ASHRAE Research Project 1837-TRP The Effects of Ventilation in Sleeping Environments

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Summary

- ASHRAE research project 1837-RP on "The effects of ventilation in sleeping environments"
- Launched on October 1, 2019
- Partners: Technical University of Denmark and JiaoTong University, China
- Duration: 36 months (extension granted)
- Completion: April 30, 2023 (new date)
- Funding: US$ 230,541 (ASHRAE), US$366,541 (total)

Promised activities (in a nutshell)

- Summary of standards defining bedroom conditions
- Summary of literature on ventilation and sleep quality
- Cross-sectional studies in bedrooms to characterize ventilation conditioms
- Intervention studies in bedrooms

Specific aim

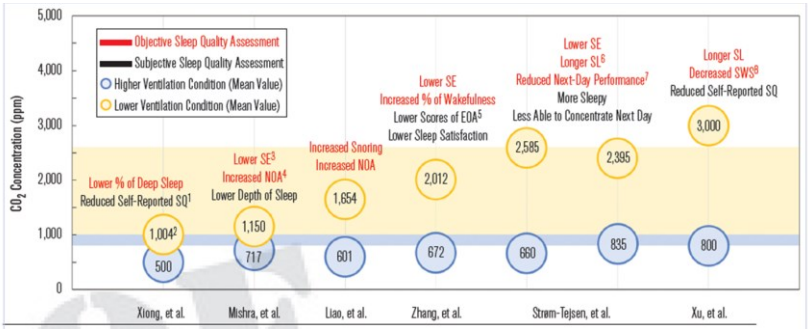
- Amendment to ASHRAE Standard 62.2 ” Ventilation and Acceptable Indoor Air Quality in Residential Buildings”

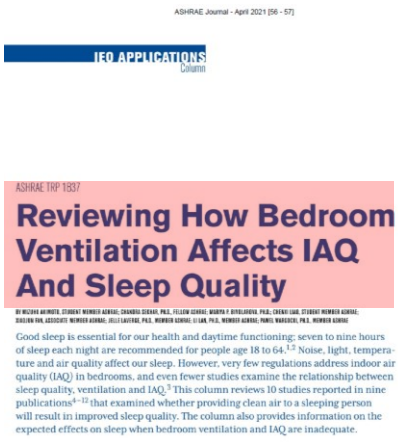
Additional studies (extensions)

- Survey of bedroom conditions (prior to and after the COVID-19 lockdown)
- Laboratory studies on the effects of ventilation, pure CO_2, temperature and ventilation noise on sleep quality
- Examining bedroom and door opening behavior
- Estimation of CO_2 generation rate for sleeping people (young adults and elderly)
- Estimation of emission rates of bioeffluents from sleeping people using PTR-MS-TOF
- Comparison of performance of different sleep trackers against polysomnograph (PSG)

Review of literature and standards

Summary of studies examining the effects of ventilation on sleep quality




ASHRAE Journal - April 2021 [56 - 57]

IEQ APPLICATIONS
Column

ASHRAE TRP 1337

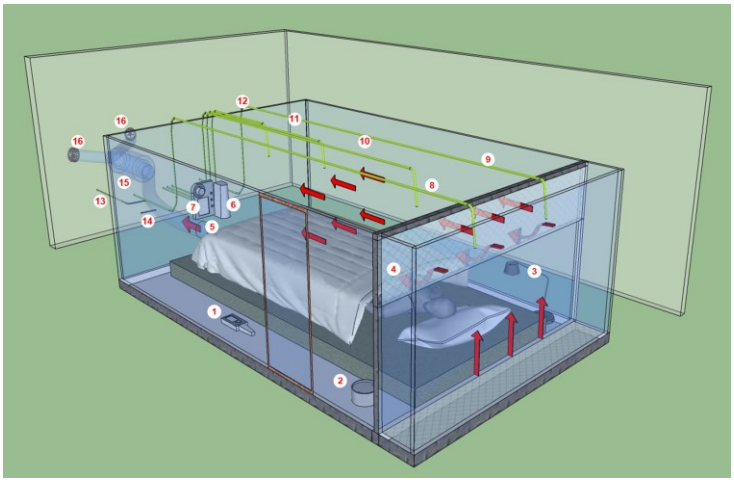
Reviewing How Bedroom Ventilation Affects IAQ And Sleep Quality

Good sleep is essential for our health and daytime functioning; seven to nine hours of sleep each night are recommended for people age 18 to 64.[1,2] Noise, light, temperature and air quality affect our sleep. However, very few regulations address indoor air quality (IAQ) in bedrooms, and even fewer studies examine the relationship between sleep quality, ventilation and IAQ.[3] This column reviews 10 studies reported in nine publications[4–12] that examined whether providing clean air to a sleeping person will result in improved sleep quality. The column also provides information on the expected effects on sleep when bedroom ventilation and IAQ are inadequate.

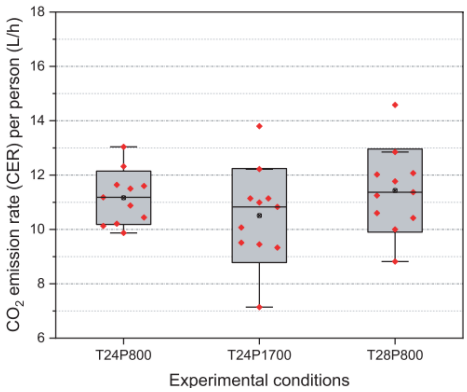
- Scanty information on whether the reported ventilation rates would disturb sleep quality
- <750 ppm bedroom CO_2 undisturbed sleep quality range
- >2600 ppm bedroom CO_2 disturbed sleep quality range with possible reduced next-day cognitive performance

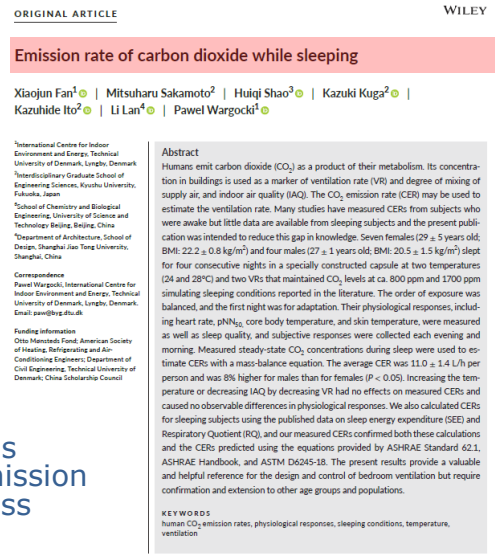
Laboratory experiments

Laboratory setup, the sleeping capsule



Estimating the emission rate of CO_2





ORIGINAL ARTICLE

WILEY

Emission rate of carbon dioxide while sleeping

Xiaojun Fan[1] | Mitsuharu Sakamoto[2] | Huiqi Shao[3] | Kazuki Kuga[2] | Kazuhide Ito[2] | Li Lan[4] | Pawel Wargocki[1]

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Funding information
Otto Mønsteds Fond; American Society of Heating, Refrigerating and Air-Conditioning Engineers; Department of Civil Engineering, Technical University of Denmark; China Scholarship Council

Abstract

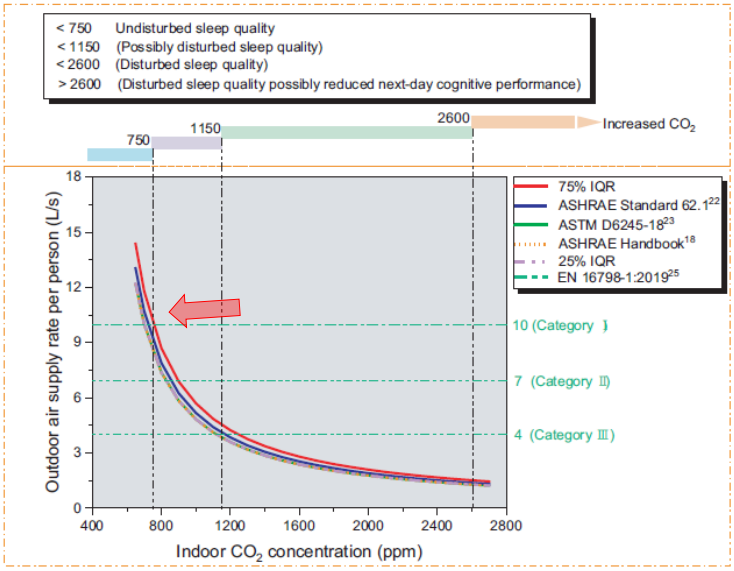
Humans emit carbon dioxide (CO_2) as a product of their metabolism. Its concentration in buildings is used as a marker of ventilation rate (VR) and degree of mixing of supply air, and indoor air quality (IAQ). The CO_2 emission rate (CER) may be used to estimate the ventilation rate. Many studies have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

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

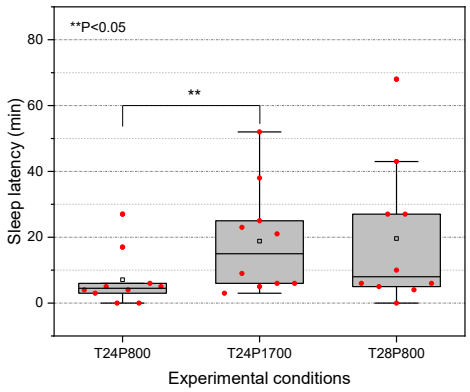
- CO_2 emission rates of sleeping people is around 11 L/h, 40% lower than the emission rates when awake. Fairly constant across studies.

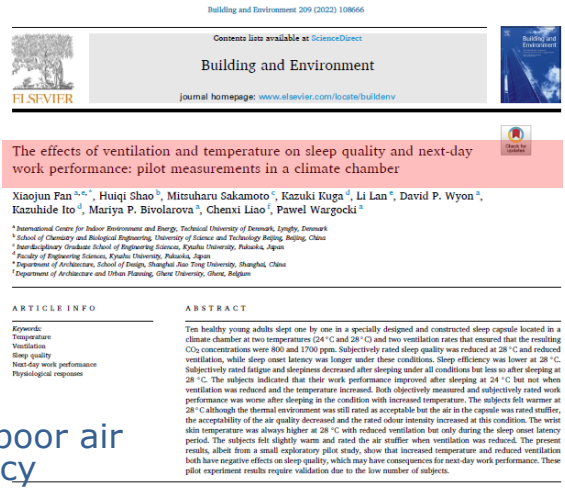
Implications

- Current evidence suggest the rates above 10 L/sp (CO_2 levels below 750 ppm) will ensure undisturbed sleep



The effects of ventilation and temperature on sleep quality

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Building and Environment

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

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ARTICLE INFO

Keywords:
Temperature
Ventilation
Sleep quality
Next-day work performance
Physiological responses

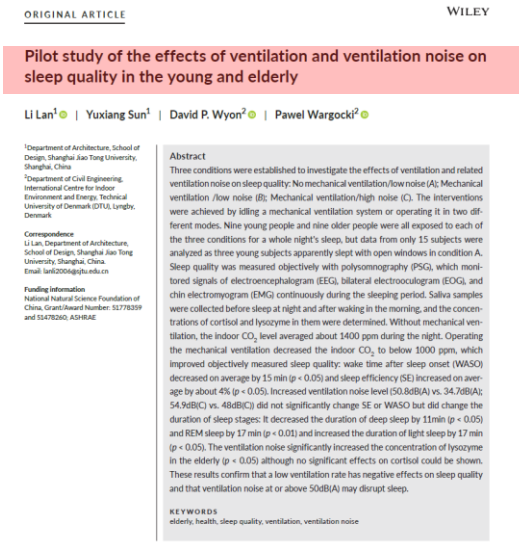
ABSTRACT

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

- Both elevated temperatures and poor air quality increase sleep onset latency (more time needed to fall asleep)

The effects of ventilation and ventilation noise on sleep quality

- Poor ventilation resulted in reduced sleep quality measured objectively by polysomnography.
- Ventilation noise was perceived as less acceptable and could be shown objectively to have disrupted sleep, effectively cancelling the positive effects of improving the ventilation
- Occupants are expected not to operate ventilation as intended in bedrooms if ventilation noise is too high
- Any potential sources of noise should be eliminated


ORIGINAL ARTICLE

WILEY

Pilot study of the effects of ventilation and ventilation noise on sleep quality in the young and elderly

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Funding information
National Natural Science Foundation of China, Grant/Award Number: 51778359 and 51478260; ASHRAE

Abstract

Three conditions were established to investigate the effects of ventilation and related ventilation noise on sleep quality: No mechanical ventilation/low noise (A); Mechanical ventilation /low noise (B); Mechanical ventilation/high noise (C). The interventions were achieved by idling a mechanical ventilation system or operating it in two different modes. Nine young people and nine older people were all exposed to each of the three conditions for a whole night's sleep, but data from only 15 subjects were analyzed as three young subjects apparently slept with open windows in condition A. Sleep quality was measured objectively with polysomnography (PSG), which monitored signals of electroencephalogram (EEG), bilateral electrooculogram (EOG), and chin electromyogram (EMG) continuously during the sleeping period. Saliva samples were collected before sleep at night and after waking in the morning, and the concentrations of cortisol and lysozyme in them were determined. Without mechanical ventilation, the indoor CO_2 level averaged about 1400 ppm during the night. Operating the mechanical ventilation decreased the indoor CO_2 to below 1000 ppm, which improved objectively measured sleep quality: wake time after sleep onset (WASO) decreased on average by 15 min ($p < 0.05$) and sleep efficiency (SE) increased on average by about 4% ($p < 0.05$). Increased ventilation noise level (50.8dB(A) vs. 34.7dB(A); 54.9dB(C) vs. 48dB(C)) did not significantly change SE or WASO but did change the duration of sleep stages: It decreased the duration of deep sleep by 11min ($p < 0.05$) and REM sleep by 17 min ($p < 0.01$) and increased the duration of light sleep by 17 min ($p < 0.05$). The ventilation noise significantly increased the concentration of lysozyme in the elderly ($p < 0.05$) although no significant effects on cortisol could be shown. These results confirm that a low ventilation rate has negative effects on sleep quality and that ventilation noise at or above 50dB(A) may disrupt sleep.

KEYWORDS
elderly, health, sleep quality, ventilation, ventilation noise

Field experiments: surveys, cross-sectional and interventions

The survey in Danish bedrooms, contd

- Mechanical ventilation in bedrooms reduce disturbance to sleep caused by stuffy and too cool air; the more disturbances to sleep (and the more objects in bedrooms being potential sources of pollution) the poorer sleep quality

Science of the Total Environment 798 (2021) 149209

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A survey of bedroom ventilation types and the subjective sleep quality associated with them in Danish housing

Chenxi Liao [a,b,*,**], Mizuho Akimoto [b,c], Mariya Petrova Bivolarova [b], Chandra Sekhar [b,d], Jelle Laverge [a], Xiaojun Fan [b], Li Lan [e], Pawel Wargocki [b]

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HIGHLIGHTS

- Sleep disturbance caused by stuffy air reduces sleep quality in people's life.
- Mechanical ventilation in bedrooms reduces stuffy air and "too cool" during sleep.
- Fish tank, printer, carpet and TV placed in bedrooms decrease sleep quality.

GRAPHICAL ABSTRACT

The effects of the COVID-19 lockdown on bedroom use and sleep quality

- More stress and new working style
- No changes to sleep patterns
- Bedroom converted to office
- Around 40% ventilated bedrooms more often
- Got up later and went to bed later
- Around 33% felt their sleep quality decreased

Massive online questionnaire survey

- **in the capital region of Denmark.**
- **impact of the COVID-19 pandemic on bedroom environment and sleep changes**

January to March 2020

Before the 1st lockdown

517 people responded

March to April 2021

After the 2nd lockdown

182 people responded

The survey in Chinese bedrooms

- Subjectively assessed sleep quality was significantly affected by heat in transitional season, cold, heat and noise in the summer, cold, heat, dryness and noise in winter
- Sleep quality was significantly correlated with decorations in the bedroom; presence of a plant increased the risk of poor subjectively rated sleep quality
- Outdoor surroundings including highway, railway track, active airport decreased subjectively assessed sleep quality
- The sleep quality of respondents with ventilation time longer than 15 min was significantly improved
- Sleeping with door opened was considered to improve sleep quality

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Five hypotheses concerned with bedroom environment and sleep quality: A questionnaire survey in Shanghai city, China

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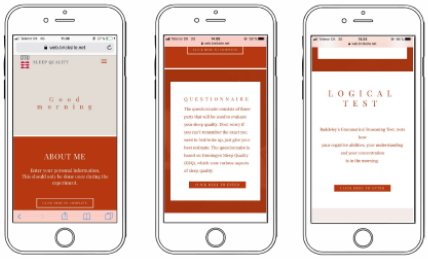
ARTICLE INFO

Keywords:
Sleep quality
Bedroom environment
Outdoor surroundings
Ventilation behaviour
Urban governance

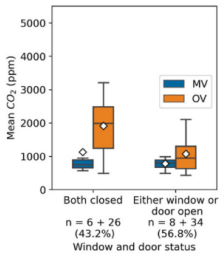
ABSTRACT

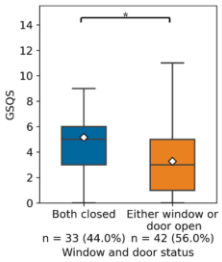
Based on the researches conducted in recent decades, five hypotheses concerned with bedroom environment and sleep quality were proposed. In order to verify these hypotheses, we conducted a questionnaire survey which lasted one year in Shanghai. This questionnaire contained questions on inhabitants' basic information, inhabited environment, living habits and sleep quality. A total of 1130 valid questionnaires (540 males, 590 females) were obtained. Results showed that inhabitants' sleep quality was significantly affected by heat in transitional season, cold, heat and noise in summer, cold, heat, dryness and noise in winter, respectively. People living in the bedrooms without plants had a 74.5% chance of getting better sleep than those living in rooms with plants. Artificial facilities (objects or areas constructed with certain functions) around houses had a significant negative effect on inhabitants' sleep quality, but no significant impact of natural landscape (original landscape of nature) was found. Ventilation was an effective way to improve bedroom environment. The frequency of ventilation in the morning was significantly correlated with sleep quality ($p < 0.05$), and ventilation time longer than 15 min per day helped significantly improve the inhabitants' sleep quality ($p < 0.05$); during sleep period, compared with the inhabitants in sealed bedrooms, the average sleep quality of inhabitants who opened doors increased by 26.0%, 4.7% and 13.9% in transitional season, summer and winter, respectively, but opened windows had no obvious effect. Generally, the five hypotheses were highly or moderately verified, which could play an important guiding role in future studies.

Measurements during field studies



A week-long cross-sectional study, DK





- Sleeping with either windows or doors open was associated with improved subjectively rated sleep quality
- Poor perceived air quality was associated with decreased subjectively rated sleep quality
- Higher mean CO_2 levels were associated with increased drop in skin temperature during sleep
- A higher drop in skin temperature was associated with increased fraction of deep sleep

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A cross-sectional field study of bedroom ventilation and sleep quality in Denmark during the heating season

Chenxi Liao [a,b,*], Xiaojun Fan [b], Mariya Bivolarova [b], Jelle Laverge [a], Chandra Sekhar [d], Mizuho Akimoto [c], Anna Mainka [e], Li Lan [f], Pawel Wargocki [b]

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ARTICLE INFO

Keywords:
CO2
Perceived air quality
Air change rates
GSQS
Sleep tracker
Wrist skin temperature

ABSTRACT

Parameters describing the bedroom environment and sleep quality were measured overnight for one week in 84 randomly selected actual bedrooms in Denmark from September to December 2020. The median age of participants was 26 years (interquartile range (IQR) [24-32] years); 41 were males. Carbon dioxide (CO_2), temperature, and relative humidity were measured continuously. Sleep quality was assessed by the Groningen Sleep Quality Scale (GSQS) on two mornings and was assessed using wrist-worn sleep trackers. Skin temperature was monitored continuously. Bedroom indoor air quality (IAQ) was rated by participants on two occasions just before sleep in the evening and upon waking up in the morning. Measurements from 75 bedrooms were complete. The median [IQR] of mean CO_2, air temperature and relative humidity measured during sleep were 1,120 [741–4,804] ppm, 23.4 [22.3–24.4]°C, and 48.6 [44.7–55.4]%. The median [IQR] of GSQS was 4.0 [1.0-6.0] suggesting medium to poor subjectively rated sleep quality; the objectively measured sleep efficiency, and percentage of light, deep and REM sleep were in normal ranges: 88.1 [86.1–89.5]%, 59.4 [54.9–64.5]%, 18.3 [15.0–21.7]%, and 23.0 [18.4–26.4]%. The subjectively-assessed sleep quality decreased when perceived IAQ was reduced. Opening the bedroom door or window, which is a proxy for enhanced ventilation, also improved subjectively-assessed sleep quality and IAQ. The cross-sectional nature of the study prompts the validation of the present results with protocols that include measurements of other pollutants besides CO_2 as well as the examination of underlying mechanisms. Nevertheless, they strongly suggest that keeping high bedroom IAQ is essential.

A week-long cross-sectional study, PRC

- The sleep quality of females in households was slightly better than that of males; females had a slightly higher slow-wave sleep and sleep efficiency
- Compared to males, air temperature and CO_2 concentration (ventilation) had a greater impact on the sleep quality of females, whereas noise level had a lower impact
- Slow-wave sleep was negatively correlated with air temperature and CO_2 concentration, and sleep efficiency was significantly negatively correlated with noise level
- During the sleep period, the most comfortable air temperature and relative humidity were estimated to be 24.8°C and 64%

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Journal of Thermal Biology

journal homepage: http://www.elsevier.com/locate/jtherbio

Environmental factors affecting sleep quality in summer: a field study in Shanghai, China

Xinbo Xu, Zhiwei Lian *, Jingyun Shen, Li Lan, Yuxiang Sun

School of Design, Shanghai Jiao Tong University, Shanghai, 200240, China

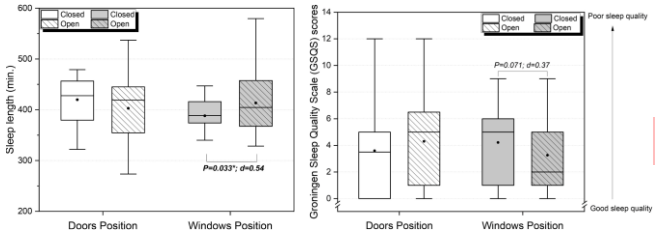
ARTICLE INFO

Keywords:
Bedroom environment
Gender difference
Physiological parameters
Sleep quality
Subjective questionnaire

ABSTRACT

Although the environment can greatly influence an individual's sleep quality, China is yet to conduct comprehensive research on the topic. This study investigated the bedroom environment and sleep quality of 41 households during summer in Shanghai. Bedroom environments were comprehensively evaluated through environmental perception questionnaires filled by participants after waking up every morning. Parameters, such as air temperature, relative humidity, CO_2 concentration, and noise level were continuously monitored. Furthermore, participants' sleep quality was observed using both subjective questionnaires and physiological measures. Environmental measurements showed that the most comfortable air temperature and relative humidity was 24.8 °C and 64%, respectively. Physiological measurements showed that the average duration of slow wave sleep (SWS) and sleep efficiency (SE) was 73.8 min and 86.7%, respectively. Additionally, SWS was negatively correlated with air temperature ($r = -0.377$, $p = 0.015$) and CO_2 concentration ($r = -0.362$, $p = 0.02$), and SE was negatively correlated with noise level ($r = -0.32$, $p = 0.042$). The subjective and objective results consistently indicated that higher air temperature, CO_2 concentration, and noise level leads to poor sleep quality in summer. In addition, air temperature and CO_2 concentration had a greater impact on the sleep quality of males, while noise level had a greater impact on the sleep quality of females.

Window/door opening in bedrooms, intervention study, DK



- CO_2 decreased with both window and door open, but only open window improved perceived air quality.
- Objectively measured and subjectively rated sleep quality improved only when window was open

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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

Xiaojun Fan [a,*], Chenxi Liao [b], Mariya P. Bivolarova [a], Chandra Sekhar [c], Jelle Laverge [b], Li Lan [d], Anna Mainka [e], Mizuho Akimoto [f], Pawel Wargocki [a]

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ARTICLE INFO

Keywords:
Bedroom ventilation
Intervention
Air quality
Sleep quality
Next-day cognitive performance

ABSTRACT

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

Summary conclusions

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Take-home messages, tentative

- Ensure adequate bedroom ventilation; revise ventilation standards to bring the focus on bedroom ventilation
- Keep CO_2 below 700-800 ppm (best), 1100-1200 ppm (as a minimum)
- Use outdoor air (if not polluted and warm); door opening to bedroom brings little or no benefit for sleep quality
- Quiet mechanical ventilation systems are essential in bedrooms as otherwise the benefits for sleep quality are cancelled; recommended airflow rate is 10 L/s per person independently of age
- Avoid sources of pollution in bedrooms
- Avoid elevated temperatures; it is difficult to fall asleep and to stay asleep when the bedroom is too hot
- Sleep quality seems to be enhanced when bedroom temperatures are warm when falling asleep and when waking but cool in between
- There is no single temperature that is ideal at all stages of the night

- The quantitative effect on next-day performance still unknown

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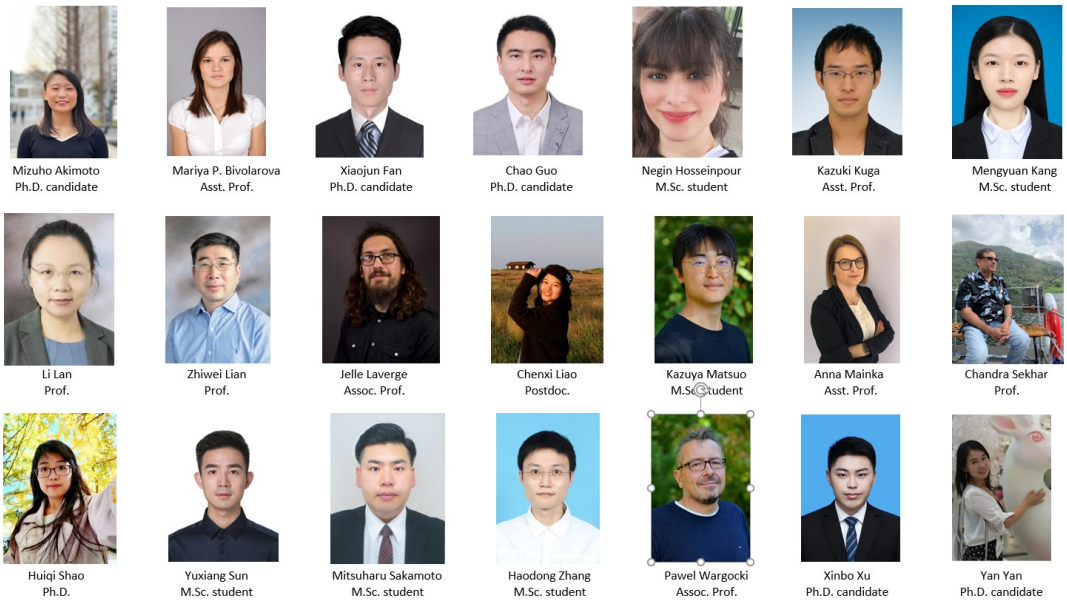
Acknowledgments (WC team)



QUESTIONS……