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The effects of programmed air temperature changes on sleep quality and energy saving in bedroom

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ABSTRACT

Bedroom air-conditioning is often programmed to cause the air temperature to follow either a *Rise-Fall* or an inverted *Fall-Rise* shaped course during the night, and there are rational arguments for both. The effects of these two programmed air temperature changes were investigated by creating three thermal conditions: a reference condition with constant temperature (26 °C), a *Rise-Fall* change condition (26 °C–27 °C–28 °C–27 °C–26 °C), and a *Fall-Rise* change condition (28 °C–27 °C–26 °C–27 °C–28 °C). Twelve healthy young people (6 females and 6 males, mean age 23 years) slept in a climate chamber with multiple of their physiological parameters monitored continuously. No significant difference in thermal comfort or sleep quality was found among the three conditions. The subjects had better next-day performance in the *Fall-Rise* condition than in the other two conditions. Simulation results show that compared with the reference condition, the total cooling load of a simulated bedroom is reduced by 27.8% in the *Rise-Fall* and 34.3% in the *Fall-Rise* condition. These results indicate that a slight increase of air temperature within thermal comfort range during the later period of sleeping (as simulated in the *Fall-Rise* condition) could better prepare the body for wake up, and also could save energy.

1. Introduction

Normal human sleep proceeds in cycles of rapid eye movement (REM) and non-REM (NREM) sleep, usually four or five of them per night. The NREM is further divided into three stages: N1, N2, and N3, the last of which is also called delta sleep or slow-wave sleep (SWS) [1,2]. Thermal environment could greatly affect human sleep, since the thermoregulatory systems were shown to be strongly linked to the mechanisms regulating sleep [3–5]. Air temperatures higher (34 °C and 37 °C) or lower (21 °C and 24 °C) than 29 °C (the thermal neutral temperature for subjects slept without covering) have been shown to decrease SWS and REM, and increase the frequency and duration of wakefulness [6]. However, these results are based on semi-nude subjects and not taking into account the effects of bed covers and clothing which are generally used in real-life situations [7]. When typical seasonal coverings were used, studies show that the subjects took longer time to fall asleep and experienced shorter SWS as the indoor air temperature (±3–4 °C) moderately deviated from the neutral temperatures (26 °C in summer and 20 °C in winter) [8–10]. Thus, providing a thermally comfortable sleeping environment is important for sleep maintenance and contributes positively to human health and their daytime activities.

An investigation shows that 60–90% people complained that they were sleepless at summer night due to the hot weather in Hot Summer and Cold Winter (HSCW) Zone of China [11]. With the economic development and the increased requirement for thermal comfort, air conditioners are becoming commonly accepted as necessary and conventional in bedroom in hot summer area. Our survey in Shanghai indicates that 90% of 800 families would use a bedroom air conditioner during sleep in summer [12]. Yoshino et al. reported that more than 90% of bedrooms have installed air-conditioners in Shanghai and Chongqing, and that the use of air conditioners peaked during sleeping hours [13]. The long operation time makes energy consumption of air-conditioning in sleeping spaces, such as bedrooms of residential buildings, guest rooms in hotels and wards in hospitals, an increasingly important contributor to the total energy consumption [14]. However the current thermal comfort theories and standards are mainly concerned with people in waking state [15]. The ANSI/ASHRAE 55-2010 states that it does not apply to sleeping or bed rest [16]. In the European standard EN 15251, the recommended minimum operative temperature for heating is 21 °C and maximum for cooling is 25.5 °C in the bedroom of category I buildings, however, these recommended temperatures are the same as that of office buildings [17]. The stan-

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dard CIBSE Guide A considers the difference in clothing and activity between sleeping and waking people, and recommends that the winter operative temperature range is 17 °C–19 °C, and the summer range is 23 °C–25 °C in bedrooms [18]. Although a well-agreed thermal neutral temperature cannot be determined yet, a same thermal neutral temperature of 26 °C was confirmed in two studies that used typical summer covering [15]. These evidences indicate that the values stipulated in the current standards may not be appropriate for sleeping people and that it is necessary to study the thermal comfort requirement of sleeping people.

Studies have shown that the core temperature of human body during night sleep could be changed by air temperature cycles. By using slow thermal transients of reduced amplitude (±3 °C) around 29 °C (thermoneutrality in humans sleeping nude), Dewasmes et al. advanced the minimum of rectal temperature of sleeping subjects [19]. Wakamura and Tokura demonstrated that a gradual decrease of air temperature in the evening and a gradual increase in the morning (*Fall-Rise* change) could accelerate both the nocturnal decrease of core temperature and its morning increase, and in turn, should improve the quality of sleep [20]. In contrast, a sleeping-mode algorithm is often applied in China to control the operation of air conditioner without testing its effects on human sleep: the setting temperature of the air conditioner is increased for a period of time and then decreased to its initial value during the night (*Rise-Fall* change). As the core temperature during sleep is related with sleep sensation, it is speculated that change of air temperature during sleep could induce different sleep quality. Such effects of air temperature change on sleep quality has been investigated in our former study; compared with the reference condition in which a constant neutral temperature of 26 °C was maintained, we observed poorer sleep quality in the *Rise-Fall* condition, but not in the *Fall-Rise* condition [21]. However, the reported poorer sleep quality in the *Rise-Fall* condition may be solely due to the delayed onset of sleep, which was caused by the cooler environment (an air temperature of 25 °C) created during the initial phase of the sleeping period [21]. In the present study the initial temperature of the *Rise-Fall* condition was increased to be 26 °C to confirm the effects of air temperature change on occupant's thermal comfort, sleep quality, and next-day work performance. The potential energy conservation of the air temperature changes was also analyzed.

2. Methodologies

2.1. Human subject experiment

2.1.1. Subjects

Twelve healthy Chinese students (6 females and 6 males, 21–28 years old, mean ± SD: 23.1 ± 2.1 years) without sleep disorders gave their informed consent to participate into this study. Their sleep quality and disturbances over a 1-month time interval was assessed by using of Pittsburgh Sleep Quality Index (PSQI) questionnaire [22]. If the candidate had a PSQI global score >5, which is suggestive of a significant sleep disturbance, he/she was excluded. They were nonsmokers, free of chronic diseases, asthma, allergy and hay fever, and were not taking any medications. The information was obtained from a questionnaire distributed during recruitment; none was examined medically. The subjects were asked to avoid alcohol, caffeine, and intense physical activity at the daytime during their four-day experiment. They were instructed to wear the same clothing (short-sleeved nightshirt, an estimated insulation value of 0.36 clo) in the experiment. At night they slept on a mattress bed and were covered with a double-layered cotton sheet. The covering material was fixed and the insulation level of the covering materials (including the clothing) was estimated to be 1.64 clo [23]. This study was approved by an ethics committee.

2.1.2. Measurements

2.1.2.1. Physiological measurements. The continuous monitoring of electroencephalogram (EEG), electrooculogram (EOG) and electromyogram (EMG) makes it possible to quantify sleep quality. EEG (F4-M1, C4-M1, O2-M1, F3-M2, C3-M2, O1-M2), bilateral EOG, and mental EMG were recorded using a 32 channel EEG machine (EEG-9000, Nihon-Kohden), at a sampling rate of 500 Hz. Sleep stages were visually scored every 30 s based on the 2007 American Academy of Sleep Medicine (AASM) Manual for the Scoring of Sleep and Associated Events [2]. The calculated sleep statistics included Total Sleep Time (TST) – total time scored as sleep (in minutes), Sleep Efficiency (SE) – percentage of time in bed actually spent sleeping (%), Sleep Onset Latency (SOL) – the time between lights off and the first occurrence of stage N1 sleep (the start of sleep) (in minutes), and Total duration of stage N1, N2, N3 and REM stage (in minutes). Higher sleep efficiency, higher duration of N3 stage, and shorter sleep onset latency indicate higher sleep quality. Due to the limited recording device, the EEG signal of 6 subjects was recorded and analyzed.

Four local skin temperatures (including chest, forearm, anterior thigh, and anterior calf) were continuously measured with a platinum film resistance system developed by our research team [24]. All resistances (accuracy: ±0.1 °C) were connected to a multichannel data acquisition system that automatically collected data with a sampling interval of 10s. Mean skin temperature (MST) was calculated as the sum of local skin temperatures and their respective weight factors [25].

2.1.2.2. Subjective questionnaires. The subjects reported their subjective perception of sleep quality on five numerical scales. They assessed the *calmness of sleep*, *ease of falling asleep*, *ease of awakening*, *freshness after awakening*, and *satisfaction with sleep* (Table 1). Higher score of these items indicate higher sleep quality. A 7-point scale (-3-cold, -2-cool, -1-slightly cool, 0-neutral, 1-slightly warm, 2-warm, 3-hot) was used to register thermal sensation. Thermal comfort was casted on a 6-point scale (-3-very uncomfortable, -2-uncomfortable, -1-slightly uncomfortable, 1-slightly comfortable, 2-comfortable, 3-very comfortable).

2.1.2.3. The neurobehavioral performance tests. Four neurobehavioral tests were presented to subjects in the following order [26–28]: *Overlapping* (a test engaged strategic processes as well as working memory resources in perceptive and spatial reasoning operations), *Picture recognition* (a visual recognition memory and attention test), *Number Calculation* (a mental arithmetical test), and *Choice Reaction Time* (a sustained attention test measuring response speed and accuracy to visual signals). Different versions of tests having similar difficulty level were prepared. The tests were presented on a PC and were self-paced; the reaction/processing time was recorded by the computer clock. Speed (response time) and accuracy (% of corrects) were used as measures of performance.

2.1.3. Experimental conditions and procedure

The experiment was conducted from July to August in Shanghai using two identical climate chambers in which the same thermal environment was controlled [21]. Three conditions were created by changing the air temperature between the three levels: 26 °C, 27 °C, and 28 °C. In our former study 26 °C was shown to be the neutral temperature for sleeping with a total (clothing plus bedcover) insulation of 1.64 clo [8,21]. The temperature of 28 °C was expected and confirmed to be the upper limit temperature for establishment of a comfortably warm environment for sleep [21], and 27 °C was a transitional level between 26 °C and 28 °C. Fig. 1A illustrates the detailed changes of set-point that took place in the two changing-temperature conditions and the C1-Constant-temperature condition that served as the baseline condition. It can