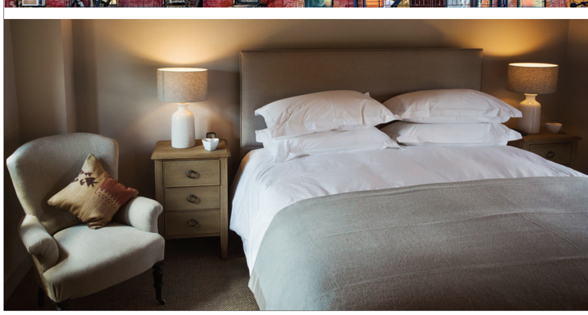
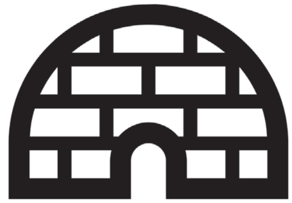
An overview of Ventilation and IAQ Standards for sleeping environments

Chandra Sekhar, PhD
Professor
Fellow ASHRAE & ISIAQ
Department of the Built Environment
College of Design and Engineering
National University of Singapore
bdgscs@nus.edu.sg

Elements of NATURAL & BUILT Environments - affecting our HOMES
….. our BEDROOMS








We sleep over 30 years during our life-time. Where would you rather like your bedroom to be?

Impact on Bedroom Environmental Conditions

Traffic Noise
OA Pollution

Outdoor Light

Outdoor Thermal
Light
OA Pollution

Thermal comfort
Visual Comfort
IAQ acceptability
Aural Comfort

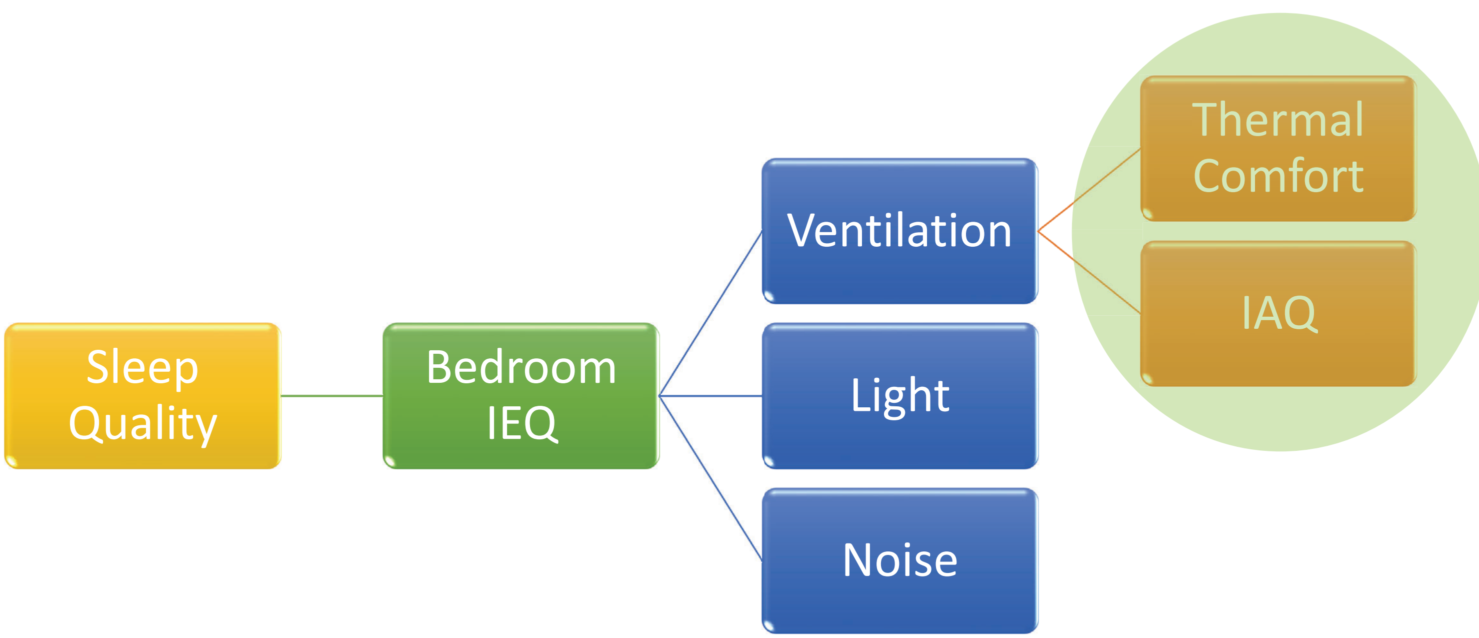
Systematic literature review by Ohayon et al., 2018:

The National Sleep Foundation expert panel, whilst noting that there were no tools or measures of sleep satisfaction applied to the general population and directly associated with good health, made some significant determinations concerning sleep quality -

- *Appropriate sleep satisfaction elements include how an individual feels about their sleep, immediately after their sleep, and during the subsequent day;*
- *Sleep environmental factors include bedding comfort, bedroom temperature, noise and light;*
- *Sleep initiation entails the time taken to fall asleep;*
- *Maintenance parameters include the ease with which one falls back to sleep after awakening during a sleep period, amount of sleep on all days, and undisturbed sleep.*

A quality sleep for rejuvenation, good health and well-being to each of us is much more than just finding a bed and a place to sleep. Increasingly, in a fast-paced urbanised world, this is not easy to come by.

Ohayon, Maurice M., Michael C. Chen, Edward Bixler, Yves Dauvilliers, David Gozal, Giuseppe Plazzi, Michael V. Vitiello, Michael Paskow, Anita Roach, Max Hirshkowitz, A provisional tool for the measurement of sleep satisfaction, Sleep Health, Volume 4, Issue 1, 2018, Pages 6-12, https://doi.org/10.1016/j.sleh.2017.11.002



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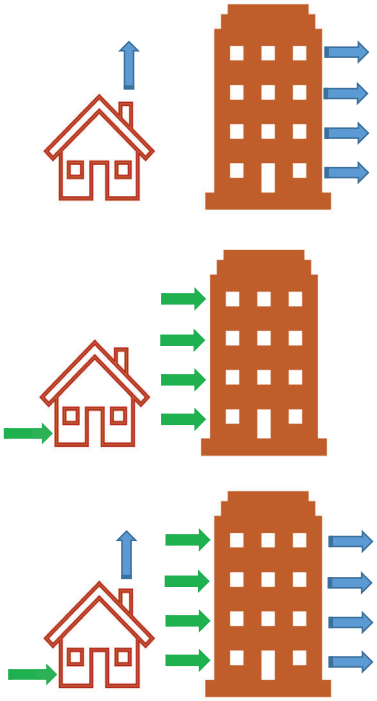
Bedroom ventilation: Review of existing evidence and current standards

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

[a] Department of Building, School of Design and Environment, National University of Singapore, Singapore
[b] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Denmark
[c] Department of Architecture, Waseda University, Japan
[d] Department of Architecture and Urban Planning, Ghent University, Belgium
[e] Department of Architecture, School of Design, Shanghai Jiao Tong University, China

Ventilation in Residential Buildings



	Balanced MV	Unbalanced MV	NV	NV + Extraction
PULL only				✓
PUSH only		✓		
PUSH-PULL	✓			

Objectives

- An understanding of what is available as sound scientific knowledge concerning bedroom ventilation characteristics across different climate zones. This knowledge was then connected to the potential effects on sleep quality
- An insight into the selected major standards for bedroom ventilation and IAQ across different parts of the world
- To see if the thermal environment's interaction effect with CO_2 on sleep quality was reported or bedroom ventilation had an effect on the thermal environment

Methods

- Web of Science search – IRJ papers in this millennium
- Keywords - Residential buildings, bedrooms, sleep quality, ventilation, IAQ, thermal comfort, CO_2, field studies, heating, and cooling
- More than 200 papers collected – 46 shortlisted
- ***Papers classified in 6 categories:***
  1) Ventilation in bedrooms showing CO_2 levels
  2) Ventilation in bedrooms showing air change rates (ACR)
  3) Ventilation in bedrooms showing ACR and CO_2 levels
  4) Ventilation and sleep quality
  5) Personal ventilation and sleep quality
  6) Ventilation in the whole house/dwelling
- ASHRAE, CEN and 15 country-specific standards reviewed

Review Findings

			Mechanical Ventilation[1]														Natural Ventilation	CO_2 level	
Ref Number	Country/Region	Standard	SUPPLY - Air Flow Quantity/Air Change Rate								EXHAUST - Air Flow Quantity/Air Change Rate						Minimum openable area to outdoor (% of floor area being ventilated)	CO_2 level above ambient (ppm)	
			L/s		(L/s.m²)		(L/s.person)		(h^{-1})		L/s	L/s	h^{-1}	L/s	h^{-1}				
			Whole dwelling	Bedroom	Whole dwelling	Bedroom	Whole dwelling	Bedroom	Whole dwelling	Bedroom	Whole dwelling	Enclosed Kitchen		Bathroom				Whole dwelling	Bedroom
[22]	ASHRAE	ASHRAE Std 62.2, 2019	-	-	(0.17-0.74)[2]	-	-		-	-	-	-	5[3]	10[3]	-	-	-	-
[23]	CEN	EN 16798-1:2019																
		Category I	-	-	0.49	-	10		0.7	2.9[4]	-	28-56	-	14-21[5]	-	Supply[6] 60 cm²/room; Extract[7] 100 cm²/room	550	380
		Category II	-	-	0.42	-	7		0.6	2.0[4]	-	20-40	-	10-15[5]	-		800	550
		Category III	-	-	0.35	-	4		0.5	1.2[4]	-	14-28	-	7-10.5[5]	-		1350	950
		Category IV	-	-	0.23	-	-		0.4	-	-	10-20	-	5-7.5[5]	-		1350	950
[24]	Belgium	NBN D-50-001 (1991)	20.8-41.7	7-20	1[8]	-	-	-	-	-	-	20.8	-	13.9 - 20.8	-	-	-	-
[25]	Norway	TEK17 (2017)	-	-	0.33 (min 0.19)[9]	-	-	7.2	-	-	-	10 -30	-	15-30	-	-	-	-
[26]	Denmark	BR18 (2019)	-	-	0.3	0.3	-	-	-	-	-	20	-	10-15		-	-	-
[27]	Austria	ONORM H 6038 (2014)	-	-	-	-	4.17-8.33	5.56	min[9] 0.15	-	-		-		-	-	-	-
[28]	Sweden	Boverket, BFS2014:13-BBR21	-	-	0.35	-	-	-	-	-	-		-		-	-	-	-
[29]	France	Arrete 24.03.82 (1983)	-	-	-	-	-	-	-	-	9.7 -37.5[10]	5.6-12.5[10]	-		-	-	-	-
[30]	Germany	DIN 1946-6 (2019)	4.17-79.2	-	-	-	-	-	-	-	-	12.5	-	12.5	-	-	-	-
[31]	Netherlands	NNI (2006)	7	7	0.9	-	-	-	-	-	-	21	-	14	-			
[32]	UK	HM Government (2010)	21.1	-	0.3	-	-	-	-	-	-	30	-		-	-	-	-
[33]	China	GB 50736-2012	-	-	-	-	-	-	0.45-0.70[11]	-	-		3		3	-	-	-
[34]		GB/T 18883-2002	-	-	-	-	8.33	-	-	-	-		-		-	-	< 580	-
[35]		Design manual for heating and air conditioning, 2008. Lu Yaoqing	-	-	-	-	-	-	1	1	-		3		3	-	-	-
[37]	Japan	Japan Building Standard Law (1950, 2003)	-	-	-	-	5.56		-	-	-		-		-	5%	-	-
[39]	South Korea	KMOCT 2006-11-512	-	-	-	-	-		0.7	-	-		-		-	-	-	-
[40]	Indian	IS 3362-1977	-	-	-	-	-		3	3	-		-		-	-	-	-

1 - Mechanical ventilation consists of the provision of ventilation rate in terms of SUPPLY Ventilation [air flow quantity (L/s.m², L/s.person), Air Change Rate (h^{-1})] or EXHAUST Ventilation [airflow quantity (L/s), Air Change Rate (h^{-1})].
2 - This is the total range of ventilation rate provided in ASHRAE Standard 62.2, obtained from the LOWEST to the HIGHEST across all dwellings. There are sub categories based on dwelling size and number of bedrooms in each size that would result in different numbers. Total dwelling ventilation rates are specified for different sizes and number of bedrooms on the assumptions of minimum 2 persons in the smallest sized dwelling (studio or 1-bedroom dwelling) and an additional person for each additional bedroom. For higher occupant densities, an additional 3.5 L/s per person is required.
3 - These are continuous local exhaust airflow rates. Kitchen extract is based on kitchen volume. ASHRAE 62.2-2019 also provides a separate demand-controlled local ventilation exhaust airflow rates.
4 - Corresponding ACH for a 10 m² room (ht=2.5 m, Volume=25 m³) with two persons, and ventilation airflow rates of 4, 7 and 10 L/s.person.
5 - Includes bathroom or shower (with or without toilets), toilets and other wet areas.
6 - Supply - Bedrooms and living rooms.
7 - Extract - Kitchen, bathrooms, toilets.
8 - Specific minimum rates for room type provided.
9 - During non-occupancy.
10 - Range is for the number of main rooms upto 7.
11 - Includes a range of floor areas (< 10 m² and >m 50 m²).

Chandra Sekhar, Mizuho Akimoto, Xiaojun Fan, Mariya Bivolarova, Chenxi Liao, Li Lan and Pawel Wargocki, 2020. Bedroom ventilation: Review of existing evidence and current standards. Building and Environment, Volume 184. https://doi.org/10.1016/j.buildenv.2020.107229
Chandra Sekhar, Mizuho Akimoto, Xiaojun Fan Mariya Bivolarova, Chenxi Liao, Li Lan, Pawel Wargocki, 2021. Corrigendum to "Bedroom ventilation: Review of existing evidence and current standards" [J. Build. Environ. 184 (2020) 107229](S0360132320306004)(10.1016/j.buildenv.2020.107229) 1016/j.buildenv.2021.107983

So, what are the standards telling us?

MV			
Whole dwelling	Supply airflow	4.2–80 L/s 0.2–1.0 L/s.m²	4–10 L/s.person 0.15–3 h^{-1} (ACH)
	Exhaust ventilation	9.7–35 L/s	
Bedroom	Supply airflow	7–20 L/s 0.3 L/s.m²	5.6–7.2 L/s.person 1–3 h^{-1} (ACH)
Enclosed kitchen	Exhaust ventilation	5.6–56 L/s 3–5 h^{-1} (ACH)	
Bathroom	Exhaust ventilation	5.6–30 L/s 3 h^{-1} (ACH)	

NV		
Room	Supply	Min. operable area: 60 cm²/room Min. wall opening of "floor area": 5%
	Extract	Min. operable area: 100 cm²/room

Review Findings

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

Ref Number	Author(s)	Year	Lower ventilation condition		Higher ventilation condition		Observed significant effects on parameters describing sleep quality at lower ventilation condition measured objectively or rated by occupants: Sleep quality parameters measured objectively	Sleep quality rated subjectively
[15]	Mishra et al.	2018	average CO2	1150 ppm	average CO2	717 ppm	Lower sleep efficiency Increased number of awakenings	Lower depth of sleep
[16]	Strøm-Tejsen et al.	2016	average CO2 ACH average CO2 ACH	2585 ppm (1730 to 3900 ppm) 0.17 h-1 2395 ppm (1620 to 3300 ppm) 0.24 h-1	average CO2 ACH average CO2 ACH	660 ppm (525–840 ppm) 1.8 h-1 835 ppm (795–935 ppm) 1.1 h-1	Shorter sleep onset latency Lower sleep efficiency Reduced next-day performance of a logical thinking task	More sleepy and less able to concentrate on the next day
[17]	Xiong et al.	2020	average CO2	1327 ppm (shared occupancy) 1004 ppm (single occupancy)	average CO2	around 500 ppm	Lower % of deep sleep	Reduced self-reported sleep quality
[18]	Laverge and Janssens	2011	Peak CO2	3000 to 4500 ppm	Peak CO2	1000 to 2500 ppm	Higher sleep efficiency Increased number of awakenings	Less rested Lighter sleep Increased number of awakenings
[19]	Liao et al.	2020	average CO2 median CO2	1654 ppm 1550 ppm	average CO2 median CO2	601 ppm 585 ppm	Increased snoring Increased number of awakenings	N/A
[68]	Lan et al.	2019	–	–	average CO2	around 1400 ppm	N/A	N/A
[69]	Zhang et al.	2018	–	–	steady state CO2	around 1750 ppm	N/A	N/A
[70]	Irshad et al.	2018	average CO2	750 ppm	average CO2	620 ppm	Shorter sleep onset latency Reduction in the shifting between sleep stages, from NREM to REM, and to wake stage	N/A
[71]	Xia et al.	2020	–	–	average CO2	around 700 ppm	N/A	N/A
[72]	Kim et al.	2010	average CO2	1258 ppm (winter) 1276 ppm (spring)	average CO2	428 ppm (summer)	N/A	N/A

Conclusions

1) Most existing ventilation standards do not prescribe specific ventilation requirements for bedrooms - ventilation in bedrooms is merely the result of ventilation requirements for the entire dwelling.
2) Wide range of ventilation rates measured in bedrooms using different methods; mostly carbon dioxide concentration and air change rates were measured.
3) Reported mean CO2 concentrations ranged from 428 to 2585 ppm, and the mean air change rates from 0.2 to 4.9 h^{-1}.
4) Ventilation rates (indicated by the measured carbon dioxide concentration) are lower during heating seasons, especially in naturally ventilated, as well as in bedrooms when the air conditioning is in operation.
5) Bedroom temperatures were lower during heating seasons.
6) Scanty information on whether the reported ventilation rates would disturb sleep quality. Few studies that have been performed to date suggest that sleep quality will not be negatively affected when ventilation rates are such that CO2 levels remain below 750 ppm, while CO2 levels above 2600 ppm would disturb sleep quality and have a negative effect on the next-day cognitive performance. These results require validation.

Two new Residential Issue Briefs published by ASHRAE

June 2021

ASHRAE

Residential Buildings Committee (RBC) Residential Issue Brief:

Wildfire Smoke Hazards for Dwelling Occupants

The Issue

Wildland fires are occurring with increased frequency and intensity throughout many areas of the world. This is due to accumulated fuels from forest management practices that suppressed fires over many decades, combined with extended periods of hot and dry conditions associated with climate change (Abatzoglou et al. 2016; Boer et al. 2009; Dennison et al. 2014; Rasker 2015; Schoennagel et al. 2017; Westerling et al. 2006).

The smoke from wildland fires contains fine particulate matter ($PM_{2.5}$) – as much as 90 percent of the particle mass emitted from a wildfire is made up of $PM_{2.5}$ or smaller particles (Groβ et al. 2013; Vicente et al. 2013). $PM_{2.5}$ consists of ultrafine particles, toxic particle-phase constituents, and many irritant gases including acrolein, formaldehyde, organic acids (O'Dell et al. 2020) and carbon monoxide. When fires reach and burn buildings, the human-produced materials add toxic constituents to the smoke, including polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs). Burning of buildings during wildfires is increasing due to many factors, including larger fires and the larger footprint of development at or near the wildland-urban interface (Radeloff et al. 2018; Schoennagel et al. 2017).

June 2022

ASHRAE

Residential Buildings Committee (RBC) Residential Issue Brief:

Ventilation, IEQ and Sleep Quality in Bedrooms

The Issue

Sleep is essential for health and well-being. We spend a major part of our life at home, about a third in bedrooms, which gets much higher for vulnerable populations like babies and the elderly. This holds even greater significance in lockdowns, as evidenced during the unprecedented COVID-19 global pandemic. As a general principle, sleep hygiene recommendations tend towards maintaining a cool, dark and quiet sleeping environment. A 2018 review attempted to define environmental conditions in sleeping environments for optimal sleep quality and proposed temperature and humidity ranging generally between 17-28 °C and 40-60% RH, all forms of noise being less than 35 dB, complete darkness and avoidance of blue light immediately before and during sleep, ventilation using sea-level air quality, and passive design using architectural features to incorporate the above elements into bedroom design (Caddick et al., 2018).

Residential Building—Temperate Climate

Science and Technology for the Built Environment

Taylor & Francis

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uhvc21

Detailed characterization of bedroom ventilation during heating season in a naturally ventilated semi-detached house and a mechanically ventilated apartment

Chandra Sekhar , Mariya Bivolarova , Mizuho Akimoto & Pawel Wargocki

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To link to this article: https://doi.org/10.1080/23744731.2020.1845019

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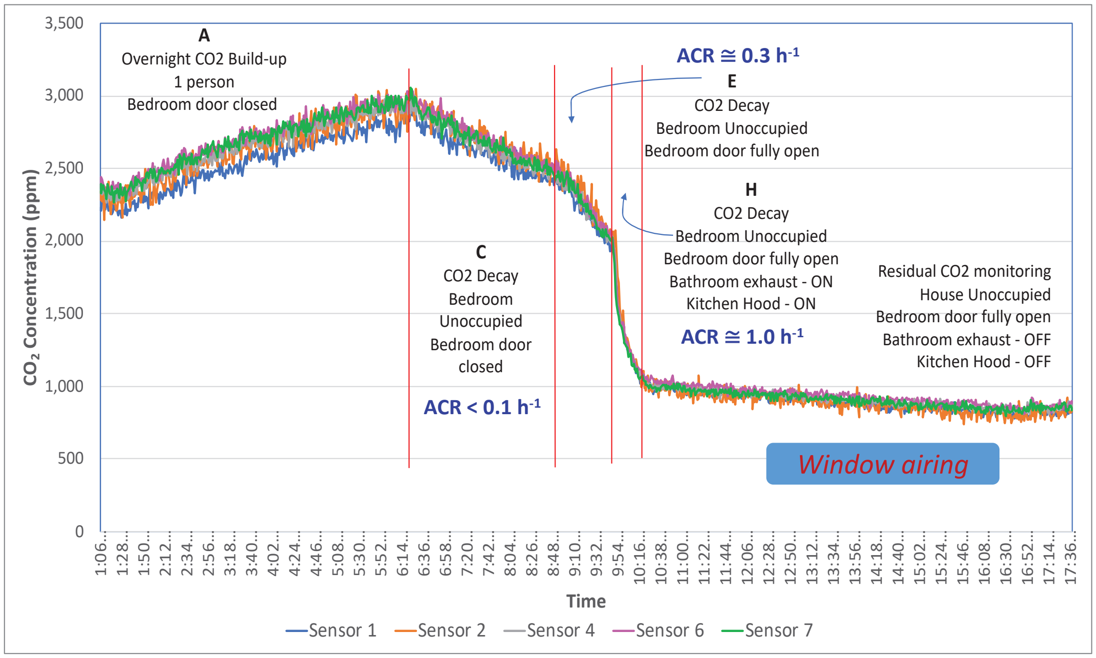
Bedroom ventilation is crucial for providing good indoor air quality, which may contribute to achieving undisturbed sleep. This study presents a detailed characterization of bedroom carbon dioxide (CO_2) profiles and ventilation during the heating season in Denmark. The measurements were made in a naturally ventilated (NV) semi-detached house, equipped with trickle vents on the windows and doors (augmented if needed with exhaust fans), and a mechanically ventilated (MV) apartment. The location of sensors in and around the immediate breathing zone of a sleeping person had measurable effect on the absolute level of CO_2 only in the NV bedroom and not in the MV bedroom. Using the decay of occupant-generated CO_2, the estimated breathing zone air change rate (ACR) was around $0.4\,h^{-1}$ and $0.6\,h^{-1}$ for the NV and MV bedrooms respectively. This was adequate for an average breathing zone CO_2 level of 1000 ppm for the MV bedroom but not for the NV bedroom. The CO_2 emission rate of 7.9–10.9 L/h.person during sleep, obtained from bedroom CO_2 measurements, was lower than the estimated values of 12.8–13.9 L/h.person, using currently proposed methods in standards. Thermal comfort parameters during all the experimental sessions in both bedrooms were well within recommended levels.

Sekhar C, Bivolarova M, Akimoto M, Wargocki P. Detailed characterization of bedroom ventilation during heating season in a naturally ventilated semi-detached house and a mechanically ventilated apartment. *Science and Technology for the Built Environment.* 2021;27:2, 158-180.
doi: 10.1080/23744731.2020.1845019

Temperate Climate: Heating Season, Natural Ventilation

Semi-detached house with two levels, trickle vents on windows and doors, bedrooms on upper level

Residential Building—Temperate Climate

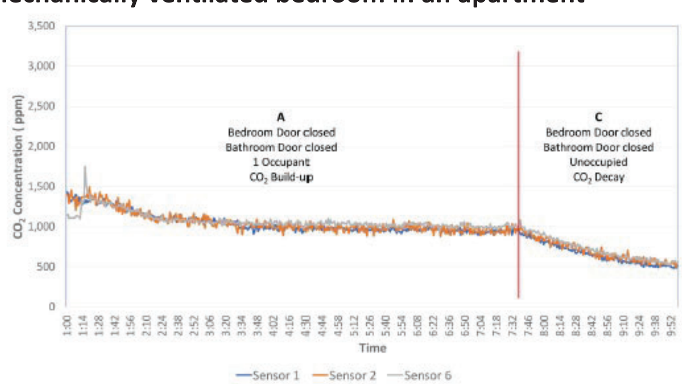


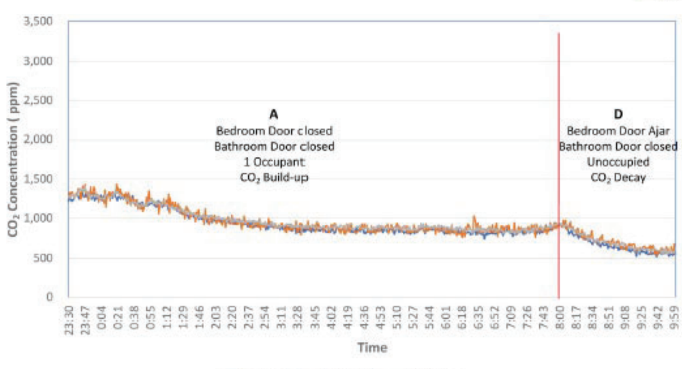
Bedroom CO_2 measurements

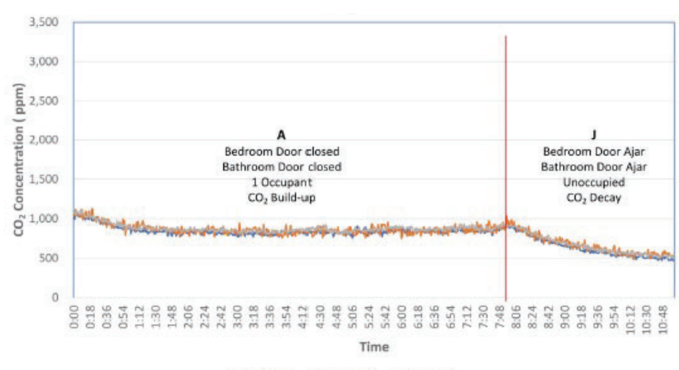
Temperate Climate: Heating Season, Mechanical Ventilation

Mechanically ventilated bedroom in an apartment

Residential Building—Temperate Climate

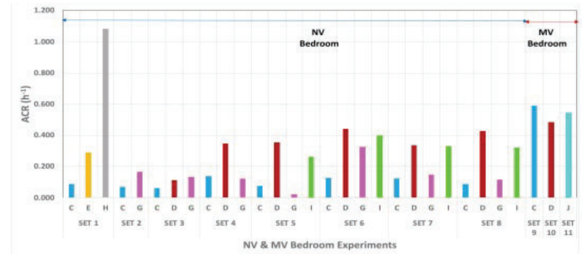




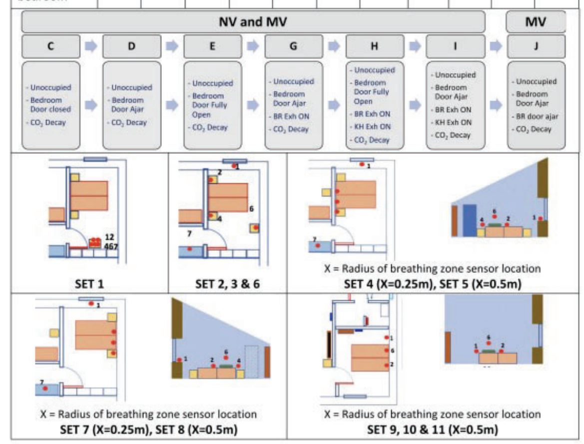


Main results and conclusions

- An experimental protocol involving several interventions, was developed - degree of opening of bedroom door, position of the sensors in the bedroom and in the breathing zone of a sleeping person, position of the bed and the use of bathroom/kitchen hood exhaust fans.
- Clear benefit in keeping the NV bedroom door open in achieving better ventilation - bathroom and kitchen hood exhaust fans further enhance bedroom ventilation.
- Trickle vents offer an enhanced ventilation in the NV bedroom when coupled with some level of extraction but not much with bedroom door closed.
- Location of the sensors in both NV/MV bedrooms important in estimating local ventilation rates close to a sleeping person.
- Position of the bed in the bedroom has no significant impact on the absolute CO2 levels measured if the measurements are made only in the immediate vicinity of the breathing zone.
- In typical MV bedrooms [similar to the one studied: 3.2 m 2.7 m (23 m^3)], an ACR of about 0.6 h^{-1} is envisaged to be adequate to keep the average CO2 concentration close to the breathing zone of a sleeping person to be about 1000 ppm. However, in typical NV bedrooms equipped with trickle vents [similar to the one studied: 4.5 m 2.7 m (38 m^3)], an ajar bedroom door coupled with bathroom and kitchen hood exhaust fans that results in a practically achievable ACR of 0.4 h^{-1}, still does not keep breathing zone CO2 level to be around 1000 ppm.
- The CO2 emission rate during sleep was obtained from CO2 measurements in bedrooms with NV and trickle vents and with balanced MV and found to be 7.9–10.9 L/ h.person, which was lower than the estimated values, 12.8–13.9 L/h.person, using methods that are currently proposed in standards/guidelines.



	NV Bedroom							MV Bedroom			
	SET 1	SET 2	SET 3	SET 4	SET 5	SET 6	SET 7	SET 8	SET 9	SET 10	SET 11
Trickle Vents Open	✓	✓	×	✓	✓	✓	✓	✓	n/a	n/a	n/a
Occupant in bedroom	1	1	1	1	1	2	1	1	1	1	1



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Residential Building—Tropical Climate

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Enhancement of ventilation performance of a residential split-system air-conditioning unit

S.C. Sekhar*

Department of Building, National University of Singapore, 4 Architecture Drive, Singapore 117566, Singapore

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Abstract

The design of ventilation performance of air-conditioning systems in large commercial and office buildings is quite established. However, it is not the same with the designs of air-conditioning systems in most residential buildings. Split system air-conditioning units are commonly employed in residential buildings in the tropics due to their convenience in terms of energy conservation, aesthetics, flexibility, acoustic performance and ease of operation. Such units are also popular among small offices, shopping complex and even as supplementary air-conditioning units beyond normal office-hours in large commercial and office buildings. This paper presents findings from a recent study of the ventilation performance and indoor air quality (IAQ) in a master bed room of a condominium unit in Singapore, employed with a split system air-conditioning unit. The attached bathroom is equipped with an exhaust fan, whose operation and its impact on the resulting ventilation characteristics was also studied. Four adults occupied the room throughout the course of the experiments. It was observed that the carbon dioxide level in the bed room can exceed 2000 ppm without the exhaust fan in about 2 h. The operation of the exhaust fan quickly lowered the level of carbon dioxide to about 1000 ppm. The findings suggest the need to design for ventilation provision in split system air-conditioning units.

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Keywords: Ventilation; Residential buildings; Air change rate; Carbon dioxide; Tropics

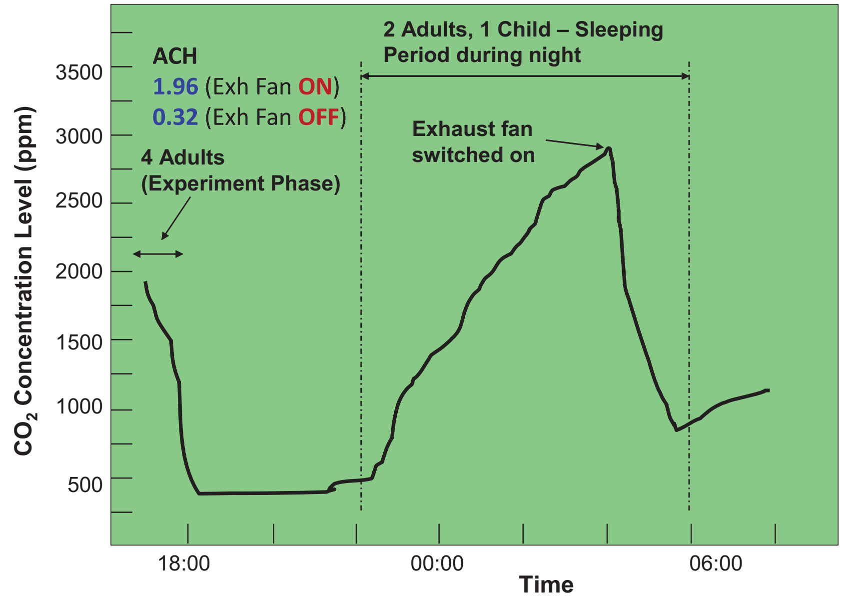
Residential Building - Tropical Climate

High-Rise Residential Apartment

Split-System AC Unit

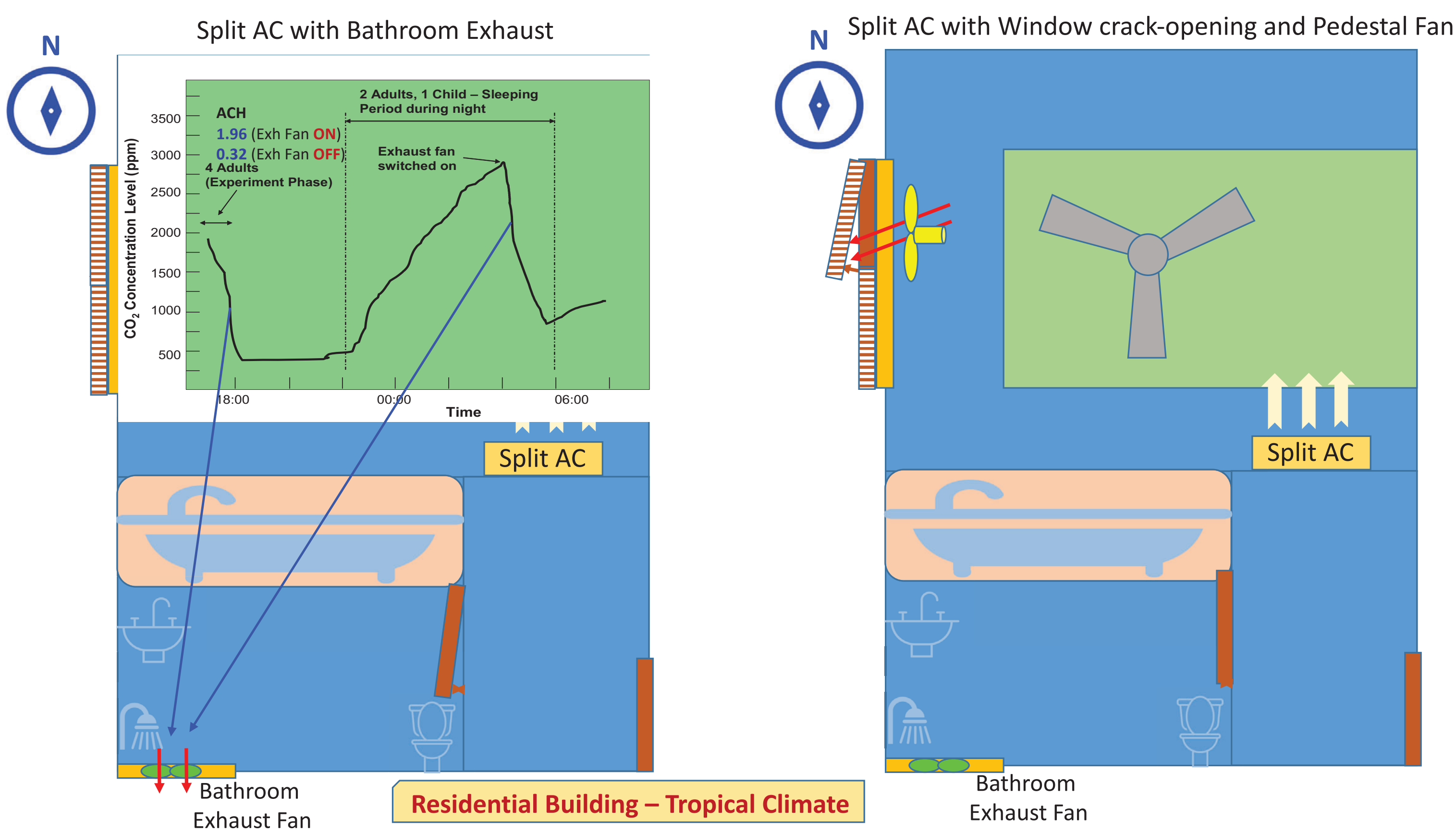
Residential Building—Tropical Climate

Tropical Climate: Split-System AC Unit, High-Rise Residential Apartment

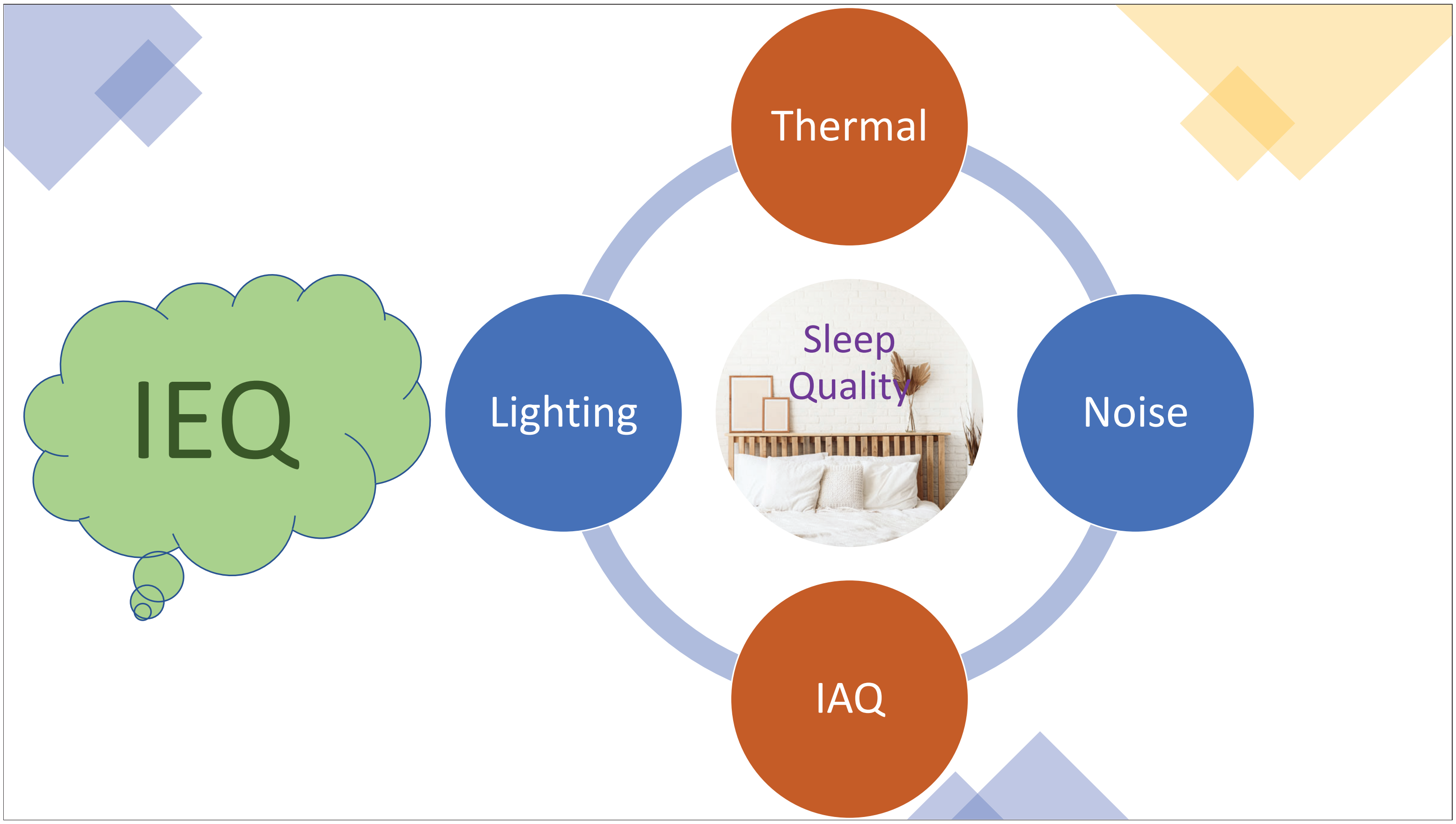


CO_2 concentration during measurement and night-time sleeping periods

Sekhar SC. Enhancement of ventilation performance of a residential split-system air-conditioning unit. *Energy and Buildings.* 2004;*36*(3), 273-279. doi: 10.1016/j.enbuild.2003.12.004



Residential Building – Tropical Climate



- Thank You for your Attention

Professor Chandra Sekhar
Fellow ASHRAE, Fellow ISIAQ
bdgscs@nus.edu.sg

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

SJTU

Thermal environment and sleep quality

Li Lan, PhD

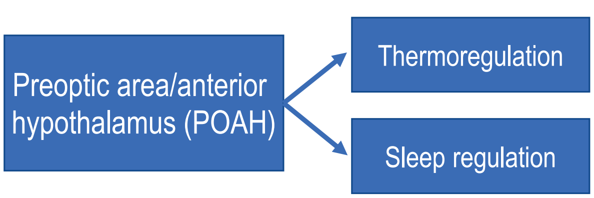
Department of Architecture, School of Design
Shanghai Jiao Tong University

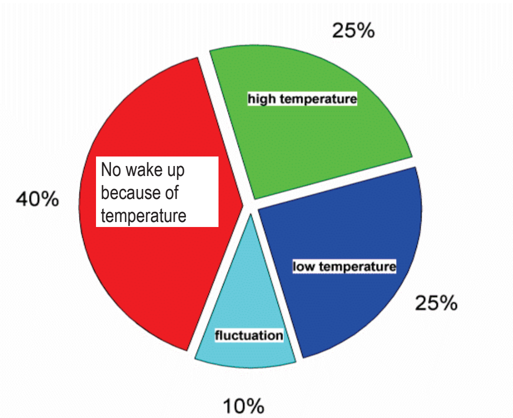
Jan 12, 2023

饮 水 思 源 • 爱 国 荣 校

1. Why thermal environment

- **Sleep quality should be affected by thermal environment**
  - ✓ POAH regulate both heat loss and sleep activity
- **Many problems were found in bedrooms**
  - ✓ Stuffy air, high CO_2 concentration, thermal discomfort…

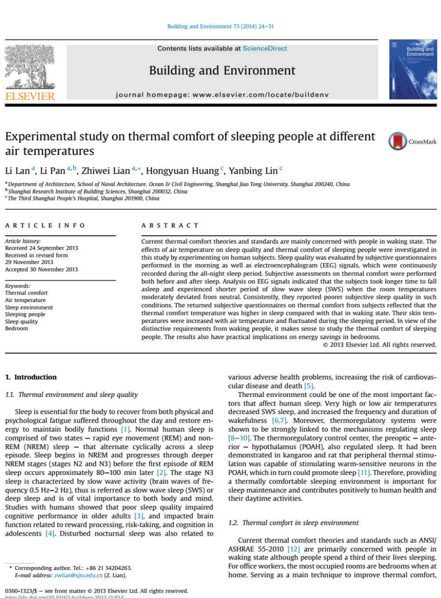




(Lin & Deng. 2006, Energy Build)

2. Indoor temperature and sleep

- **Temperatures deviated from thermal neutral decreased sleep quality**


Building and Environment 73 (2014) 24–31

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Experimental study on thermal comfort of sleeping people at different air temperatures

Li Lan, Li Pan, Zhiwei Lian, Hongyuan Huang, Yanbing Lin


Taylor & Francis

Investigation of sleep quality under different temperatures based on subjective and physiological measurements

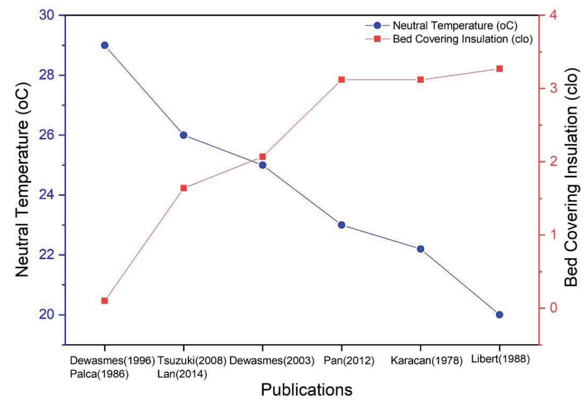
Li Pan, Zhiwei Lian, and Li Lan

Introduction

HVAC&R Research, 18(5):1030–1043, 2012. Copyright © 2012 ASHRAE.

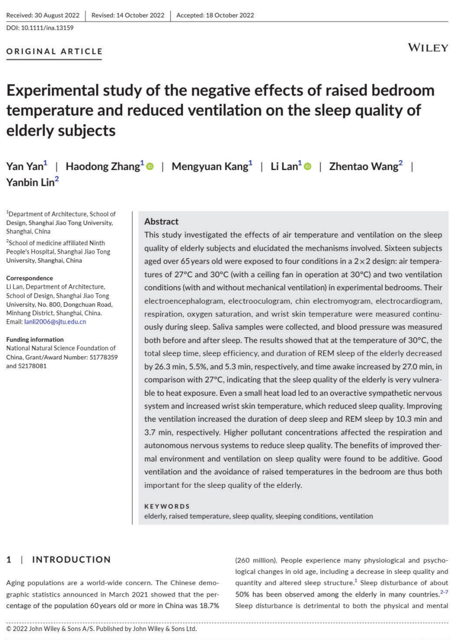
ISSN: 1078-9669 print / 1938-5587 online

DOI: 10.1080/10789669.2012.667037



2. Indoor temperature and sleep

- **A slightly raised indoor temperature reduced sleep quality**


Received: 30 August 2022 | Revised: 14 October 2022 | Accepted: 18 October 2022

DOI: 10.1111/ina.13159

ORIGINAL ARTICLE

WILEY

Experimental study of the negative effects of raised bedroom temperature and reduced ventilation on the sleep quality of elderly subjects

Yan Yan | Haodong Zhang | Mengyuan Kang | Li Lan | Zhentao Wang | Yanbin Lin

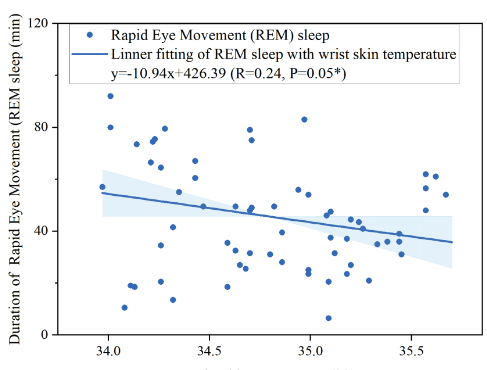
Abstract

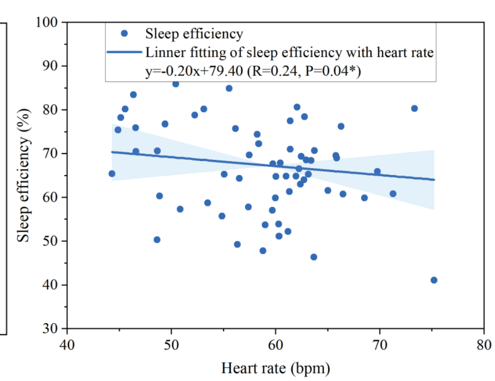
1 | INTRODUCTION

Indoor Air. 2022;32:e13159.

https://doi.org/10.1111/ina.13159

					Temperature effects		
Physiological responses	T27/MV	T27/NMV	T30/MV	T30/NMV	F	p	f
Wrist skin temperature (°C)	34.7 ±0.5	34.7 ±0.5	34.8 ±0.5	34.9 ±0.5	**6.36**	**0.02***	**0.67**
Heart rate (bpm)	58.6 ±7.4	58.5 ±7.4	59.3 ±7.4	59.2 ±7.8	**6.38**	**0.02***	**0.67**
PNN_{50} (%)	14.9 ±17.3	13.8 ±16.7	11.4 ±13.9	11.3 ±12.0	**3.69**	**0.07**	**0.50**





2. Indoor temperature and sleep

- **Air temperature was the dominant factor influencing sleep quality in summer Shanghai**


Building and Environment 208 (2022) 108572

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Association of bedroom environment with the sleep quality of elderly subjects in summer: A field measurement in Shanghai, China

Yan Yan, Li Lan, Haodong Zhang, Yuxiang Sun, Xiaojun Fan, David Peter Wyon, Pawel Wargocki

	(26-32°C)	(36-88%)	(400-2400ppm)
Objective sleep parameters	$B(Ta)^P$	$B(RH)^P$	$B(CO_2)^P$
Time in bed (min)	$-92.35^{0.12}$	$-38.07^{0.87}$	$-2.71^{0.49}$
Total sleep time (min)	$\mathbf{-86.59^{0.02}}$*	$-23.63^{0.56}$	$\mathbf{-1.65^{0.05}}$*
Sleep efficiency (%)	$\mathbf{-7.96^{0.01}}$**	$-2.55^{0.08}$	$-0.21^{0.10}$
Wake time (min)	$\mathbf{15.37^{0.04}}$*	$5.23^{0.13}$	$0.44^{0.23}$
REM sleep (min)	$\mathbf{-32.97^{0.04}}$*	$-14.40^{0.56}$	$-1.52^{0.21}$
Light sleep (min)	$\mathbf{-38.90^{0.02}}$*	$\mathbf{-11.85^{0.04}}$*	$\mathbf{-0.33^{0.03}}$*
Deep sleep (min)	$-27.34^{0.27}$	$-9.90^{0.44}$	$-1.01^{0.14}$

*$P < 0.05$; **$P \le 0.01$.

3. Sleeping micro-environment

- **Conductive cooling on back and head maintained sleep quality at 32°C**


Received: 8 June 2017 | Accepted: 22 September 2017

DOI: 10.1111/ina.12428

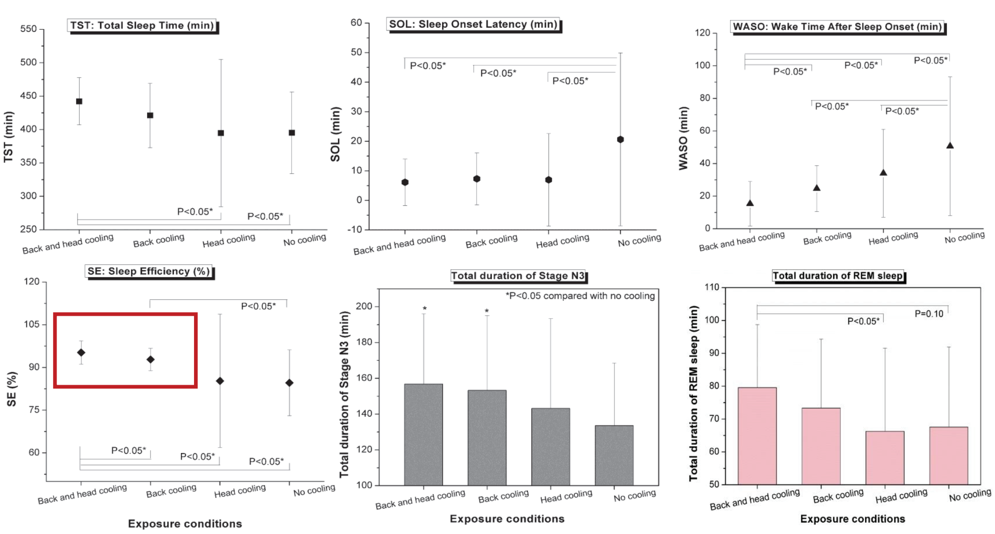
ORIGINAL ARTICLE

WILEY

Local body cooling to improve sleep quality and thermal comfort in a hot environment

L. Lan | X. L. Qian | Z. W. Lian | Y. B. Lin

Indoor Air. 2018;28:135–145.



3. Sleeping micro-environment

- **Covering heating and mattress heating improved sleep quality at 7°C**


Energy & Buildings 210 (2020) 109687

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Bed heating improves the sleep quality and health of the elderly who adapted to no heating in a cold environment

Lulu Xia[a], Li Lan[a,*], Jieyu Tang[a], Yijun Wan[a], Yanbin Lin[b], Zhentao Wang[b]

[a] Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai 200240, China
[b] School of Medicine affiliated Ninth People 's Hospital, Shanghai Jiao Tong University, Shanghai 201900, China

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Sleep quality
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Skin temperature
Blood pressure

ABSTRACT

Since aging is associated with a progressive decrease in thermoregulation, a cold bedroom environment may have negative effects on the sleep quality of the elderly. This study investigated the effects of two bed heating methods (covering heating and mattress heating), compared with no heating, on sleep quality of the elderly without sleep disorders in a cold environment. Twelve elderly who did not use any heating in daily life participated into this field intervention experiment, which was performed in their own bedrooms. Sleep quality was subjectively evaluated using questionnaires in the morning and objectively measured with a wristband which continuously monitored throughout the sleep period. Skin temperatures and blood pressure were measured. The subjects felt thermally comfortable when slept in all conditions. Compared with no heating, covering heating and mattress heating increased the total sleep time by 35.5 min and 20.3 min, and decreased the sleep onset latency by 13.3 min and 18.3 min. Compared with mattress heating and no heating, the covering heating decreased the wake after sleep onset by 28.7 min and 12.5 min, and increased the sleep efficiency by 2.8% and 5.7%. Both two heating methods increased the bed temperature and reduced the skin temperature gradient between the chest and calf. The systolic blood pressure measured in the morning was significantly lower in the covering heating than in no heating. These results suggest that, without changing thermal comfort, bed heating improved micro thermal environment, sleep quality and health of the elderly without sleep disorders in a cold environment.

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1. Introduction

In China, the number of the elderly is expected to account for 25% of the total population by 2030. Some physical and psychological changes, including decrease of sleep quality, greatly affect the health and life quality of the elderly [1,2]. Large population-based epidemiologic studies indicate that sleep complaints and sleep problems are common in the elderly [3–5]. Sleep disturbance increases the risk of heart disease, arthritis, obesity, and has negative effects on restorative and immune function, endocrine function, cardiovascular system and brain function in the elderly [1,6–10]. Thermal environment is one of the primary causes of sleep disturbance [11–16]. With biological ageing, many factors related to thermoregulation are impaired in the elderly [3,17]. Therefore, providing a thermally comfortable sleeping environment is critical for sleep maintenance and the health of the elderly.

In Hot Summer and Cold Winter (HSCW) area of China, in which region no central heating is provided, the averaged bedroom temperature in winter is as low as 12.7 °C [18]. The thermal environment is worse in the rural areas, as confirmed in a field survey in the bedrooms of thirty-nine elderly people in a rural area of this region [19]. The results show that the mean air temperature in the bedroom was 7.1 ± 2.3 °C, and about 50% of the respondents used local heating methods in cold winter, mainly the electric blankets.

Tokura et al. reported that the use of electric blankets inhibited the decrease of the rectal temperature of young people during sleep, exerting hygienical problems for normal sleep [20]. However, Okamoto et al. found that heating the lower body extremity of young people by electric blankets decreased the cold stress and maintained stability and thermoregulation during sleep [21]. The

Abbreviations: ADL, activities of daily living; BP, blood pressure (mmHg); DBP, diastolic blood pressure (mmHg); ES, effect size; RHc, relative humidity near the human side of the covering (%); RHm, relative humidity near the human side of the mattress (%); HSCW, hot summer and cold winter; MBRH, the mean bed relative humidity (%); MBT, the mean bed air temperature (°C); MST, mean skin temperature (°C); PSQI, Pittsburgh sleep quality index; REM, rapid-eye movement; SBP, systolic blood pressure (mmHg); SE, sleep efficiency (%); SOL, sleep onset latency (min); Tc, air temperature near the human side of the covering (°C); Tm, air temperature near the human side of the mattress (°C); TST, total sleep time (min); WASO, wake after sleep onset (min).

* Corresponding author.
E-mail address: lanli2006@sjtu.edu.cn (L. Lan).

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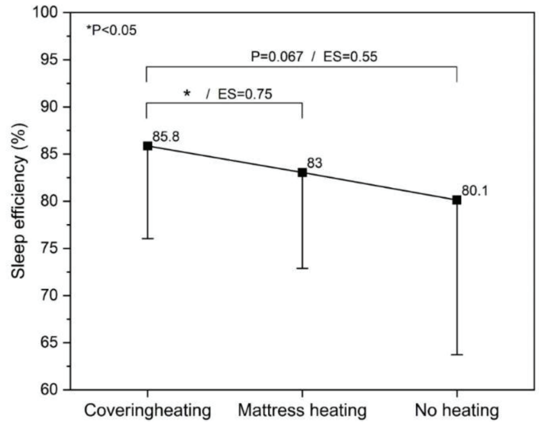
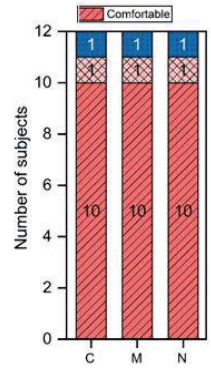
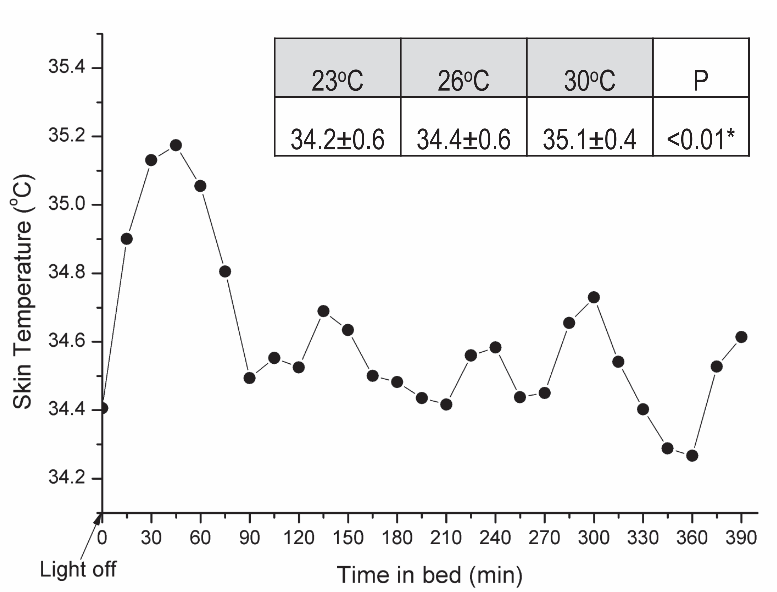




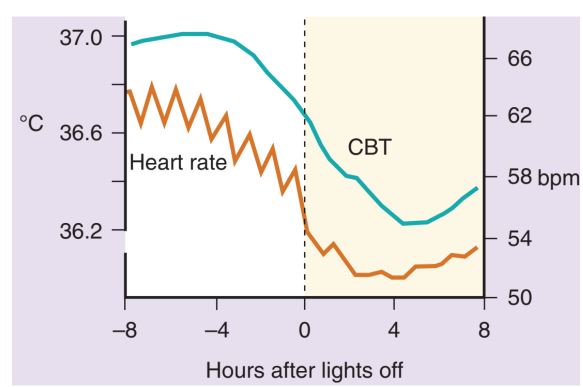
Thermal comfort voting

4. The importance of skin temperature

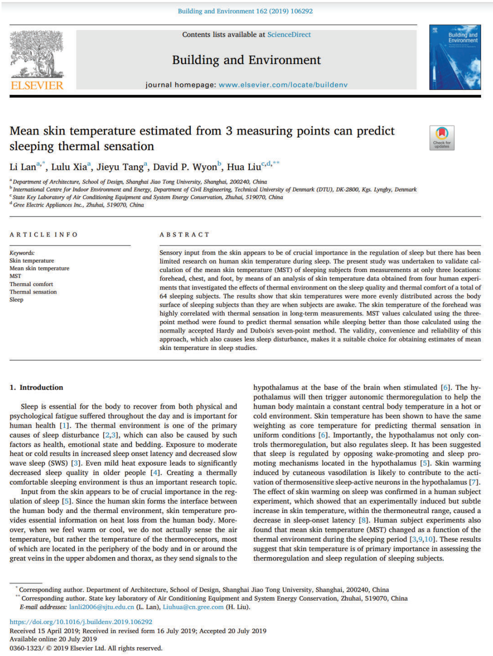
- **Mean skin temperature increases with air temperature and fluctuates during the entire sleep period**



23°C	26°C	30°C	P
34.2±0.6	34.4±0.6	35.1±0.4	<0.01*



4. The importance of skin temperature



Building and Environment 162 (2019) 106292

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journal homepage: www.elsevier.com/locate/buildenv

Mean skin temperature estimated from 3 measuring points can predict sleeping thermal sensation

Li Lan[a,*], Lulu Xia[a], Jieyu Tang[a], David P. Wyon[b], Hua Liu[c,d,**]

[a] Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai, 200240, China
[b] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark (DTU), DK-2800, Kgs. Lyngby, Denmark
[c] State Key Laboratory of Air Conditioning Equipment and System Energy Conservation, Zhuhai, 519070, China
[d] Gree Electric Appliances Inc., Zhuhai, 519070, China

ARTICLE INFO

Keywords:
Skin temperature
Mean skin temperature
MST
Thermal comfort
Thermal sensation
Sleep

ABSTRACT

Sensory input from the skin appears to be of crucial importance in the regulation of sleep but there has been limited research on human skin temperature during sleep. The present study was undertaken to validate calculation of the mean skin temperature (MST) of sleeping subjects from measurements at only three locations: forehead, chest, and foot, by means of an analysis of skin temperature data obtained from four human experiments that investigated the effects of thermal environment on the sleep quality and thermal comfort of a total of 64 sleeping subjects. The results show that skin temperatures were more evenly distributed across the body surface of sleeping subjects than they are when subjects are awake. The skin temperature of the forehead was highly correlated with thermal sensation in long-term measurements. MST values calculated using the three-point method were found to predict thermal sensation while sleeping better than those calculated using the normally accepted Hardy and Dubois's seven-point method. The validity, convenience and reliability of this approach, which also causes less sleep disturbance, makes it a suitable choice for obtaining estimates of mean skin temperature in sleep studies.

1. Introduction

Sleep is essential for the body to recover from both physical and psychological fatigue suffered throughout the day and is important for human health [1]. The thermal environment is one of the primary causes of sleep disturbance [2,3], which can also be caused by such factors as health, emotional state and bedding. Exposure to moderate heat or cold results in increased sleep onset latency and decreased slow wave sleep (SWS) [3]. Even mild heat exposure leads to significantly decreased sleep quality in older people [4]. Creating a thermally comfortable sleeping environment is thus an important research topic.

Input from the skin appears to be of crucial importance in the regulation of sleep [5]. Since the human skin forms the interface between the human body and the thermal environment, skin temperature provides essential information on heat loss from the human body. Moreover, when we feel warm or cool, we do not actually sense the air temperature, but rather the temperature of the thermoreceptors, most of which are located in the periphery of the body and in or around the great veins in the upper abdomen and thorax, as they send signals to the hypothalamus at the base of the brain when stimulated [6]. The hypothalamus will then trigger autonomic thermoregulation to help the human body maintain a constant central body temperature in a hot or cold environment. Skin temperature has been shown to have the same weighting as core temperature for predicting thermal sensation in uniform conditions [6]. Importantly, the hypothalamus not only controls thermoregulation, but also regulates sleep. It has been suggested that sleep is regulated by opposing wake-promoting and sleep promoting mechanisms located in the hypothalamus [5]. Skin warming induced by cutaneous vasodilation is likely to contribute to the activation of thermosensitive sleep-active neurons in the hypothalamus [7]. The effect of skin warming on sleep was confirmed in a human subject experiment, which showed that an experimentally induced but subtle increase in skin temperature, within the thermoneutral range, caused a decrease in sleep-onset latency [8]. Human subject experiments also found that mean skin temperature (MST) changed as a function of the thermal environment during the sleeping period [3,9,10]. These results suggest that skin temperature is of primary importance in assessing the thermoregulation and sleep regulation of sleeping subjects.

* Corresponding author. Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai, 200240, China
** Corresponding author. State key laboratory of Air Conditioning Equipment and System Energy Conservation, Zhuhai, 519070, China
E-mail addresses: lanli2006@sjtu.edu.cn (L. Lan), Liuhua@cn.gree.com (H. Liu).

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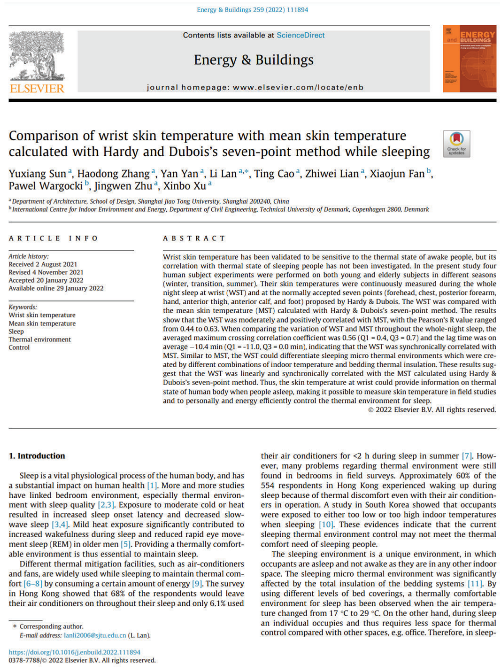

Energy & Buildings 259 (2022) 111894

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Comparison of wrist skin temperature with mean skin temperature calculated with Hardy and Dubois's seven-point method while sleeping

Yuxiang Sun[a], Haodong Zhang[a], Yan Yan[a], Li Lan[a,*], Ting Cao[a], Zhiwei Lian[a], Xiaojun Fan[b], Pawel Wargocki[b], Jingwen Zhu[a], Xinbo Xu[a]

[a] Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai 200240, China
[b] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Copenhagen 2800, Denmark

ARTICLE INFO

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Mean skin temperature
Sleep
Thermal environment
Control

ABSTRACT

Wrist skin temperature has been validated to be sensitive to the thermal state of awake people, but its correlation with thermal state of sleeping people has not been investigated. In the present study four human subject experiments were performed on both young and elderly subjects in different seasons (winter, transition, summer). Their skin temperatures were continuously measured during the whole night sleep at wrist (WST) and at the normally accepted seven points (forehead, chest, posterior forearm, hand, anterior thigh, anterior calf, and foot) proposed by Hardy & Dubois. The WST was compared with the mean skin temperature (MST) calculated with Hardy & Dubois's seven-point method. The results show that the WST was moderately and positively correlated with MST, with the Pearson's R value ranged from 0.44 to 0.63. When comparing the variation of WST and MST throughout the whole-night sleep, the averaged maximum crossing correlation coefficient was 0.56 (Q1 = 0.4, Q3 = 0.7) and the lag time was on average –10.4 min (Q1 = -11.0, Q3 = 0.0 min), indicating that the WST was synchronically correlated with MST. Similar to MST, the WST could differentiate sleeping micro thermal environments which were created by different combinations of indoor temperature and bedding thermal insulation. These results suggest that the WST was linearly and synchronically correlated with the MST calculated using Hardy & Dubois's seven-point method. Thus, the skin temperature at wrist could provide information on thermal state of human body when people asleep, making it possible to measure skin temperature in field studies and to personally and energy efficiently control the thermal environment for sleep.

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1. Introduction

Sleep is a vital physiological process of the human body, and has a substantial impact on human health [1]. More and more studies have linked bedroom environment, especially thermal environment with sleep quality [2,3]. Exposure to moderate cold or heat resulted in increased sleep onset latency and decreased slow-wave sleep [3,4]. Mild heat exposure significantly contributed to increased wakefulness during sleep and reduced rapid eye movement sleep (REM) in older men [5]. Providing a thermally comfortable environment is thus essential to maintain sleep.

Different thermal mitigation facilities, such as air-conditioners and fans, are widely used while sleeping to maintain thermal comfort [6–8] by consuming a certain amount of energy [9]. The survey in Hong Kong showed that 68% of the respondents would leave their air conditioners on throughout their sleep and only 6.1% used their air conditioners for <2 h during sleep in summer [7]. However, many problems regarding thermal environment were still found in bedrooms in field surveys. Approximately 60% of the 554 respondents in Hong Kong experienced waking up during sleep because of thermal discomfort even with their air conditioners in operation. A study in South Korea showed that occupants were exposed to either too low or too high indoor temperatures when sleeping [10]. These evidences indicate that the current sleeping thermal environment control may not meet the thermal comfort need of sleeping people.

The sleeping environment is a unique environment, in which occupants are asleep and not awake as they are in any other indoor space. The sleeping micro thermal environment was significantly affected by the total insulation of the bedding systems [11]. By using different levels of bed coverings, a thermally comfortable environment for sleep has been observed when the air temperature changed from 17 °C to 29 °C. On the other hand, during sleep an individual occupies and thus requires less space for thermal control compared with other spaces, e.g. office. Therefore, in sleep-

* Corresponding author.
E-mail address: lanli2006@sjtu.edu.cn (L. Lan).

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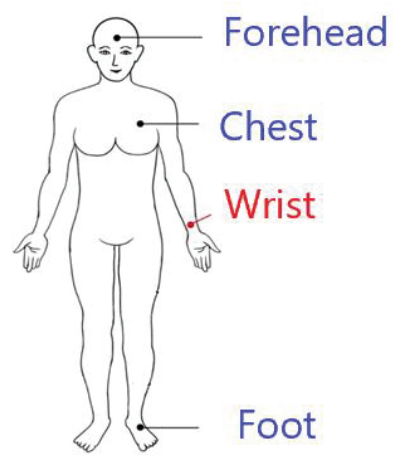

Summary

- Human sleep quality was sensitive to change of air temperature; temperatures moderately deviated from thermal neutral impaired sleep quality, while the neutral temperature is closely related to thermal insulation
- Sleep quality could be improved while energy saving was achieved when the air temperature cycled properly; more studies are needed to identify the optimum cycle
- Control bed micro-environment energy efficiently by using of local heating, cooling and/or ventilation system
- Skin temperature is a good index for predicting the thermal state of human body while sleeping

Thank you

Li Lan, PhD, Professor

Shanghai Jiao Tong University

E-mail: lanli2006@sjtu.edu.cn

Ventilation and IAQ in bedrooms

CONTENT

- What is the IAQ in bedrooms?
- Does ventilation work to control IAQ?
- What are the relevant metrics for bedroom ventilation?
- What is still unknown?

IAQ IN BEDROOMS

Statistical description of mean CO_2 and air change rate (ACR) during sleep.

	Mean	Std.	min	Percentile 25th	Percentile 50th	Percentile 75th	max
Mean CO_2 (ppm)	1305.3	942.4	427.5	638.0	981.8	1547.6	4803.7
ACR (h^{-1})	1.1	1.3	0.1	0.3	0.6	1.5	4.9

CO_2: 1000 ppm (Cat. II, Central European Standard)
ACR: 2.0 h^{-1} (Cat. II, Central European Standard)

Statistical description of bedroom pollutants during sleep.

	Mean	Std. Dev.	min	Percentile 25th	Percentile 50th	Percentile 75th	max
NO_2 (ppb)	5.7	5.9	0.2	1.7	3.4	7.1	30.2
VOCs (ppb)	187.7	80.9	84.1	146.7	166.2	204.0	445.9
PM_{10} (μg·m^{-3})	24.5	26.0	3.9	7.1	11.0	36.4	99.4
$PM_{2.5}$ (μg·m^{-3})	5.0	4.0	2.0	2.3	2.8	7.1	19.5

NO_2: 10 ppb (WHO standard)
VOCs: 600 ppb (Portuguese standard)
PM_{10}: 15 μg·m^{-3} (WHO standard)
$PM_{2.5}$: 5 μg·m^{-3} (WHO standard)

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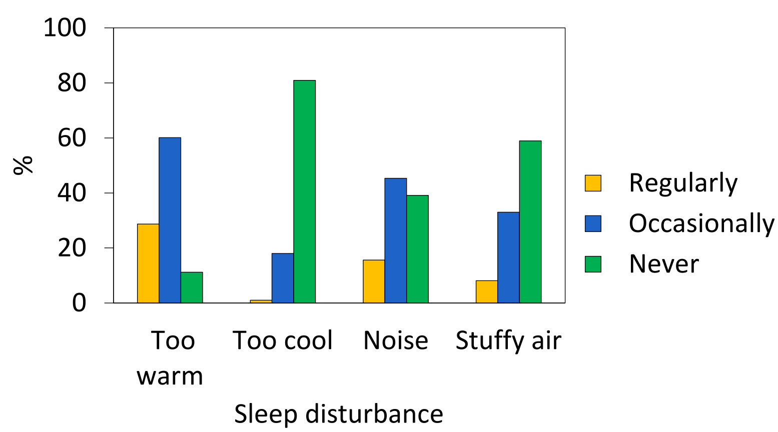
A QUESTIONNAIRE SURVEY



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

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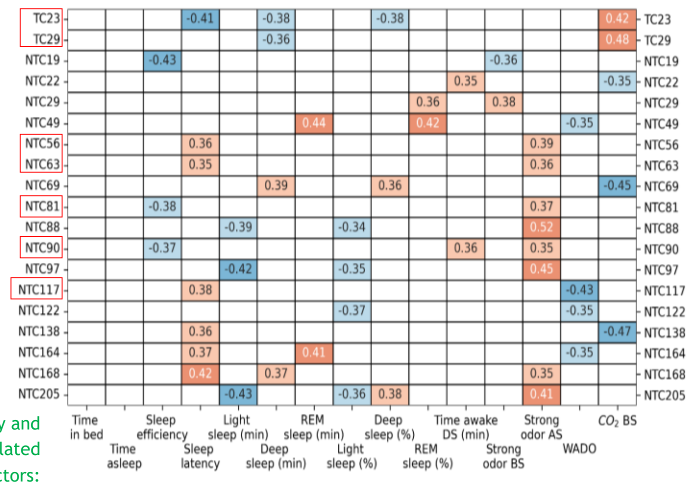
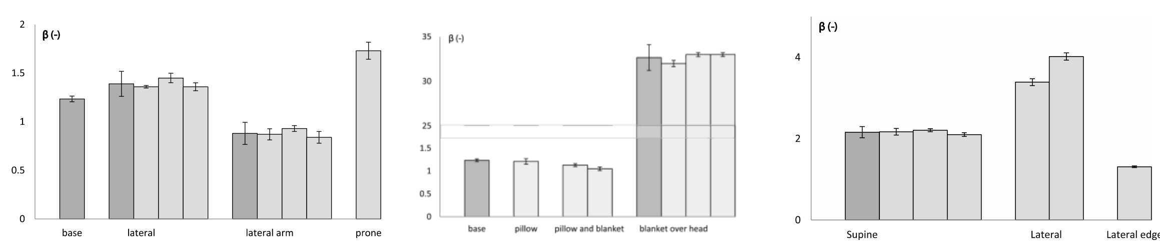
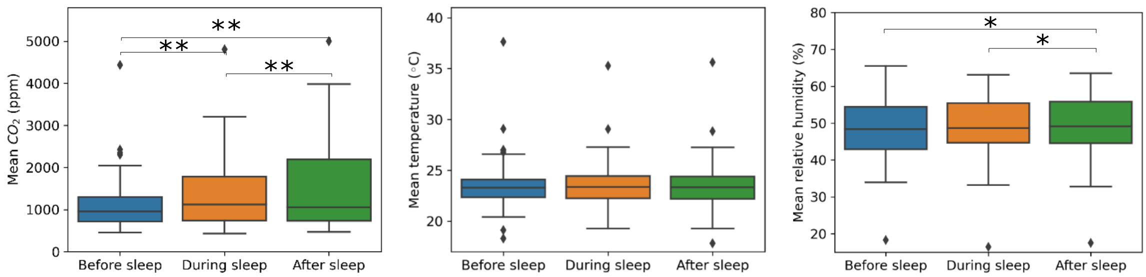
Targeted and non-targeted compounds:

19 compounds: 2 TC + 17 NTC
[258 compounds: 43 TC + 215 NTC]



Sleep quality and sleep-related ventilation factors:





Distribution of CO_2 level, mean temperature, and relative humidity before, during, and after sleep. The diamond indicates outliers.
* p-value < 0.05, ** p-value < 0.01.

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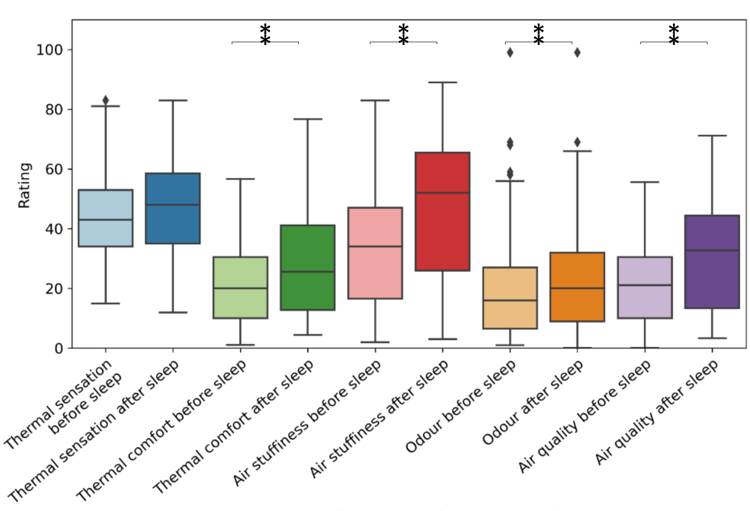

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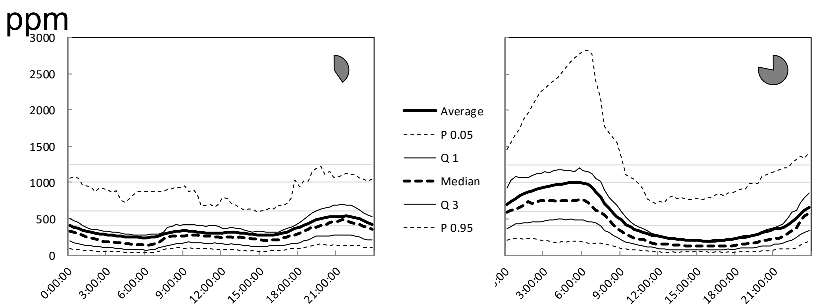
Distribution *of the perception of thermal comfort and air quality before and after sleep. IEQ, indoor environmental quality. The diamond indicates outliers. ** p-value < 0.01.*

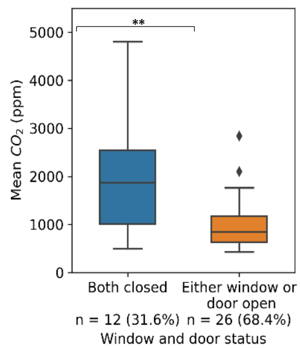


Living room exposure to carbon dioxide

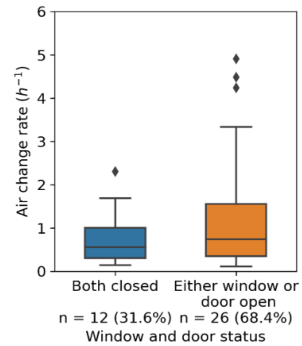
Bedroom exposure to carbon dioxide

VENTILATION AS STRATEGY

GHENT UNIVERSITY



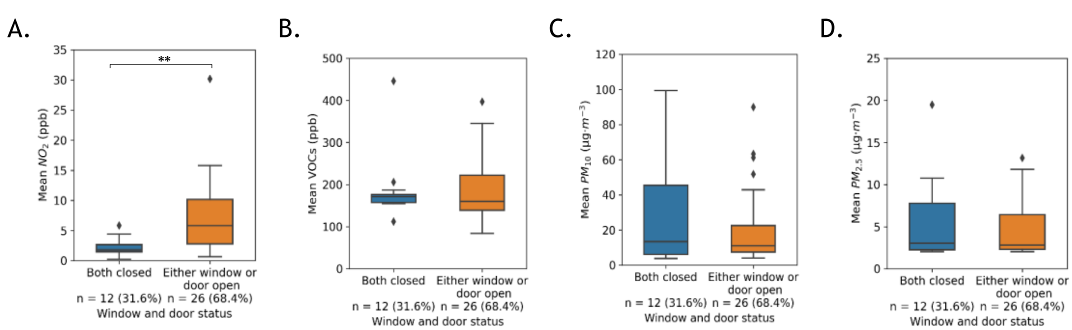
Mean CO_2 levels between two “window and door status” during sleep.
** p-value < 0.01.



Air change rate between two “window and door status” during sleep.

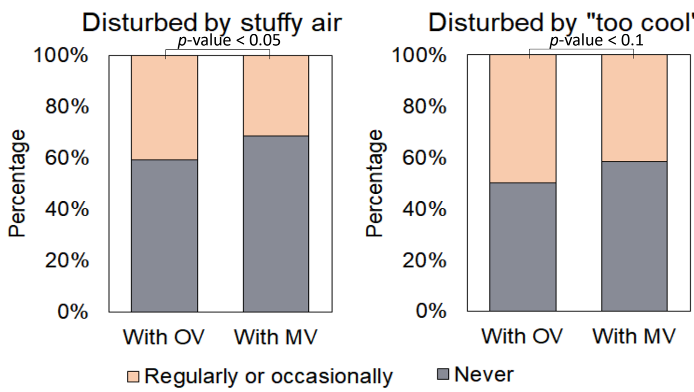
CLIMA 2022
REHVA 14th HVAC World Congress
22nd - 25th May, Rotterdam, The Netherlands
TVVL TU Delft TU/e Eindhoven University of Technology REHVA Federation of European Heating, Ventilation and Air Conditioning Associations Carrier

Results



Mean levels of indoor pollutants during sleep between two “window and door status”.
A, NO_2; B, VOCs; C, PM_{10}; D, $PM_{2.5}$.
NO_2, nitrogen dioxide; VOCs, volatile organic compounds; PM, particulate matter.
** p-value < 0.01.

A QUESTIONNAIRE SURVEY



Mechanical ventilation in bedrooms reduced responses of being disturbed by stuffy air or "too cool" conditions during sleep.
MV, mechanical ventilation; OV, other ventilation including exhaust ventilation and natural ventilation.

RELEVANT METRICS

HEALTH

- Take into account the increased exposure compared to well mixed assumption

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HEALTH & WELLBEING

=> Impact on sleep

- Impact of perceived air quality?

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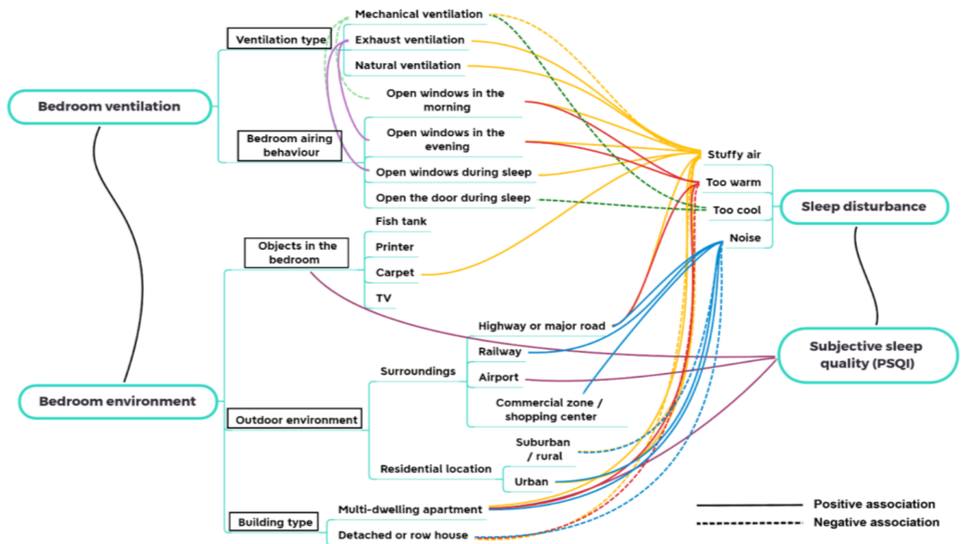
A QUESTIONNAIRE SURVEY



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HEALTH & WELLBEING

=> Impact on sleep

- Impact of perceived air quality?
- Avoiding disturbances

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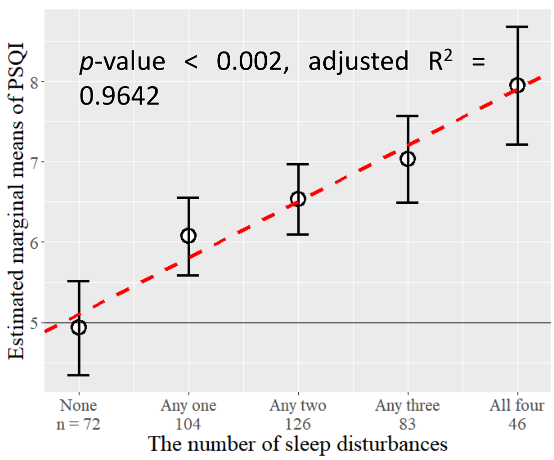
A QUESTIONNAIRE SURVEY



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

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TOWARDS SMART VENTILATION

FLANDERS INNOVATION & ENTREPRENEURSHIP flux50

Sleep quality cost

Assumptions

- Many factors influence sleep quality
- Litterature may have divergent opinions
- Sleep quality is hard to quantify from environmental parameters only

→ Improving sleep quality only from ventilation related parameters is complex

→ Detection of bad environment for sleep quality is possible

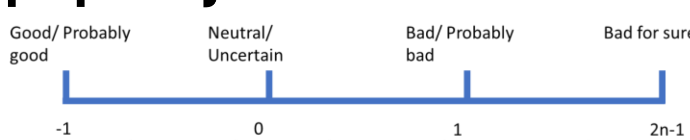
all bad conditions gathered → probability of sleep disturbance is 1

$$Sleep\ quality = \sum_1^n \frac{k_i w_i}{n}$$

Sq ≤ 0 →good

0 < Sq ≤ 1 → probably bad

Sq ≥ 1 → bad for sure



	Coefficient	Good (-1)	Neutral (0)	Probably bad (1)	Bad (2n-1=3)
T (°C)	0,0447		17-28	<17 or >28	
H° (%)	0,0447		40-60	<40 or >60	
CO2 (ppm)	0,0351		750-1150	1150-2600	2600
Noise (dB)	0,0319			35	

From assessment to health cost

- Translation, from sleep disturbance issue to DALY
  - Equivalent of DALY lost per issue
  - Probability of issue with & without sleep disturbance
  - Cost induced/issue

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HEALTH & WELLBEING

=> Impact on sleep

- Impact of perceived air quality?
- Avoiding disturbances
- Improving sleep quality in healthy subjects

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TOWARDS SMART VENTILATION

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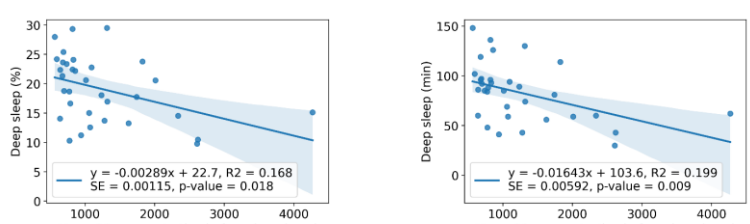

The regression line between mean $CO_{2\text{-bs}}$ concentration and deep sleep (%, min).

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TOWARDS SMART VENTILATION

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Deep sleep (min, %) in association with $CO_{2\text{-}bs}$ concentration.

Item	Beta (95% credible interval)[a]	R^2 (Q2.5 - Q97.5)
Deep sleep (%)		
$CO_{2\text{-}bs}$ concentration (/1000 ppm)	-2.9 (-5.3 – -0.5)	0.176 (0.006 – 0.376)
Deep sleep (min)		
$CO_{2\text{-}bs}$ concentration (/1000 ppm)	-16.3 (-32.3 – 0.3)	0.201 (0.003 – 0.438)

[a] analyzed by the Bayesian linear regression with the prior distribution of N(0,10).

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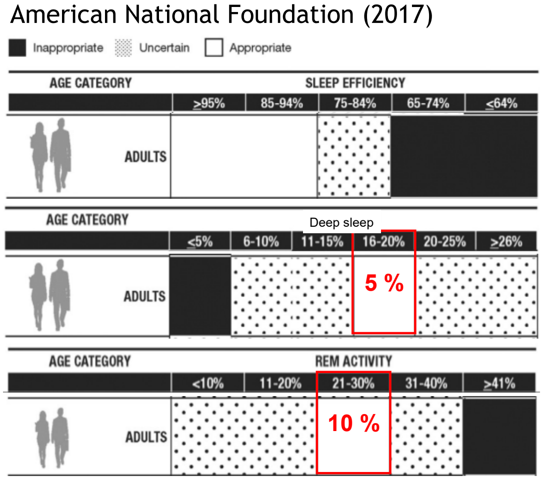
Sleep quality

American National Foundation (2017)



Statistical description of sleep parameters

Item	mean ± std.	min	25%	50%	75%	max
Sleep efficiency	88.2 ± 2.3	84.3	86.6	88.5	89.5	93.1
Deep sleep (%)	16.9 ± 4.8	6.0	13.7	17.2	20.9	24.8
REM sleep (%)	21.9 ± 5.3	12.6	17.5	23.1	25.3	32.5

Fraction of appropriate ranges

Item	below | appropriate | above
Sleep efficiency	6 (16%) | 32 (84%) | 0
Deep sleep (%)	16 (42%) | 10 (26%) | 12 (32%)
REM sleep (%)	14 (37%) | 21 (55%) | 3 (8%)

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UNKNOWNS

WHAT WE DON'T HAVE (YET)

- Good, conclusive data that supports robust assumptions on correlations between environmental factors and sleep (both disturbances and quality)
- Good conclusive data on the longterm effect of moderately reduced/improved sleep quality for healthy people
- Mechanistic understanding of observed correlations

FACULTY OF ENGINEERING
AND ARCHITECTURE

Jelle Laverge
Associate Professor

ARCHITECTURE & URBAN PLANNING

E jelle.laverge@ugent.be
T +32 9 264 37 49

architecture.ugent.be

Ghent University
@Jlaverge
Jelle Laverge

GHENT
UNIVERSITY

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

Pawel Wargocki
pawar@dtu.dk

Li Lan
lanli2006@sjtu.edu.cn

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

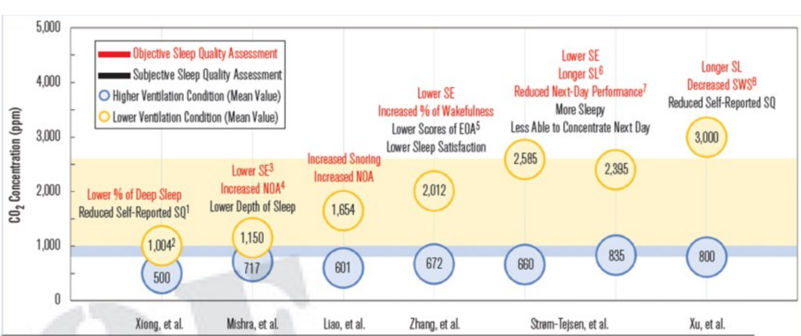
- Amendment to ASHRAE Standard 62.2 ” Ventilation and Acceptable Indoor Air Quality in Residential Buildings”

Additional studies (extensions)

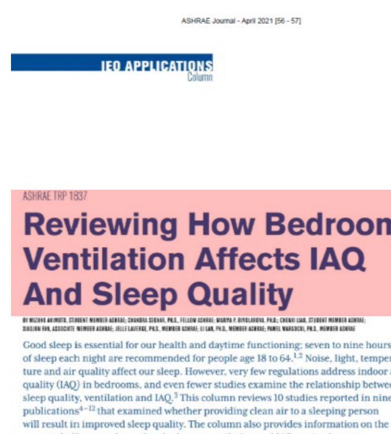
- Survey of bedroom conditions (prior to and after the COVID-19 lockdown)
- Laboratory studies on the effects of ventilation, pure CO_2, temperature and ventilation noise on sleep quality
- Examining bedroom and door opening behavior
- Estimation of CO_2 generation rate for sleeping people (young adults 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



- 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



ASHRAE Journal - April 2021 [56 - 57]

IEQ APPLICATIONS
Column

ASHRAE TRP 1837

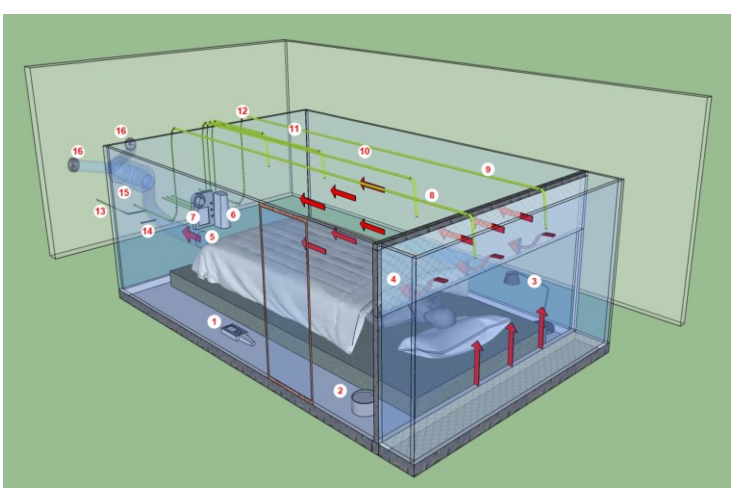
Reviewing How Bedroom Ventilation Affects IAQ And Sleep Quality

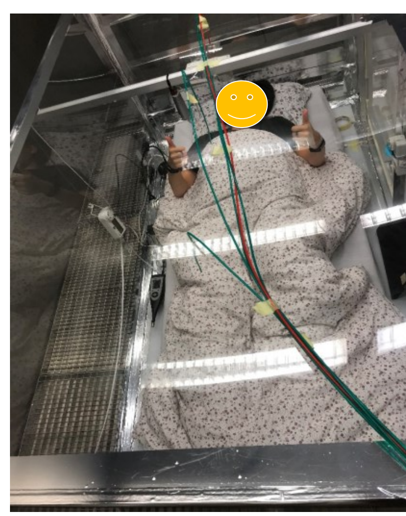
Good sleep is essential for our health and daytime functioning; seven to nine hours of sleep each night are recommended for people age 18 to 64.[1,2] Noise, light, temperature and air quality affect our sleep. However, very few regulations address indoor air quality (IAQ) in bedrooms, and even fewer 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.

Laboratory experiments

7

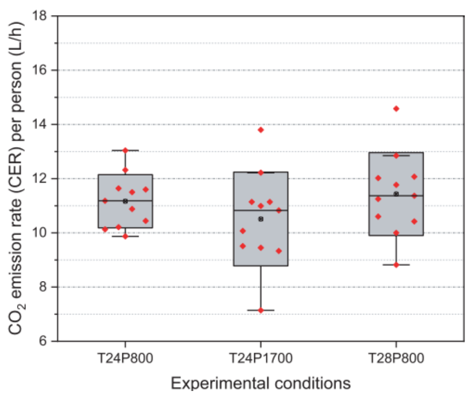
Laboratory setup, the sleeping capsule

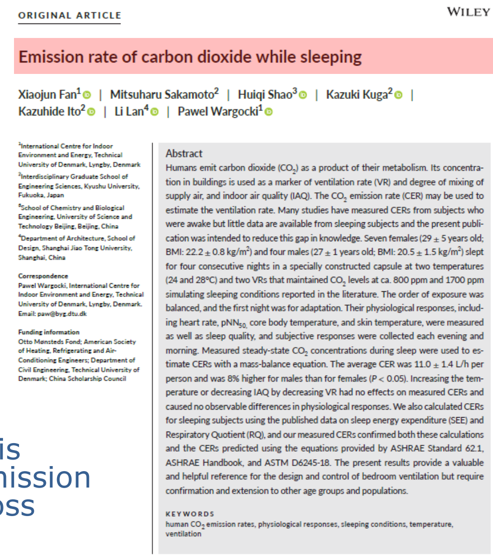




8

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]

[1]International Centre for Indoor Environment and Energy, Technical University of Denmark, Lyngby, Denmark

[2]Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Fukuoka, Japan

[3]School of Chemistry and Biological Engineering, University of Science and Technology Beijing, Beijing, China

[4]Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai, China

Correspondence
Pawel Wargocki, International Centre for Indoor Environment and Energy, Technical University of Denmark, Lyngby, Denmark.
Email: paw@byg.dtu.dk

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

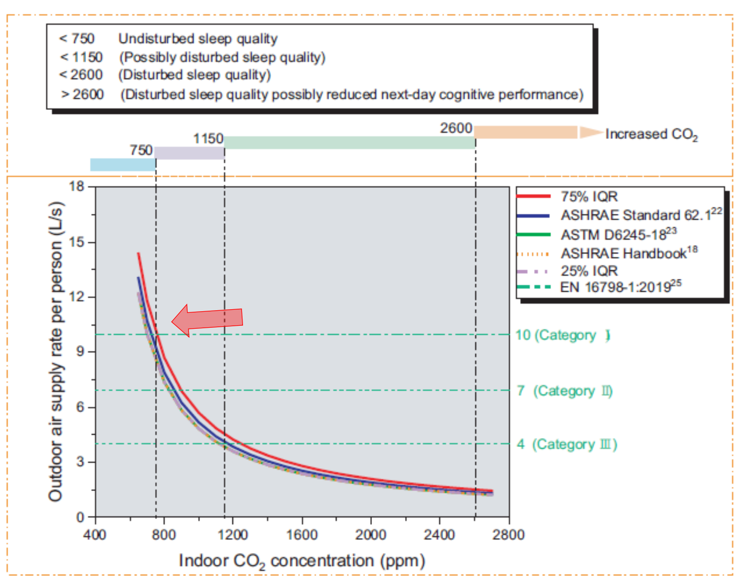
Humans emit carbon dioxide (CO_2) as a product of their metabolism. Its concentration in buildings is used as a marker of ventilation rate (VR) and degree of mixing of supply air, and indoor air quality (IAQ). The CO_2 emission rate (CER) may be used to estimate the ventilation rate. Many studies have 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

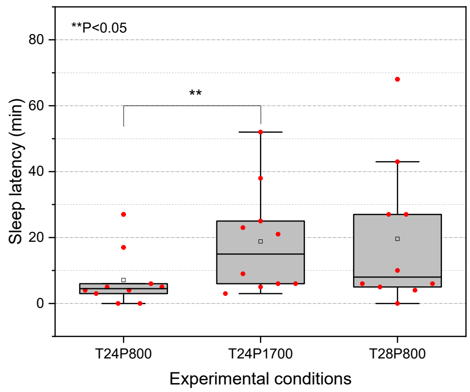
- CO_2 emission rates of sleeping people is around 11 L/h, 40% lower than the emission rates when awake. Fairly constant across studies.

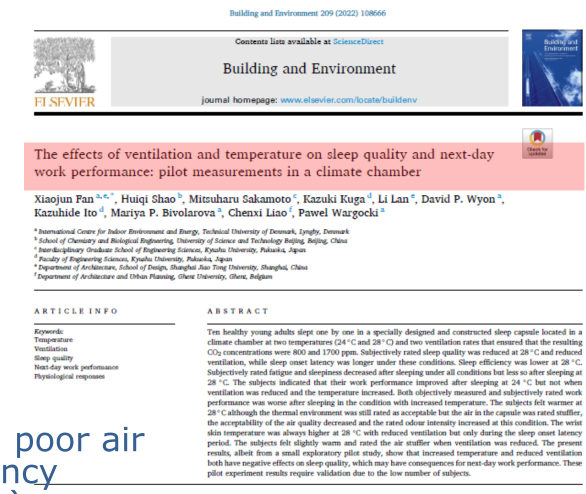
Implications

- 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

journal homepage: www.elsevier.com/locate/buildenv

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

Xiaojun Fan [a,e,*], Huiqi Shao [b], Mitsuharu Sakamoto [c], Kazuki Kuga [d], Li Lan [e], David P. Wyon [a], Kazuhide Ito [d], Mariya P. Bivolarova [a], Chenxi Liao [f], Pawel Wargocki [a]

[a] International Centre for Indoor Environment and Energy, Technical University of Denmark, Lyngby, Denmark
[b] School of Chemistry and Biological Engineering, University of Science and Technology Beijing, Beijing, China
[c] Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Fukuoka, Japan
[d] Faculty of Engineering Sciences, Kyushu University, Fukuoka, Japan
[e] Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai, China
[f] Department of Architecture and Urban Planning, Ghent University, Ghent, Belgium

ARTICLE INFO

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

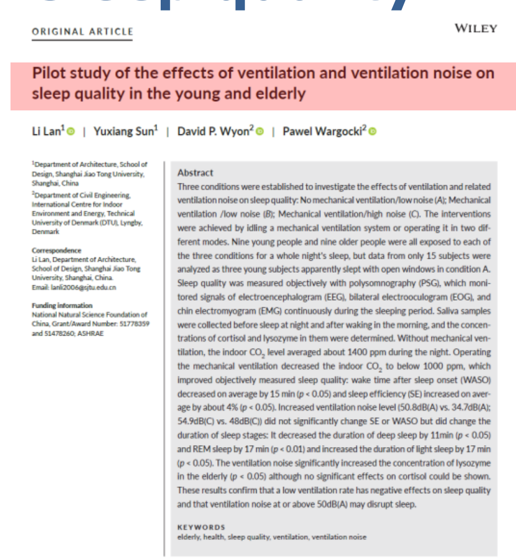
ABSTRACT

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

Li Lan[1] | Yuxiang Sun[1] | David P. Wyon[2] | Pawel Wargocki[2]

[1]Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai, China
[2]Department of Civil Engineering, International Centre for Indoor Environment and Energy, Technical University of Denmark (DTU), Lyngby, Denmark

Correspondence
Li Lan, Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai, China.
Email: lanli2006@sjtu.edu.cn

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

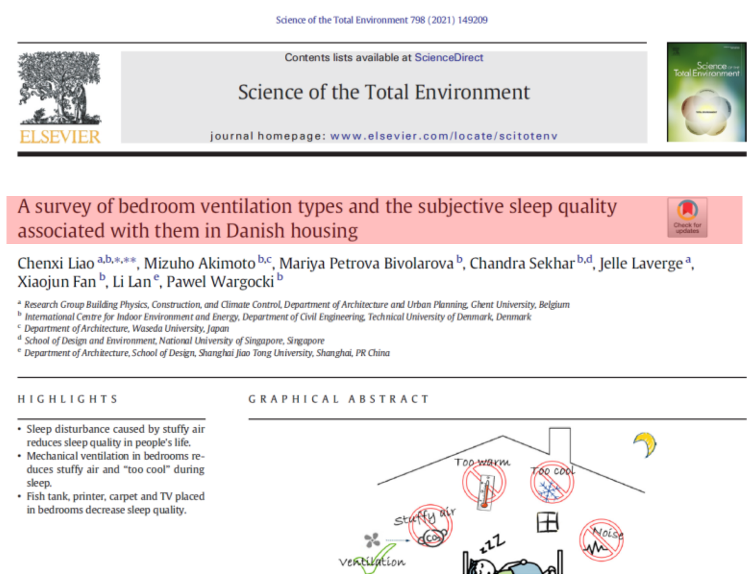
Abstract
Three conditions were established to investigate the effects of ventilation and related ventilation noise on sleep quality: No mechanical ventilation/low noise (*A*); Mechanical ventilation /low noise (*B*); Mechanical ventilation/high noise (*C*). The interventions were achieved by idling a 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

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

ELSEVIER

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]

[a] Research Group Building Physics, Construction, and Climate Control, Department of Architecture and Urban Planning, Ghent University, Belgium
[b] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Denmark
[c] Department of Architecture, Waseda University, Japan
[d] School of Design and Environment, National University of Singapore, Singapore
[e] Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai, PR China

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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journal homepage: www.elsevier.com/locate/buildenv

ELSEVIER

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

Xinbo Xu [a], Li Lan [a], Jingyun Shen [a], Yuxiang Sun [a], Zhiwei Lian [a,b,*]

[a] School of Design, Shanghai Jiao Tong University, Shanghai, 200240, China
[b] China Institute of Urban Governance, Shanghai Jiao Tong University, Shanghai, 200030, China

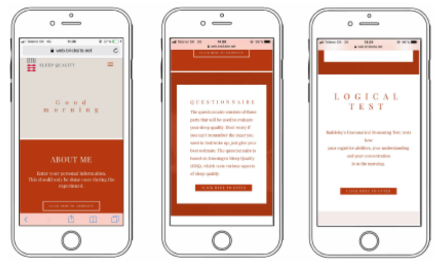
ARTICLE INFO

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

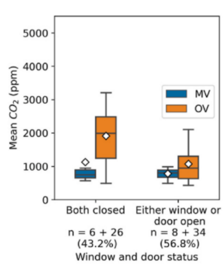
ABSTRACT

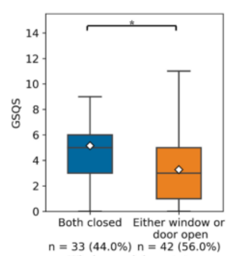
Based on the researches conducted in recent decades, five hypotheses concerned with bedroom environment and sleep quality were proposed. In order to verify these hypotheses, we conducted a questionnaire survey which lasted one year in Shanghai. This questionnaire contained questions on inhabitants' basic 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

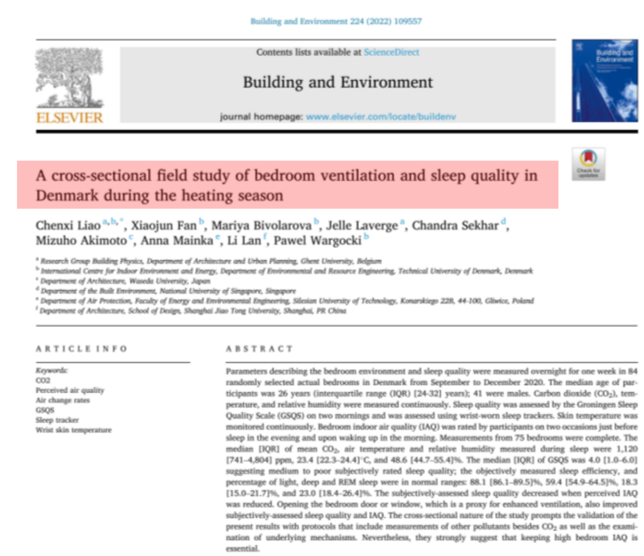


A week-long cross-sectional study, DK





- 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


Building and Environment 224 (2022) 109557

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

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]

[a] Research Group Building Physics, Department of Architecture and Urban Planning, Ghent University, Belgium
[b] International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering, Technical University of Denmark, Denmark
[c] Department of Architecture, Waseda University, Japan
[d] Department of the Built Environment, National University of Singapore, Singapore
[e] Department of Air Protection, Faculty of Energy and Environmental Engineering, Silesian University of Technology, Konarskiego 22B, 44-100, Gliwice, Poland
[f] Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai, PR China

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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ELSEVIER

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

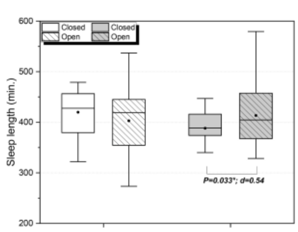
ARTICLE INFO

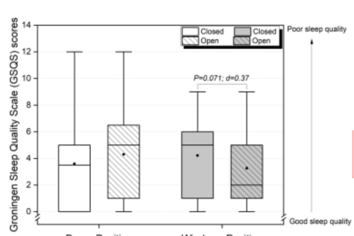
Keywords:
Bedroom environment
Gender difference
Physiological parameters
Sleep quality
Subjective questionnaire

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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ELSEVIER

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]

[a] *International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering (DTU Sustain), Technical University of Denmark, Denmark*
[b] *Research Group Building Physics, Construction, and Climate Control, Department of Architecture and Urban Planning, Ghent University, Belgium*
[c] *Department of the Built Environment, National University of Singapore, Singapore*
[d] *Department of Architecture, School of Design, Shanghai Jiao Tong University, China*
[e] *Department of Air Protection, Faculty of Energy and Environmental Engineering, Silesian University of Technology, Poland*
[f] *Department of Architecture, Waseda University, Japan*

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

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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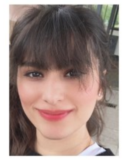
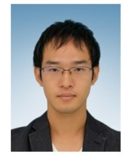
Mizuho Akimoto
Ph.D. candidate


Mariya P. Bivolarova
Asst. Prof.


Xiaojun Fan
Ph.D. candidate


Chao Guo
Ph.D. candidate


Negin Hosseinpour
M.Sc. student


Kazuki Kuga
Asst. Prof.


Mengyuan Kang
M.Sc. student


Li Lan
Prof.


Zhiwei Lian
Prof.


Jelle Laverge
Assoc. Prof.


Chenxi Liao
Postdoc.


Kazuya Matsuo
M.Sc. student


Anna Mainka
Asst. Prof.


Chandra Sekhar
Prof.


Huiqi Shao
Ph.D.


Yuxiang Sun
M.Sc. student


Mitsuharu Sakamoto
M.Sc. student


Haodong Zhang
M.Sc. student


Pawel Wargocki
Assoc. Prof.


Xinbo Xu
Ph.D. candidate


Yan Yan
Ph.D. candidate

QUESTIONS……