)	6.0 (4.0 – 8.0)#
25–28	**61 (51.7)**	**57 (48.3)**	**48 (40.0)**	**72 (60.0)**	**57 (48.3)**	**61 (51.7)**	**53 (44.9)**	**65 (55.1)**	6.4 (2.8)	6.0 (4.0 – 9.0)
29–40	**67 (63.2)**	**39 (36.8)**	**40 (37.4)**	**67 (62.6)**	**63 (59.4)**	**43 (40.6)**	**65 (60.7)**	**42 (39.3)**	6.7 (2.9)	6.0 (5.0 – 8.0)
41–78	**86 (72.3)**	**33 (27.7)**	**68 (55.7)**	**54 (44.3)**	**72 (60.5)**	**47 (39.5)**	**81 (67.5)**	**39 (32.5)**	5.9 (2.9)	5.0 (4.0 – 8.0)

Table A4. 4 to be continued.

Items	Sleep disturbance								Subjective sleep quality	
	Stuffy air in the bedroom number (%)		Too warm bedroom number (%)		Too cool bedroom number (%)		Noise in the bedroom number (%)		PSQI score	
	No	Yes	No	Yes	No	Yes	No	Yes	Mean (SD)	Median (IQR)
3. BMI										
<18.5	12 (85.7)	2 (14.3) [a]	8 (57.1)	6 (42.9)	**1 (7.1)**	**13 (92.9)****[a]	6 (42.9)	8 (57.1)	8.0 (2.8)	8.0 (6.0 – 9.0)$^{\#}$
18.5–24.9	188 (62.3)	114 (37.7)	127 (41.2)	181 (58.8)	**157 (51.8)**	**146 (48.2)**	177 (58.0)	128 (42.0)	6.2 (2.8)	6.0 (4.0 – 8.0)
25.0–29.9	77 (58.3)	55 (41.7)	64 (47.8)	70 (52.2)	**78 (58.6)**	**55 (41.4)**	77 (57.5)	57 (42.5)	6.2 (2.5)	6.0 (4.0 – 8.0)
>29.9	22 (66.7)	11 (33.3)	17 (50.0)	17 (50.0)	**20 (60.6)**	**13 (39.4)**	20 (60.6)	13 (39.4)	7.3 (3.9)	7.5 (4.0 – 10.0)
Bedroom environment										
Building characteristics										
1. Residential location										
Rural	**31 (81.6)**	**7 (18.4)***	18 (46.2)	21 (53.8)	25 (65.8)	13 (34.2)	**28 (73.7)**	**10 (26.3)****	5.4 (2.5)	5.0 (3.0 – 8.0)$^{\#}$
Suburban	**172 (63.9)**	**97 (36.1)**	125 (45.8)	148 (54.2)	139 (51.5)	131 (48.5)	**165 (60.7)**	**107 (39.3)**	6.4 (3.0)	6.0 (4.0 – 8.0)
Urban	**102 (57.0)**	**77 (43.0)**	75 (41.0)	108 (59.0)	92 (51.1)	88 (48.9)	**88 (48.6)**	**93 (51.4)**	6.3 (2.6)	6.0 (4.0 – 8.0)
2. House type										
Detached or row houses	**117 (69.2)**	**52 (30.8)***	**88 (51.8)**	**82 (48.2)***	95 (56.5)	73 (43.5)	**117 (69.2)**	**52 (30.8)****	**5.9 (2.7)**	**6.0 (4.0 – 8.0)****
Multi-dwelling apartment	**176 (59.3)**	**121 (40.7)**	**121 (39.7)**	**184 (60.3)**	155 (51.7)	145 (48.3)	**152 (50.3)**	**150 (49.7)**	**6.6 (2.9)**	**6.0 (4.0 – 9.0)**
3. Year built										
Before 1960	91 (61.1)	58 (38.9)	72 (47.4)	80 (52.6)	82 (55.0)	67 (45.0)	80 (53.3)	70 (46.7)	6.2 (2.9)	6.0 (4.0 – 8.0)
1961–1995	86 (63.7)	49 (36.3)	57 (41.0)	82 (59.0)	65 (47.4)	72 (52.6)	88 (63.8)	50 (36.2)	6.5 (3.0)	6.0 (4.0 – 8.0)
1996–2009	29 (63.0)	17 (37.0)	19 (40.4)	28 (59.6)	30 (65.2)	16 (34.8)	29 (61.7)	18 (38.3)	6.2 (2.4)	6.0 (4.0 – 8.0)
After 2010	63 (69.2)	28 (30.8)	40 (43.5)	52 (56.5)	54 (58.7)	38 (41.3)	52 (57.1)	39 (42.9)	5.9 (2.8)	5.0 (4.0 – 8.0)

Table A4. 4 to be continued.

Items	Sleep disturbance								Subjective sleep quality	
	Stuffy air in the bedroom number (%)		Too warm bedroom number (%)		Too cool bedroom number (%)		Noise in the bedroom number (%)		PSQI score	
	No	Yes	No	Yes	No	Yes	No	Yes	Mean (SD)	Median (IQR)
4. Bedroom area										
< 10 m^2	34 (63.0)	20 (37.0)	24 (42.9)	32 (57.1)	26 (47.3)	29 (52.7)	26 (47.3)	29 (52.7)	6.8 (3.0)	6.0 (5.0 – 9.0)
10–15 m^2	159 (62.8)	94 (37.2)	104 (40.5)	153 (59.5)	142 (56.1)	111 (43.9)	154 (60.2)	102 (39.8)	6.3 (2.8)	6.0 (4.0 – 8.0)
15–20 m^2	75 (57.3)	56 (42.7)	59 (44.7)	73 (55.3)	62 (47.7)	68 (52.3)	74 (56.9)	56 (43.1)	6.3 (2.7)	6.0 (4.0 – 8.0)
> 20 m^2	40 (74.1)	14 (25.9)	31 (55.4)	25 (44.6)	31 (55.4)	25 (44.6)	31 (55.4)	25 (44.6)	6.1 (2.9)	6.0 (4.0 – 9.0)
5. Bedroom floor										
– 1 or 0	110 (68.8)	50 (31.3)	79 (48.5)	84 (51.5)	93 (58.1)	67 (41.9)	**109 (67.7)**	**52 (32.3)****	6.1 (2.6)	6.0 (4.0 – 8.0)
1	85 (60.7)	55 (39.3)	60 (42.6)	81 (57.4)	70 (49.6)	71 (50.4)	**75 (53.2)**	**66 (46.8)**	6.3 (2.7)	6.0 (4.0 – 8.0)
2 or above	95 (58.6)	67 (41.4)	68 (41.0)	98 (59.0)	84 (51.5)	79 (48.5)	**87 (52.4)**	**79 (47.6)**	6.7 (3.0)	6.0 (4.0 – 9.0)
6. Natural ventilation										
No	199 (64.8)	108 (35.2)	145 (46.3)	168 (53.7)	170 (55.2)	138 (44.8)	176 (56.6)	135 (43.4)	6.4 (2.8)	6.0 (4.0 – 8.0)
Yes	109 (58.6)	77 (41.4)	75 (39.7)	114 (60.3)	92 (49.2)	95 (50.8)	110 (58.8)	77 (41.2)	6.3 (3.0)	6.0 (4.0 – 8.0)
7. Exhaust ventilation										
No	242 (64.0)	136 (36.0)	166 (43.3)	217 (56.7)	204 (54.0)	174 (46.0)	225 (59.2)	155 (40.8)	6.3 (2.9)	6.0 (4.0 – 8.0)
Yes	64 (56.6)	49 (43.4)	53 (45.3)	64 (54.7)	56 (48.7)	59 (51.3)	59 (50.9)	57 (49.1)	6.6 (2.9)	6.0 (5.0 – 8.0)
8. Mechanical ventilation										
No	**193 (59.2)**	**133 (40.8)***	141 (42.2)	193 (57.8)	165 (50.0)	165 (50.0)$^{\#}$	185 (55.9)	146 (44.1)	6.4 (2.9)	6.0 (4.0 – 8.0)
Yes	**114 (68.7)**	**52 (31.3)**	78 (46.4)	90 (53.6)	96 (58.2)	69 (41.8)	100 (59.9)	67 (40.1)	6.4 (2.7)	6.0 (4.0 – 8.0)

Table A4. 4 to be continued.

Items	Sleep disturbance								Subjective sleep quality	
	Stuffy air in the bedroom number (%)		Too warm bedroom number (%)		Too cool bedroom number (%)		Noise in the bedroom number (%)		PSQI score	
	No	Yes	No	Yes	No	Yes	No	Yes	Mean (SD)	Median (IQR)
Building surroundings										
1. Highway or major road with heavy traffic										
No	**206 (67.8)**	**98 (32.2)****	**147 (47.9)**	**160 (52.1)***	164 (53.8)	141 (46.2)	**186 (61.0)**	**119 (39.0)***	6.2 (2.8)	6.0 (4.0 – 8.0)
Yes	**103 (54.2)**	**87 (45.8)**	**73 (37.2)**	**123 (62.8)**	98 (51.3)	93 (48.7)	**100 (51.5)**	**94 (48.5)**	6.6 (2.9)	6.0 (4.0 – 8.0)
2. Railway										
No	258 (63.2)	150 (36.8)	184 (44.1)	233 (55.9)	221 (53.8)	190 (46.2)	**246 (59.4)**	**168 (40.6)***	6.3 (2.8)	6.0 (4.0 – 8.0)
Yes	51 (59.3)	35 (40.7)	36 (41.9)	50 (58.1)	41 (48.2)	44 (51.8)	**40 (47.1)**	**45 (52.9)**	6.5 (3.1)	6.0 (4.0 – 8.0)
3. Airport										
No	301 (62.8)	178 (37.2)	212 (43.4)	276 (56.6)	254 (52.8)	227 (47.2)	279 (57.6)	205 (42.4)	**6.3 (2.8)**	**6.0 (4.0 – 8.0)****
Yes	8 (53.3)	7 (46.7)	8 (53.3)	7 (46.7)	8 (53.3)	7 (46.7)	7 (46.7)	8 (53.3)	**9.4 (3.9)**	**9.0 (8.0 – 11.5)**
4. Large industrial chimneys										
No	291 (62.4)	175 (37.6)	210 (44.2)	265 (55.8)	249 (53.2)	219 (46.8)	270 (57.3)	201 (42.7)	6.3 (2.8)	6.0 (4.0 – 8.0)
Yes	18 (64.3)	10 (35.7)	10 (35.7)	18 (64.3)	13 (46.4)	15 (53.6)	16 (57.1)	12 (42.9)	7.1 (3.1)	6.5 (5.8 – 9.0)
5. Commercial zones/shopping centres										
No	268 (61.8)	166 (38.2)	198 (44.8)	244 (55.2)	233 (53.4)	203 (46.6)	**262 (59.8)**	**176 (40.2)****	6.3 (2.8)	6.0 (4.0 – 8.0)
Yes	41 (68.3)	19 (31.7)	22 (36.1)	39 (63.9)	29 (48.3)	31 (51.7)	**24 (39.3)**	**37 (60.7)**	6.9 (3.2)	6.0 (5.0 – 9.0)
Objects in bedrooms										
1. House plant										
No	150 (64.1)	84 (35.9)	100 (42.0)	138 (58.0)	123 (52.3)	112 (47.7)	131 (55.7)	104 (44.3)	6.4 (3.0)	6.0 (4.0 – 8.0)
Yes	159 (61.2)	101 (38.8)	120 (45.3)	145 (54.7)	139 (53.3)	122 (46.7)	155 (58.7)	109 (41.3)	6.4 (2.7)	6.0 (4.0 – 8.0)

Table A4. 4 to be continued.

Items	Sleep disturbance								Subjective sleep quality	
	Stuffy air in the bedroom number (%)		Too warm bedroom number (%)		Too cool bedroom number (%)		Noise in the bedroom number (%)		PSQI score	
	No	Yes	No	Yes	No	Yes	No	Yes	Mean (SD)	Median (IQR)
2. Fish tank										
No	191 (63.5)	110 (36.5)	132 (43.0)	175 (57.0)	160 (53.0)	142 (47.0)	167 (54.6)	139 (45.4)	**5.8 (2.8)**	**5.0 (4.0 – 8.0)****
Yes	118 (61.1)	75 (38.9)	88 (44.9)	108 (55.1)	102 (52.6)	92 (47.4)	119 (61.7)	74 (38.3)	**7.3 (2.8)**	**7.0 (5.0 – 9.0)**
3. Carpet										
No	**170 (67.2)**	**83 (32.8)***	107 (41.5)	151 (58.5)	132 (52.2)	121 (47.8)	139 (54.3)	117 (45.7)	**5.8 (2.8)**	**6.0 (4.0 – 8.0)****
Yes	**139 (57.7)**	**102 (42.3)**	113 (46.1)	132 (53.9)	130 (53.5)	113 (46.5)	147 (60.5)	96 (39.5)	**6.9 (2.8)**	**6.0 (5.0 – 9.0)**
4. Printer										
No	188 (64.2)	105 (35.8)	130 (43.6)	168 (56.4)	158 (53.7)	136 (46.3)	166 (55.9)	131 (44.1)	**5.8 (2.8)**	**5.0 (4.0 – 8.0)****
Yes	121 (60.2)	80 (39.8)	90 (43.9)	115 (56.1)	104 (51.5)	98 (48.5)	120 (59.4)	82 (40.6)	**7.2 (2.7)**	**7.0 (5.0 – 9.0)**
5. TV										
No	181 (62.8)	107 (37.2)	118 (40.3)	175 (59.7)#	151 (52.2)	138 (47.8)	163 (56.0)	128 (44.0)	6.2 (2.9)	6.0 (4.0 – 8.0)#
Yes	128 (62.1)	78 (37.9)	102 (48.6)	108 (51.4)	111 (53.6)	96 (46.4)	123 (59.1)	85 (40.9)	6.6 (2.9)	6.0 (5.0 – 8.0)
Bedroom airing behaviour during daytime or during sleep										
1. Windows open in the morning										
Never	**76 (65.5)**	**40 (34.5)***	**85 (73.9)**	**30 (26.1)****	57 (49.1)	59 (50.9)	68 (58.6)	48 (41.4)	6.4 (2.8)	6.0 (4.0 – 8.0)
Open for some time	**206 (54.9)**	**169 (45.1)**	**221 (59.6)**	**150 (40.4)**	159 (42.2)	218 (57.8)	192 (51.8)	179 (48.2)	6.3 (2.9)	6.0 (4.0 – 8.0)
2. Windows open in the evening										
Never	**82 (71.9)**	**32 (28.1)****	**86 (75.4)**	**28 (24.6)****	54 (47.0)	61 (53.0)	69 (60.5)	45 (39.5)#	6.3 (2.8)	6.0 (4.0 – 8.0)
Open for some time	**198 (52.8)**	**177 (47.2)**	**217 (58.5)**	**154 (41.5)**	161 (42.7)	216 (57.3)	189 (50.8)	183 (49.2)	6.5 (3.0)	6.0 (4.0 – 9.0)
4. Windows open during sleep										
Never	**234 (67.0)**	**115 (33.0)****	161 (45.6)	192 (54.4)	184 (52.7)	165 (47.3)	207 (59.0)	144 (41.0)	6.4 (2.9)	6.0 (4.0 – 8.0)
Regularly or occasionally	**74 (51.7)**	**69 (48.3)**	59 (39.9)	89 (60.1)	77 (53.1)	68 (46.9)	79 (54.1)	67 (45.9)	6.4 (2.9)	6.0 (4.0 – 8.0)

Table A4. 4 to be continued.

	Sleep disturbance								Subjective sleep quality	
Items	Stuffy air in the bedroom number (%)		Too warm bedroom number (%)		Too cool bedroom number (%)		Noise in the bedroom number (%)		PSQI score	
	No	Yes	No	Yes	No	Yes	No	Yes	Mean (SD)	Median (IQR)
5. The door open during sleep										
Never	151 (62.7)	90 (37.3)	114 (46.3)	132 (53.7)	**115 (47.7)**	**126 (52.3)***	129 (53.1)	114 (46.9)#	6.6 (3.0)	6.0 (4.0 – 9.0)
Regularly or occasionally	158 (62.7)	94 (37.3)	106 (41.4)	150 (58.6)	**147 (57.9)**	**107 (42.1)**	157 (61.6)	98 (38.4)	6.2 (2.7)	6.0 (4.0 – 8.0)
6. Trickle vent in the bedroom										
Do nothing or no vent	215 (61.6)	134 (38.4)	149 (42.1)	205 (57.9)	183 (52.3)	167 (47.7)	207 (59.0)	144 (41.0)	6.4 (2.8)	6.0 (4.0 – 8.0)
Open regularly or occasionally	94 (64.8)	51 (35.2)	71 (48.0)	77 (52.0)	79 (54.5)	66 (45.5)	79 (53.7)	68 (46.3)	6.3 (2.9)	6.0 (4.0 – 8.0)
7. Trickle vent in the other room(s)										
Do nothing or no vent	219 (61.5)	137 (38.5)	152 (42.0)	210 (58.0)	182 (50.8)	176 (49.2)#	213 (59.3)	146 (40.7)	6.4 (3.0)	6.0 (4.0 – 8.0)
Open regularly or occasionally	87 (64.9)	47 (35.1)	66 (48.2)	71 (51.8)	80 (59.3)	55 (40.7)	70 (51.5)	66 (48.5)	6.3 (2.6)	6.0 (4.0 – 8.0)

[a] analysed using Fisher's exact test.

* p-value < 0.05; ** p-value < 0.01; # p-value < 0.1. Bold indicates significant results.

PSQI, Pittsburgh Sleep Quality Index. SD, standard deviation. IQR, interquartile range.

Table A4. 5 Spearman's correlation coefficients (ρ) between sleep disturbance and the additional questions.

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	**0.231****	**0.136****	**0.151****	-0.021	**-0.106***	**0.119***	0.054	0.058	**0.100***	**0.202****	0.044	0.055	-0.021	-0.070	0.023	-0.027	0.040
2		**0.251****	**0.164****	-0.016	**-0.120****	-0.008	0.061	-0.003	**0.095***	0.015	0.064	**0.148****	-0.042	-0.042	0.062	0.023	-0.029
3			**0.173****	0.018	**-0.101***	-0.002	0.035	-0.004	0.021	0.026	0.046	0.048	**-0.131****	-0.026	0.073	-0.041	-0.051
4				0.038	-0.052	0.035	0.072	-0.063	**0.115***	0.051	0.002	0.077	-0.077$^{\#}$	**-0.099***	-0.031	**0.088***	0.052
5					0.074	**0.131****	**0.123****	**-0.108***	0.058	**-0.089***	-0.008	**0.130****	**-0.093***	**-0.213****	0.033	0.010	**-0.262****
6						0.069	-0.067	0.076$^{\#}$	-0.074	-0.078$^{\#}$	-0.076$^{\#}$	-0.014	-0.005	-0.008	-0.006	0.008	-0.020
7							0.008	0.050	0.036	-0.005	0.025	0.070	**-0.103***	**-0.094***	0.005	0.082$^{\#}$	-0.075
8								-0.018	-0.056	0.031	-0.032	-0.010	0.056	**-0.118****	0.065	-0.013	**-0.110***
9									-0.078$^{\#}$	**0.163****	0.031	0.088$^{\#}$	0.014	**0.193****	0.077$^{\#}$	-0.028	**0.089***
10										**0.126****	**0.141****	**0.194****	-0.016	**-0.104***	0.011	0.001	0.015
11											**0.378****	**0.115***	0.026	-0.012	0.048	-0.005	0.066
12												0.004	**-0.079**$^{\#}$	-0.023	-0.012	0.073	0.034
13													-0.039	**-0.104***	0.016	-0.092$^{\#}$	-0.032
14														**0.140****	0.011	-0.044	0.065
15															-0.061	-0.018	**0.161****
16																0.047	0.018
17																	-0.071

1, Noise (0, yes; 1, no); 2, stuffy air (0, yes; 1, no); 3, too warm (0, yes; 1, no); 4, too cool (0, yes; 1, no); 5, years living in Denmark (0, less than one year; 1, one to two years; 2, more than two years); 6, chronic diseases (0, no; 1, yes or secret); 7, the youngest child at home (0, no children or the youngest child was more than 5 years; 1, 5 years or less); 8, pet (0, no; 1, yes); 9, exercise (0, regularly; 1, occasionally; 2, no, I don't.); 10, essential oil (0, regularly; 1, occasionally; 2, no, I don't.); 11, earplugs (0, regularly; 1, occasionally; 2, no, I don't.); 12, eye mask (0, regularly; 1, occasionally; 2, no, I don't.); 13, meat consumption (0, don't eat fish and meat; 1, only eat fish; 2, eat meat); 14, nap (0, no; 1, yes); 15, shift job (0, no; 1, yes); 16, home is a smoking place (0, no; 1, yes); 17, smoke (0, no; 1, yes); 18, sleep habits (0, partner; 1, alone or other; 2, child(ren), 3, other).

** p-value < 0.01, * p-value < 0.05, $^{\#}$ p-value < 0.1. Bold indicates p-value < 0.05.

Table A4. 6 Spearman's correlation coefficients (ρ) between PSQI and the additional questions.

	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.011	**0.224****	**0.098***	-0.017	**0.172****	**-0.104***	-0.041	-0.021	-0.039	0.048	**0.094***	-0.007	-0.016	**0.146****
2		0.074	**0.131****	**0.123****	**-0.108***	0.058	**-0.089***	-0.008	**0.130****	**-0.093***	**-0.213****	0.033	0.016	**-0.222****
3			0.069	-0.067	0.076$^{\#}$	-0.074	-0.078	-0.076	-0.014	-0.005	-0.008	-0.006	0.012	-0.019
4				0.008	0.050	0.036	-0.005	0.025	0.070	**-0.103***	**-0.094***	0.005	0.081$^{\#}$	-0.075
5					-0.018	-0.056	0.031	-0.032	-0.010	0.056	**-0.118****	0.065	-0.010	**-0.102***
6						-0.078$^{\#}$	**0.163****	0.031	0.088$^{\#}$	0.014	**0.193****	0.077$^{\#}$	-0.031	0.081
7							**0.126****	**0.141****	**0.194****	-0.016	**-0.104***	0.011	0.001	0.027
8								**0.378****	**0.115***	0.026	-0.012	0.048	-0.009	0.047
9									0.004	-0.079$^{\#}$	-0.023	-0.012	0.072	0.028
10										-0.039	**-0.104***	0.016	-0.092$^{\#}$	-0.026
11											**0.140****	0.011	-0.042	0.067
12												-0.061	-0.021	**0.140****
13													0.049	0.018
14														-0.071

1, PSQI, Pittsburgh Sleep Quality Index; 2, years living in Denmark (0, less than one year; 1, one to two years; 2, more than two years); 3, chronic diseases (0, no; 1, yes or secret); 4, the youngest child at home (0, no children or the youngest child was more than 5 years; 1, 5 years or less); 5, pet (0, no; 1, yes); 6, exercise (0, regularly; 1, occasionally; 2, no, I don't.); 7, essential oil (0, regularly; 1, occasionally; 2, no, I don't.); 8, earplugs (0, regularly; 1, occasionally; 2, no, I don't.); 9, eye mask (0, regularly; 1, occasionally; 2, no, I don't.); 10, meat consumption (0, don't eat fish and meat; 1, only eat fish; 2, eat meat); 11, nap (0, no; 1, yes); 12, shift job (0, no; 1, yes); 13, home is a smoking place (0, no; 1, yes); 14, smoke (0, no; 1, yes); 15, sleep habits (0, partner; 1, alone or other; 2, child(ren); 3, other).

** *p*-value < 0.01, * *p*-value < 0.05, $^{\#}$ *p*-value < 0.1. Bold indicates *p*-value < 0.05.

Annex 4F

Figure A4. 3 shows additionally that increasing the number of objects in the bedroom also increased PSQI: the more objects the higher the PSQI score, indicating lower sleep quality. It is worth noting that removing all these objects would not bring PSQI below 5 in the population studied, suggesting that there could be other significant factors influencing sleep quality.

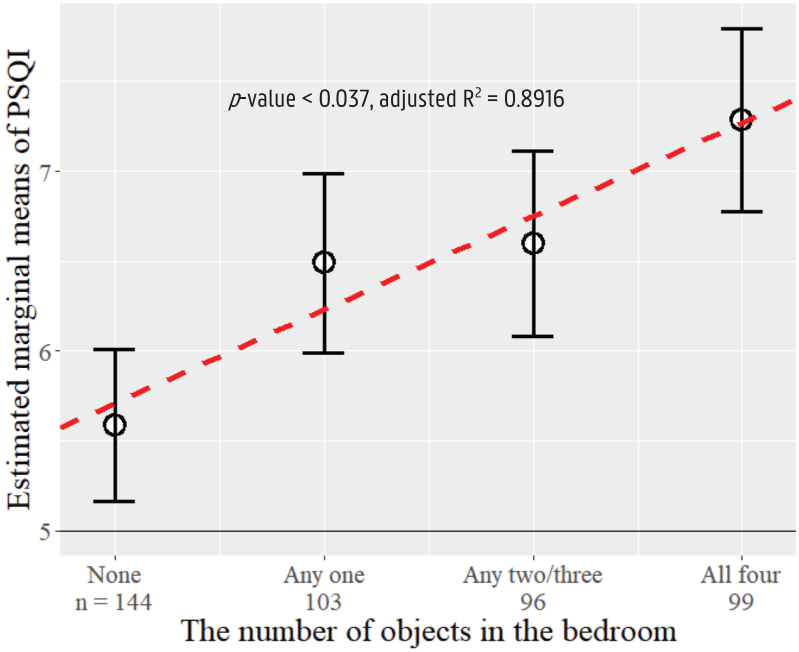


Figure A4. 3 PSQI increased with an increased number of bedroom objects: carpet, TV set, printer, and fish tank. Data were adjusted for chronic disease, exercise, age of the youngest child living at home, sleep habits and BMI. Error bars represent 95% confidence intervals of the estimated marginal means of PSQI scores. The p-value *represents a significant trend across zero to a greater number of bedroom objects and surroundings. Details are shown in Annex 4G Table A4. 8 below.*

Annex 4G

Table A4. 7 Univariate linear model of PSQI in association with the number of sleep disturbances.

Number	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
0	4.931[a]	0.297	4.347	5.515
1	6.074[a]	0.246	5.591	6.557
2	6.537[a]	0.223	6.098	6.975
3	7.034[a]	0.274	6.495	7.573
4	7.953[a]	0.372	7.222	8.684

[a] adjusted by chronic disease, exercise, age of the youngest child living at home, sleep habits and BMI.

Table A4. 8 Univariate linear model of PSQI in association with the number of objects present in the bedroom (fish tank, carpet, printer or TV).

Number	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
0	5.589[a]	0.215	5.166	6.011
1	6.490[a]	0.254	5.991	6.989
2+3	6.599[a]	0.262	6.083	7.114
4	7.286[a]	0.258	6.778	7.794

[a] adjusted by chronic disease, exercise, the youngest child's age at home, sleep habits and BMI.

Annex 5A

Evening Sleep Diary

1. Your bedroom environment NOW is as follows (mark the lines according to your feelings):

1-1.

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

1-2.

Too dry	Dry	Slightly dry	Neutral	Slightly humid	Humid	Too humid

1-3.

Too dark	Dark	Slightly dark	Neutral	Slightly bright	Bright	Too bright

1-4. Fresh air ———— Stuffy air

1-5. Quiet ———— Noisy

1-6. No odour ———— Strong odour

2. The conditions in this bedroom environment NOW could be described as follows:

2-1. Thermal comfort:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable
2-2. Air quality:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable
2-3. Acoustic comfort:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable
2-4. Visual comfort:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable

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

4. The total nap time was:
_____ minutes

5. How sleepy you are:

Very sleepy	Sleepy	Somewhat sleepy	Somewhat awake	Awake	Wide awake
○	○	○	○	○	○

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

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

7. 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
○	○	○	○

8. Did you consume the following after 4 p.m. today? (Mark all that apply.)

Coffee	Tea	Caffeinated beverages (e.g. cola)	Alcohol	Cigarette	None of the above
☐	☐	☐	☐	☐	☐

9. Was your last main meal (dinner/supper) heavy today?

Yes	No
○	○

10. Were you engaged with electronic devices with an illuminated screen for at least 15 min., approximately within 1 hour before going to sleep? (e.g. smartphone, tablet, etc.)

Yes	No
○	○

11. 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

☐	☐	☐	☐	☐

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

Yes	No
○	○

13. What time are you going to sleep tonight? ________

Morning Sleep Diary

1. What time did you wake up this morning? ________________

2. How many times did you wake up during sleep last night? ______________

3. How many adults (in total) and children (in total) slept in your bedroom last night? Adults:______; Children:______. (Write '0' if no children slept in your bedroom.)

4. Your bedroom environment NOW is as follows (mark the lines according to your feelings):

4-1.	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
4-2.	Too dry	Dry	Slightly dry	Neutral	Slightly humid	Humid	Too humid
4-3.	Too dark	Dark	Slightly dark	Neutral	Slightly bright	Bright	Too bright

4-4. Fresh air |————————| Stuffy air

4-5. Quiet |————————| Noisy

4-6. No odour |————————| Strong odour

5. The conditions in your bedroom environment NOW could be described as follows:

5-1. Thermal comfort:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable

5-2. Air quality:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable
5-3. Acoustic comfort:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable
5-4. Visual comfort:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable

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

Very sleepy	Sleepy	Somewhat sleepy	Somewhat awake	Awake	Wide awake
O	O	O	O	O	O

7. Last night, you woke up because of (mark all that apply.)

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

8. Did you sleep with door(s)/window(s) toward your bedroom open last night?

Item	Closed	Partly open (10%-40%)	Half open (˜50%)	Largely open (60%-80%)	Fully open (> 90 %)
Window (s)	O	O	O	O	O
Door (s)	O	O	O	O	O

9. DURING LAST NIGHT, your bedroom environment (cold/hot here refers to **your thermal sensation to the bed**) was as follows (mark the lines according to your feelings):

	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
9-1.							
9-2.							

	Too dry	Dry	Slightly dry	Neutral	Slightly humid	Humid	Too humid
9-3.	Too dark	Dark	Slightly dark	Neutral	Slightly bright	Bright	Too bright

9-4. Fresh air ⊢———⊣ Stuffy air

9-5. Quiet ⊢———⊣ Noisy

9-6. No odour ⊢———⊣ Strong odour

10. DURING LAST NIGHT, the conditions of your bedroom environment when you were in bed could be described as follows:

10-1. Thermal comfort:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable
10-2. Air quality:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable
10-3. Acoustic comfort:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable
10-4. Visual comfort:	Clearly acceptable	Just acceptable	Just unacceptable	Clearly unacceptable

11. How did you sleep last night? Mark True or False for each question.

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

Annex 5B

The two-sample Kolmogorov–Smirnov test was used to analyze if the distributions of the data were from the same distribution between the 1st and 2nd-night sleep.

Item	D-crit	*p*-value [a]
Minutes asleep	0.1148	0.8210
Minutes awake	0.2131	0.1255
Minutes deep sleep	0.0984	0.9327
Minutes light sleep	0.1311	0.6748
Minutes REM sleep	0.0820	0.9878
Number of awakenings	0.0984	0.9327
Time in bed	0.0984	0.9327
Sleep latency	0.2295	0.0803
CO_2 mean	0.0820	0.9878

[a] *p*-values were calculated by the two-sample Kolmogorov–Smirnov test.

Annex 5C

Table A5. 1 The number (fraction) of the categorical or ordinal variables.

Item	N (%)
Survey	
1. Personal characteristics	
(1) Gender	
Male	41 (54.7)
Female	34 (45.3)
(2) Chronic disease	
No	69 (92.0)
Yes	6 (8.0)
(3) Smoke	
Regularly	1 (1.3)
Occasionally	6 (8.0)
Never	68 (90.7)

Table A5. 1 to be continued.

Item	N (%)
(4) Shift work/study	
Daytime	60 (80.0)
Nighttime	3 (4.0)
Day and night (on shift)	12 (16.0)
(5) location	
Urban	16 (21.3)
Suburban or rural	59 (78.7)
2. Sleep habits	
(1) Sleep with windows open	
Regularly	13 (17.3)
Occasionally	19 (25.3)
Never	43 (57.3)
(2) Sleep with the door open	
Regularly	27 (36.0)
Occasionally	6 (8.0)
Never	42 (56.0)
(3) Sleep with	
a. Sleep alone	
No	39 (52.0)
Yes	36 (48.0)
b. Sleep with spouse or partner	
No	45 (60.0)
Yes	30 (40.0)
c. Sleep with child(ren)	
No	74 (98.7)
Yes	1 (1.3)
d. Other [a]	
No	69 (92.0)
Yes	6 (8.0)
3. Building characteristics	
(2) Air terminal	
Yes	15 (20.0)
No	60 (80.0)

Table A5. 1 to be continued.

Item	N (%)
Sleep diaries	
1. Info	
(1) Night number	
1	31 (41.3)
2	44 (58.7)
(2) Filled out at the night of weekdays	
Monday	13 (17.3)
Tuesday	31 (41.3)
Wednesday	21 (28.0)
Thursday	10 (13.3)
(3) Evening sleep diary	
Not completed [b]	5 (6.7)
Completed	70 (93.3)
(4) Morning sleep diary	
Not completed [b]	2 (2.7)
Completed	73 (97.3)
2. Number of people in the bedroom during the night	
(1) Adult number	
1	50 (66.7)
2	25 (33.3)
(2) Children number	
0	73 (97.3)
1	1 (1.3)
2	1 (1.3)
(3) Sleepers number [c]	
One adult	50 (66.7)
Two adults	23 (30.7)
Two adults + one kid	1 (1.3)
Two adults + two kids	1 (1.3)
3. Bedroom window and door statues during last night	
(1) Window statues	
Closed	50 (66.7)
Partly open (10%-40%)	23 (30.7)
Half open (~50%)	1 (1.3)
Largely open (60%-80%)	0 (0)
Fully open (> 90 %)	1 (1.3)

Table A5. 1 to be continued.

Item	N (%)
(2) Door statues	
Closed	49 (65.3)
Partly open (10%-40%)	1 (1.3)
Half open (~50%)	5 (6.7)
Largely open (60%-80%)	3 (4.0)
Fully open (> 90 %)	17 (22.7)
(3) Window closed [d]	
Closed	50 (66.7)
Open (incl. partly, half, largely, and fully open)	25 (33.3)
(4) Door closed [d]	
Closed	49 (65.3)
Open (incl. partly, half, largely, and fully open)	26 (34.7)
(5) Window and door statues [d]	
Both closed	33 (44.0)
Only the door open	17 (22.7)
Only windows open	14 (18.7)
Both open	11 (14.7)
(6) Window and door closed [d]	
Both closed	33 (44.0)
Open either the windows or door	42 (56.0)
4. Others	
(1) Nap times during the day (times)	
0	64 (85.3)
1	10 (13.3)
2	1 (1.3)
(2) The total nap time (minutes)	
0	64 (85.3)
15	1 (1.3)
25	1 (1.3)
30	4 (5.3)
40	1 (1.3)
50	1 (1.3)
60	2 (2.7)
100	1 (1.3)

Table A5. 1 to be continued.

Item	N (%)
(3) Exercise throughout the day	
a. In the morning	
No	64 (85.3)
Yes	11 (14.7)
b. In the afternoon	
No	60 (80.0)
Yes	15 (20.0)
c. In the evening	
No	65 (86.7)
Yes	10 (13.3)
d. At night	
No	74 (98.7)
Yes	1 (1.3)
e. Did not exercise	
No	42 (56.0)
Yes	33 (44.0)
(4) Dinner time	
a. Before 18:00	
No	71 (94.7)
Yes	4 (5.3)
b. 18:00-20:00	
No	43 (57.3)
Yes	32 (42.7)
c. 20:00-21:00	
No	53 (70.7)
Yes	22 (29.3)
d. After 21:00	
No	63 (84.0)
Yes	12 (16.0)
(5) Heavy dinner	
No	45 (60.0)
Yes	30 (40.0)
(6) Screen time more than 15 min before bed	
No	7 (9.3)
Yes	68 (90.7)

Table A5. 1 to be continued.

Item	N (%)
(7) Coffee, tea, etc. consumed after 4 p.m.	
a. Coffee	
No	61 (81.3)
Yes	14 (18.7)
b. Tea	
No	61 (81.3)
Yes	14 (18.7)
c. Caffeinated beverages (e.g. cola)	
No	74 (98.7)
Yes	1 (1.3)
d. Alcohol	
No	68 (90.7)
Yes	7 (9.3)
e. Cigarette	
No	74 (98.7)
Yes	1 (1.3)
f. None of the above	
No	38 (50.7)
Yes	37 (49.3)
(8) Consumption to help sleep	
a. Pills	
No	75 (100)
Yes	0 (0)
b. Herbal tea	
No	75 (100)
Yes	0 (0)
c. Essential oil	
No	74 (98.7)
Yes	1 (1.3)
d. Others	
No	72 (96.0)
Yes	3 (4.0)
e. Did not use anything to help me sleep	
No	9 (12.0)
Yes	66 (88.0)

Table A5. 1 to be continued.

Item	N (%)
(9) Healthy statue	
No	63 (84.0)
Yes	12 (16.0)
(10) Woke up times	
0	29 (38.7)
1	20 (26.7)
2	9 (12.0)
3	10 (13.3)
4	3 (4.0)
5	3 (4.0)
6	0 (0)
7	1 (1.3)
(11) Woke up reasons last night	
a. Stress	
No	71 (94.7)
Yes	4 (5.3)
b. Sleep environment (bed temperature, humidity, noise, light, and air quality)	
No	61 (81.3)
Yes	14 (18.7)
c. Physical discomfort (e.g. muscle pain, headache, etc.)	
No	71 (94.7)
Yes	4 (5.3)
d. Other	
No	51 (68.0)
Yes	24 (32.0)
e. Did not wake up	
No	46 (61.3)
Yes	29 (38.7)
(12) Sleepy level	
a. Before bed	
Very sleepy	6 (8.0)
Sleepy	18 (24.0)
Somewhat sleepy	34 (45.3)
Somewhat awake	13 (17.3)
Awake	3 (4.0)
Wide awake	1 (1.3)

Table A5. 1 to be continued.

Item	N (%)
(12) Sleepy level	
b. After bed	
Very sleepy	9 (12.0)
Sleepy	15 (20.0)
Somewhat sleepy	30 (40.0)
Somewhat awake	10 (13.3)
Awake	11 (14.7)
Wide awake	0 (0)
5. Groningen Sleep Quality Index (GSQS)	
(1) Question 1 (Q1)	
Yes	26 (34.7)
No	49 (65.3)
(2) Q2	
Yes	51 (68.0)
No	24 (32.0)
(3) Q3	
Yes	55 (73.3)
No	20 (26.7)
(4) Q4	
Yes	30 (40.0)
No	45 (60.0)
(5) Q5	
Yes	54 (72.0)
No	21 (28.0)
(6) Q6	
Yes	40 (53.3)
No	35 (46.7)
(7) Q7	
Yes	57 (76.0)
No	18 (24.0)
(8) Q8	
Yes	44 (58.7)
No	31 (41.3)
(9) Q9	
Yes	58 (77.3)
No	17 (22.7)

Table A5. 1 to be continued.

Item	N (%)
(10) Q10	
Yes	31 (41.3)
No	44 (58.7)
(11) Q11	
Yes	70 (93.3)
No	5 (6.7)
(12) Q12	
Yes	22 (29.3)
No	53 (70.7)
(13) Q13	
Yes	64 (85.3)
No	11 (14.7)
(14) Q14	
Yes	67 (89.3)
No	8 (10.7)
(15) Q15	
Yes	69 (92.0)
No	6 (8.0)
6. Regroup variables	
(1) Age	
< 26	28 (37.3)
26 - 75	47 (62.7)
(2) BMI	
18.5 – 29.9	66 (88.0)
<18.5 or > 30.0	9 (12.0)
(3) CO_2 median	
< 750	20 (26.7)
750 - 1150	20 (26.7)
1150 - 2600	26 (34.7)
> 2600	9 (12.0)
(4) binary CO_2 median	
420.9 - 1121.4	37 (49.3)
1121.4 - 4866.0	38 (50.7)
(5) Temperature median	
17 - 28	73 (97.3)
< 17 or > 28	2 (2.7)

Table A5. 1 to be continued.

Item	N (%)
(6) Relative humidity median	
40 - 60	55 (73.3)
< 40 or > 60	20 (26.7)
(7) Temperature + relative humidity	
Optimal range (17 – 28 °C and 40 – 60 %)	54 (72.0)
Inappropriate temperature or relative humidity	21 (28.0)
(8) Thermal comfort	
Unacceptable before sleep	1 (1.3)
Unacceptable during sleep	7 (9.3)
Unacceptable after sleep	5 (6.7)
(9) Air quality	
Unacceptable before sleep	2 (2.7)
Unacceptable during sleep	2 (2.7)
Unacceptable after sleep	8 (10.7)
(10) Acoustic comfort	
Unacceptable before sleep	4 (5.3)
Unacceptable during sleep	3 (4.0)
Unacceptable after sleep	4 (5.3)
(11) Visual comfort	
Unacceptable before sleep	2 (2.7)
Unacceptable during sleep	0 (0)
Unacceptable after sleep	4 (5.3)

Annex 5D

Table A5. 2 Distribution of bedroom environment perception and the difference between window and door status.

Item	Quartiles						
	Mean ± std.	Min	25%	50%	75%	Max	*p*-value [a]
1. Bedroom environment perception before sleep							
(1) Cold (0) – Hot (100)	45.4 ± 14.9	15.0	34.0	43.0	53.0	83.0	
Window and door closed	45.2 ± 15.9	16.0	33.5	43.0	59.0	83.0	0.794
Either window or door open	45.6 ± 14.3	15.0	34.0	44.0	53.0	81.0	
(2) Too dry (0) - Too humid (100)	47.1 ± 10.3	17.0	44.0	49.0	51.0	72.0	
Window and door closed	46.7 ± 11.7	17.0	39.5	48.0	51.5	72.0	0.415
Either window or door open	47.4 ± 9.2	17.0	46.4	49.0	50.3	67.0	

Table A5. 2 to be continued.

Item	Quartiles						
	Mean ± std.	Min	25%	50%	75%	Max	*p*-value [a]
(3) Too dark (0) - Too bright (100)	31.8 ± 17.9	5.0	18.0	27.0	40.5	83.0	
Window and door closed	30.5 ± 18.3	5.0	17.0	25.0	33.8	83.0	0.318
Either window or door open	23.0 ± 18.8	2.0	10.0	17.0	31.0	75.0	
(4) Fresh (0) - Stuffy air (100)	34.6 ± 20.3	2.0	16.5	34.0	47.0	83.0	
Window and door closed	38.3 ± 19.7	4.0	26.0	38.0	53.0	83.0	0.136
Either window or door open	31.7 ± 20.6	2.0	12.5	31.0	46.0	76.0	
(5) Quiet (0) - Noisy (100)	23.3 ± 19.7	1.0	8.0	17.0	33.0	77.0	
Window and door closed	23.5 ± 20.6	1.0	7.0	18.5	35.8	77.0	0.705
Either window or door open	24.8 ± 13.5	5.6	14.4	22.2	37.2	49.9	
(6) No (0) - Strong odour (100)	20.2 ± 18.8	1.0	6.5	16.0	27.0	99.0	
Window and door closed	22.8 ± 18.8	1.0	7.0	17.0	32.5	69.0	0.202
Either window or door open	18.1 ± 18.8	1.0	6.0	14.0	22.7	99.0	
(7) Thermal comfort [b]	21.8 ± 14.3	1.1	10.0	20.0	30.6	56.7	
Window and door closed	19.5 ± 14.7	1.1	6.7	15.6	29.2	56.7	*0.063*
Either window or door open	21.8 ± 17.4	1.1	7.8	15.6	39.4	63.3	
(8) Air quality [b]	22.2 ± 15.1	0.0	10.0	21.1	30.6	55.6	
Window and door closed	26.2 ± 16.2	4.4	11.1	25.6	44.4	54.4	**0.041**
Either window or door open	19.0 ± 13.6	0.0	7.5	18.9	24.7	55.6	
(9) Acoustic comfort [b]	21.5 ± 17.3	1.1	7.8	16.7	29.4	91.1	
Window and door closed	21.3 ± 17.3	1.1	7.8	20.0	27.2	91.1	0.890
Either window or door open	49.7 ± 15.2	25.0	35.0	49.0	63.5	83.0	
(10) IEQ [c]	21.8 ± 11.6	1.1	15.0	19.6	27.0	50.0	
Window and door closed	24.3 ± 12.2	5.9	15.6	19.6	34.4	50.0	0.265
Either window or door open	19.9 ± 10.8	1.1	12.8	21.3	24.4	46.7	
2. Bedroom environment perception during sleep							
(1) Cold (0) – Hot (100)	46.6 ± 16.3	6.0	34.0	48.0	57.5	83.0	
Window and door closed	46.5 ± 15.2	16.0	32.0	49.0	54.0	76.0	0.806
Either window or door open	46.7 ± 17.2	6.0	34.0	47.5	59.0	83.0	
(2) Too dry (0) - Too humid (100)	46.2 ± 13.0	13.0	38.0	48.0	51.0	83.0	
Window and door closed	45.8 ± 13.0	18.0	38.0	47.0	50.0	76.0	0.696
Either window or door open	46.5 ± 13.1	13.0	37.8	48.5	51.0	83.0	
(3) Too dark (0) - Too bright (100)	26.2 ± 14.7	6.0	17.0	20.0	34.5	69.0	
Window and door closed	28.5 ± 16.2	6.0	17.0	21.0	45.0	69.0	0.224
Either window or door open	24.4 ± 13.2	7.0	17.0	18.0	26.1	55.0	

Table A5. 2 to be continued.

Item	Quartiles						
	Mean ± std.	Min	25%	50%	75%	Max	*p*-value [a]
(4) Fresh (0) - Stuffy air (100)	37.0 ± 21.2	3.0	17.0	36.0	54.5	88.0	
Window and door closed	42.3 ± 19.6	6.0	31.0	46.0	56.0	78.0	**0.045**
Either window or door open	32.9 ± 21.7	3.0	13.0	31.0	49.0	88.0	
(5) Quiet (0) - Noisy (100)	17.6 ± 16.6	0.0	6.5	12.0	21.5	81.0	
Window and door closed	20.0 ± 18.7	0.0	8.0	14.0	23.0	81.0	0.221
Either window or door open	15.8 ± 14.8	2.0	6.0	12.0	18.9	60.0	
(6) No (0) - Strong odour (100)	20.0 ± 18.2	1.0	7.0	16.0	25.7	98.0	
Window and door closed	22.0 ± 17.4	1.0	9.0	19.0	30.0	79.0	0.145
Either window or door open	18.4 ± 18.9	1.0	5.0	12.5	22.7	98.0	
(7) Thermal comfort [b]	24.7 ± 15.5	0.0	12.2	23.3	35.6	60.0	
Window and door closed	26.4 ± 14.8	0.0	14.4	25.6	35.6	60.0	0.255
Either window or door open	23.3 ± 16.1	1.1	8.9	18.3	35.6	58.9	
(8) Air quality [b]	24.7 ± 14.4	2.2	11.1	24.4	37.2	62.2	
Window and door closed	27.9 ± 13.9	3.3	16.7	26.7	38.9	62.2	0.124
Either window or door open	22.3 ± 14.5	2.2	10.3	23.3	31.1	51.1	
(9) Acoustic comfort [b]	17.3 ± 14.2	1.1	6.1	13.3	23.9	65.6	
Window and door closed	19.7 ± 16.5	3.3	7.8	13.3	27.8	65.6	0.361
Either window or door open	15.4 ± 12.0	1.1	5.8	12.8	22.2	57.8	
(10) IEQ [c]	22.2 ± 11.8	1.5	13.0	20.7	30.9	48.1	
Window and door closed	24.7 ± 12.4	2.6	14.8	23.0	34.8	48.1	0.153
Either window or door open	20.3 ± 11.1	1.5	12.7	18.7	26.9	41.9	
(11) Visual comfort [b]	14.9 ± 12.3	2.2	6.1	11.1	20.0	46.7	
Window and door closed	18.2 ± 14.0	2.2	6.7	14.4	26.7	46.7	*0.066*
Either window or door open	12.3 ± 10.2	2.2	5.6	8.9	17.3	44.4	
3. Bedroom environment perception after sleep							
(1) Cold (0) – Hot (100)	47.6 ± 15.8	12.0	35.0	48.0	58.5	83.0	
Window and door closed	46.0 ± 16.3	12.0	33.0	45.5	55.3	80.0	0.442
Either window or door open	38.5 ± 21.7	4.0	23.0	34.0	54.5	82.0	
(2) Too dry (0) - Too humid (100)	47.7 ± 14.2	18.0	39.5	49.0	53.5	90.0	
Window and door closed	45.2 ± 17.5	18.0	31.5	47.0	52.5	90.0	*0.058*
Either window or door open	49.7 ± 10.7	18.0	45.8	50.0	56.0	69.0	
(3) Too dark (0) - Too bright (100)	38.2 ± 22.1	4.0	21.0	33.0	53.0	82.0	
Window and door closed	38.0 ± 22.6	4.0	20.0	32.5	56.3	82.0	0.757
Either window or door open	26.2 ± 22.1	1.0	11.0	18.0	37.0	90.0	

Table A5. 2 to be continued.

Item	Quartiles						
	Mean ± std.	Min	25%	50%	75%	Max	*p*-value [a]
(4) Fresh (0) - Stuffy air (100)	46.3 ± 24.2	3.0	26.0	52.0	65.5	89.0	
Window and door closed	55.6 ± 22.4	4.0	41.5	61.0	68.5	89.0	**0.002**
Either window or door open	39.0 ± 23.3	3.0	13.8	40.5	61.3	86.0	
(5) Quiet (0) - Noisy (100)	24.5 ± 19.1	1.0	10.5	19.0	32.5	90.0	
Window and door closed	23.1 ± 16.5	2.0	8.8	21.8	30.3	63.0	0.823
Either window or door open	27.4 ± 14.8	5.6	12.8	26.7	41.7	54.4	
(6) No (0) - Strong odour (100)	24.3 ± 20.3	0.0	9.0	20.0	32.0	99.0	
Window and door closed	28.9 ± 20.4	0.0	12.0	25.0	45.0	69.0	**0.046**
Either window or door open	20.7 ± 19.7	2.0	7.8	13.5	28.3	99.0	
(7) Thermal comfort [b]	26.6 ± 16.5	4.4	12.8	25.6	41.1	76.7	
Window and door closed	26.1 ± 17.8	4.4	11.7	22.2	39.2	76.7	0.575
Either window or door open	24.9 ± 21.2	2.2	8.9	15.6	43.3	91.1	
(8) Air quality [b]	30.4 ± 16.9	3.3	13.3	32.8	44.4	71.1	
Window and door closed	35.9 ± 16.5	8.9	22.2	41.1	46.7	71.1	**0.009**
Either window or door open	26.1 ± 16.2	3.3	9.7	27.2	38.9	57.8	
(9) Acoustic comfort [b]	20.1 ± 16.7	2.2	7.2	15.6	27.8	91.1	
Window and door closed	24.9 ± 21.2	2.2	8.9	15.6	43.3	91.1	0.154
Either window or door open	16.3 ± 11.0	2.2	6.7	15.6	23.2	44.4	
(10) IEQ [c]	25.7 ± 12.7	3.7	16.7	25.2	33.9	63.8	
Window and door closed	29.4 ± 13.3	7.0	23.0	26.3	40.7	63.8	**0.038**
Either window or door open	22.8 ± 11.5	3.7	14.8	23.1	30.4	46.3	

[a] calculated by the Mann-Whitney *U* test.

[b] 0, clearly acceptable; 49.1, just acceptable; 50.1, just unacceptable; 100, clearly unacceptable.

[c] defined as "(thermal comfort + air quality + acoustic comfort)/3".

IEQ, indoor environmental quality.

Bold indicates significant results.

Italic indicates 0.05< *p*-value < 0.1

Annex 5E

Table A5. 3 The difference of bedroom environment perception between after and before sleep (after – before).

Item	Min	25%	50%	75%	Max	*p*-value
(1) Cold (0) – Hot (100)	-38.0	-7.0	2.0	10.0	49.0	0.204 [a]
Window and door closed	-34.0	-6.5	2.0	9.0	49.0	0.724 [b]
Either window or door open	-38.0	-11.3	2.0	10.0	34.0	
(2) Too dry (0) - Too humid (100)	-29.0	-3.0	0.0	5.0	26.0	0.388 [a]
Window and door closed	-29.0	-11.0	0.0	6.5	23.0	0.195 [b]
Either window or door open	-20.0	-1.0	0.3	5.0	26.0	
(3) Too dark (0) - Too bright (100)	-66.0	-9.0	3.0	15.0	67.0	*0.057*[a]
Window and door closed	-45.0	-11.5	1.0	13.5	67.0	0.345 [b]
Either window or door open	-66.0	-4.3	4.0	18.0	62.0	
(4) Fresh (0) - Stuffy air (100)	-63.0	-1.0	**9.0**	28.0	74.0	**< 0.001** [a]
Window and door closed	-15.0	1.0	14.0	31.5	72.0	0.189 [b]
Either window or door open	-63.0	-3.3	8.5	20.3	74.0	
(5) Quiet (0) - Noisy (100)	-74.0	-6.1	3.0	10.0	73.0	0.309 [a]
Window and door closed	-45.0	-5.5	2.0	10.0	73.0	0.873 [b]
Either window or door open	-74.0	-7.8	3.0	9.3	52.0	
(6) No (0) - Strong odor (100)	-52.0	-2.0	**2.0**	10.0	57.0	**0.007** [a]
Window and door closed	-52.0	-2.0	1.0	18.5	57.0	0.822 [b]
Either window or door open	-49.0	-1.3	3.5	9.0	47.0	
(7) Thermal comfort	-28.9	-2.2	**2.2**	12.2	38.9	**0.005** [a]
Window and door closed	-28.9	-4.4	1.1	9.4	33.3	0.180 [b]
Either window or door open	-22.2	-1.4	3.3	17.2	38.9	
(8) Air quality	-23.3	-2.2	**4.4**	18.9	47.9	**< 0.001** [a]
Window and door closed	-6.7	-2.2	3.3	21.7	43.3	0.665 [b]
Either window or door open	-23.3	-2.5	5.6	18.1	47.9	
(9) Acoustic comfort	-63.3	-7.8	0.0	6.7	74.4	0.623 [a]
Window and door closed	-33.3	-5.6	2.2	7.2	74.4	0.115 [b]
Either window or door open	-63.3	-12.8	-1.1	5.0	33.3	
(10) IEQ	-27.4	-1.9	4.1	11.1	28.6	**0.001**
Window and door closed	-18.2	-0.7	4.8	11.7	28.6	0.430
Either window or door open	-27.4	-2.5	2.6	8.7	25.2	

[a] calculated by the non-parametric Wilcoxon matched-pairs signed-ranks.

[b] calculated by the Mann-Whitney *U* test.

Bold indicates significant results.

Italic indicates 0.05< *p*-value < 0.1.

Annex 5F

Table A5. 4 Distribution of the physical environmental parameters during and before sleep and the difference between window and door status.

Item	Quartiles						p-value [a]
	Mean ± std.	Min	25%	50%	75%	Max	
1. Before sleep [b]							
(1) Mean CO_2 (ppm)	1085.1 ± 621.9	450.9	713.0	950.7	1297.4	4432.5	
Window and door closed	1315.1 ± 752.3	538.6	787.9	1076.3	1590.5	4432.5	**0.002**
Either window or door open	904.5 ± 424.6	450.9	648.7	785.1	1052.3	2303.2	
(2) Mean temperature (◦C)	23.5 ± 2.5	18.3	22.3	23.3	24.1	37.6	
Window and door closed	24.0 ± 3.2	18.3	22.3	23.2	24.7	37.6	0.536
Either window or door open	23.2 ± 1.6	19.1	22.3	23.3	24.0	27.0	
(3) Mean RH (%)	48.7 ± 8.1	18.3	42.9	48.3	54.4	65.5	
Window and door closed	49.6 ± 8.4	37.0	42.9	48.3	57.4	65.5	0.662
Either window or door open	48.0 ± 8.0	18.3	42.5	48.7	53.1	60.5	
(4) Maximum light (lux)	47.9 ± 187.8	3.9	3.9	11.8	23.7	1572.8	
Window and door closed	25.9 ± 35.1	3.9	11.8	19.7	27.6	177.4	0.241
Either window or door open	65.1 ± 249.1	3.9	3.9	11.8	19.7	1572.8	
2. During sleep							
(1) Mean CO_2 (ppm)	1381.9 ± 871.7	427.5	741.2	1119.9	1781.8	4803.7	
Window and door closed	1851.3 ± 1011.2	490.5	942.5	1631.9	2535.3	4803.7	**< 0.001**
Either window or door open	1013.1 ± 506.7	427.5	624.2	888.0	1222.4	2840.0	
(2) Mean temperature (◦C)	23.5 ± 2.3	19.3	22.3	23.4	24.4	35.3	
Window and door closed	24.1 ± 2.8	19.4	22.5	23.5	24.8	35.3	0.150
Either window or door open	23.0 ± 1.8	19.3	21.9	23.3	24.2	27.3	
(3) Mean RH (%)	49.2 ± 8.5	16.4	44.7	48.6	55.4	63.2	
Window and door closed	50.4 ± 9.1	35.2	42.5	48.6	59.7	63.2	0.461
Either window or door open	48.2 ± 8.0	16.4	44.9	48.9	53.0	61.3	
(4) The 95th percentile of light (lumens/ft2)	14.7 ± 12.8	3.9	3.9	11.8	19.7	87.1	
Window and door closed	25.7 ± 35.0	3.9	11.2	18.5	27.6	177.4	0.223
Either window or door open	64.6 ± 248.5	3.9	3.9	11.8	19.7	1569.3	
3. Within 10 min after sleep							
(1) Mean CO_2 (ppm)	1381.9 ± 871.7	427.5	741.2	1119.9	1781.8	4803.7	
Window and door closed	1851.3 ± 1011.2	490.5	942.5	1631.9	2535.3	4803.7	**< 0.001**
Either window or door open	1013.1 ± 506.7	427.5	624.2	888.0	1222.4	2840.0	
(2) Mean temperature (◦C)	23.4 + 2.5	17.8	22.2	23.3	24.4	35.6	
Window and door closed	24.1 ± 2.8	19.6	22.6	23.5	24.8	35.6	*0.078*
Either window or door open	22.8 ± 2.0	17.8	21.7	23.2	24.2	27.3	

Table A5. 4 to be continued.

Item	Quartiles						*p*-value [a]
	Mean ± std.	Min	25%	50%	75%	Max	
(3) Mean RH (%)	49.5 + 8.8	17.5	44.4	49.2	55.9	63.5	
Window and door closed	51.0 ± 9.4	35.9	42.1	49.7	61.3	63.5	0.311
Either window or door open	48.4 ± 8.2	17.5	45.1	49.0	53.2	63.3	
(4) Maximum light (lumens/ft2)	28.2 + 49.3	3.9	3.9	11.8	22.3	272.0	
Window and door closed	27.7 ± 45.5	3.9	5.9	14.4	23.7	187.9	0.393
Either window or door open	28.7 ± 52.6	3.9	3.9	11.8	19.7	272.0	

[a] calculated by the Mann-Whitney *U* test.
[b] calculated from the range of 10 min before sleep start time and 10 min after sleep start time.
std., standard deviation.
Bold indicates significant results.
Italic indicates 0.05< *p*-value < 0.1.

Annex 5G

Table A5. 5 Distribution of GSQS and sleepiness after sleep between window and door status.

Item	Quartiles						
	Mean ± std.	Min	25%	50%	75%	Max	*p*-value [a]
1. GSQS	4.1 ± 3.2	0	1.0	4.0	6.0	14.0	
Window and door closed	5.2 ± 3.3	0	3.0	5.0	6.5	14.0	**0.010**
Either window or door open	3.3 ± 2.9	0	0.8	3.0	5.0	11.0	
2. Sleepiness after sleep (0, very sleepy; 5, widely awake)	2.0 ± 1.2	0	1.0	2.0	3.0	4.0	
Window and door closed	1.7 ± 1.3	0	1.0	2.0	2.0	4.0	**0.035**
Either window or door open	2.2 ± 1.1	0	2.0	2.0	3.0	4.0	

[a] calculated by the Mann-Whitney *U* test.
GSQS, Groningen Sleep Quality Index.

Annex 5H

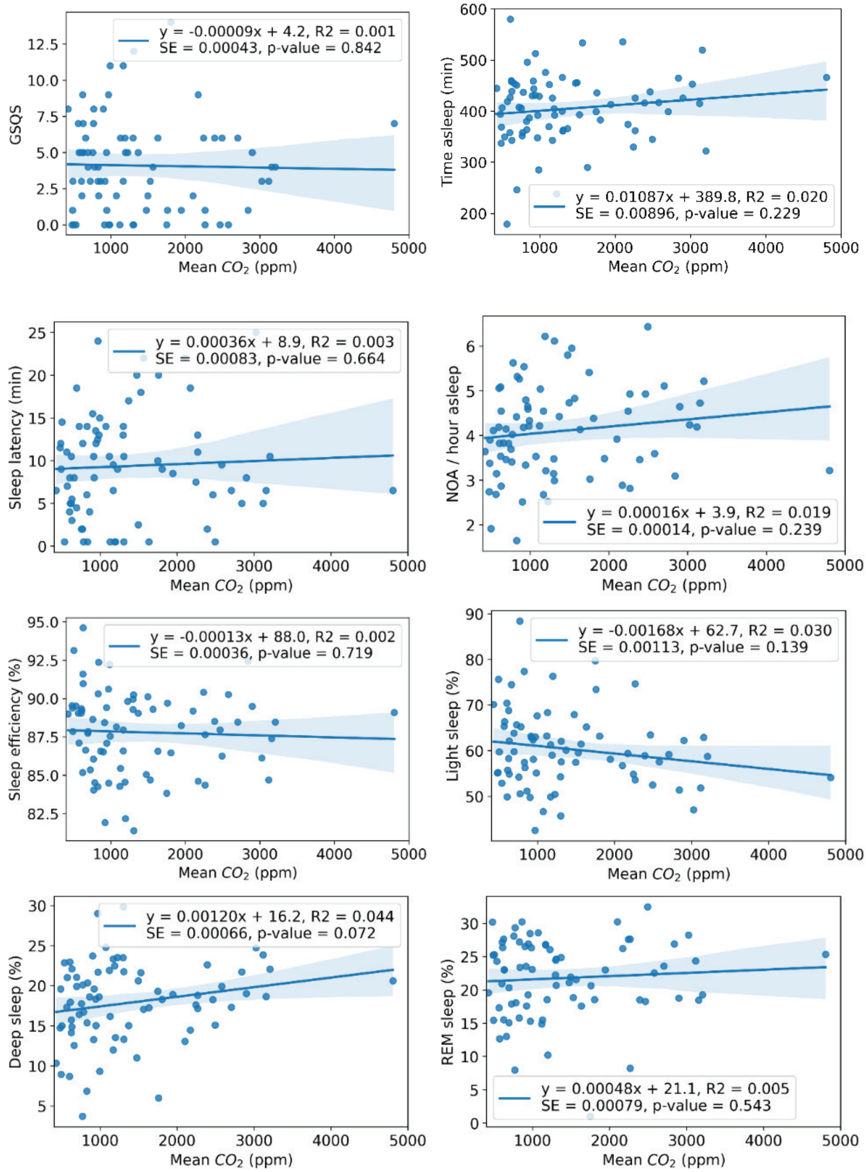


Figure A5. 1 The regression lines between mean CO_2 and sleep parameters.

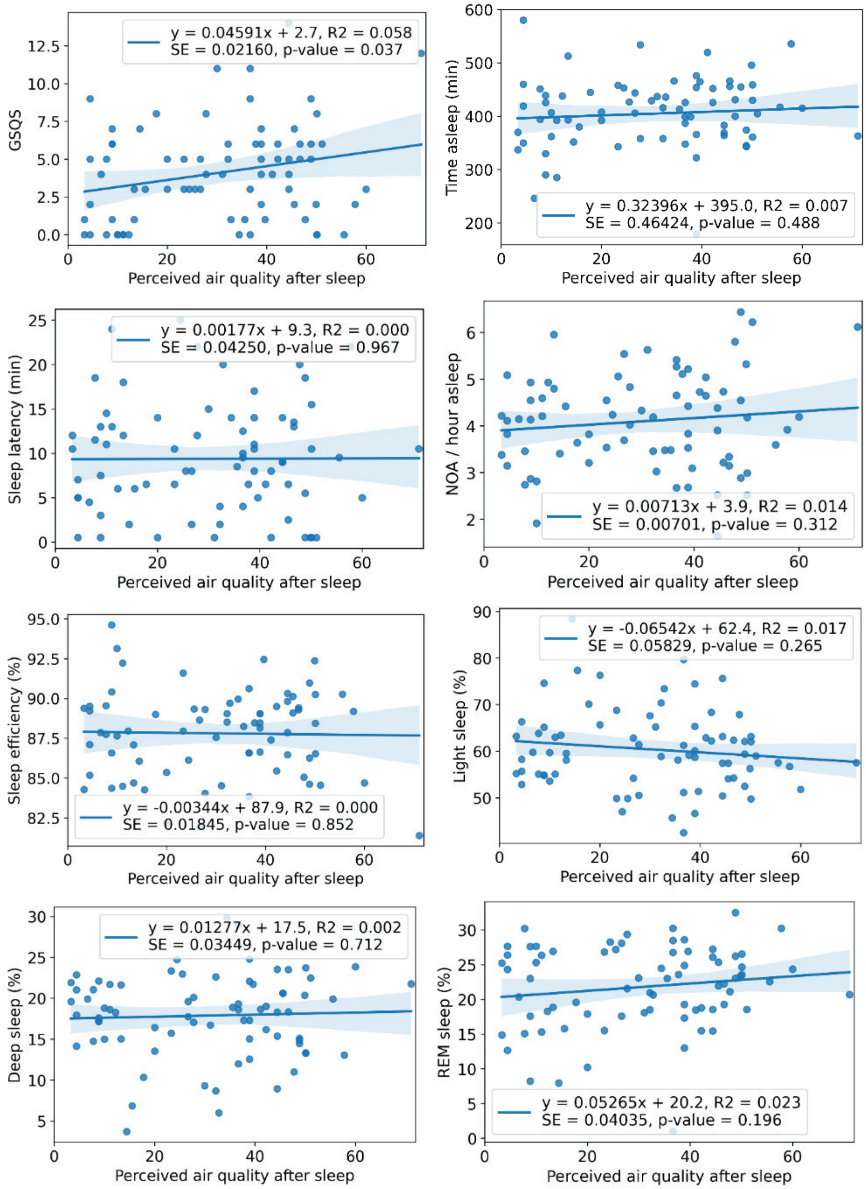


Figure A5. 2 The regression lines between perceived air quality and sleep parameters.

Annex 5I

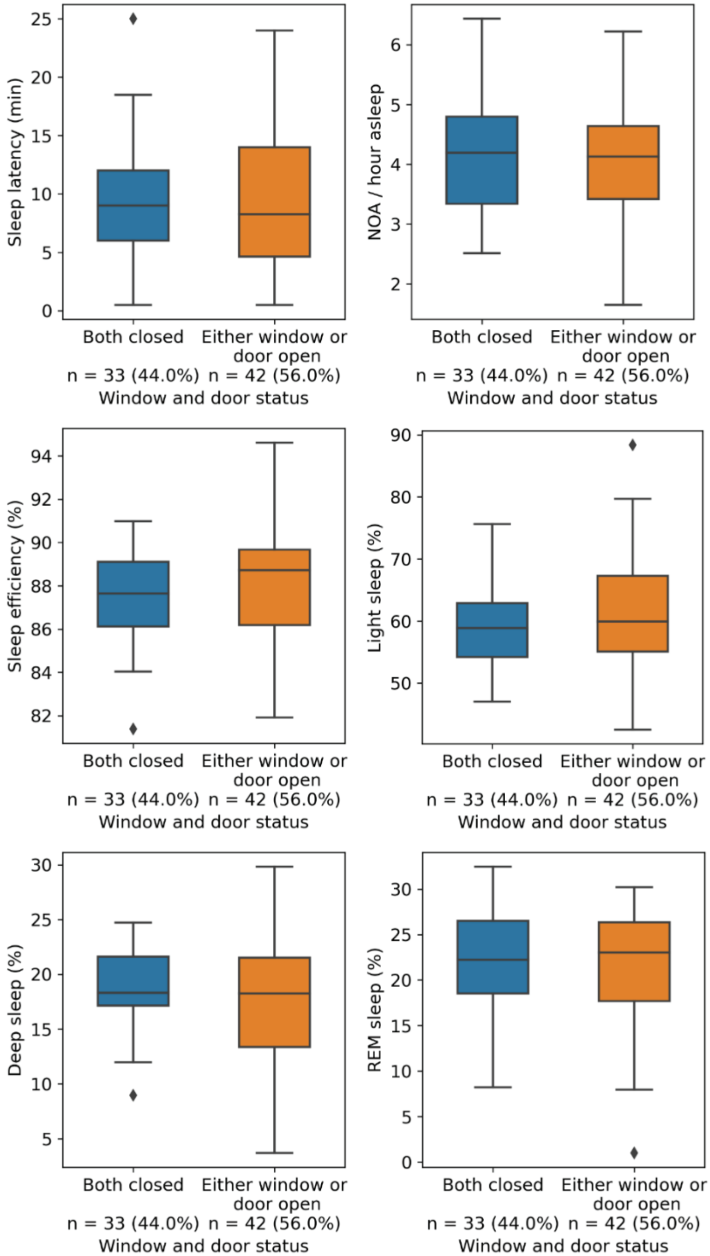


Figure A5. 3 The difference of the objective sleep parameters between window and door status.

Annex 5J

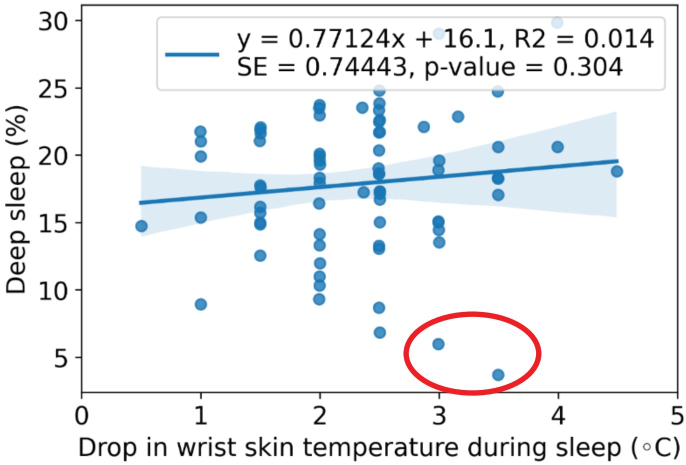


Figure A5. 4 The regression line between drop in wrist skin temperature and deep sleep (%). Red circle indicates removed points in Figure 5. 12.

Annex 5K

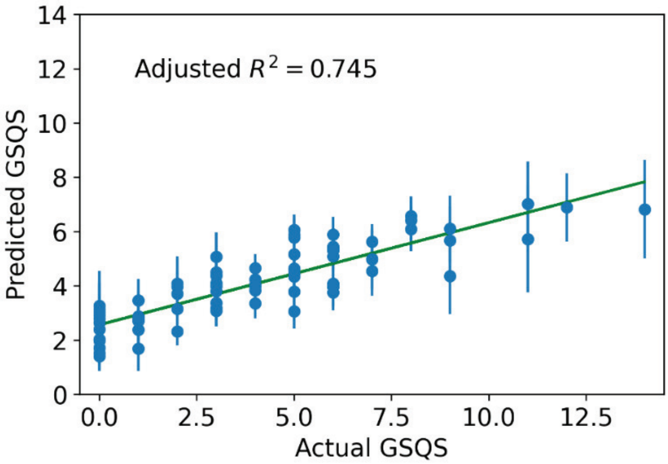


Figure A5. 5 Comparison between predicted and actual GSQS.
GSQS, Groningen Sleep Quality Index.

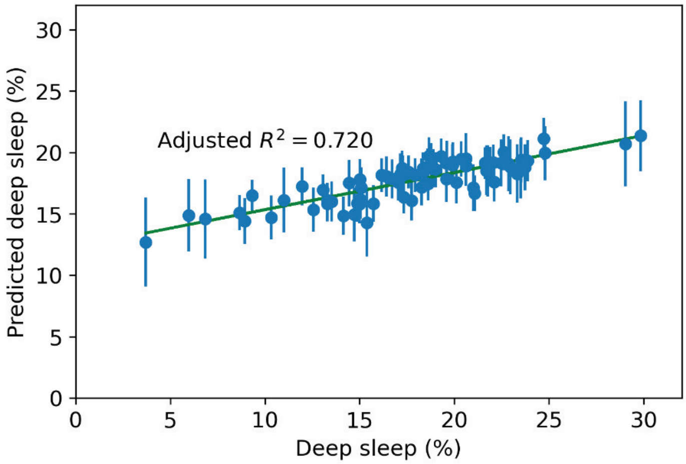


Figure A5. 6 Comparison between predicted and actual deep sleep (%).

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