Studies of Subjective Sleep Thermal Comfort and Adaptive Behaviors in Chinese Residential Buildings in Nine Cities

Weiping Hong[1], *Junjie* Liu[1], *Jingjing Pei*[1] and *Dayi* Lai[2,*]

[1]Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China

[2]Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai 200240, China

Abstract. Sleep thermal comfort greatly impacts the quality of sleep. For residents from different climate regions, their level of sleep thermal comfort may have a large difference due to the variations in climate, and other adaptive factors such as the changes in bedding system insulation, the use of air conditioners, and the opening of windows. To study the thermal comfort and adaptive behaviors of Chinese residents in different regions during sleeping period, this study conducted a long-term survey in nine cities in China from February 2018 to September 2018. For northern residents, they achieved a slight higher than neutral sleep thermal sensation in winter due to the use of central heating system. In summer, the sleep thermal sensation of severe cold (SC) region residents had a significant increase. In the south, although without central heating in winter, southern residents maintained a near neutral thermal sensation, partly because of the high bedding system insulation. Although the summer night outdoor air temperature was high in hot summer and cold winter (HSCW) and hot summer and warm winter (HSWW) regions, the occupants from the two regions actively used the air conditioners to help achieving sleep thermal comfort. The results of this study provide valuable information for designers, researchers, and policy makers to create a comfortable nighttime thermal environment in China.

1 Introduction

Sleep accounts for nearly a third of a person's lifetime and is helpful for eliminating fatigue, enhancing immunity, and maintaining mental health of people. Akiko Noda et al. [1] showed that short sleep duration and poor sleep quality impaired cognitive performance in older adults. Eva H. Telzer et al [2] scanned functional magnetic imaging for 46 adolescents, and found that poor sleep may impact their brain function and cognition. Thus, ensuring a good sleep quality is a very meaningful topic.

Sleep thermal comfort is an important factor affecting sleep quality. Currently, most sleep thermal comfort studies were conducted in the laboratory, and some useful conclusions have been drawn. By recording standard electrophysiological and analyzing sleep stages of six male subjects [3], Haskell et al. demonstrated that

* Corresponding author: dayi_lai@sjtu.edu.cn

29 ºC was a comfortable sleep temperature for naked human. Rohles et al. measured EEG's and skin temperature of six men and six women, and reported the sleep comfort temperature range was 21.1~32.2 ºC [4]. Although laboratory studies can precisely control experimental conditions and obtain relatively reliable results, the results may differ from actual situations. Field study were useful for studying daily conditions. Wyndham carried out a field study for 14 days at Weipa in the hot humid tropics of Australia, and found the night maximum comfortable temperature was 25.5 ºC [5]. Kim and Chun investigated the bedroom environment and sleep quality of 24 women in Korea. Their study showed that the comfort temperature range was 19.8~27.0 ºC, 23.4~26.9 ºC, and 27.2~30.3 ºC in the seasons of winter, spring and summer, respectively [6]. These field studies were conducted for a short period of time in limited climate zones. In addition, these studies mainly focused on indoor air temperature, while other adaptive features, such as the changes of the thermal resistance of bedding system, the opening of windows, and the usage of air conditioner at night were not studied.

Since residents in different cities are exposed to various climates and they may exhibit different adaptive behaviors to modify their sleep environment, it is essential to study these differences. In this paper, we demonstrated the results of a sleep thermal comfort survey in nine cities in five climate zones in China. The subjective of sleep thermal sensation and adaptive behaviors of residents were presented.

2 Method

2.1 Measurement campaign

The sleep thermal comfort field campaign was carried out from February, 2018 to September, 2018. The campaign investigated 166 residents from 9 cities in five climate zones in China. The classification of climate zones in this study was based on thermal design code for civil buildings in China (GB50176-2016) [7]. The code defines five climate zones, namely, severe cold (SC), cold (C), hot summer and cold winter (HSCW), mild (M), and hot summer and warm winter (HSWW), on the basis of the average air temperatures in the coldest and hottest month. As shown in Figure 1, the monitored apartments were located in cities of Urumqi (SC), Shenyang (SC), Beijing (C), Tianjin (C), Xi'an (C), Shanghai (HSCW), Chongqing (HSCW), Kunming (M) and Shenzhen (HSWW), with 13, 14, 12, 21, 17, 19, 16, 24 and 30 occupants participated in the survey, respectively. To facilitate further comparison, this study divided China into the north and south areas, according to the mean air temperature of January. If mean January temperature of the city was higher than 0ºC, it is deemed as from southern China, otherwise, it is regarded as from northern China. According to this rule, Urumqi, Shenyang, Beijing, Tianjin and Xi'an belong to the northern China, and Shanghai, Chongqing, Kunming and Shenzhen belong to southern China. Apartments in Cities from northern China use central heating in winter.

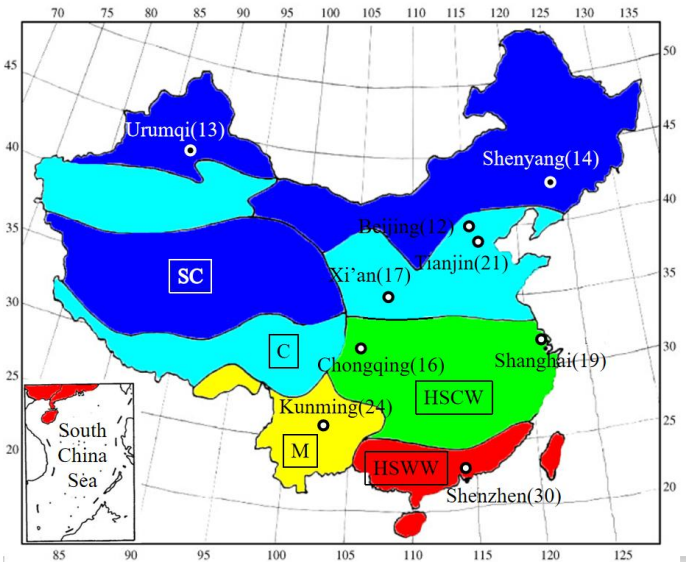

Fig.1. Location of the monitored cities and the number of monitored house.

2.2 Data acquisition

This study collected two categories of data, including subjective evaluation of sleep thermal comfort related parameters, and objective environmental parameters.

2.2.1 Post-sleep questionnaires

A link containing the online questionnaire was sent to the cellphone of interviewees in the morning to ask them to recall sleep related information last night, including subjective seven-point sleep thermal sensation (-3=cold, -2=cool, -1=slightly cool, 0=neutral, 1=slightly warm,

2=warm, 3=hot), clothing and bedding conditions, air conditioner usage, and window opening status during the sleep period.

A small amount of financial incentive was sent to the respondents with the questionnaire link to promote participation. Residents filled in the questionnaire voluntarily. Taking into account the working days and weekdays, the questionnaire was distributed for every ten days, generally on Wednesday and Sunday.

2.2.2 Temperature and humidity measurement

The indoor data of air temperature and humidity was continuously monitored. However, because we are still checking the data quality of the indoor air temperature and humidity, this paper does not present this information. Besides indoor air temperature and humidity, a two-hour average outdoor air temperature was obtained from the nearest weather stations.

3 Results and analysis

This section first analyzed the sleep thermal sensation. Then, the behavioral adjustment including air conditioner usage, window opening status, and bedding system insulation of residents in different climate zones were compared.

3.1 Thermal sensation and outdoor temperature

Figure 2 shows the average value of subjective sleep thermal sensation vote (TSV) and the corresponding outdoor air temperature in different climate zones. The outdoor air temperature was averaged from 22:00 to 8:00.

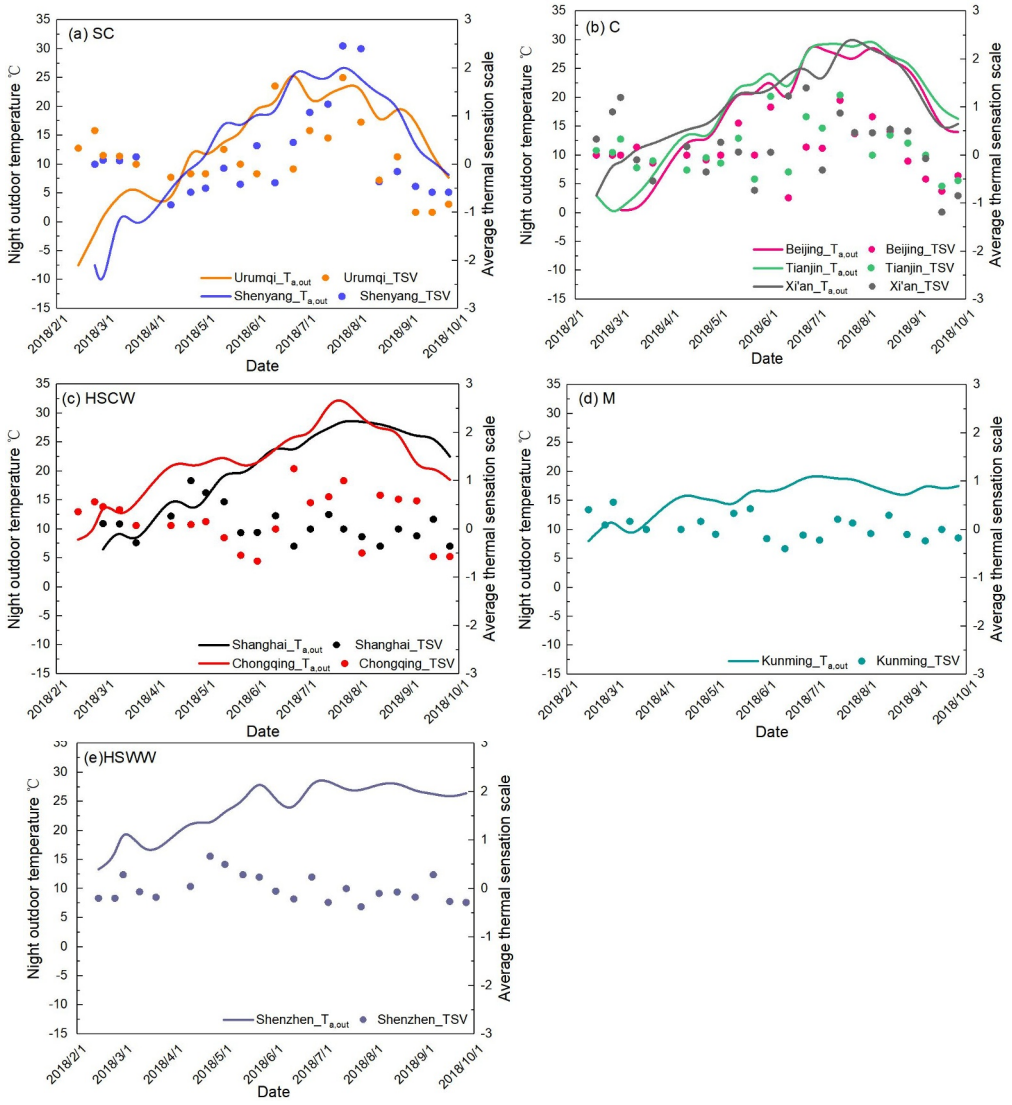

Fig 2. Outdoor air temperature and average sleep TSV in monitored cities in: (a)SC; (b)C; (c)HSCW; (d)M; (e)HSWW zones.

3.1.1 Northern area

As can be seen from Figure 2(a) and (b), at the start of the survey, the outdoor night temperature in the northern cities were very low. But due to the central heating system, bedroom temperature in northern homes was usually above 18°C, according to code for design of heating ventilation and air conditioning (GB50019-2011) [8]. The sleep thermal sensation of residents in SC and C climate zones were neutral to slightly warm in winter. However, when the heating stopped around mid-March to early April, the sleep thermal sensation slightly decreased. After April, the sleep thermal sensation gradually increased with the increase of outdoor air temperature. In addition, the thermal sensation slightly fluctuated with the fluctuation in outdoor air temperature. However, in June, the sleep thermal sensation showed great increase for residents in both SC and C regions. The level of increase in SC region was greater than that in C region. As can be seen from Figure 3(a), the average sleep thermal sensation in Shenyang was greater than 2 (warm) in the end of July. In contrast, the mean sleep thermal sensation for residents in C region never exceed 1.5. The reason for the difference in sleep thermal sensation between SC and C regions may be largely attributed to the difference in the usage of air conditioners, which was be demonstrated in Section 3.2.

3.1.2 Southern area

Figure 2 (c), (d), and (e) show the average sleep thermal sensation and the corresponding outdoor temperatures for studied cities in the HSCW, M, and HSWW climate zones. At the beginning of the investigation at February, the nighttime outdoor air temperature for southern areas was lower than 12 °C. Although apartments from these cities had no central heating system, it is very interesting to find the average values of subjective evaluation of sleep thermal sensation were still around neutral level. The residents may have already adapted to the environment.

It is also interesting to see that with the raise in outdoor air temperature, the sleep thermal sensation did not show significant increase in HSCW and HSWW regions. The mean thermal sensations were always within the -1 to 1 range. The significant usage of air conditioners may help residents from these regions to cope with the heat. Kunming from the M region, due to its mild climate, exhibited the smallest fluctuation in sleep thermal sensation.

3.2 Air conditioner usage and window opening status at night

Opening windows and using air conditioners are two important adaptive measures to adjust the sleep thermal environment. Figure 3 shows the percentage of surveyed residents who opened windows or used air conditioners during sleep.

3.2.1 Northern area

As shown in Figure 3(a), residents from SC region never open windows until late May when the outdoor air temperature was lower than 18 °C. The percentage of SC residents who opened windows during sleep increased from June, but the percentage was still lower than those from other regions. In contrast, around 20% percent of residents from C region leave their windows open even in winter. The window opening behavior increased from Mid-April and peaked in July. With the further increase in outdoor air temperature in August, residents in C region begun to close windows and use air conditioners to cool the bedrooms. A distinctive supplementary pattern between window opening and air conditioner usage can be found for C region. That is, residents from C region close windows when using air conditioners. In comparison, for SC region, only very few residents from Shenyang used air conditioner in August.

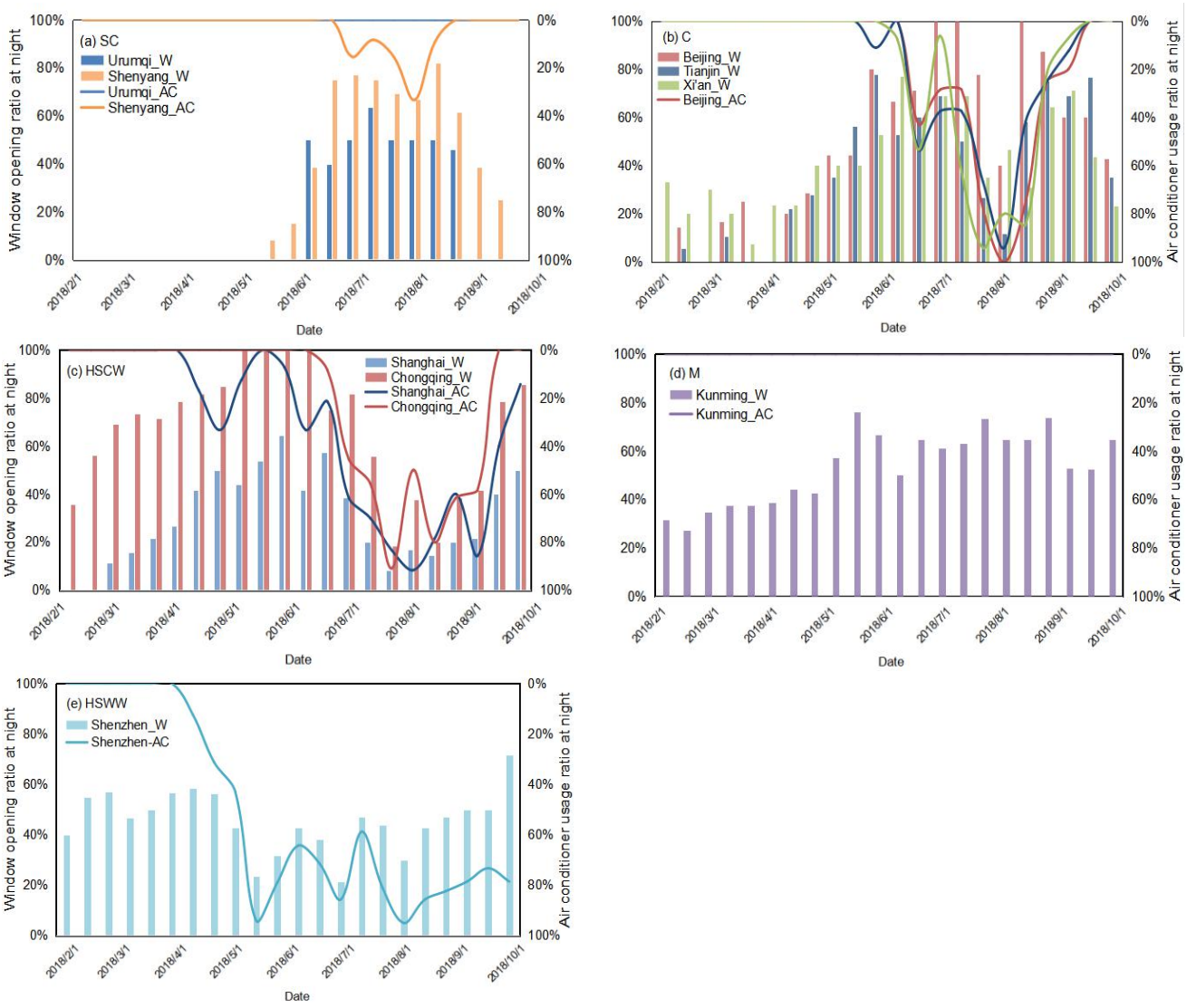

Fig. 3. Window (W) opening ratio and air conditioner (AC) usage ratio in cities in: (a)SC; (b)C; (c)HSCW; (d)M; (e)HSWW climate zones.

3.2.2 Southern area

Compared with northern residents, southern residents opened window more frequently at night, as shown in Figure 3(c), (d), (e). As the outdoor climate became warmer, the window opening ratio for HSCW and M regions increased. However, for HSWW region, the increasing trend was not obvious. With the further increase in outdoor air temperature, residents in Shenzhen (from HSWW) and Shanghai (from HSCW) started to use air conditioners in early April. In contrast to Shanghai residents, Chongqing residents began to use air conditioner in the middle of June. Instead of using air conditioners, Chongqing residents preferred to open windows to cool down the space. However, in August, opening windows was not enough for Chongqing residents to adapt themselves, and the usage of air conditioner significantly increased. It is also worth noting that most residents closed windows when using air conditioners. For residents from Kunming from mild climate region, since the night outdoor air temperature was always below 20 ºC, there was no need to use air conditioners.

3.3 Bedding system insulation

In addition to the use of air conditioners and windows to

control the overall indoor thermal environment, occupants can also adjust the thermal insulation of the bedding system to change the microclimate during sleep. Figure 4 shows the changes in thermal resistance of the bedding system in the investigated cities. The thermal resistance of the bedding system is the sum of the thermal resistance of the quilt and the sleeping clothing. The insulation value of quilts and pajamas were referred to Lin and Deng [9], and the database in ASHREA 55 [10], we chose the similar bedding system and used the method of interpolation. The solid line represents the results from the five cities in northern China, while the dotted line represents the results from the four cities in southern China.

At the start of March, since the northern cities still used central heating, the bedding insulation for northern residents was lower than that of southern residents. However, the central heating in northern areas terminated around early April. To cope with this, the residents in northern areas increased the insulation of bedding system, and the bedding insulation in northern cities were higher than that in southern cities. During June, July, and August, as more southern residents started to use air conditioner, they generally used thicker quilt than the northern residents. Due to the its lowest outdoor air temperature, Kunming residents used the highest insulation for the bedding system in summer.

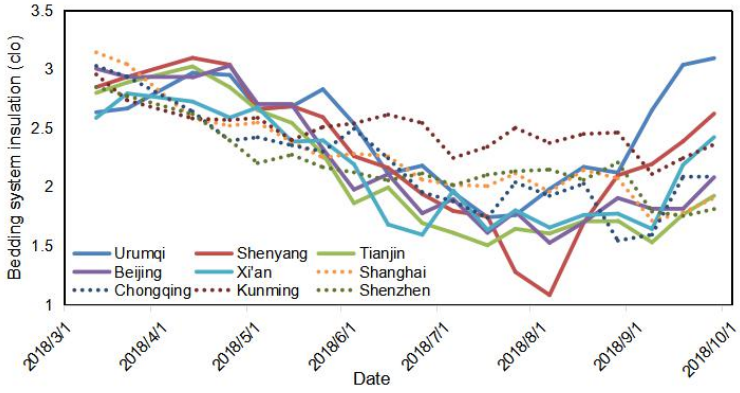

Fig. 4. Total insulation of bedding system in the nine monitored cities

4.Discussion

The central heating period in the northern part of China (SC and C climate zones) is divided according to the outdoor daily average temperature. The heating is stopped when the average daily outdoor air temperature is above 5 ºC [11], but the night temperature was still quite low. Therefore, after the termination of central heating, it is recommended that the northern residents use some individual equipment, such as the electric blanket and air conditioner to ensure the thermal comfort of the residents at night to improve the quality of sleep.

It is interesting to see that the average sleep thermal sensation for southern residents was more stable than that of the northern residents. In winter, southern residents used high bedding insulation to keep warm, and in summer, they employed air conditioners to cool the bedroom. For northern residents, the central heating helps them to create a comfortable sleeping thermal environment. However, in summer, the adaptive measures took by northern residents were not enough for them to maintain a good sleep thermal comfort.

The questionnaire also conclud the using of electric blanket at night. And we found that it is not common for residential to use electric blankets at night, usually the fixed few people. In the northern of China, due to the central heating in winter, there was barely residents use electric blanket. And in the southern of China, the fixed one or two occupants in every cities tend to using from November to February. From this phenomenon it can be seen that there have significant individual differences in thermal sensation.

There were several limitations in this paper due to the nature of field survey. First, this study asked the

participants to recall their sleep thermal sensations after waking up. However, people may not have conscious memory during their sleep. The subjective evaluation method may only reflect the situation right before sleep and after wake up. Second, to prevent survey fatigue, the question about the quilt and clothing was simplified. The insulation value obtained in this study may not be very accurate, but it provides an obvious trend, as shown in Figure 4. Third, because we are still evaluating the data quality of the monitored indoor air temperature and humidity, the result was not analyzed and presented.

5 Conclusion

In residential buidlings, in addition to the design fo the budilding, the behavioral habits, occupants' thermal sensation and requirements of comfort have a major impact on the energy consumption. This study conducted field campaign of sleep thermal comfort in nine cities in China to understand the actual situation of sleep quality and therml sensation, and the behavioral habits at night. The following conclusions can be drawn from the analysis of the obtained data:

(1) In winter, due to the use of central heating, northern residents had a slightly higher than neutral thermal sensation during sleep. Although central heating system was not used in southern areas, the southern residents managed to maintain a near neutral thermal sensation, partly due to the use of high insulation bedding system.

(2) With the termination of central heating, the average sleep thermal sensation of northern residents decreased to slightly cool. The northern residents used higher bedding insulation to compensate the cool environment.

(3) In summer, due to the frequent use of air conditioners, residents from HSCW and HSWW regions could still keep a near neutral thermal sensation. However, northern residents were not used to using air conditioners, their subjective thermal sensation during sleep can be as high as 2.5. Residents from M region had the most stable sleep thermal sensation due to the mild outdoor climate.

Acknowledgement

This research was partially supported by the national key project of the Ministry of Science and Technology, China, on "Green Buildings and Building Industrialization" through Grant No. 2016YFC0700500. We would like to express our gratitude to Prof. Kailiang Huang from Shenyang Jianzhu University; Prof. Yiwen Jian from Beijing University of Technology; Prof. Yuexia Sun, Prof. Jingjing Pei, Prof. Hejiang Sun, and Prof. Xiong Shen from Tianjin University; Prof. Haiguo Yin from Xi'an University of Architecture and Technology; Prof. Hongwei Tan from Tongji University, Dr. Yao Gao from Shenzhen Institute of Building Research Co., Ltd.; and all the graduate students for their help in discussing results and collecting data for the investigation.

References

1. Miyata S, Noda A, Iwamoto K, et al. J. SLEEP RES **22**, 535 (2014).
2. Telzer E H, Fuligni A J, Lieberman M D, et al. J. Neuroimage, **71**, 275 (2013).
3. Haskell E H , Palca J W , Walker J M , et al. J. CLIN NEUROPHYSIOL. **51**, 494 (1981).
4. Rohles F H, Munson D M. J. ENVIRON PSYCHOL, **1,** 207 (1981) .
5. Wyndham C H. J. Br J Ind Med. **20**, 110 (1963).
6. Kim M, Chun C, Han J. J. INDOOR BUILDT ENVIRON. **19**, 123 (2010).
7. GB50176-2016. S. China Architecture and Building Press. (In Chinese, 2016).
8. GB50019-2011. S. China Construction Information: Heating and Cooling. (In Chinese,2011).
9. Lin Z, Deng S. J. BUILD ENVIRON. **43**, 905 (2008).
10. ASHRAE 55. S. Atlanta: ASHRAE, (2004).
11. GB50736-2012. S. China Architecture and Building Press. (In Chinese,2002).