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

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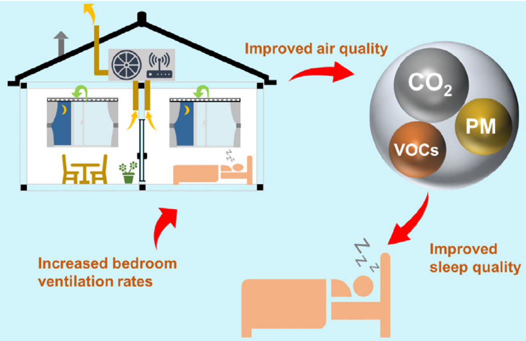
HIGHLIGHTS

- A single-blind field intervention study was conducted in bedrooms with extract ventilation systems and air inlet vents.
- Three ventilation conditions (low, moderate, and high settings) were established by remotely controlling the fan speed
- When the ventilation rate was set to low by altering the fan speed settings, the levels of CO_2 and $PM_{2.5}$ were increased.
- Objectively measured sleep quality was improved when the ventilation rate was increased by increasing the fan speed.

GRAPHICAL ABSTRACT



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ABSTRACT

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

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1. Introduction

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

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

Bedroom ventilation and its effects on sleep quality have only recently been in focus (e.g., (ASHRAE Residential Buildings Committee, 2022)). Bedroom ventilation can be improved by opening a window or door, by specially designed natural ventilation, or by a dedicated mechanical ventilation system, i.e., mechanical extract ventilation with outdoor air inlet vents to the bedroom or a fully balanced system with supply and exhaust ventilation (Liao et al., 2021a; Sekhar et al., 2020a, 2020b). Current standards and guidelines often stipulate ventilation rates for the entire dwelling and generally lack specific recommendations for the ventilation of bedrooms (Sekhar et al., 2020a). An attempt to provide some recommendations was recently made, in which a tentative relationship between sleep quality and bedroom ventilation indicated by the carbon dioxide (CO_2) concentration was developed based on published data, although they were limited (Akimoto et al., 2021; Sekhar et al., 2020a). The association suggests that bedroom ventilation should ensure that the CO_2 concentration remains ≤ 800 ppm, which would correspond to a ventilation rate of at least 10 L/s per person using published CO_2 emission data from sleeping people (Fan et al., 2021). According to this relationship, ventilation rates at which CO_2 levels are ≥ 1150 ppm would consistently disturb sleep and ≥ 2600 ppm would additionally reduce next-day work performance. More research is needed to validate this proposed relationship.

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

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

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

2. Methods

2.1. Approach

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

2.2. Participants

Prior Power Analysis (G*Power) was performed to determine the minimum sample size with the following settings: ANOVA with repeated measurements within factors, effect size of 0.5, a statistical power of 0.8, a non-sphericity correction factor of 0.5, and a correlation among repeated measures of 0.5; the settings were derived from previous studies (Cohen, 1988; Fan et al., 2022b; Lan and Lian, 2010; Yan et al., 2022b). The analysis indicated that fifteen participants was the minimum size.

The study invitation was sent via an existing smartphone application of the participating company (referred to in the following as the “app”) as a push notification to several thousand customers who had installed the ventilation system in their dwellings and were using the app to control it; 172 agreed to participate (response rate <10 %), and 34 who met the selection criteria described in detail below were recruited; two of them shared the same bedroom. They were divided into three groups to ensure proper balancing and sufficient sample size even if there were some unexpected problems. Of the 34 participants, 29 completed the four-week measurements but usable data for analysis were available for only 23 participants, which is still higher than the minimum sample size of 15. All the occupants who agreed to participate completed an online questionnaire during the recruitment process. The questionnaire was used to collect anthropometric data, information on health conditions and dietary habits, the characteristics of their bedrooms, dwellings, and surroundings, the bedroom ventilation system and airing behaviour, work pattern and sleep habits including the questions allowing derivation of the Pittsburgh Sleep Quality Index (PSQI) describing whether they had experienced any problems with sleep over the past month prior to the study. A similar questionnaire has been used in previous studies (Fan et al., 2022a; Liao et al., 2022, 2021a). We did not verify or double-check the information provided by the participants. Table 1 summarizes the anthropometric data of all 29 participants who completed the measurements. As reported by the participants, they all were daytime workers, free of chronic disease (such as asthma, rhinitis, hay fever, eczema, headache, and diabetes), with no hearing/smelling impairment, and were not taking any medication or sleeping pills during the experimental period. The exclusion criteria included a history of alcohol or drug abuse and any significant sleep disorder over the past month.

As shown in Table 1, most participants were males, non-smokers (although three smokers were included because of the small sample size), had been living in Belgium for ≥2 years prior to this study, had no children living at home throughout the measurements, and did not experience sleep problems (for all subjects, the PSQI score (Buysse et al., 1989) was below 8 and for the majority it was below 5). The BMI of these participants was ≥18.5 kg/m^2. Half the participants were below 40 years old and half of the total were office workers.

Table 1
Description of participants and their bedrooms.

Items	29 participants who completed the study	23 participants for whom usable data were available [a]	12 participants for whom usable data were available [b]
Sex			
Male	23	17	12
Female	6	6	0
Age (y)			
≤ 40 (27–40)	14	13	6
> 40 (41–64)	15	10	6
BMI (kg/m^2)			
< 18.5	2	2	0
18.5-24.9	10	8	6
>24.9	17	13	6
Time resident in Belgium			
≤ 1 year	3	2	1
≥ 2 years	26	21	11
Smoking			
Yes	3	2	1
No	26	21	11
The age of the youngest child at home			
No child at home	21	16	7
6–15 (y)	8	7	5
Working/studying from home			
Yes, I work/study in other functional room at home	13	11	7
No, I work/study in office	16	12	5
Sleeping alone during weekdays, excluding holidays			
Yes, I sleep alone	11	9	4
No, I sleep with spouse or partner	18	14	8
Dwelling type			
Multistory apartment building	6	4	2
Row-house (joined to another house)	11	9	5
Detached house (not joined to another house on either side)	12	10	5
Bedroom floor			
0 (Ground floor)	3	3	1
1	22	17	10
> 1	4	3	1
Major bedroom renovations (e.g. change of window(s), carpet(s), bedroom furniture(s), etc.)			
New building	5	4	2
Yes, in the last 6 months	1	1	1
Yes, 6 months to 1 year ago	3	3	1
Yes, over 1 year ago	8	7	4
No, it has not been renovated	12	8	4
PSQI score			
≤ 5	20	17	10
6–8	9	6	2

[a] Notable differences in CO$_2$ concentrations were observed between low and high ventilation rate settings.

[b] Notable differences in CO$_2$ concentrations were observed across the three ventilation rate settings.

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

The recruited participants were provided with all necessary information about the study and detailed instructions via email and videos posted on a

YouTube channel (https://www.youtube.com/@jonatan7988/featured). They were asked to keep their lifestyle unchanged during the entire experiment.

The experimental plan included a control group but too few responses from this group made it impossible to use them in the analyses.

2.3. Measurements

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

The bedroom environmental quality was continuously monitored at intervals of 5 min with the Sense unit (Renson Inc., Belgium). It had a built-in temperature sensor (accuracy: ±0.2 °C; range: 0 to 65 °C), a humidity sensor (accuracy: ±2 %; range: 10 to 90 %), a CO_2 sensor (accuracy: ± 30 ppm + 3 % of reading; range: 400 to 5000 ppm), and particulate matter (PM) sensors allowing measurements of particles with an aerodynamic diameter ≤1 μm (PM_1), 2.5 μm ($PM_{2.5}$), 4 μm (PM_4), and 10 μm (PM_{10}) (accuracy: ± 10 μg/m^3; range: 0 to 100 μg/m^3); all sensors were factory calibrated and we did not perform any further verifications of their performance. The Sense unit also provided measurements of the total concentration of volatile organic compounds (TVOCs), although as we could not verify the quality of measurement or what types of pollutants caused the response of the sensor we did not use these data in the main analyses; they are however presented for reference in the Appendix. The Sense unit also measured sound pressure level in dB(A), but the operation of the fan in the PM sensor could corrupt these measurements and they were thus not included in the main analyses. They are presented in the Appendix for reference.

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

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

Cognitive performance was measured using a 3-minute version of the Baddeley test of grammatical reasoning to examine how well people understand sentences of various levels of syntactic complexity (Baddeley, 1968). This test was selected because it was used in previous studies measuring the effects of bedroom ventilation on sleep quality and had been found to be sensitive (Fan et al., 2022b, 2022a; Strøm-Tejsen et al., 2016). We also used this test as it is short. Other tests could be used instead, e.g., similar to those used by Klausen et al.(Klausen et al., 2023). The online version of the test created with ClassMarker was performed by the participants immediately before they went to sleep in the evening and after they woke up in the morning.

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

We also estimated the ventilation rates in bedrooms on the nights when the bedroom occupancy was available from the morning sleep diary, based on a mass balance model. The CO_2 emission rate was assumed to be 11 L/h per person for sleeping adults (Fan et al., 2021) and 10 L/h per person for sleeping children (Klausen et al., 2023). The outdoor CO_2 concentration was assumed to be 420 ppm (https://www.co2.earth/). The calculated 95th percentile of measured CO_2 ($CO_{2-95\%tile}$) was used to indicate steady-state CO_2 concentration (Fan et al., 2022a), though the steady-state may not be established in all bedrooms during sleep.

2.4. Ventilation conditions

The bedrooms in the present study were ventilated with outdoor air that was drawn into the bedroom by the extract ventilation system through trickle vents mounted on windows. Each dwelling had its own dedicated ventilation system. The ventilation system consisted of an electronically commutated (EC) fan with control dampers connected externally. The system was connected to the Cloud through the Internet and could be controlled remotely. The fan had a large impeller and a high-tech active variable pressure-controlled operation so the ventilation rate could be changed by altering the fan speed without noticeable changes in the noise level; this may not be the case for bedrooms having other ventilation systems. The air was exhausted in the present study via the exhaust grill that was present in each bedroom.

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

We intended to study the effects of three ventilation rates: low, moderate and high. With the help of and after consulting with the engineers from the manufacturer of the ventilation system, we estimated that the lowest ventilation rate that could be reasonably controlled would be 3 m^3/h and the highest ventilation rate which would not create noise problems and cold draught would be 30 m^3/h. We supplemented these two ventilation rates with a moderate level corresponding to 10 m^3/h to create a logarithmic progression. With one person sleeping in a bedroom these three extract flowrates would correspond to CO_2 concentrations of above 3000 ppm and below 800 ppm under steady-state conditions for the low and the high ventilation rate setting, respectively. We selected these levels to be able to verify the tentative relationship between bedroom ventilation and sleep quality proposed by Sekhar et al. (Sekhar et al., 2020a) and Akimoto et al. (Akimoto et al., 2021). Higher CO_2 levels resulting from increased occupancy were also acceptable as they have previously been found in bedrooms (Bekö et al., 2010; Sekhar et al., 2020a). The actual total ventilation rates, including infiltration and adventitious ventilation obtained through opening the windows, if any, (Schiavon, 2014) that were estimated from the measured CO_2 concentrations differed from these intended settings; they are presented in Tables 2 and 4 and Figs. 2 and 5. This gave rise to some analytical limitations, as described below.

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

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

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

2.5. Experimental design

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

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

2.6. Selection of data for the analyses

The process of data selection is shown in Fig. 1. Thirty-four participants were recruited. A full set of measurements was available for twenty-nine participants; in the case of other participants recruited for the experiment, the instruments were lost in shipment for two of them, one did not sleep in his/her bedroom during one of the weeks, and two withdrew. We also excluded three participants with missing data and one who slept for <5 h, as this is significantly less than what is recommended by the National Sleep Foundation in the U.S. (Hirshkowitz et al., 2015). Consequently, we examined the data from 25 bedrooms and found that in two bedrooms, there had been no significant differences in the measured CO_2 levels between conditions, indicating that the intervention had been unsuccessful; we were unable to find out why and so excluded these data. Data from 23 bedrooms was thus available for the analysis.

We used $CO_{2\text{–}95\%\text{tile}}$ during sleep as a method to evaluate the success of the intervention; this concentration included the CO_2 produced by any other people sleeping in the bedrooms and was used as a proxy for the ventilation rate (Fan et al., 2022a). The time-series CO_2 concentration measured during sleep was also compared between conditions to verify the success of the intervention. Other outcomes were classified based on the actual ventilation conditions. The data from each participant in a given ventilation rate were then averaged and analyzed.

We found that clear differences between the three different ventilation rate settings could only be observed in 12 bedrooms while notable differences (≥ 120 ppm was selected considering the precision of the measurement) between the low and high ventilation rate settings were found in all of the 23 bedrooms selected as described above. We therefore decided to perform analyses separately for these two data sets. Table 1 shows the characteristics of participants in these 23 and 12 bedrooms.

2.7. Statistical analysis

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

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

3. Results

3.1. Twelve bedrooms

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

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

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

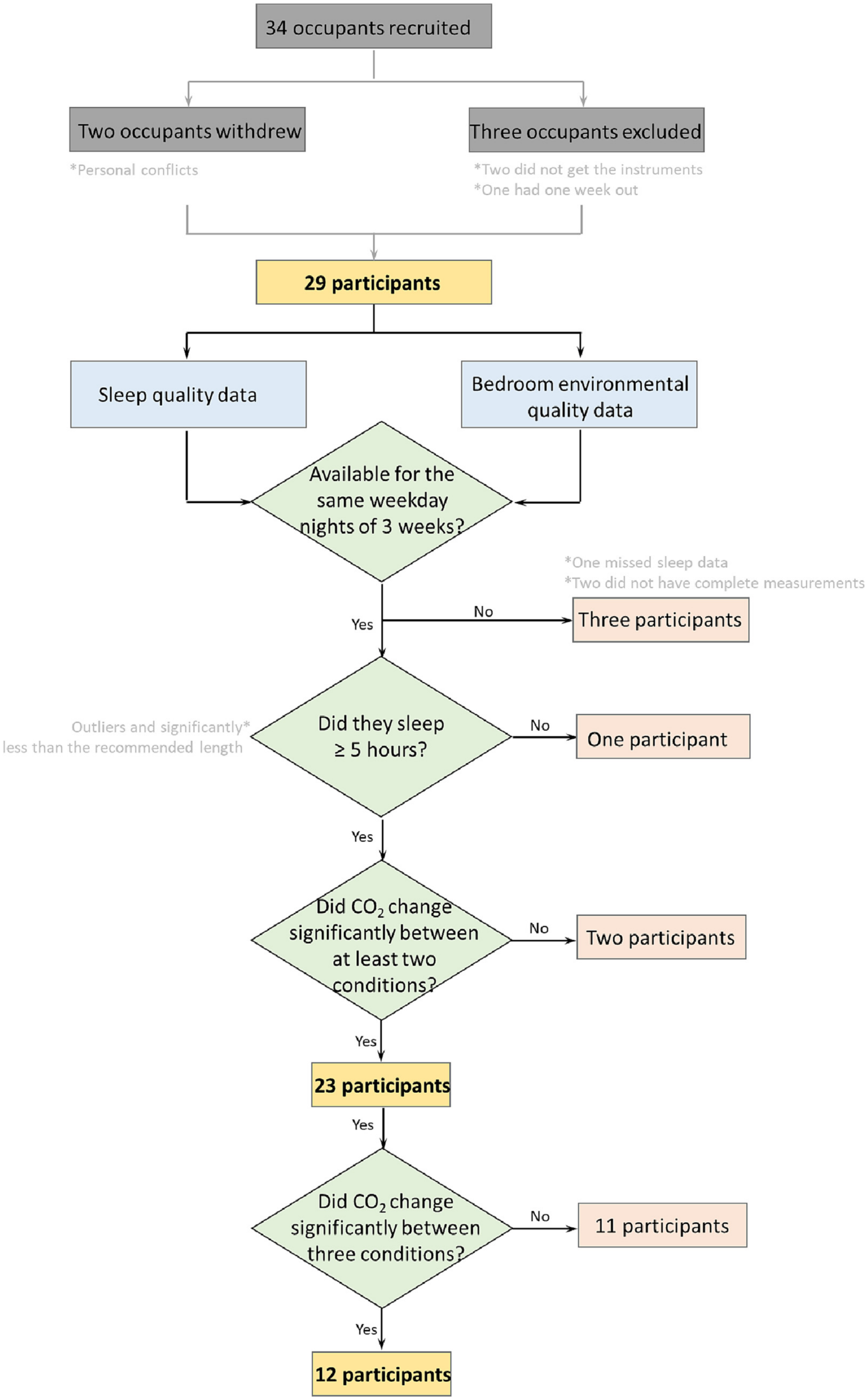

Fig. 1. The flow chart describing the data screening and pre-processing.

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

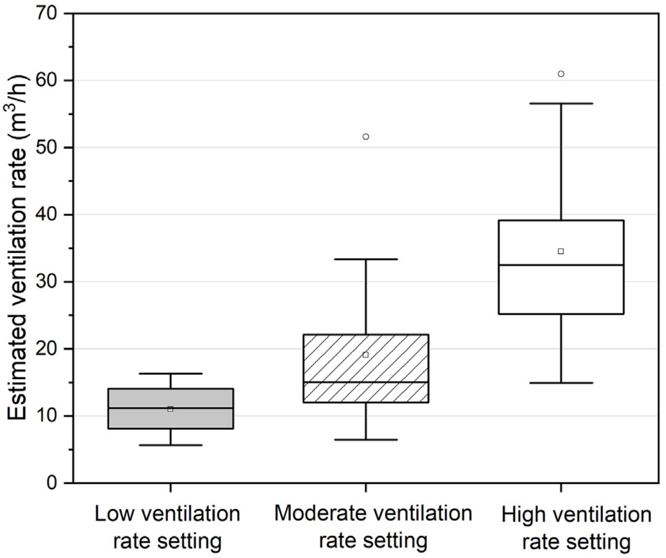

Fig. 2. The estimated ventilation rates in bedrooms at the three ventilation rate settings.

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

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

3.2. Twenty-three bedrooms

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

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

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

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

4. Discussion

The present results show that at the low ventilation rate setting the conditions in the bedrooms were the worst, and that they had negative effects on sleep quality. Increasing the ventilation rate improved both bedroom air quality and sleep quality. The former was indicated by lower CO_2 levels, while the latter by more deep sleep, less light sleep and fewer awakenings. We also observed lower $PM_{2.5}$ and TVOCs concentrations (Fig. S2 in the Appendix) but we did not include them in the main analyses for the reasons indicated earlier. The differences in deep sleep approached significance only between the low and high ventilation rate settings, which is probably because of the small sample size. The intervention did not change the temperature and although we did not monitor clothing and bedding insulation, we do not expect that participants experienced thermal discomfort during sleep especially because the temperatures were at a moderate level and any discomfort could be easily avoided by adjusting thermostat, pajamas or duvet. Consequently, we believe that the effects observed in this study can be attributed to improved air quality as a result of changes in bedroom ventilation. These changes probably affected the respiratory system and the autonomic nervous system, as suggested by Yan et al. (2022b). However, no mechanism for the observed results can be identified because no physiological measurements were carried out. The present results are similar to what have been reported in the literature, in the case of laboratory studies (Fan et al., 2022b; Lan et al., 2021; Xu et al., 2020; Yan et al., 2022b), field intervention studies (Fan et al., 2022a; Liao et al., 2021b; Mishra et al., 2018; Strøm-Tejsen et al., 2016) and cross-sectional studies (Liao et al., 2022; Xiong et al., 2020; Yan et al., 2022a; Zhang et al., 2021). We believe that compared with other studies the results in the present study are unique because the effects were observed in bedrooms in actual dwellings, not in dormitories or laboratories, with adult participants and by changing the set-points of a pre-installed extract ventilation system. Confirmation in bedrooms with a fully balanced mechanical system is still required.

No significant effects on next-day work performance were observed in the present study, nor were such effects observed by Fan et al. (2022a, 2022b) who also used the Baddeley test to examine cognitive work performance. These results differ from the findings observed by Strøm-Tejsen et al. who found that the performance of the Baddeley test was reduced after sleeping in bedrooms with poor ventilation (Strøm-Tejsen et al., 2016). This discrepancy is probably caused by differences in exposure conditions. In the present study and in the studies of Fan et al. (2022a, 2022b), the $CO_{2\text{-Avg}}$ concentrations were below 2000 ppm while in the study of Strøm-Tejsen et al. (2016) they reached nearly 2500 ppm, which may suggest that higher levels of pollutants are needed to cause measurable effects on performance. There could also be other reasons for these differences and this should be further investigated in future studies. It is important to note that in the present study and in the study of Strøm-Tejsen et al. (2016) the effects of poor sleep and exposure to poor air quality on work performance could not be separated, whereas in the study of Fan et al. (2022b), the Baddeley test was always performed under neutral conditions outside the

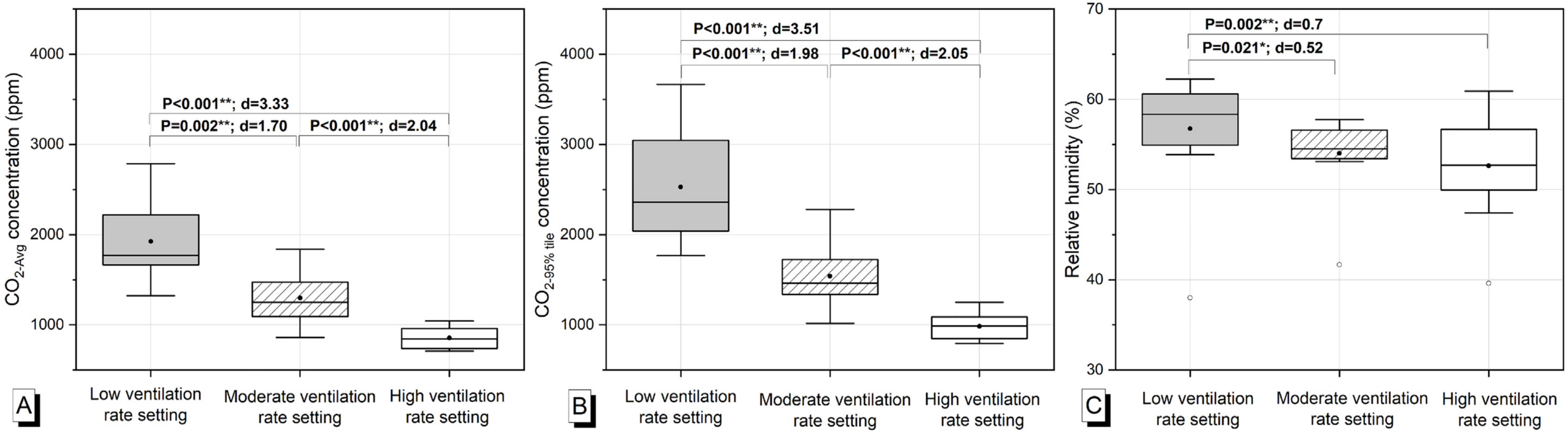

Fig. 3. (A) CO$_{2\text{-Avg}}$ concentration; (B) CO$_{2\text{–95\%tile}}$ concentration; (C) relative humidity at the three different ventilation rate settings. $^{**}p \leq 0.01$; $0.01 < {}^{*}p \leq 0.05$.

Table 3

Measured sleep quality parameters at the three ventilation rate settings and recommendations for good sleep quality. $**p \leq 0.01$; $0.01 < *p \leq 0.05$.

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

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

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

bedroom after sleeping under different ventilation conditions. Future experiments should attempt to discriminate between the effects on performance attributable to poor sleep quality and exposure to poor air quality during the test of cognitive performance. They should also investigate other tests and methods to examine cognitive performance in connection with sleep quality.

The present study does support to some extent the tentative relationship between bedroom ventilation (as indicated by the $CO_{2\text{-Avg}}$ concentration) and sleep quality proposed in two recent reviews (Akimoto et al., 2021; Sekhar et al., 2020a). The relationship predicts that no effects of bedroom ventilation on sleep quality are to be expected at a $CO_{2\text{-Avg}}$ concentration below 800 ppm, while concentrations above 1150 ppm would be expected to cause significant negative effects on conventional measures of sleep quality. In the comparison between low and high ventilation rate settings that was available in 23 bedrooms in the present study, the $CO_{2\text{-avg}}$ concentration was 1369 ppm and 812 ppm, respectively. The CO_2 concentration under the three ventilation rate settings that was available in 12 bedrooms was 1927, 1298, and 856 ppm in the comparison between the low, moderate and high ventilation rate settings, respectively. The results from the 12 bedrooms suggest that there could be a threshold at which no further improvement in sleep quality can be obtained by increasing ventilation (Fig. 4), but this interpretation is however not supported by the results from 23 bedrooms because the percentage of deep sleep significantly increased at the high ventilation rate setting (Table 5). More research is therefore needed to provide additional data and determine at which bedroom ventilation rate no disturbance to sleep quality would occur due to poor air quality. At present, it would appear that concentrations of $CO_{2\text{-Avg}}$ below 800 ppm corresponding to a ventilation rate above 10 L/s per person would meet this goal (Fan et al., 2021).

All of the bedrooms in the present study had extract ventilation with trickle vents installed on the windows. This means that the bedrooms were ventilated directly with outdoor air. A previous intervention study in Denmark showed that ventilating bedrooms with outdoor air by opening the windows improved sleep quality, but this was not observed when they were ventilated with air from other rooms in the dwelling by opening an internal door (Fan et al., 2022a). We can assume that no air from other rooms in the dwellings entered the bedroom in the present study because we asked participants to sleep with the internal door to the bedroom closed. The air used for ventilating bedrooms in the present study was assumed to be clean (although it was not filtered) as shown by the levels of PM. This solution should only be used in areas with low outdoor air pollution. Additionally, this ventilation principle can allow penetration of ambient noise into the bedroom. This was observed by e.g. Strøm-Tejsen et al. where subjects reported higher noise levels when the windows were open (Strøm-Tejsen et al., 2016). We could not verify whether the ambient noise influenced the sleep quality in the present study. However because the windows were closed and the opening of the trickle vent was unchanged (and kept at the lowest setting) there is no reason to expect changes in the noise penetrating from outdoors under the different exposure conditions in the present experiment. The noise caused by the ventilation system did not differ between the ventilation rate settings when the ventilation settings were determined in empirical trials prior to the experiment, although we could not verify these assumptions because, as indicated in the Methods section, the measurements of sound pressure levels by the Sense unit (Fig. S3 in the Appendix) were considered to be unreliable and only limited data on noise perception was included in the diaries reported by the participants. The available data from the Sense unit indicated no difference in the measured acoustic conditions between the conditions established in the bedrooms.

The relative humidity was lower at the higher ventilation rate settings, as would be expected, but the change in relative humidity was very small. The relative humidity was on average between 50 % and 60 %, the levels at which sleep quality was not disturbed in the studies by Cao et al. (2021) and Fan et al. (2022b). We therefore do not expect that changes in relative humidity played an important role for modifying the observed effects on sleep in the present experiments. The effects of relative humidity above 50 % on sleep quality should however be investigated at elevated temperatures (Cao et al., 2021; Wyndham, 1963) and where allergic responses are expected due to the presence of house dust mites (Hou et al., 2021; Sun et al., 2022; Wickman et al., 1991).

One limitation of the present work is that the actual ventilation rates in bedrooms were higher than was planned, especially at the low and moderate ventilation rate settings. This could influence the outcomes and the ability of the study to detect effects on sleep quality and cognitive performance. We stipulate three reasons for this difference: 1) The extract ventilation system did not work as expected; 2) The method used to estimate the ventilation rate was imprecise; and 3) More air infiltrated to the bedroom than was expected from the pilot experiments. We believe that the last reason is the most plausible because the air-tightness of the bedrooms may have differed. Following the experimental protocol, we did not enter the bedrooms to measure the ventilation rates that were established at the three different settings and could not readjust the ventilation system or verify the reasons for the observed differences. However, we were able to show significant and substantial differences between the ventilation rates resulting from the highest and the lowest ventilation rate settings in the 23 out of 25 bedrooms that had complete data and in the 12 bedrooms where we could use the data at all three ventilation rate settings, and although twelve bedrooms was slightly fewer than the required minimum sample size of 15 indicated by the Power Analysis, we could still show significant differences between conditions in some measures of sleep quality. Another important limitation of the study was that because of missing data we could not ensure proper balancing of exposures among all participants. As shown in Table 6, we used a Latin Square design in which the conditions would be changed according to the predetermined sequence in 12, 11 and 11 bedrooms. The data available did not meet our objective of proper balancing (Table 6) but it is not possible to determine whether this had any effects on the observed results.

We included bedrooms where more than one people were sleeping, which also allows extrapolation of the findings to realistic conditions. The presence of another person could exacerbate the negative effects caused by reduced ventilation on sleep (one person could disturb the sleep of the other person), but we could not verify this through extended analyses

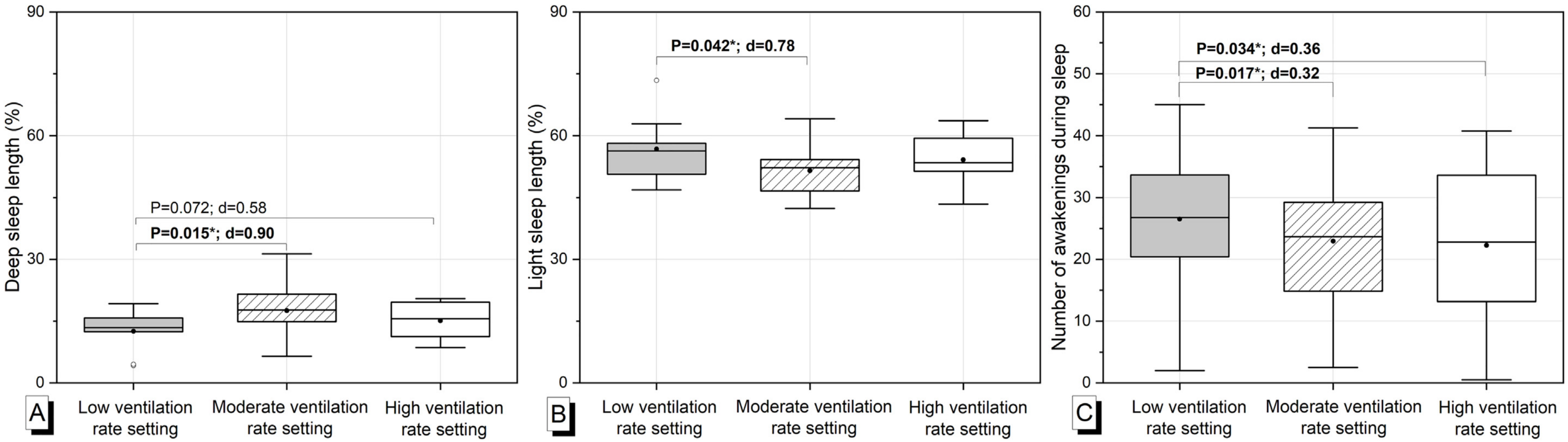

Fig. 4. (A) Deep sleep; (B) light sleep; and (C) the number of awakenings at the three ventilation rate settings. $0.01 < {}^{*}p \leq 0.05$.

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

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

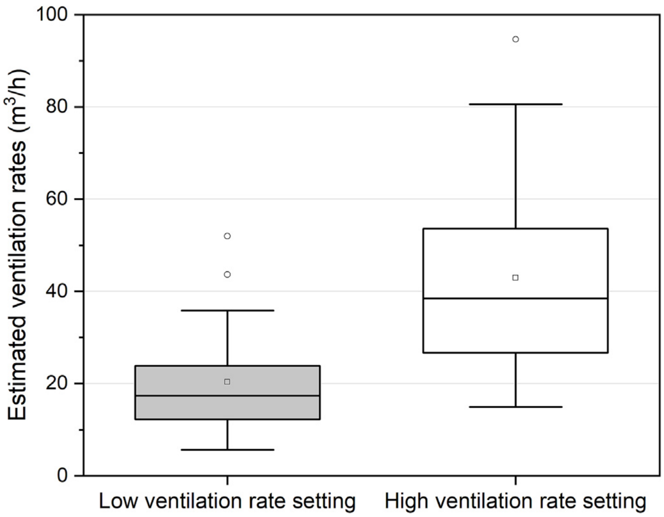

Fig. 5. Estimated ventilation rates during sleep at the low and high ventilation rate settings.

because of the small sample size and lack of sleeping data of another person in the bedroom. This aspect should be investigated in future studies.

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

Although we recruited 34 participants, only the measurements from 23 bedrooms were usable and we could not use the data from the diaries because only a limited number of usable responses were available. The recruitment invitation was sent to several thousand potential participants, but <10 % responded, and only 34 met the selection criteria. These numbers show how difficult it is to perform field studies of the type described in the present paper. It is more feasible to perform studies of the effects of bedroom conditions on sleep quality in "living labs" (simulated dwellings) or in climate chambers.

Many participants had a BMI ≥ 24.9 kg/m^2 which could have biased the results. Although we performed within-subject analyses, this might not be able to control for any effects of BMI on sleep quality. However, our participants had PSQI score generally ≤5 indicating that they did not have any habitual problems with sleep (PSQI score ≤ 5 is judged as a normal sleep with no any deviations or anomalies). We therefore do not expect that the differences in BMI might have biased the observed relationships.

The objective of the present study was to examine the effects of bedroom ventilation on sleep quality in normal bedrooms, maintaining realism and keeping participants blind to the interventions. Because many measurements were made, analyses examining other research questions could be performed such as the influence of other characteristics of the dwellings. These may be reported separately. The present results are valid for healthy adults (27–64 years old) who do not have any significant sleep disturbance (PSQI score generally ≤5) or use sleep medication and for outdoor weather conditions with moderate temperatures. Extrapolation to other groups and other climatic conditions requires further research. The observed effects on sleep quality occurred on average within the range of sleep quality parameters recommended by the U.S. National Sleep Foundation (Hirshkowitz et al., 2015; Ohayon et al., 2017). The long-term consequences of these results for health and general well-being must be examined in future studies. Our population was too small and our exposures were too short for it to be possible to draw sound conclusions on long-term effects on the general population.

5. Conclusions

Despite the difficulties in performing field intervention measurements in actual bedrooms, the present study was able to confirm the previously reported benefits of improved bedroom ventilation for objectively measured indicators of sleep quality and it supports the importance of maintaining a minimum ACH higher than the normally recommended 0.5 h^{-1} in dwellings (Wargocki et al., 2002); this would correspond to 19.5 m^3/h for the median volume of bedrooms in the present study (39 m^3). A median ventilation rate below this level increased the concentrations of $PM_{2.5}$ and CO_2 in bedrooms, indicating that the concentrations of other air pollutants, especially bioeffluents, were also higher. The study was a single-blind intervention with participants who had no sleep disorders. Similar studies of different populations in different climates and better control of ventilation are still required.

CRediT authorship contribution statement

Xiaojun Fan: Conceptualization, Investigation, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft. **Chenxi Liao:** Conceptualization, Investigation, Methodology. **Kazuya Matsuo:** Formal analysis. **Kevin Verniers:** Investigation, Writing – review & editing. **Jelle Laverge:** Conceptualization, Data curation, Methodology, Investigation, Funding acquisition, Project administration, Resources,

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

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

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

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

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

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

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

Writing – review & editing. **Brecht Neyrinck:** Investigation. **Ivan Pollet:** Investigation. **Lei Fang:** Writing – review & editing. **Li Lan:** Writing – review & editing. **Chandra Sekhar:** Writing – review & editing. **Pawel Wargocki:** Supervision, Conceptualization, Data curation, Methodology, Investigation, Funding acquisition, Project administration, Resources, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.163805.

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