The Effects of Bedroom Mechanical Ventilation on Health and Sleep Quality

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ABSTRACT

Sleep is essential for overall health and well-being. The quality and efficiency of sleep are strongly influenced by the sleep environment, including indoor air quality. This study investigates the influence of mechanical ventilation on bedroom air quality during sleep and its impact on sleep efficiency and quality. Objective and subjective measurements were conducted to assess the effects of operating a mechanical ventilation system. The results showed that both objective and subjective evaluations of sleep quality demonstrated the improvement of sleep quality when the ventilation system was in operation. Conversely, when the ventilation system was not used, the objective indicator of sleep efficiency was lower, indicating an increase in sleep disturbances. These findings suggested that maintaining low CO_2 concentrations could enhance the sleep efficiency and quality. These findings provide foundational insights for further studies on appropriate sleep environment.

KEYWORDS

Sleep efficiency, Sleep quality, Mechanical ventilation, Bedroom environment, CO_2 concentrations

1 INTRODUCTION

1.1 Background

Sleep is essential for energy restoration, physical and mental recovery, and maintaining bodily functions, accounting for approximately one-third of the total time (M.R. Opp, 2009). The quality of sleep is influenced by various internal factors, such as indoor environmental conditions, individuals' health status, and emotional state. Good sleep is generally crucial for human health and well-being, and many factors of indoor environmental quality (IEQ) affect the quality of sleep including air temperature and relative humidity, air velocity, concentration of particle matter, lighting levels, noise levels, and ventilation rates. While most people may not consciously perceive environmental changes during sleep, research findings are suggesting that indoor environmental factors such as indoor air quality, temperature, and relative humidity (RH) have a significant impact on sleep quality (Lan et al, 2017, He et al, 2019). Indoor air quality and thermal environment significantly contribute to the recovery of psychological and physical fatigue accumulated during sleep (Lan et al., 2014; Wang et al., 2015). To ensure sleep quality, it is important to have an appropriate thermal environment, lighting, noise control, and healthy indoor air quality. Zhang et al. (2021) suggest that the sleep environment, in contrast to factors like psychological state and physical conditions, can be easily modified and controlled. Therefore, conducting additional research is deemed valuable to gather conclusive evidence on the significant impact of indoor environmental factors, such as air quality, temperature, and relative humidity, on sleep quality. Healthy indoor air refers to air that contains sufficient oxygen, has lower carbon dioxide levels, and contains normal air ions. Additionally, there is an increasing interest in creating healthier and safer indoor spaces due to the recent COVID-19 pandemic. Bedrooms in residential spaces often have smaller volumes compared to living rooms and are more likely to lack ventilation systems. As occupants may not consciously implement planned ventilation in the bedroom, adequate ventilation is crucial for maintaining good indoor air quality. There is limited research focusing on the impact of bedroom air quality and ventilation on sleep quality (Xiong et al., 2020; Storm-Tejsen, 2016). Therefore, this study aims to analyse the difference in sleep efficiency based on the operation of bedroom ventilation systems.

1.2 Scope of the study

In this study, we analyzed the difference in sleep efficiency depending on the operation of the ventilation system in an experimental testbed with two bedrooms, which was designed to replicate a real residential environment. A total of four university students participated in the experiment. Participants slept in separate bedrooms within the environmental chamber. The ventilation system was controlled while the participants were sleeping, and changes in carbon dioxide concentrations were monitored. Objective sleep efficiency was measured using Actigraph during sleep, and participants' subjective evaluation of sleep quality was conducted after the experiment to assess the appropriateness related to ventilation during sleep from a comfort perspective.

2 METHOD

2.1 Experimental facility and subjects

This study aimed to analyse the difference in sleep efficiency of occupants based on the operation of the ventilation system during sleep in a typical residential space. The study included a total of four healthy young adults, two males and two females in their 20s. The experiments were conducted in the Smart Living Testbed, a chamber designed to simulate a residential unit (dimensions: length (L) 8m x width (W) 5m x height (H) 2.7m) (Figure 1). The experimental testbed, as shown in Figure 1, was located inside a bigger indoor space with climate control systems. There are two bedrooms in the testbed, and participants of the same gender entered their rooms to sleep respectively. Participants were instructed to exclude factors that could affect the experiment, such as excessive physical exertion, alcohol consumption, smoking, and should try to maintain their normal lifestyle. Additionally, to eliminate factors that could affect the experiment, participants were provided with sleepwear and bedding, and were encouraged to sleep from 12 AM to 8 AM.

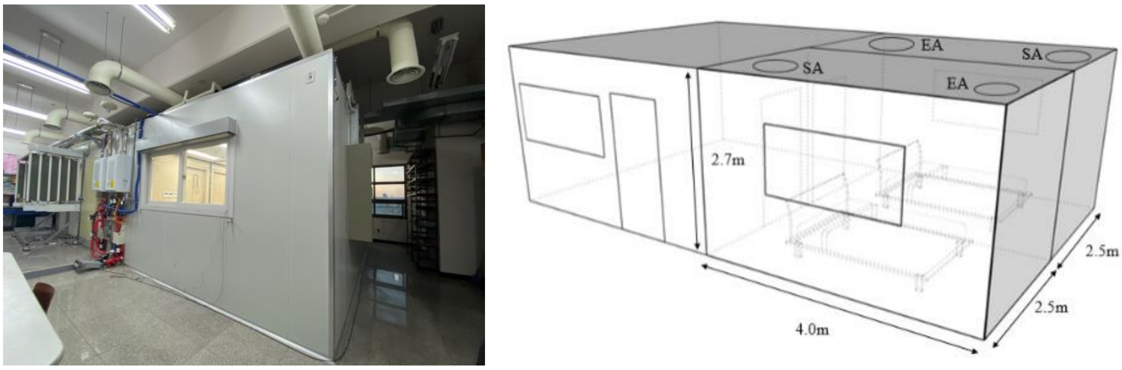


Figure 1: Images of the Smart Living Testbed for sleep experiments

2.2 Experimental design

To investigate the impact of indoor air quality on sleep, sleep experiments were conducted with a mechanical ventilation system. The experimental conditions were set to be identical except for the use of the ventilation systems. The ventilation system was operated within a range (150m^3/h) that had been determined through pre-experiments to ensure it did not disturb the participants' sleep. The qualitative evaluation of sleep was conducted using a sleep questionnaire, and the quantitative evaluation was performed using Actigraph (Table 1). Actigraph is a research-oriented device based on technology that measures sleep and wakefulness activity, allowing for accurate investigation of sleep patterns in healthy adults or patients(Figure 2). Although Actigraph cannot classify sleep stages, it provides data on total sleep time, sleep onset latency, sleep efficiency, and the number of awakenings during sleep. The questionnaire used in this study evaluated subjective sleep quality based on the criteria proposed by Zilli et al., including 6 items such as calmness of sleep, ease of falling asleep, ease of awakening, freshness after awakening, satisfaction about sleep, and sufficient sleep (Zilli et al, 2009). Each item included five levels (Fully, Fairly, Moderately, Not much, and Not at all), with higher level indicating higher sleep quality. The question regarding sufficient sleep is scored on a 1-point scale, with "Yes" or "No" options. The total score for the 6 items is 26 points. Previous research has shown that the results of this questionnaire align with EEG measurements (Lan et al., 2014).

Figure 2: Sleep efficiency measurement bands(Actigraph)

Table 1: Sleep assessment methodology

Criteria	Variables	Unit/Range	Interpretation	Interval
Sleep quality (Zilli et al, 2009)	Survey	0-26	0 = bad, 26 = good(Sleep Quality)	Daily
Actigraph	Length of sleep	minutes	-	1 min
	No. of awakenings		-	1 min
	Sleep efficiency	0%-100%	-	Daily

Each experimental session was conducted from 22:00 (10:00 PM) to 8:30 the following day, as shown in Figure 3. The participants attended the orientation of the experiment and changed cloth into the provided sleepwear. They were provided with an 8oz standard bedding. On the day of each experiment, participants arrived at the experiment site 2 hours before the start of the experiment and wore the equipment, and acclimatized to the experimental environment. Sleep was initiated at 24:00 (12:00 AM) after lights were turned off, and the evaluation of the previous night's sleep was conducted upon waking up.

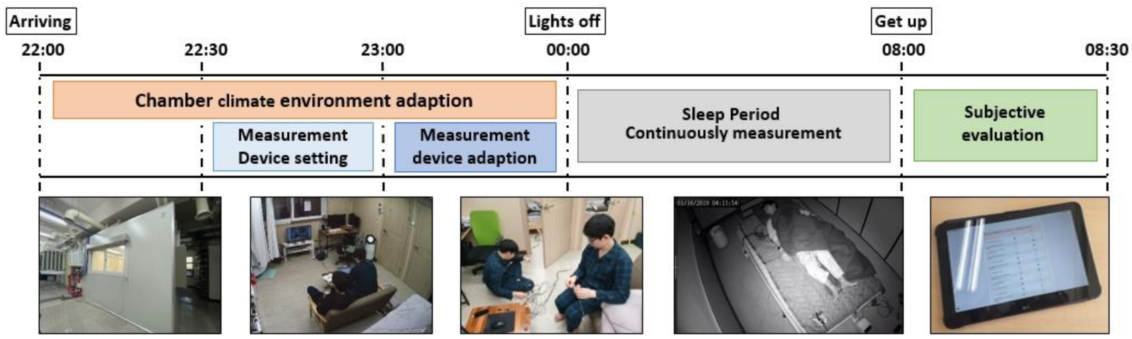


Figure 3: Experimental procedure

3 RESULT

The carbon dioxide (CO_2) levels according to the operation of the ventilation system are presented in Figure 4. In Case A, the ventilation system was operated, while in Case B, the ventilation system was not operated. In Case A, where the ventilation system was operating, the CO_2 concentrations ranged from a minimum of 394 to a maximum of 573 ppm. In contrast, in Case B, where the ventilation system was not operating, the CO_2 concentrations ranged from a minimum of 449 to a maximum of 1,321 ppm. Before the experiment, with no occupants in the bedroom, the initial CO_2 concentrations were measured between 394 and 575 ppm. Subsequently, in Case A (ventilation on) the CO_2 concentrations remained at similar levels to the initial measurements, whereas in Case B, the CO_2 concentrations gradually increased. The average CO_2 concentration in Case A was 492 to 537 ppm, while in Case B, it ranged from 1,019 to 1,152 ppm. In Case B, the CO_2 concentration increased from an initial average of 495 ppm to a maximum of 1,321 ppm. It can be concluded that without the operation of the ventilation system, the CO_2 concentration increased due to the occupants' respiration. Therefore, when the ventilation system was not in operation in this testbed, it was not able to meet the requirements for indoor CO_2 concentration levels specified in international ventilation standards such as ASHRAE and CEN.

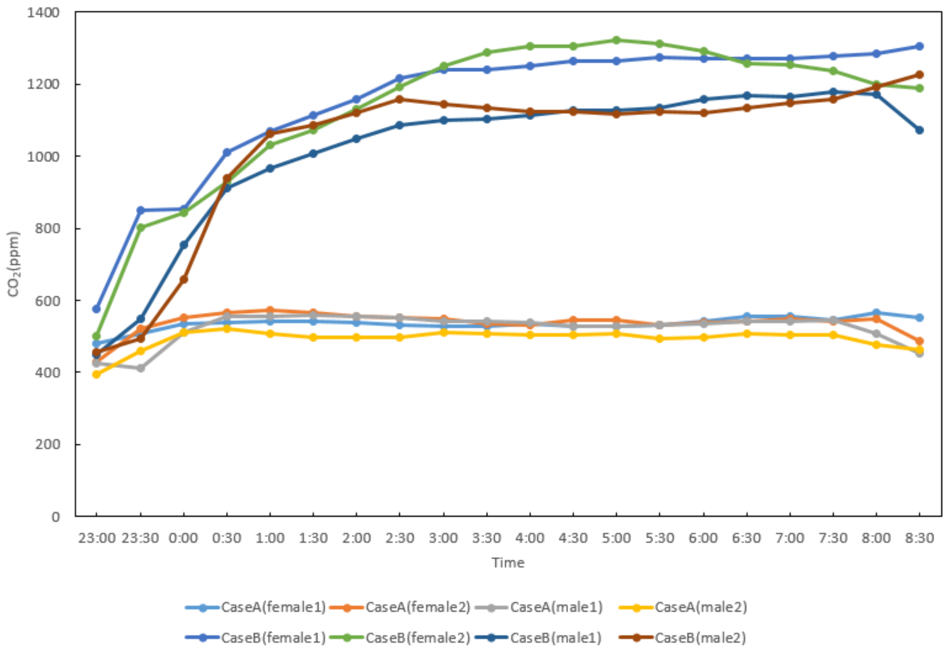
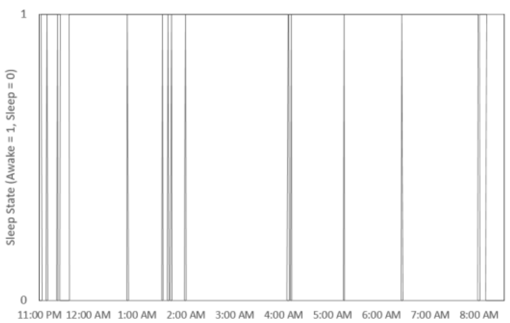
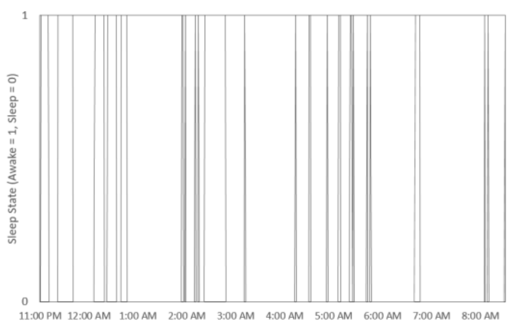
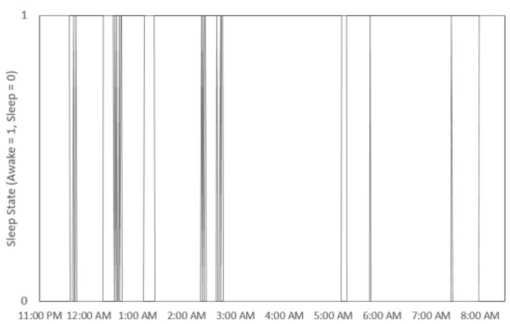
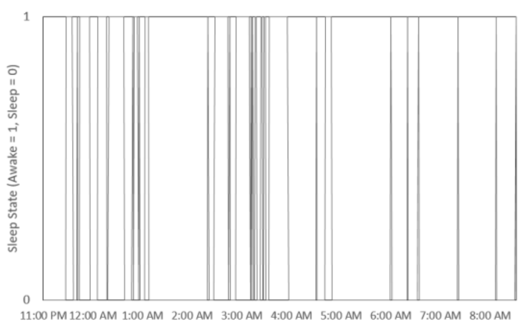


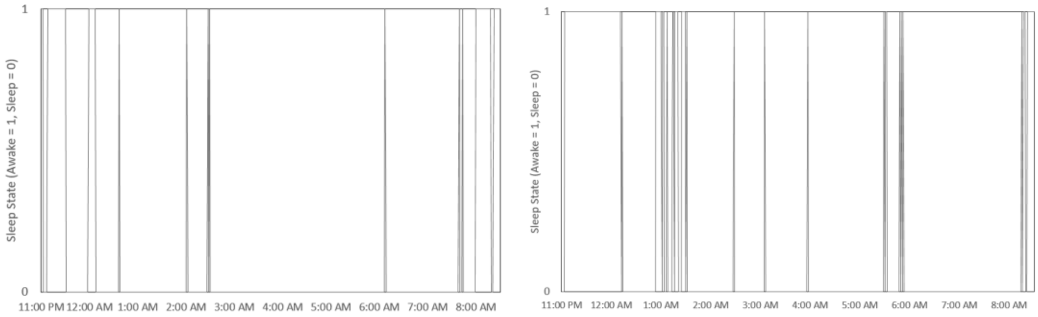
Figure 4: CO_2 Concentration

The quantitative evaluation of participants' sleep was measured using Actigraph. Table 2 presents the participants' sleep movements for each case. The more movements during sleep, the lower the sleep efficiency. In Case A, the average number of sleep movements ranged from 7 to 35, with a mean of 17.5. In Case B, the average number of sleep movements ranged from 29 to 94, with a mean of 52.3. Sleep movements decreased by approximately 66% when the ventilation system was operated during sleep.

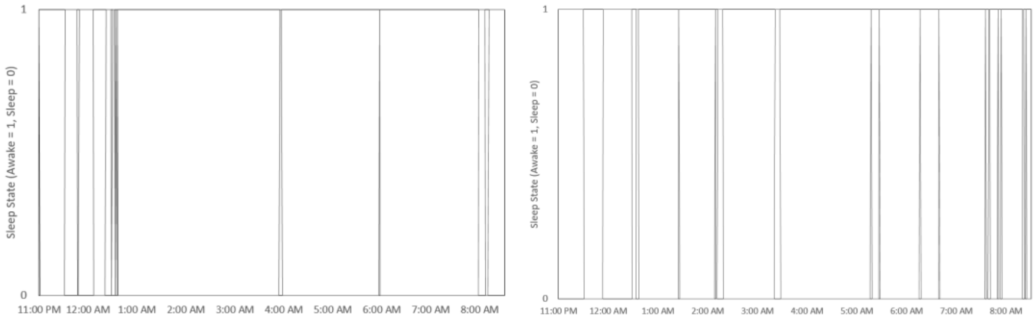
Table 2: Subject's Sleep State

	Case A (Ventilation On)	**Case B (Ventilation Off)**
Subject1		
Subject2		

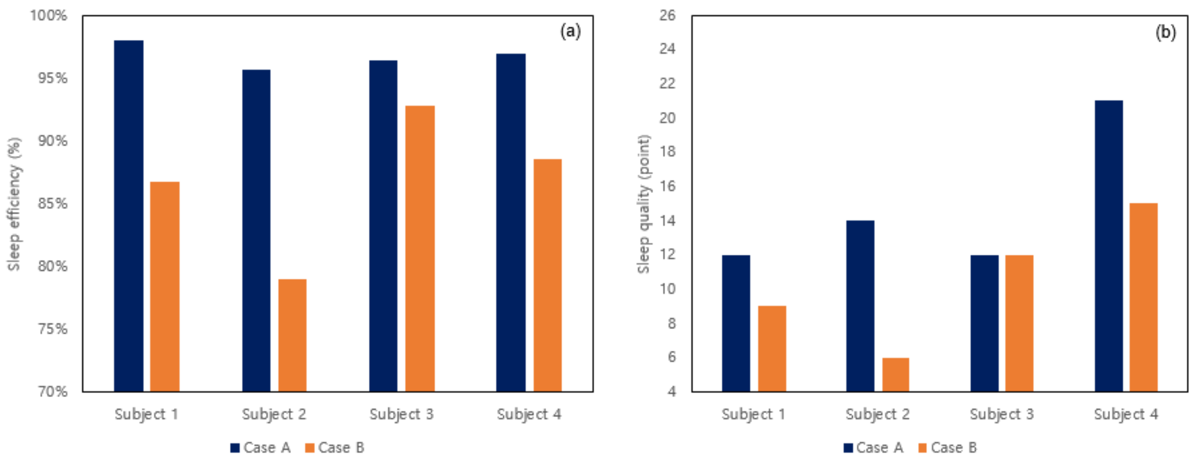
Subject3



Subject4



Investigating the individual evaluations of participants' sleep, in terms of quantitative evaluation results, the sleep quality of Subject 2 showed the most significant improvement, while Subject 3 showed the lowest improvement. The sleep efficiency of Subject 2 was the lowest in Case B, at 79%, and increased by 17.5% to 95.7% in Case A. The sleep efficiency of Subject 3 was the highest in Case B, at 92.8%, and increased by 3.7% to 96.4% in Case A. In subjective evaluation results, represented by the sleep questionnaire, Subject 2 also showed the most significant improvement, while Subject 3 reported similar sleep quality regardless of ventilation operation. The sleep quality of Subject 2 was the lowest in Case B, at 6 points, and improved by 57% to 14 points in Case A.



(a) Sleep efficiency

(b) Sleep quality

Figure 5: Sleep efficiency and quality depending on the operation of the ventilation system

The comprehensive analysis of the participants' sleep results revealed that in Case A, where the ventilation system was operational, the sleep efficiency ranged from 95.7% to 98%, with an average sleep efficiency of 97%. On the other hand, in Case B, where the ventilation system was not operational, the sleep efficiency ranged from 79% to 92.8%, with an average sleep efficiency of 86% (Table 3). This indicates that the operation of a mechanical ventilation system can lead to a maximum improvement of 17.5% in sleep efficiency.

Furthermore, the qualitative assessment using a sleep questionnaire, with a total score of 26 points, showed that in Case A, the sleep quality ranged from 12 to 21 points, with an average sleep quality of 15 points. In Case B, the sleep quality ranged from 6 to 15 points, with an average sleep quality of 10 points (Table 3). This indicates that the operation of a mechanical ventilation system resulted in a maximum improvement of 57% in sleep quality.

Table 3: Sleep assessment scores using Actigraph and questionnaires

	Case A (Ventilation On)			**Case B (Ventilation Off)**		
	Avg	**Min**	**Max**	**Avg**	**Min**	**Max**
Sleep efficiency (%)	97.0	95.7	98.0	868.8	79.0	92.8
Awakenings (No.)	17.5	7.0	35.0	52.3	29.0	94.0
Sleep quality (points)	14.8	12.0	21.0	10.5	6.0	15.0

These results indicate that the operation of the ventilation system has a positive impact on sleep efficiency and sleep quality. By maintaining appropriate CO_2 levels in a bedroom, the sleep environment could be improved, leading to a positive influence on the participants' sleep.

4 CONCLUSIONS

In this study, we investigated the impact of mechanical ventilation in bedroom on sleep quality. Objective and subjective measurements of sleep efficiency were conducted according to the operation of the ventilation system. The results showed that both objective and subjective evaluations of sleep quality were improved in the case where the ventilation system was operated. In the case where the ventilation system was not operated, the objective indicator of sleep efficiency was lower, indicating an increase in the number of awakenings during sleep. Although these research findings may not be statistically significant, the overall results suggest that improving sleep quality and efficiency can be achieved by introducing outdoor air through a mechanical ventilation system. Future research should consider increasing the number of participants for further analysis and conducting experiments with various combinations of sleep parameters. These research findings could serve as foundational data for studies on appropriate sleep environment.

5 ACKNOWLEDGEMENTS

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1A2B5B02002699). This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea (No. 20212020800120).

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