Subjective assessments of bedroom environment in the heating season in Denmark

Chenxi LIAO*[1,2], Xiaojun FAN[2], Mariya Petrova BIVOLAROVA[2], Chandra SEKHAR[3], Mizuho AKIMOTO[4], Jelle LAVERGE[1] and Pawel WARGOCKI[2]

[1] Research Group Building Physics, Construction and Climate Control, Department of Architecture and Urban Planning, Ghent University, Ghent, Belgium

[2] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark

[3] School of Design and Environment, National University of Singapore, Singapore, Singapore

[4] Department of Architecture, Waseda University, Tokyo, Japan

* *Corresponding author: Chenxi.Liao@UGent.be*

ABSTRACT

A satisfied bedroom environment is vital for the sleep quality of human beings. Thermal comfort, air quality, acoustic comfort, and visual comfort are all verified to be indispensable for the overall bedroom comfort. However, few studies reported how occupants rate those environmental aspects in their bedrooms. The present study figured out this question by online morning and evening sleep diaries conducted in the capital region of Denmark in the heating season. A total of 169 sets of responses to the sleep diaries from 82 subjects were received. Compared to those who accepted the bedroom environment, the subjects had the highest levels of the unacceptability of noise, following by stuffy air and a hot bedroom. Acoustic and thermal comfort and air quality can be improved for occupants to have a more satisfactory bedroom environment. The present study gives a sight of which aspects should be improved for people to have a better bedroom environment.

INTRODUCTION

A comfortable bedroom environment is important for occupants to achieve superior sleep quality. Caddick et al. (2018) reviewed the necessary parameters for an optimal sleep environment including ambient temperature, humidity, sound levels, light, and air quality. Temperatures influence skin temperature, which in turn varies sleep quality, exposure to light disrupts sleep since light resets the circadian pacemaker and it causes night waking; higher levels than 40 dBA leads to changes of sleep stages and an increase in sleep fragmentation; and poor air quality was also reported to be disruptive to sleep quality (Caddick et al. (2018)). Nevertheless, those studies they reviewed were almost lab or intervention studies. Not too many studies have examined how occupants rated the bedroom environment in the real world.

A recent field study in China conducted how occupants rated thermal/humid sensation and air quality in their bedrooms before and during sleep in transition seasons among 104 subjects. Odor intensity perception and air quality acceptability were rated not only for "before and after sleep", but also when the occupants returned to the bedrooms after left the bedroom for a few minutes in the morning. It was reported that 3.8% and 12.5% of occupants rated that thermal perception was unacceptable before and during sleep, respectively. 1%, 11%, and 21% of occupants unaccepted bedroom air quality before sleep, during sleep, and returning to the bedrooms, respectively (Zhang et al. (2021)).

Another study in China conducted thermal perception across various climates using a 7-point scale (cold, cool, slightly cool, neutral, slightly warm, warm, and hot) and reported that 18% of occupants living in the region of hot summer and cold winter voted "cold" in winter; the percentage was the highest among five climates they studied (Lai et al. (2021)).

Meng et al. (2020) examined the sound environment of college students in the dorm in China using an 11-point scale for sound perception before sleep, during sleep, and after waking up. They indicated that noise perception before sleep was the most significant, followed by "after waking up", and the sound perception was slightly lower during sleep (Meng et al. (2020)).

Molina & Yaguana (2018) investigated how occupants rated temperature, air quality, and illumination in their homes or bedrooms, either in the morning, afternoon, or night, using a 7-level satisfaction scale and mixed other methods. They reported a positive perception of air quality and thermal comfort in the bedrooms. Air quality and illuminance rated by occupants differed from the local and international regulations. More similar studies are needed for different types of buildings or construction systems, and climates (Molina & Yaguana (2018)).

Another field study from Kallawicha et al. (2020) included perceived bedroom temperature and air quality for people during sleep in real situations to analyze the association between bedroom environment and sleep quality. The three-point (hot, moderate, and cold) and four-point scales (bad, moderate, good, and very good) were used for rating bedroom temperature and air quality, respectively. while the results of them were not reported.

Strøm-Tejsen et al. (2016) conducted an intervention study and the subjects perceived air quality during sleep. It was reported that the average perception of air quality either with the fan on or off was close to the middle point of the continuous scale, which referred to as neither fresh nor stuffy. No significant difference of perceived air quality was found between the fan on and off, although CO_2 levels, the marker of air quality, with the fan off were more than twice with them with it on (Strom-Tejsen et al. (2016)). This indicated that it may not be easy for occupants to perceive air quality after staying a long time in a room.

The studies above performed how occupants rated the environment either in their bedrooms or for intervention conditions. However, not all bedroom environmental aspects related to sleep were considered, or the time of rating was only indicated as "during sleep" in some studies. More comprehensive sleep-related time stages for rating the bedroom environment are needed.

The present study aimed to investigate how occupants rated the environment in their bedrooms before, during, and after sleep in the heating season in a temperate climate region. Perception of thermal, humidity, light, sound, air quality, and odor were all included as parts of the bedroom environment.

METHODS

The present study was launched from September to December 2020 in the capital region of Denmark, where belongs to a temperate climate zone. Online sleep diaries were used for the participants to rate the bedroom environment before, during, and after sleep.

Participants

The participants were recruited by sending an invitation e-mail to all the respondents from our previous online survey study or by posting a poster on social media. Those interested in the present study replied to the invitation e-mail, or filled out their contact information by scanning the QR code on the poster. The present study applies to the General Data Protection Regulation in the European Union.

The participants were asked to keep their regular sleep patterns during the period for replying to the sleep diaries.

Online sleep diary

Sleep diaries were in two versions for filling in evenings and mornings. The participants were asked to reply to the online sleep diaries for at least two continuous nights of sleep within ten minutes before and after sleep from Monday evening to Friday morning. Bedroom environment was rated for three time stages – "before sleep" in the evening sleep diary, and "during sleep" and "after sleep" in the morning sleep diary.

Perception and acceptability of the bedroom environment were rated by the continuous visual analogue scales ranged from 0 to 100. The example of the format is shown in Figure 1. The scales of the perception of thermal, humidity, and light were equally divided into seven parts, and the corresponding labels were marked on them. The labels are located at the scales of 0, 14.3, 28.6, 42.9, 57.2, 71.5, 85.7, and 100. Regarding the scales of acceptability, 0 – 49.9 and 50.1 – 100 refer to "acceptable" and "unacceptable", respectively. The participants were forced to rate to be acceptable or unacceptable to the bedroom environment since the point of 50 was not available. "clearly acceptable", "just acceptable", "just unacceptable", and "clearly unacceptable" were labeled on those scales.

The terms "NOW" and "DURING LAST NIGHT" were used for "before or after sleep" and "during sleep", respectively. "Cold/hot" was indicated the perception to the bed when using for rating thermal perception "during sleep".

The information of sex, age, height, and weight were also collected.

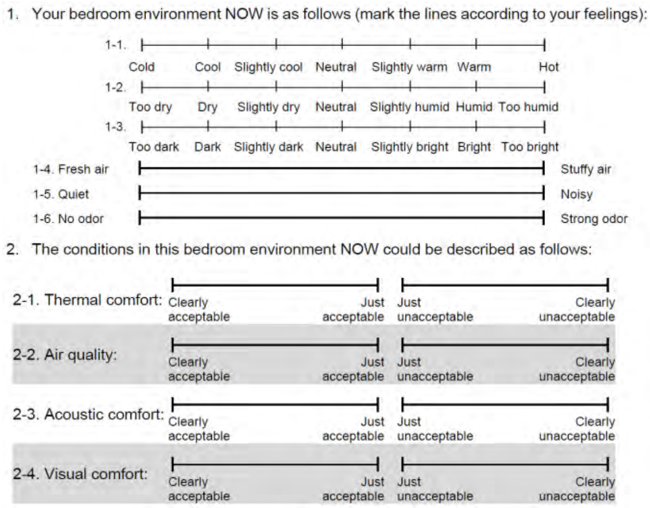

Figure 1. An example format to rate the perception and acceptability of the bedroom environment.

Statistical analyses

Statistical analyses were performed using R Studio (version 1.3.1093, Boston, MA, USA). All analyses were considered statistically significant when the *p*-value was less than 0.05 (2-tailed).

Whether there was a difference in the perception of bedroom environment between "during sleep" and "before or after sleep" was analyzed by the Wilcoxon matched-pair signed-ranks test. Linear regression models were used to analyze the quantity of the change in perception from acceptability to unacceptability for the bedroom environment.

RESULTS

A total of 169 sets of evening and morning sleep diaries were received from 82 bedroom occupants. 54.9% of them were males and the overall median (interquartile range, IQR) of age was 27.0 (24.3 – 32.0) years. The median (IQR) of body mass index (BMI) was 22.4 (20.8 – 24.2).

Table 1. Statistical data of the perception of the bedroom environment.

Item	Min.	1st Q.	Median	Mean	3rd Q.	Max.	*p*-value
1. Thermal perception (0, Cold; 100, Hot)							
Before sleep	5	34	**43**	45.0	56	84	**0.005**
During sleep	5	36	50	48.4	59	83	Ref.
After sleep	11	34	47	46.7	58	83	0.173
2. Humidity perception (0, Too dry; 100, Too humid)							
Before sleep	16	44	49	47.7	52	81	0.603
During sleep	2	39	49	47.2	53	92	Ref.
After sleep	15	37	49	47.3	54	90	0.764
3. Light perception (0, Too dark; 100, Too bright)							
Before sleep	5	18	**31**	34.1	49	94	**<0.001**
During sleep	2	17	20	26.7	35	69	Ref.
After sleep	2	20	**33**	39.0	52	86	**<0.001**
4. Air freshness/stuffiness (0, Air fresh; 100, Air stuffy)							
Before sleep	1	17	33	34.6	51	83	0.399
During sleep	1	19	35	36.2	52	88	Ref.
After sleep	0	26	**50**	45.2	66	89	**<0.001**
5. Sound perception (0, Quiet; 100, Noisy)							
Before sleep	1	8	**17**	22.5	33	78	**0.013**
During sleep	0	7	15	19.5	26	81	Ref.
After sleep	0	9	**21**	25.4	36	98	**<0.001**
6. Odor perception (0, No odor; 100, Strong odor)							
Before sleep	1	7	16	20.6	27	99	0.571
During sleep	0	7	16	18.9	26	98	Ref.
After sleep	0	10	**20**	24.5	35	99	**<0.001**

Min., minimum; Q., quartile; max., maximum; Ref, reference. P-values were calculated from the Wilcoxon matched-pair signed-ranks test. Bold indicates significant results.

Table 1 shows the statistical data of the perception of the bedroom environment. According to medians, the participants rated thermal perception as to be neutral during or after sleep, but slightly cool before sleep. Also, the humidity was generally neutral rated for the three time stages. The light was rated as to be dark during sleep and slightly dark before or after sleep. The air was rated as to be fresh before and during sleep, while it was rated as to be neither fresh nor stuffy after sleep. The sound was rated to be quieter during sleep compared to it before or after sleep. The odor during or before sleep was rated to be not as strong as it after sleep. Overall, air stuffiness increased on the largest rating difference of 17 from before to after sleep. As for the other bedroom environmental perception, the differences in ratings of the three stages were not considerable.

Table 2 shows the number and percentage of the observations for the perception of the bedroom environment. A higher number of observations showed the perception of "cool or cold" before sleep, compared to the ratings for "during or after sleep". It is worth noting that almost twice the number of observations had ratings of the air to be stuffy after sleep compared to the number before bed. This was also the most changeable bedroom environmental aspect between before and after sleep.

Table 2. The number and percentage of the observations for the perception of the bedroom environment.

Item	Category, n (%)		
1. Thermal perception	Cool/cold	Neutral	Warm/hot
Before sleep	109 (64.5)	3 (1.8)	57 (33.7)
During sleep	83 (49.1)	10 (5.9)	76 (45.0)
After sleep	92 (54.4)	8 (4.7)	69 (40.8)
2. Humidity perception	Dry	Neutral	Humid
Before sleep	96 (56.8)	12 (7.1)	61 (36.1)
During sleep	96 (56.8)	13 (7.7)	60 (35.5)
After sleep	98 (58.0)	8 (4.7)	63 (37.3)
3. Light perception	Dark	Neutral	Bright
Before sleep	129 (76.3)	6 (3.6)	34 (20.1)
During sleep	147 (87.0)	5 (3.0)	17 (10.1)
After sleep	114 (67.5)	8 (4.7)	47 (27.8)
4. Air quality perception	Fresh	Neutral	Stuffy
Before sleep	123 (72.8)	3 (1.8)	43 (25.4)
During sleep	120 (71.0)	3 (1.8)	46 (27.2)
After sleep	84 (49.7)	1 (0.6)	84 (49.7)
5. Sound perception	Quiet	Neutral	Noisy
Before sleep	147 (87.0)	1 (0.6)	21 (12.4)
During sleep	156 (92.3)	1 (0.6)	12 (7.1)
After sleep	149 (88.2)	0 (0)	20 (11.8)
6. Odor perception	No odor	Neutral	Strong odor
Before sleep	152 (89.9)	1 (0.6)	16 (9.5)
During sleep	158 (93.5)	1 (0.6)	10 (5.9)
After sleep	150 (88.8)	1 (0.6)	18 (10.7)

Table 3 shows the statistical data of the acceptability of the bedroom environment. Generally, the occupants accepted thermal comfort, air quality, acoustic comfort, and visual comfort before, during, and after sleep. According to medians, the occupants accepted thermal comfort more before and during sleep compared to them after sleep. The level of acceptability decreased from before to after sleep. The acceptability of acoustic comfort, as well as visual comfort, was the highest during sleep among the three time stages. The levels of acceptability of thermal comfort and air quality was the lowest "before sleep" and "during and after sleep", respectively, showing by the highest scale.

Table 4 shows the number and percentage of the observations for the acceptability of the bedroom environment. Before sleep, the number of observations, which showed unacceptability to acoustic comfort, was the highest; during sleep, the number of unacceptability to the thermal comfort was the highest; after sleep, the number of observations, which showed unacceptability to air quality was the highest. For those who did not accept the thermal comfort, six and two observations had the perception of hot and cold, respectively, before bed; nine and four observations during sleep; and five and five observations after sleep.

The thermal perception was divided into two subgroups – "cool/cold" and "warm/hot" and the two subgroups were converted to 0 – 100 scales for building the following linear regression models. The higher the scale, the colder/hotter the occupants perceived.

Table 3. Statistical data of the acceptability of bedroom environment.

Item	Min.	1st Q.	Median	Mean	3rd Q.	Max.	*p*-value
1. Thermal comfort [a]							
Before sleep	1.0	9.9	19.9	22.7	35.4	63.4	0.903
During sleep	0.0	9.9	**22.1**	24.3	36.6	63.4	Ref.
After sleep	0.0	13.2	**26.6**	27.3	42.1	76.8	**0.002**
2. Air quality [a]							
Before sleep	0.0	9.9	**18.8**	22.2	33.2	60.1	**0.034**
During sleep	1.0	12.1	**23.2**	24.3	36.6	73.4	Ref.
After sleep	1.0	14.3	**31.0**	30.4	44.3	75.7	**<0.001**
3. Acoustic comfort [a]							
Before sleep	1.0	7.7	**16.6**	21.6	32.1	91.2	**0.007**
During sleep	0.0	6.6	**13.2**	17.6	24.3	65.7	Ref.
After sleep	0.0	6.6	**15.4**	20.8	31.0	95.7	**0.004**
4. Visual comfort [a]							
Before sleep	1.0	6.6	**13.2**	17.5	22.1	92.3	**<0.001**
During sleep	0.0	6.6	**9.9**	13.9	18.8	47.7	Ref.
After sleep	0.0	6.6	**15.4**	19.4	28.8	65.7	**<0.001**

[a] 0, clear acceptable; 49.9, just acceptable; 50.1, just unacceptable; 100, clear unacceptable. Ref., reference. *P*-values were calculated from the Wilcoxon matched-pair signed-ranks test. Bold indicates significant results.

Table 4. The number and percentage of the observations for the acceptability of bedroom environment.

Item	Acceptable, n(%)	Unacceptable, n(%)
1. Thermal comfort		
Before sleep	161 (95.3)	8 (4.7)
During sleep	156 (92.3)	13 (7.7)
After sleep	159 (94.1)	10 (5.9)
2. Air quality		
Before sleep	163 (96.4)	6 (3.6)
During sleep	163 (96.4)	6 (3.6)
After sleep	147 (87.0)	22 (13.0)
3. Acoustic comfort		
Before sleep	158 (93.5)	11 (6.5)
During sleep	162 (95.9)	7 (4.1)
After sleep	159 (94.1)	10 (5.9)
4. Visual comfort		
Before sleep	166 (98.2)	3 (1.8)
During sleep	169 (100)	0 (0)
After sleep	163 (96.4)	6 (3.6)

Linear regression models were built to predict bedroom environmental perceptions based on whether or not accepted the bedroom environment. The results are shown in Table 5. Humidity perception was not included since no direct ratings regarding the corresponding comfort. The level that occupants perceived hot during sleep increased 22.96 in the condition of unacceptability to thermal comfort compared to acceptability. Air stuffiness rated for the three time stages increased 26.91 – 27.46 in the condition of unacceptability to air quality compared to acceptability. The level that occupants perceived strong odor increased 13.07 in the condition of unacceptability to air quality compared to acceptability. Noisy levels rated increased 38.97 – 41.44 in the condition of unacceptability to acoustic comfort compared to acceptability. As for thermal comfort (cold) and visual comfort (bright), there were no significant differences in ratings between acceptable and unacceptable assessments.

DISCUSSION

Subjective perception of bedroom environment in the heating season in Denmark was carried out in the present study. Perception and acceptability of the bedroom environment were rated for three sleep-related time stages – before, during, and after sleep by the online evening and morning sleep diaries.

The results indicate that acoustic comfort and air quality can be improved for occupants to have a more satisfactory bedroom environment.

25.4%, 27.2%, and 49.7% of observations showed unacceptability to bedroom air quality before, during, and after sleep. The percentages were higher than another study conducted in China, where 1%, 11%, and 21% of occupants unaccepted bedroom air quality. This indicates that more occupants unaccepted bedroom air quality in the heating season than transition seasons. Also, different situations of buildings, such as ventilation systems, and the number of occupants in the bedrooms would be reasons for the differences as well (Zhang et al. (2021)). Moreover, the observations in the study of Zhang et al. were all from individual occupants, while there were at least two observations from the same occupant in the present study. This also induced some bias for direct comparison. The odor was also related to bedroom air quality, especially after sleep (Table 5).

The sound perception was rated as to be the noisiest before sleep, followed by "after sleep", while the quietest during sleep. Also, a fewer number of observations showed the perception of noisy or unaccepted acoustic comfort during sleep than before or after sleep. This result was similar to the study of Meng et al. (2020), whose results were mentioned in the introduction.

4.7%, 7.7%, and 5.9% of observations showed unacceptability to thermal perception before, during, and after sleep, respectively. Zhang et al. (2021) reported a higher percentage of 12.5% of occupants who unaccepted bedroom thermal perception during sleep, while only 3.8% of occupants unaccepted it before sleep. Lai et al. (2021) reported a higher percentage of 18% of occupants voted "cold" during the region of hot summer and cold winter (HSCW) in winter, compared to the present study and the study of

Zhang et al. (2021). The outdoor temperature range was from 6°C to 21°C during the transition seasons in Beijing, China, where the study of Zhang et al. (2021) performed. The average outside temperature ranges from 0 to 10 °C during the coldest month in the region of HSCW, and the lowest temperature can reach below 0°C (Wikipedia (2020)). In China, no central heating systems were in the region of HSCW, and also the heating systems were not running during transition seasons in Beijing, while heating systems could be chosen to operate as long as the occupants wanted in Denmark. Therefore, a higher percentage of observations showed unacceptability to bedroom thermal perception in cool/cold seasons in the studies in China compared to Denmark.

Table 5. Linear regression analyses of the perception of bedroom environment.

Item	Beta (95% CI)	*p*-value [a]
1. Thermal comfort (hot)		
Acceptable	Reference	-
Unacceptable before sleep	13.57 (-6.2 – 33.34)	0.522
Unacceptable during sleep	**22.96 (6.98 – 38.94)**	**0.030**
Unacceptable after sleep	13.32 (-3.22 – 29.87)	0.339
2. Thermal comfort (cold)		
Acceptable	Reference	-
Unacceptable before sleep	3.88 (-22.76 – 30.52)	0.999
Unacceptable during sleep	13.66 (-7.61 – 34.94)	0.410
Unacceptable after sleep	11.79 (-6.17 – 29.76)	0.392
3. Air quality (air stuffy)		
Acceptable	Reference	-
Unacceptable before sleep	**26.91 (10.99 – 42.83)**	**0.007**
Unacceptable during sleep	**26.97 (10.37 – 43.56)**	**0.010**
Unacceptable after sleep	**27.46 (17.3 – 37.62)**	**< 0.001**
4. Air quality (Strong odor)		
Acceptable	Reference	-
Unacceptable before sleep	11.53 (-3.29 – 26.34)	0.126
Unacceptable during sleep	4.04 (-9.34 – 17.42)	0.252
Unacceptable after sleep	**13.07 (4.56 – 21.59)**	**0.018**
5. Acoustic comfort (noisy)		
Acceptable	Reference	-
Unacceptable before sleep	**41.44 (31.45 – 51.43)**	**< 0.001**
Unacceptable during sleep	**38.97 (27.49 – 50.46)**	**< 0.001**
Unacceptable after sleep	**40.46 (28.84 – 52.08)**	**< 0.001**
6. Visual comfort (Bright)		
Acceptable	Reference	-
Unacceptable before sleep	18.16 (-2.78 – 39.09)	0.533
Unacceptable during sleep	- [b]	-
Unacceptable after sleep	-2.68 (-20.19 – 14.84)	0.762

[a] *p*-values were adjusted by the false discovery rate method. [b] All the observations showed acceptability to visual comfort during sleep. All models were adjusted by sex, age (interquartile range), and BMI (below 25.0, and 25.0 or above). CI, confidential interval. Bold indicates significant results.

All the occupants accepted visual comfort during sleep in the present study, although some occupants rated it a little bit bright. Exposure to light before and after sleep also affects sleep quality and architecture (Caddick et al. (2018)). Future studies will be conducted for this analysis.

There are strengths and limitations in the present study. Almost all the environmental aspects related to sleep were considered. The bedroom environment was rated not only "during sleep", but also "before and after sleep". The samples were mainly limited to young adults, while a more general population and a larger sample size are required for generalizing the results.

For our future plans, subjective and objective measured sleep quality and monitored bedroom environmental parameters will be reported and the associations of them and bedroom environmental perception will be analyzed to have a more comprehensive conclusion for the field measurement study.

CONCLUSIONS

Subjective assessments of bedroom environment were rated by occupants in the present study. Compared to those who accepted the bedroom environment, the subjects had the highest levels of the unacceptability of noise, following by stuffy air and a hot bedroom. Overall, occupants accepted the bedroom environment, but still, acoustic and thermal comfort and air quality can be improved for achieving a better bedroom environment, although the results might not be representative of the population because of the limited sample size. Enough ventilation in winter is necessary for bedrooms to reduce the perception of the stuffy air of occupants.

ACKNOWLEDGEMENTS

The authors would like to thank Jørn Toftum for guiding the online sleep diary website and all the participants. This study was supported by a grant from the Research Foundation – Flanders (FWO), Belgium.

REFERENCES

Caddick, Z.A., K. Gregorya, L. Arsintescua and E.E. Flynn-Evans (2018). "A review of the environmental parameters necessary for an optimal sleep environment". *Building and Environment*, 132, 11–20. https://doi.org/10.1016/j.buildenv.2018.01.020

Kallawicha, K., S. Boonvisut, H. Jasmine Chao and T. Nitmetawong (2020). "Bedroom environment and sleep quality of apartment building residents in urban Bangkok". *Building and Environment*, 188, 107474. https://doi.org/10.1016/j.buildenv.2020.107474

Lai, D.Y., J. Liu, Z. Wu, J. Pei, Y. Qi, H. Zhang and H. Yoshino (2021). "Thermal comfort diversity in Chinese urban residential buildings across various climates". *Energy and Buildings*, 231, 110632. https://doi.org/10.1016/j.enbuild.2020.110632

Meng, Q., J. Zhang, J. Kang and Y. Wu (2020). "Effects of sound environment on the sleep of college students in China". *Science of the Total*

Environment, 705, 135794. https://doi.org/10.1016/j.scitotenv.2019.135794

Molina, F.Q. and D.B. Yaguana (2018). "Indoor Environmental Quality of Urban Residential Buildings in CuencaEcuador: Comfort Standard". *Buildings*, 8(7), 1–19. https://doi.org/10.3390/buildings8070090

Strøm-Tejsen, P., D. Zukowska, P. Wargocki and D.P. Wyon (2016). "The effects of bedroom air quality on sleep and next-day performance". *Indoor Air*, 26(5), 679–686. https://doi.org/10.1111/ina.12254

Wikipedia (2020). "Hot summer cold winter zone". https://en.wikipedia.org/wiki/Hot_summer_cold_winter_zone

Zhang, X., G. Luo, J. Xie and J. Liu (2021). "Associations of bedroom air temperature and CO2 concentration with subjective perceptions and sleep quality during transition seasons". *Indoor air*, 00, 1–14. https://doi.org/10.1111/ina.12809