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

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ABSTRACT

Indoor Air Quality (IAQ) and sleep quality measurements over a period of two weeks were performed all night in 40 bedrooms in Denmark during the heating season. In the first week, the bedroom conditions were typical of what participants would normally experience during sleep. In the second week, the participants were asked to open the doors or windows if they had been closed or the opposite. A change in the 95th percentile of the measured CO2 concentration by more than 200 ppm in the expected direction on the same weekdays of the two-week measurement period was taken to indicate that an effective intervention had taken place. The measurements in the 29 bedrooms that met this criterion were grouped depending on how the windows or doors had been manipulated. Objectively measured and subjectively rated bedroom IAQ improved when the windows were open except that the NO2 concentration was slightly higher. Sleep was longer under this condition and sleep quality was subjectively assessed to be better. Similar effects were not observed when the doors were open although the 95th percentile of CO2 concentration decreased by as much as when the windows were open. No effects were seen in the 11 bedrooms in which the change to the bedroom conditions made by the participants did not change the CO2 concentration by at least 200 ppm, as would be expected. The present study provides evidence that sufficient dilution and/or removal of pollutants is necessary to ensure good bedroom IAQ and good sleep quality.

1. Introduction

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

Although limited in number, existing studies show that poor indoor air quality (IAQ) in bedrooms negatively affects sleep quality; these studies mainly focused on how changing bedroom ventilation will affect sleep quality. The IAQ in bedrooms is often characterized by measuring carbon dioxide (CO2) which is a marker of ventilation effectiveness in the presence of building occupants [11]. Recently Sekhar et al. [12] and Akimoto et al. [13] summarized these studies and found that CO2 levels in many bedrooms are high indicating inadequate ventilation and implying poor bedroom IAQ. They also proposed a tentative relationship between bedroom CO2 concentration during sleep and sleep quality. This relationship suggests that CO2 concentration should be <800 ppm to avoid negative effects on sleep quality, that between 800 ppm and 1100 ppm sleep quality may be negatively affected, that levels above 1100 ppm have consistently been shown to have negative effects on sleep quality and that sleeping at levels >2600 ppm is likely to reduce next-day cognitive performance. Recent studies by Fan et al. [6] and Lan et al. [14] support these conclusions.

A few studies measured IAQ and pollutants in bedrooms. Canha et al. summarized these studies in a review and found that most studies...
measured mainly $\text{CO}_2$; in some studies particles, carbon monoxide, total volatile organic compounds (VOCs), and formaldehyde were also monitored [15]. Some of these pollutants exceeded limit values prescribed by standards and guidelines [16,17], although their impact on sleep quality has not yet been elucidated [18].

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

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

Only a few field intervention studies have been conducted to investigate the effects of window and door opening on bedroom ventilation, IAQ, and sleep quality [5,30,34–36]. Canha et al. [30] explored the effects on IAQ during sleep of four different window and door configurations in one naturally ventilated bedroom. They found that ventilation rates were increased significantly by opening the window, door, or both, resulting in a lower level of some pollutants, particularly $\text{CO}_2$. However, they also observed the presence of some pollutants that originated outdoors or from other parts of a dwelling, especially particulate matter. Strom-Tejsen et al. [5] showed that increasing the ventilation rate by opening the window or turning on inaudible outdoor air inlet fans in dormitory rooms reduced sleep onset latency, increased sleep efficiency, improved subjectively rated sleep quality, improved next-day cognitive performance and reduced $\text{CO}_2$ concentration during sleep. Laverge and Janssens [36] reported that window opening in eight naturally ventilated dormitory rooms caused participants to report being more rested and reduced the measured duration of light sleep. The measured $\text{CO}_2$ concentration was also reduced. Liao et al. [35] found in a study with 27 subjects that window opening reduced snoring and the number of awakenings at night. Mishra et al. [34] observed that window or door opening in 17 bedrooms resulted in deeper sleep as reported by the participants; lower $\text{CO}_2$ concentrations were found, and the objectively measured number of awakenings at night decreased, sleep efficiency increased.

The studies mentioned above either did not monitor sleep quality, were cross-sectional or generally carried out in dormitories with students [5,30,34–36]. Not all of them focused on the effects of window and door opening on the levels of different pollutants in bedrooms and sleep quality. Concentration of $\text{CO}_2$ was a major metric used to characterize bedroom IAQ, however the effect on IAQ could be different, depending on whether the doors or windows were open even though both actions can have similar effects on $\text{CO}_2$ levels in bedrooms. Taking these limitations into account, our study was designed to supplement the evidence on the types of benefits that can be expected when sleeping with bedroom doors or windows open.

2. Method

2.1. Approach

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

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

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

2.3. Measurements

2.3.1. Physical measurements of the bedroom environment

Sixteen boxes, in which instruments for measuring CO₂, air temperature, relative humidity (RH) and a data logger, a light sensor and a tablet with a 4-G internet connection provided by either a SIM card or a router had been installed contained also an actigraphy watch, a skin temperature sensor attached to a wristband made of Velcro and a multi-divider socket, were prepared and used in the study (Fig. S1 in the SI). In eight of the boxes a portable IAQ monitor had also been installed.

Air temperature, RH, and CO₂ concentration were continuously monitored at intervals of 5 min using a Vaisala GMW90R (Vaisala Corporation, Finland) connected to a HOBO UX120-006 M 4-channel analogue data logger (Onset computer corporation, USA). The HOBO U12-012 data logger had a built-in light sensor (Onset computer corporation, USA), which measured and recorded the illuminance every 5 min. Selected pollutants (VOCs, nitrogen dioxide (NO₂), particulate matter with the aerodynamic diameter ≤1 μm (PM₁₀), 2.5 μm (PM₂.₅), and 10 μm (PM₁₀₀)) were measured by the IAQ monitor Flow 2 (Plume Labs, France) at intervals of 1 min, as in two of our previous studies [6, 39]. The accuracy and specifications of all the instruments are listed in Table S2 in the SI. The CO₂ sensors were calibrated just before the study began, while the other sensors were factory calibrated.

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

2.3.2. Objective measurement of sleep quality

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

2.3.3. Subjective responses and questionnaires

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

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

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

| Table 1 | Anthropometric information about the 40 participants (Mean ± SD). |
|---------|----------------------------------------------------------------|
| Items   | In total³             | Bedrooms in which the 95th percentile of CO₂ concentration between two weeks differed by |
|         |                      | ≥200 ppm                  | ≤200 ppm |
|         | Doors Open vs Closed | Windows Open vs Closed    |
| Nights No. where the data was obtained | 58 | 20 | 23 | 15 | 11 |
| Participants No | 40 | 13 | 16 | 11 |
| Sex     | 40 Females | 7 | 6 |
|          | Males       | 8 | 9 |
|         | 7 | 6 |
| Age (y) | 32 ± 12 | 28 ± 4 | 28 ± 3 | 30 ± 10 |
| Body Mass Index (kg/m²) | 22.8 ± 3.6 | 22.2 ± 3.2 | 26.6 ± 3.5 | 20.0 ± 1.4 |
| Living in Denmark | ≥1 year | 36 | 6 | 6 | 8 | 4 | 6 |
|          | <1 year     | 4 | 1 | 0 | 1 | 1 | 0 |
| Smoker  | 2 | 0 | 1 | 0 | 0 |
| Chronic diseases Yes | 3 | 0 | 1 | 0 | 0 |
| No      | 36 | 7 | 5 | 9 | 4 | 5 |
| Shift worker Yes | 5 | 0 | 1 | 0 | 2 | 2 |
| No      | 34 | 7 | 6 | 9 | 3 | 3 |
| PSQI²   | 6 ± 3 | 5 ± 2 | 6 ± 5 | 6 ± 2 | 5 ± 3 | 6 ± 2 | 5 ± 1 |

³ Two participants did not answer all the questions.
⁴ Pittsburgh Sleep Quality Index [38].
⁵ Two participants shared bedroom.
windows or doors had been open that night, current sleepiness level and finally, subjective sleep quality as indicated by the answers to the questions in the Groningen Sleep Quality Scale (GSQS) [41]. A question regarding deep sleep was reported separately as it did not count toward the total GSQS score.

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

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

2.3.4. Cognitive performance

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

2.3.5. Physiological measurements

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

2.3.6. Estimation of ventilation rates

Metabolically generated CO₂ was used to estimate ventilation rates from the rate of decay of the measured CO₂ concentration each morning [39,46,47]. The participants were asked to avoid re-entering their bedroom for at least 30 min and to leave the bedroom conditions as they had been during the previous night during this period. The 95th percentile of the CO₂ concentration during sleep was also calculated and used to estimate the ventilation rate. This was assumed to be close to the steady-state CO₂ concentration.

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

2.4. Experimental procedure

The participants received detailed instructions via email and in the envelope supplied together with the instrumentation box; videos with all the necessary instructions were posted on YouTube (https://www.youtube.com/channel/UC8luzg7Ulfjcd-217HuOmmA/videos). Fig. 1 shows the measurement procedure for each night during the two-week-long experimental period; evening and morning sleep diaries were not taken every night.

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

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

2.5. Screening and classification of measured data

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

Measurements from the two-week measurements were available for 64 bedrooms. We screened raw data and excluded the measurements from 24 bedrooms because they were incomplete (Fig. S3 in the SI). The reasons for exclusion were as follows: for two participants only a single week of objectively measured sleep data was available; three participants had no historical CO₂ data; two participants completed their sleep diaries in only one week; four participants did not have objectively measured sleep data and a completed sleep diary for the same weekday nights in both weeks; four participants made an intervention that was not comparable between weeks (for example they opened the doors with the windows closed in the first week, while in the second week they opened the windows with the doors closed); one participant did not make any interventions; the rest either did not report making the intervention or the changes in CO₂ concentration did not match the intervention they claimed to have made, e.g., the CO₂ concentration was higher when they had reported sleeping with open windows or doors.

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Fig. 1. An example of the experimental procedure with the sleep diaries for one night. Participants adopted these procedures without completing the sleep diaries on the other nights each week.
We thus used data from only 40 participants in the analyses. We compared the 95th percentile of CO₂ concentration for the same weekday nights in each of the two weeks. The bedrooms in which the difference in the 95th percentile of CO₂ concentration was >200 ppm were used in the analysis of the effects of an intervention; we chose 200 ppm considering the accuracy of the CO₂ sensors and to account for the possibility of incomplete mixing, and to ensure that there was a measurable change in bedroom ventilation. Twenty-nine bedrooms met this criterion.

As our focus was on the effects of open bedroom doors and windows, the data from the 29 bedrooms in which the 95th percentile CO₂ differed by >200 ppm between weeks were compared between two conditions depending on the window and door status in each of the two weeks. In one group, consisting of 13 bedrooms, the doors were either open or closed each week, while the windows were always closed. In another group consisting of 16 bedrooms, the windows were either open or closed during each week while the doors in most of the bedrooms were closed. In one bedroom the door was always open independently of whether the windows were open or closed; in four bedrooms the windows were open together with open doors while the doors were closed when the windows were closed.

The data from the 11 bedrooms in which the 95th percentile CO₂ differed by ≤200 ppm between weeks were analysed for any difference in effect between two cases: Closed condition (the windows and doors were closed except for one bedroom where the doors were open for two weeks); Open condition (windows or doors were open). These analyses were treated as a form of control as no effects were expected considering that the CO₂ concentration differed so little between the two weeks, indicating that the intervention had not affected bedroom ventilation to any meaningful extent.

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

2.6. Analysis

A Shapiro-Wilk test was used to examine whether the data were normally distributed. For normally distributed data, a paired-samples t-test was used, but we otherwise used the non-parametric Wilcoxon Matched-Pairs Signed-Ranks test. The data that had been measured or reported by the participants were dependent variables. While all other parameters were independent variables in the analyses, the status of window and door opening were independent variables while all other parameters measured or reported by the participants were dependent variables.

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

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

3. Results

The characteristics of the 40 bedrooms from which data were analysed are summarized in Table 2. They were primarily non-smoking spaces located in multi-story apartment buildings in suburban areas.

### Table 2

| Items                        | In total | Bedrooms in which the 95th percentile of CO₂ concentration between two weeks differed by |
|------------------------------|----------|---------------------------------|
| Building types               |          |                                 |
| Detached house               | 9        | 1                               |
| Row-house                    | 3        | 0                               |
| Multi-story apartment building| 24       | 11                              |
| Others, (i.e. cottages)      | 2        | 0                               |
| Non-smoking dwellings        |          |                                 |
| Yes                          | 38       | 12                              |
| No                           | 2        | 1                               |
| Built year of the buildings  |          |                                 |
| Before 1960                  | 10       | 6                               |
| 1961–1981                    | 4        | 2                               |
| 1982–1995                    | 1        | 0                               |
| After 2010                   | 7        | 1                               |
| Don’t know                   | 15       | 4                               |
| Dwellings’ location          |          |                                 |
| Urban                        | 8        | 0                               |
| Suburban                     | 31       | 12                              |
| Rural                        | 1        | 1                               |
| Living in dormitory          |          |                                 |
| Yes                          | 9        | 1                               |
| No                           | 30       | 12                              |
| Bedroom located floor        |          |                                 |
| <0 (basement)                | 0        | 0                               |
| ≥1st floor                   | 16       | 9                               |
| Bed size (m²)                |          |                                 |
| 36 ± 12 ± 22 ± 11 ± 35 ± 12 | 24       | 10                              |
| Bedroom ventilation          |          |                                 |
| Mechanical ventilation       | 8        | 2                               |
| Exhaust ventilation          | 28       | 8                               |
| Natural ventilation          | 3        | 3                               |
| Occupants during sleep       |          |                                 |
| ≥2                           | 15       | 9                               |

a Two participants did not answer all the questions.

b Residential location was deduced from the zip codes. Urban regions refer to the areas with the first two numbers of zip codes 26 or below; suburban regions refer to the areas with the first two numbers of postcodes 26–31, 34–36, 40, 50–52, 70, 80–82, and 90–92, and the other areas in the capital region of Denmark are rural.

c Bedrooms with air terminals were considered to have a fully balanced mechanical ventilation system, bedrooms with trickle vents and air terminals in the bathroom were considered to have mechanical ventilation with exhaust only; others were naturally ventilated bedrooms.

but a few were in a student dormitory building. Many of the buildings had been constructed before the 1980s and after the 2010s. The average volume and floor area of the bedrooms were approximately 36 m³ and 13 m², respectively. According to the incidence of air terminals reported by the participants, most of the bedrooms had exhaust ventilation. We did not verify this information or whether the ventilation systems were in operation at night to avoid the need to enter the bedrooms. More than half of the bedrooms were singly occupied during the measurement period. The information for all 64 surveyed bedrooms is presented in Table S4 in the SI. Table 3 shows the objectively measured bedroom environmental quality during sleep. The air change rate was on average lower than the statutory minimum of 0.5 h⁻¹ when the doors and windows were closed but when they were open it increased considerably. The mean 95th percentile of CO₂ concentration (and the mean CO₂ concentration during sleep was reduced from 2916 ppm to 1415 ppm (mean concentration was reduced from 2362 ppm to 1293 ppm) when the doors were open and from 2310 ppm–904 ppm (mean from 1820 ppm–761 ppm)
Fig. 2. (A) The acceptability of IAQ; (B) odour intensity; and (C) air freshness before, during (recalled), and after sleep under the different conditions. Cohen’s d. **P < 0.01; *P < 0.05.

Table 3

| Parameters | >200 ppm | ≤200 ppm |
|------------|----------|----------|
|            | Doors Position | Windows Position | Closed | Open | P-value | d | Closed | Open | P-value | d |
| Air change rate (h⁻¹) | 0.29 ± 0.78 ± 0.007** 0.62 | 0.34 ± 1.21 ± <0.001** 1.08 | 0.001** 0.785 0.44 |
| 95th percentile of CO₂ concentration (ppm)¹ | 2916 ± 1415 ± 0.01 | 2310 ± 904 ± <0.001** 1.98 | 2310 ± 904 ± <0.001** 1.98 |
| Mean CO₂ concentration (ppm)² | 2362 ± 1293 ± <0.001** 1.80 | 1820 ± 761 ± <0.001** 2.02 | 975 ± 893 ± 0.015* 0.19 |
| NO₂ (ppb)³ | 728 ± 465 | 706 ± 273 | 46 ± 425 |
| VOCs (ppb)⁴ | 198.6 ± 164.1 ± 0.086 0.62 | 205.6 ± 156.0 ± 0.001** 0.86 | 170.9 ± 169.1 ± 0.867 0.05 |
| PM₁₀ (μg/m³)⁵ | 24.1 ± 23.1 ± 0.594 0.04 | 46.8 ± 26.3 ± 0.002* 0.70 | 26.8 ± 46.6 |
| PM₂.⁵ (μg/m³)⁶ | 4.7 ± 3.1 ± 0.45 ± 2.9 0.039 0.06 | 5.4 ± 3.9 ± 2.5 0.124 0.47 | 4.1 ± 3.8 ± 2.9 0.701 0.13 |
| Temperature (°C) | 24.7 ± 24.7 ± 0.774 0.03 | 23.2 ± 22.4 ± 0.008** 0.51 | 24.3 ± 23.7 ± 0.175 0.36 |
| Relative humidity (%) | 54 ± 7 51 ± 7 <0.001** 0.54 | 53 ± 6 48 ± 6 <0.001** 0.78 | 44 ± 8 42 ± 10 0.278 0.20 |
| Illuminance (Lux) | 11.3 ± 12.5 ± 0.420 0.14 | 11.4 ± 10.2 ± 0.794 0.16 | 8.9 ± 6.3 10.6 ± 0.638 0.14 |
| Percent CO₂ concentration ≤1100 ppm | 1110 ppm | 1110 ppm | 1110 ppm |

¹ The windows and doors were both closed except for one bedroom with the doors open.
² The windows were open.
³ The number of bedrooms with the CO₂ concentration <1100 ppm, which according to Refs. [12,13] indicates the level below which there are effects on sleep quality: > 200 ppm group: doors closed - 0 bedroom, doors open – 3 bedrooms of 13, windows closed – 1 bedroom, windows open 12 bedrooms of 16 bedrooms; < 200 ppm group: closed - 7 bedrooms, open - 7 bedrooms of 11 bedrooms.
⁴ The number of bedrooms with the CO₂ concentration <1100 ppm, which according to Refs. [12,13] indicates the level below which there are effects on sleep quality: > 200 ppm group: doors closed - 0 bedroom, doors open – 6 bedrooms of 13, windows closed – 2 bedrooms, windows open 13 bedrooms of 16 bedrooms; < 200 ppm group: closed - 8 bedrooms, open - 9 bedrooms of 11 bedrooms.

* Data from six participants with nine nights of measurements was available when the doors were closed or open; Data from 10 participants with 14 nights of measurements was available when the windows were closed or open; Data from 9 participants with 13 nights of measurements was available when the difference in the 95th of CO₂ concentration was ≤200 ppm between two weeks.

** When the windows were open.

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

The mean NO₂ concentration during sleep increased when either the doors or windows were open; when a window was open, the NO₂ concentration was higher, though not significantly (P < 0.10). The concentrations of VOCs and PM₁₀ were significantly lower when the windows were open, indicating that they originated indoors. Boor et al. summarized in a review that particles could be suspended by body movements in bed [50], which is likely to explain the observed higher PM₁₀ concentration with the windows closed. Door opening also tended to reduce the level of VOCs (P < 0.10). The concentrations of PM₂.⁵ and PM₁₀ and the illuminance level were unaffected by either intervention.

In the bedrooms in which the 95th percentile CO₂ concentration differed by ≤ 200 ppm between weeks it still decreased when the windows and/or doors were opened although it remained in the range of 900-1100 ppm. No other measurements differed between weeks in this failed intervention group.

Subjective ratings of the bedroom environment are shown in Table S5 in the SI. Significant differences in the ratings following post-hoc analysis are summarized in Figs. 2 and 3. The acceptability of bedroom IAQ increased (Fig. 2A), and the odour intensity decreased...
There was a small but significant improvement in the ratings of air freshness when the doors were open, while in the case of window opening the improvement was greater and showed that the air was rated as much fresher (Fig. 2C). Thermal sensation decreased when the windows were open from around neutral to slightly cool; no such effect was observed when the doors were open (Fig. 3A). There were no significant differences between weeks in the measured wrist skin temperature (Fig. S4 in the SI). However, the skin temperature was from the sleep period, and the acceptability of the thermal environment, which was rated while awake, improved when the windows were open, again with no similar effects when the doors were open (Fig. 3B). No other significant differences were observed.

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

Objectively measured sleep quality was compared with what is currently recommended by the U.S. National Sleep Foundation [51]. The results are tabulated in Table S6 in the SI and show that the sleep quality of the participants in the present study would not be regarded as poor. There were no significant differences in objectively measured sleep length under the different conditions. Cohen’s d. $^{*} P < 0.05$.
parameters defining sleep quality (Table S6 in the SI) except for sleep duration, which was significantly longer when the windows were open (Fig. 4). There were no differences in objectively measured sleep quality between weeks in the failed intervention group.

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

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

4. Discussion

Our results show that opening windows or doors significantly reduced CO₂ concentration during sleep. This is conventionally interpreted to indicate that in both cases bedroom IAQ improved. However, this was not the case as shown by other measurements. Only when the windows were open did the participants rate bedroom IAQ better. Sleep quality also improved in this condition, which is consistent with the published studies reviewed in the Introduction section [34–36]. No such improvements were seen when the doors were open. We believe that door opening did not provide adequate removal and dilution of pollutants in bedrooms even though we were not able to confirm this hypothesis with the limited measurements that were made. The reduced levels of CO₂ when the doors were open suggest that air from other parts of the dwelling was either drawn or diffused into the bedrooms. The CO₂ concentration of this air was low during the sleep period, as other spaces in the dwelling were not occupied, and consequently the bedroom CO₂ concentration was reduced, though not by as much as when the windows were open (Table 3).

As shown in the review by Canha et al., bedroom air during sleep contains numerous pollutants whose levels are higher than the limit values prescribed by the standards and guidelines [15]. These pollutants can enter bedrooms from other parts of the dwelling [30]. For example, cooking oil fumes originating from the kitchen were associated with overall poor sleep quality [52]. Additionally, exposure to increased PM₁₀ concentration was significantly associated with increased obstructive sleep apnea [53], which may disturb sleep. A recent cross-sectional study showed that sleep stages were affected during exposures to NO₂, PM₂.₅, and O₃; as a result some decreases in cognitive capacity were observed [54]. Finally, Chen et al. concluded that long-term exposures to PM₁₀, PM₂.₅, and NO₂ were associated with poor sleep quality in rural China [55]. If proper removal or dilution of these and other pollutants is not achieved by the air that enters bedrooms, no improved bedroom IAQ and sleep quality should be expected. This may have been the case when the internal doors were open in the present study, even though the total concentration of VOCs was lower. On the other hand, window opening was able to provide sufficient dilution and removal of some of these pollutants. For example, the present study showed that the total concentration of VOCs and PM₁₀ levels were lower when window opening was increased NO₂ concentration, which thus presumably originated outdoors. This could counteract the positive effect of reduced exposure to other pollutants because exposure to NO₂ can increase the risk of sleep apnea [56]. Future studies should closely look at the impact of outdoor air pollution on sleep quality and consequently
It is worth noting that in an earlier study involving multiple CO$_2$ measurements in a bedroom having windows with fully open trickle vents, Sekhar et al. showed that the bedroom was better ventilated by the incoming outdoor air through the trickle vents, which was further enhanced with the assistance of a kitchen hood or bathroom extraction fan if an internal bedroom door was open [25]. We are unable to verify whether this occurred in the present study because the operation of ventilation systems during the measurements period was not checked, as mentioned earlier. The CO$_2$ measurements just outside the bedroom door would help characterize the airflow direction in future studies.

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

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

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Fig. 7. of the participants who reported (recalling after sleep) having a “deep sleep” under the different conditions. Cohen’s d. *P < 0.05.
found to result in better sleep is thus a conservative conclusion.

The present results support the tentative relationship between bedroom ventilation (as indicated by mean CO\textsubscript{2} level) and sleep quality that has been recently suggested \cite{12,13}. According to this relationship, no effects on sleep quality would be predicted in bedrooms with doors open, as observed in the present study. The present results support the recommendation that the outdoor air supply rate in bedrooms should be \textgreater\ 10 L/s per person \cite{39} to ensure that sleep quality is undisturbed and that the resulting CO\textsubscript{2} concentration is below 750 ppm.

A change in the 95\textsuperscript{th} percentile of the CO\textsubscript{2} concentration that was less than 200 ppm was insufficient to produce any measurable changes in the outcomes in the present study, lending support to the analysis. There could be many reasons why the change in the 95\textsuperscript{th} percentile of the CO\textsubscript{2} concentration after the intervention was lower than 200 ppm in 11 bedrooms. The most plausible reason is that five of them had mechanical ventilation and five had extract ventilation, so opening windows or doors would have had a very limited effect on CO\textsubscript{2} levels which were already low. The recently published paper analysing all results from the present study collected in the first week showed that the CO\textsubscript{2} concentration measured in bedrooms with mechanical ventilation was lower compared with bedrooms with other types of ventilation \cite{37}, which further supports this interpretation.

An apparent effect on next-day cognitive performance was seen in the present study at a mean CO\textsubscript{2} level of 1800 ppm, lower than the 2600 ppm suggested by the above authors as the threshold for such effects. However, although next-day cognitive performance improved significantly after sleeping in bedrooms with windows open and did not improve significantly after sleeping with windows closed, which is compatible with a beneficial effect of sleeping with open windows, no significant difference in performance could be shown between the conditions with windows open and closed. The present results therefore do not constitute an extension of the findings of Strøm-Tejsen et al. \cite{5} to lower CO\textsubscript{2} concentrations.

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

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

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

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

| First week to second week | Bedrooms in which the 95\textsuperscript{th} percentile of CO\textsubscript{2} concentration between two weeks differed by |
|---------------------------|---------------------------------------------------------------|
|                           | \textgreater\ 200 ppm ≤ 200 ppm                              |
|                           | Doors Open vs Closed Window Open vs Closed Open vs Closed    |
| Changing from open doors to closed doors | 5 (8) - - - -                                               |
| Changing from closed doors to open doors | 8 (12) - - - -                                             |
| Changing from open windows to closed windows | 6 (8) - - - -                                            |
| Changing from closed windows to open windows | - - - - - -                                                 |
| Changing from open windows or doors to closed windows and doors | - - - - - -                                               |
| Changing from closed windows and doors to open windows or doors | - - - - - -                                               |

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

5. Limitations

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

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

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

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

The estimation of ventilation rates from the decay rate of metabolically generated CO₂ requires several assumptions including the level of CO₂ in the air supplied to bedrooms and good mixing within the bedrooms. The estimated ventilation rate reflects the local conditions where the CO₂ concentration was measured and should not be assumed to apply to the entire volume of the bedroom. A discussion of air distribution and exposure is important in this context, as depending on the sleep position and air distribution, which can be influenced by the position of the bed in relation to the window and the door, the actual exposure of participants could be different from what was estimated from the measured CO₂ concentration [25,50,66,67]. We were not able to examine the air distribution in the bedrooms. However, as we compared the effects of high and low levels of CO₂ in the same bedrooms, our results are valid even without a knowledge of air mixing. In future studies it would be useful to measure the actual exposures of sleeping occupants and the air distribution in bedrooms.

Our results are based on a smaller number of observations than was intended. One reason is that we used stringent inclusion criteria, including that the sleeping diaries should have been completed on the same weekday night in each week of the two-week measurements and that the intervention must have changed the 95th percentile of CO₂ by more than 200 ppm. Confirmation in studies with a larger sample size and longer duration would be useful.

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

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

6. Conclusions

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

CRediT authorship contribution statement

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

Declaration of competing interest

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2022.109630.

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