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Sleep Quality and Adaptive Thermal Comfort under Various Energy Use Modes

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ABSTRACT

There are limited studies on the impact of room temperature on sleep quality, particularly outside laboratories. Also, limited studies investigated the impact of thermal control on sleep quality and energy related matters, while heating and cooling are responsible for 40% of the energy use in buildings. This work investigated the impact of thermal comfort on the sleep quality, gender differences, ventilation mode and thermal control systems, which lead to differences in the energy use. Field test studies of thermal comfort were applied between 2010 and 2014. 13,728 datasets from 61 buildings and 135 participants were collected in participants' bedrooms in Japan. The results indicated that female participants had lower comfort temperature, as compared to men, before sleep during the cold months. Otherwise, no significant difference was found between their comfort temperatures, which is in disagreement with the existing research. The sleep quality was improved when thermal sensation was between slightly cool and neutral; and the comfort temperature between 17-27°C. Natural ventilation had a consistent impact on the sleep quality, as compared to heating and cooling modes. Opening a window improved the sleep quality during the warm months; while reduced it during the cold months. This suggested extra care regarding the natural ventilation to improve the sleep quality and to reduce the energy demand of the building.

Keywords: thermal comfort, sleep quality, energy, bedroom, gender

1. INTRODUCTION

The room temperature directly affects the energy performance of the building, as heating and cooling are responsible for 40% of the energy use in buildings [1]. Studies suggest that by changing the temperature by 5°C, up to 69% energy can be saved [2-4]. Comfort temperature of men has been reported to be lower than women [5,6]. Irshad et al. [7] found that women required warmer sleeping conditions, as compared to men. Room temperature affects the sleep quality; yet, limited studies investigated it [8]. High core body temperature has a negative impact on the sleep quality [9] and a warm room temperature prevents the core body temperature to drop [10]. Temperatures over 26°C are considered, as overheating; however, Nicol [11] reports 29-31°C, as comfortable for sleeping. Cold temperatures during the sleep are reported to increase health problems [12]. Inappropriate temperature settings result in sleep disruptions [13] and lack of sleep, which negatively affect health [14]; mental health and wellbeing [15]; mood [16]; obesity and weight gain [17]; reaction time and cognitive distortions [18]; sustained attention [19]; school, Eathletic and cognitive performances [19-21]. Insufficient sleep is associated with higher morbidity and mortality rates [22]. The use of thermal control can enhance the sleep quality [23]. However, most studies take place in laboratories, rather than the subject's bedroom and the real life context [24]. However, sleeping in a new environment affects the sleep quality, as "half of the brain sleeps lighter than the other half, as if it is standing guard ..., due to the potentially less safe context" [8]. By sleeping in a familiar environment, the performances of the two sides of the brain are similar, particularly in Non Rapid Eye Movement (NREM) sleep [24]. Stage 3 of NREM, is restorative (e.g. tissue repair and human growth hormones) and more difficult to gain sufficient quantity [8]. This work investigated the impact of the room temperature and ventilation modes on the sleep quality and energy use in the real life context of

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residential bedrooms in Japan. The comfort temperature before and after sleep, the impact on the sleep quality, gender related differences, and the impact of heating, cooling and natural ventilation were explored.

2. RESEARCH METHODS

Field test studies of thermal comfort were applied in bedrooms in residential buildings in Japan between July 2010 and August 2014. Overall, 13,728 datasets from 61 buildings and 135 participants (67 males and 68 females) were collected. The buildings were mixed mode, equipped with heating, cooling, openable windows, and pedestal fans. The occupants set the system according to their needs and seasonal changes. During the survey, the participants responded to a questionnaire before and after sleep each night. Meanwhile, environmental measurements (e.g. dry bulb temperature, relative humidity and mean radiant temperature) were recorded. Both surveys had thermal comfort questions, while after sleep survey included a sleep question, as presented in Table 1. The comfort temperature was calculated by Griffiths method using 0.50 regression slope [25].

Table 1 Thermal sensation, preference, comfort, sleep depth

No.	Thermal sensation	Thermal preference	Overall comfort	Sleep depth
1	Very cold	Much warmer	Very uncomfortable	Very shallow
2	Cold	A bit warmer	Uncomfortable	Shallow
3	Slightly cold	No change	Slightly uncomfortable	Slightly shallow
4	Neutral	A bit cooler	Slightly comfortable	Slightly deep
5	Slightly hot	Much cooler	Comfortable	Deep
6	Hot		Very comfortable	Very deep
7	Very hot			

3. ANALYSIS

Majority of the respondents reported a neutral thermal sensation, no change thermal preference, slightly comfortable, and slightly deep to deep sleep quality, as demonstrated in Figure 1.

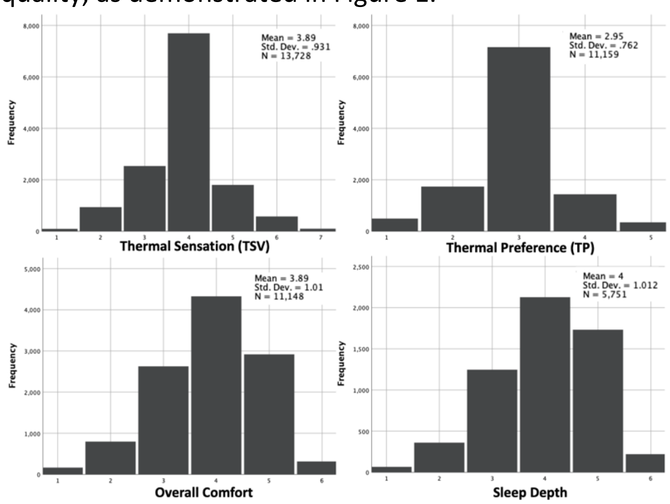

Figure 1 TSV, TP, overall comfort and sleep depth

Sleep quality had a significant relationship with both thermal sensation and comfort temperature, as demonstrated in Figure 2. The sleep quality was higher between slightly cool and neutral; and between 17°C and 27°C comfort temperatures. Although there was a relationship between sleep quality with thermal preference and overall comfort, it was not as significant.

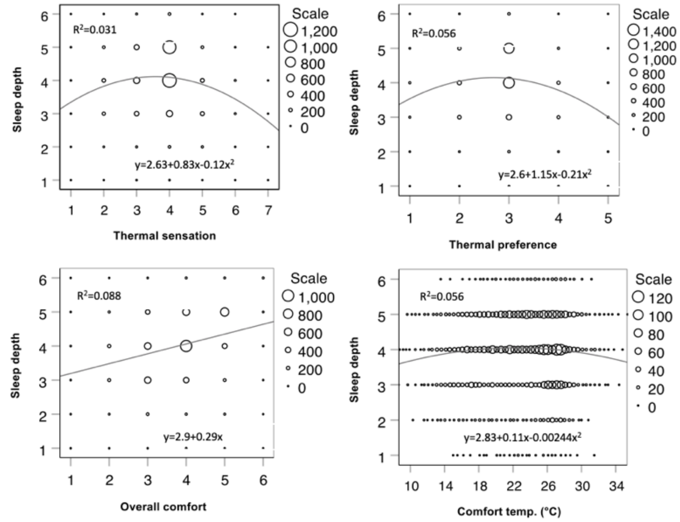

Figure 2 The relationship with sleep quality

During the free running (FR) and cooling (CL) modes, male and female respondents had similar comfort temperatures throughout the year as low as 15°C in February and as high as 27.5°C in July and August, as shown in Figure 3. The cooling mode was in operation between May and October with a narrower comfort temperature band (24-27.5°C). During the heating (HT) mode, the comfort temperature of women was found up to 4°C lower than men, which may be due to higher clothing layers for women. Women's lower comfort temperature is in disagreement with most research suggesting higher comfort temperature for women [5-7].

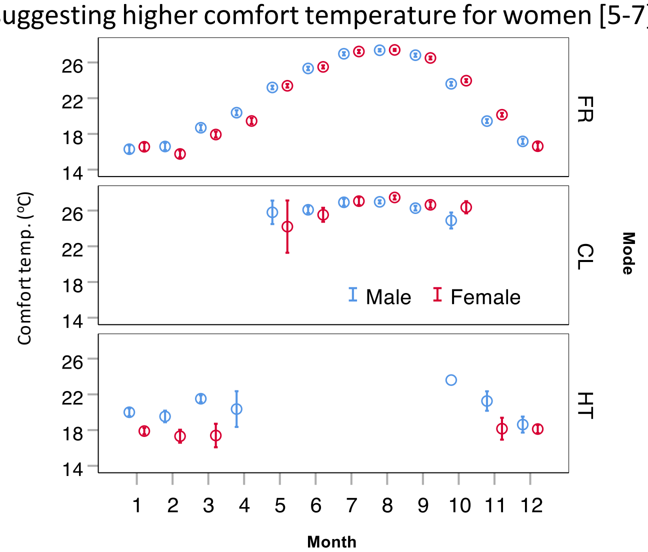

Figure 3 Comfort temperatures of men and women

Further investigation reveals that mainly the comfort temperature of women before sleep during the heating mode was significantly lower than that of men. However, this gap was less significant after they woke up, as demonstrated in Figure 4.

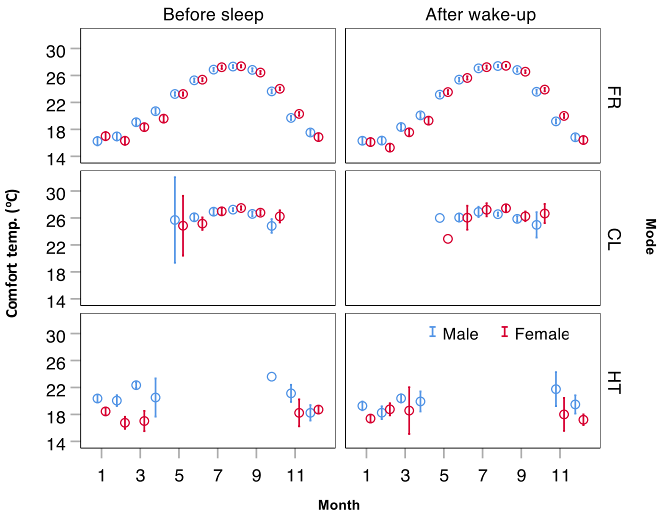

Figure 4 Comfort temperature before and after sleep

The sleep quality was significantly reduced when the windows were closed during the warm months between July and September, as demonstrated in Figure 5. In the cold month of November, the opposite was observed, as the open window resulted in lower sleep quality. During the other months, no significant difference was found.

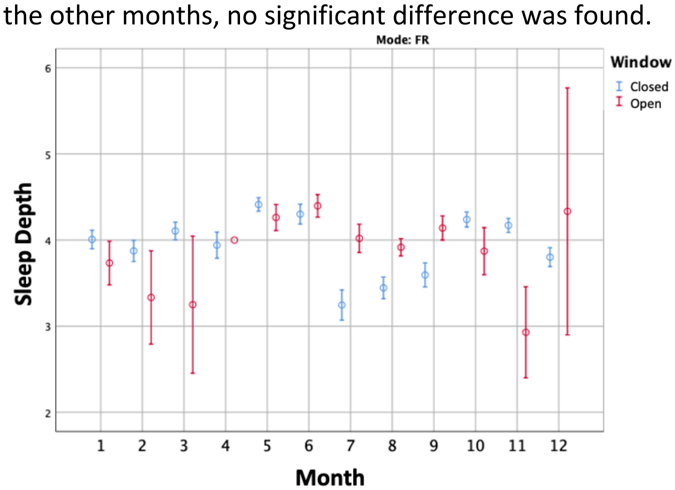

Figure 5 Sleep quality and window opening

As demonstrated in Figure 6, sleep depth was mainly around slightly deep. However, it was more consistent in the natural ventilation (FR) mode, while it sometimes slightly dropped towards slightly shallow during the heating (HT) mode in Autumn. During the cooling (CL) mode in Spring, sleep quality seemed lower, but there were not enough data for cooling in this season to conclude.

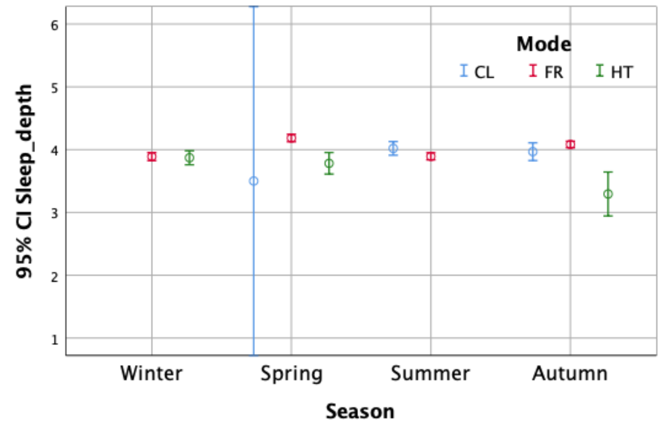

Figure 6 Sleep depth and ventilation mode

Natural ventilating was the least energy consuming system and it had a more consistent impact on the sleep quality. However, when the window was left open during the winter or when it was closed during the summer, it resulted in lower sleep quality. This suggested that the appropriate use of the windows was likely to improve the sleep quality, while reducing the energy use. Also, changing the set point of temperature by 5°C is likely to save energy (up to 69%) [2-4]. Thus, a combination of natural ventilation and changing the set point of temperature are likely to reduce the energy demand.

4. DISCUSSION AND CONCLUSION

The results indicated the following key findings:

- Female participants had a lower comfort temperature before sleep, as compared to men during the cold months. This is in disagreement with the findings of Irshad et al. [7].
- Except before sleep comfort temperature during the cold months, no significant difference was found between the comfort temperature of men and women. This is in disagreement with the majority of research comparing the comfort temperatures of male and female subjects, reporting higher comfort temperatures for women [5,6].
- The sleep quality had a significant relationship with thermal sensation; and it was improved when thermal sensation was between slightly cool and neutral.
- The sleep quality had a significant relationship with participants' comfort temperature; and it was improved, when the temperature ranged between 17°C and 27°C.
- Natural ventilation, which was the most energy efficient system, had a more consistent impact on the sleep quality, while heating and cooling modes sometimes had a slightly negative impact. Opening a

window during the warmer months was found to have a positive impact on the sleep quality, while it had a negative impact during the cooler months. Thus, it is suggested that the correct use of natural ventilation is likely to improve the sleep quality, while reducing the energy use of the building.

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