THE EFFECT OF CO_2 CONTROLLED BEDROOM VENTILATION ON SLEEP AND NEXT-DAY PERFORMANCE

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Abstract

Both sleep and good indoor air quality are generally considered to be important for human health and well-being. In the present study, sleep quality and next-day performance were measured in identical single-occupancy dormitory rooms located in a quiet area North of Copenhagen. The 16 international students participating as subjects, half of them women, were sleeping in their own rooms and maintained their habitual life style, with a few restrictions on alcohol and caffeine consumption. The subjects were exposed to two conditions, each for one week, with one high and one low rate of ventilation, resulting in average CO_2 levels of around 835 and 2395 ppm, respectively. A fan controlled by a CO_2 sensor was used to supply outside air to establish the condition with low CO_2 level. In the condition with high CO_2 concentration the fan was switched off. The subjects were instructed to adjust the electric heater that was installed below the window to ensure thermal comfort and average room temperature did not differ between conditions. The indoor environment was assessed based on online morning questionnaires and physical measurements of room air temperature, relative humidity and CO_2 concentration. The subjects' sleep quality and next-day performance were assessed from subjective responses that were obtained by using visual analogue scales and the Groningen Sleep Quality scale, from one test of logical thinking, one diagnostic test of cue-utilisation, and in terms of movement data recorded on wristwatch-type actigraphs.

The results show positive effects of a higher ventilation rate on the subjectively assessed freshness of the air, on the subjects' mental state and their feeling of being rested. There was also a significant and positive effect on the sleep efficiency measured by the actigraphs and the expected significant and positive effect on performance. However, there were some negative effects of the higher ventilation rate on the rated intensity of mouth dryness and skin dryness.

Keywords: indoor air quality, sleep quality, actigraph, ventilation rate, mental performance

1 Introduction

People spend one third of their life sleeping, 12-14 hours/day during infancy and 7-8 hours/day during adulthood. Good sleep is generally considered to be essential for human health and well-being. Many factors are thought to influence sleep quality, among those the indoor environmental quality (IEQ) parameters which include: air temperature and relative humidity, air velocity, particulate matter concentration, illumination level, sound level and ventilation rate. Bekö et al. (2010) reported that 57% of the bedrooms of Danish children did not fulfil the minimum ventilation requirements stipulated in EN 15251 (2007). Studies by Tynjälä et al. (1999) and Meijer et al. (2000) of children in Finland and Holland respectively showed a strong correlation between sleep quality and the ability to concentrate the next day. Both studies show that good and refreshing sleep is an important determinant of general well-being among adolescents.

The effect of air quality on sleep has earlier been examined by the authors of the present paper (Strøm-Tejsen et al., 2014). In the previous study occupants of 14 identical single-occupancy dormitory rooms were exposed to two conditions – open/closed window, each for one week, resulting in night-time average CO_2 levels of 660 and 2585 ppm. Sleep was assessed from movement data recorded on wristwatch-type actigraphs and from online morning questionnaires including the Groningen Sleep Quality scale, questions about the sleep environment, next-day well-being and SBS symptoms, and two tests of mental performance. Although no significant effects on the sleep quality scale or on next-day performance could be shown, there were significant and positive effects of an open window on the actigraph-measured sleep latency and on the subjects' assessment of the freshness of the air, their ability to fall asleep and nasal dryness. There was a negative effect on reported lip dryness.

The objective of the present study was to investigate the effect of CO_2 controlled ventilation on sleep quality and next-day well-being. The working hypothesis was that subjects would sleep better during the night and perform better the following day in the CO_2 controlled ventilation condition.

2 Methods

2.1 Facilities, subjects and experimental conditions

The experiment was performed in 16 identical rooms in the Campus Village at the Technical University of Denmark (DTU) located in Kgs. Lyngby (Copenhagen area). The Campus Village consists of twenty units, each including ten identical simple rooms (3.6 m in length, 3.0 m in width and 2.4 m in height) with one double-framed window located opposite the door. During the experimental period an air vent placed in the outer wall was removed and the hole in the wall was used to provide outside air using an ultra-low noise computer fan controlled by a CO_2 sensor. The fan noise of maximum 22 dB was minimised using a silencer. The rooms were furnished with a sofa/bed, a wardrobe, a desk, and sometimes additional private furniture. Each housing unit includes common toilet, bath and kitchen facilities with mechanical exhaust, creating a negative pressure in the corridor. The 16 subjects from 12 nations, with an equal number of males and females, were exposed to two experimental conditions, ventilation and no ventilation, in a balanced order of exposure, each condition lasting one week. In the condition "ventilation" the fan was turned on when the CO_2 concentration reached approx. 900 ppm, while in the condition "no ventilation" the fan was always switched off. During daytime the subjects were allowed to close or open the window according to their preferences, but the window was closed during the night. They were asked to adjust the electric heater below the window to achieve their preferred thermal condition for sleeping in both conditions, and to maintain their habitual life style, although with restricted alcohol and caffeine consumption.

Students suffering from asthma, allergy, sensitive skin or sleeping disorders, and people smoking or using medication were excluded from the experiment based on information collected in a recruitment questionnaire and a background questionnaire. The background questionnaire was based on the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989), which contains questions about sleeping habits during the past month.

The experiment was performed from Friday the 28^{th} of February to Friday the 4^{th} of April 2014 with minimum outdoor temperatures between -3°C and 4°C at night. The experimental condition in the rooms was changed on Fridays, however, only data from the four nights between Monday and Friday were analysed to allow the subjects to adapt to the condition during the first three nights.

2.2 Physical measurements and questionnaires

Two measuring stations were used, one in the centre of each side wall, to record the air temperature, relative humidity and CO_2 concentration with 5-minute intervals. A HOBO U12-012 data logger measured the air temperature and relative humidity with an accuracy of ± 0.35 K and ± 2.5%, respectively. A Vaisala GM20 CO_2 sensor, calibrated for the range 0-5000 ppm, recorded the CO_2 levels with an accuracy of ± (2% of range + 2% of reading).

***Figure 1**: Philips Actiwatch*

During the two experimental weeks the subjects were asked to wear an actigraph (Figure 1) on the wrist of their non-preferred hand. Actigraphy is a well-established and well-validated method for field studies of sleep (Kushida et al., 2001). It recorded a measure of gross motor activity in each successive minute, a measure that can be used to visualise rest activity patterns and quantify physical activity.

Every morning the subjects were asked to fill in an on-line questionnaire no later than 10 minutes after waking up. It consisted of questions about sleep quality, sleep environment, SBS symptoms, sleep symptoms and well-being the previous day. Two on-line behavioural tests were applied, a Grammatical Reasoning Test (Baddeley, 1968) and the Tsai-Partington Numbers Test (Ammons, 1955), the latter with the modifications introduced by Wyon (1969). The questionnaire included fifteen questions from the Groningen Sleep Quality (GSQ) Scale (Mulder Hajonides et al., 1980) which were to be marked true or false. It also included visual-analogue scales rating 7 aspects of the sleep environment, 13 SBS symptoms, 4 aspects of sleep quality and 2 next-day symptoms. Additional questions were about clothing worn during sleep, reasons for any awakenings, how many times the subjects woke up or got out of bed, and what time they went to bed and woke up.

2.3 Data processing

The measurements of air temperature, relative humidity and CO_2 concentration are assumed to be Normally distributed and are presented in the paper as average, minimum, maximum and standard deviation values. The data from the online morning questionnaire were tested for Normality using the Shapiro-Wilks Test. Data from the Tsai-Partington Numbers Test, Baddeley's Reasoning Test, and the actiwatches were not Normally distributed and the non-parametric Wilcoxon Matched-Pair Signed-Ranks Test was therefore used to analyse the within-subject differences between the two experimental conditions. The P-values reported in the Results section are for a 2-tailed test of the difference between conditions of the 4-day mean values except where otherwise stated.

3 Results and discussion

3.1 Physical measurements of the indoor environment

The average night-time air temperature in the 16 rooms was very similar in both experimental conditions – 21.9°C without ventilation and 21.8°C with ventilation. There were considerable differences between individual subjects, with a minimum average value of 13.7°C and a maximum of 27.7°C. The temperature was on average 0.9 K higher in the condition with ventilation for 6 of the 16 subjects, and 0.5 K lower for the remaining 10 subjects. The female subjects were on average exposed to a 3 K higher temperature than the male subjects which indicates that women might prefer higher bedroom temperatures and therefore adjusted the electric heater in their room to a higher heat output. The same difference of 3 K was found in the previous study by Strøm-Tejsen et al. (2014), which included 7 males and 7 females.

The night-time average values of relative humidity for each subject were in the range between 38% to 69% for the condition without ventilation and 34% to 55% for the condition with ventilation. As expected all subjects experienced lower humidity with ventilation due to the intake of dry outdoor air to the room. The average without ventilation was 52%, and 40% with ventilation. Both of these average values

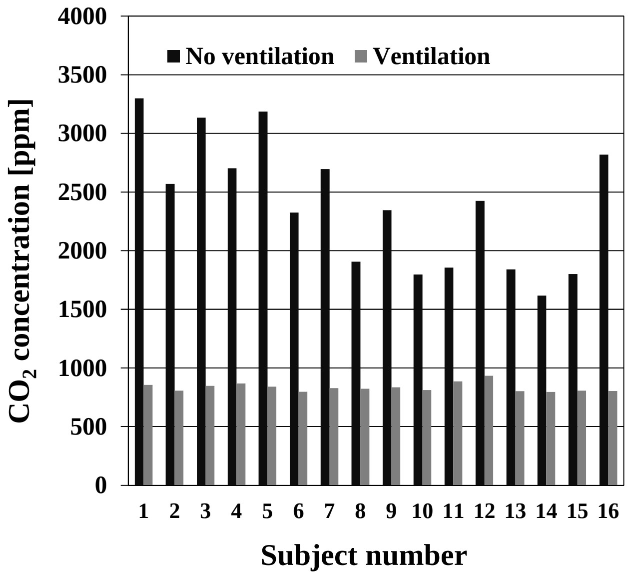

***Figure 2**: Comparison of the CO_2 concentration during night-time, each bar representing a 4-day average*

are well within the range considered comfortable and healthy in dwellings (EN 15251, 2007).

Average night-time values of the **CO_2 concentration** in the 16 rooms during the experiment are shown in Figure 2, documenting the large effect of the intervention. The average values of CO_2 concentration for the individual subjects were between 1620 ppm to 3300 ppm for the condition without ventilation and 795 ppm to 935 ppm when the ventilation was on, giving a total average CO_2 concentration of 2395 ppm and 835 ppm, respectively. This corresponds to a difference of 4-5 times in air exchange rate – approx. 0.24 ACH in the condition without ventilation and 1.1 ACH with ventilation, corresponding to approx. 1.7 and 7.9 l/s/person. The ventilation rate in the condition without ventilation does not meet the requirements for bedrooms given in EN 15251 (2007). The standard recommends 10, 7 and 4 l/s/person for Category I, II and III, respectively.

3.2 Morning questionnaire

The results from the Wilcoxon Signed-Rank Test are summarised in Table 1 where P-values with statistically significant differences are shown in bold. The tests were all 2-tailed except for the hypothesis of improved performance with improved ventilation.

Table 1*: Results from the statistical analysis of the morning questionnaire with P-values from the Wilcoxon Signed-Rank Test*

Variable	P-value	Comments	Variable	P-value	Comments
GSQ SCALE			SBS SYMPTOMS		
Score	0.0664	Better with ventilation	Nasal dryness	0.6417	
SLEEP ENVIRONMENT			Nose blocked	0.5014	
Temperature	0.2663		Mouth dryness	**0.0386**	**More dry with ventilation**
Air humidity	0.3520		Skin dryness	**0.0299**	**More dry with ventilation**
Freshness of air	**0.0052**	**More fresh with ventilation**	Eye dryness	0.6603	
Air movement	0.2052		Eye clearness	0.2052	
Noise	0.2775		Lip dryness	0.1961	
Illumination	0.2220		Thirst	0.5321	
Isolation of cover	0.3388		Headache	0.6417	
SLEEP SYMPTOMS			Mental state	**0.0174**	**Better with ventilation**
Quality of sleep	0.9176		Alertness	0.9176	
Duration of sleep	0.9176		Rested	**0.0465**	**Rested with ventilation**
Lightness of sleep	0.3936		Wellbeing	0.0703	Better with ventilation
Ability to fall asleep	0.2775		BADDELEY'S TEST		
NEXT-DAY SYMPTOMS			Score (1-tail test)	**0.0368**	**Better with ventilaton**
Sleepiness	0.0703	Less sleepy with ventilation	TSAI-PARTINGTON TEST		
Ability to concentrate	0.3520		Score	0.2330	

P-values are 2-tailed. Bold: P<0.05.

Results for the variables with statistically significant differences and with a clear tendency are presented graphically as quartiles in Figures 3-10. Each box represents the interquartile range, and the horizontal line dividing the box is the median.

The difference between conditions on the **Groningen Sleep Quality** (GSQ) Scale did not reach significance (P<0.0664), although there was a tendency for the subjects to report sleeping better with ventilation (Figure 3). A similar (non-significant) tendency was found in the previous study by Strøm-Tejsen et al. (2014).

The results of the statistical analysis of the assessments of the **Sleep environment**, show a significant difference only for **Freshness of air** (P<0.0052), see Figure 4. The subjects reported the air to be fresher in the condition with ventilation, as expected, since the experiment took place in a residential area away from possible sources of outdoor pollution.

The statistical analysis of reported **Sleep symptoms** did not show significant differences. There were no significant effects of the intervention on the **Next-day symptoms**, but there was an almost significant tendency for the subjects to feel less sleepy (P<0.0703) the day after sleeping with the ventilation running (Figure 5).

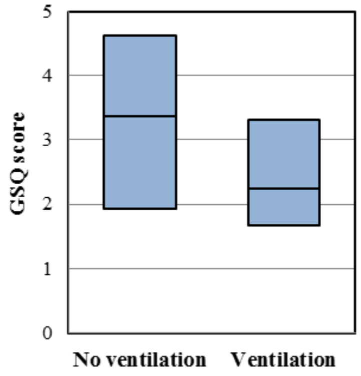

Figure 3: Score from the GSQ scale

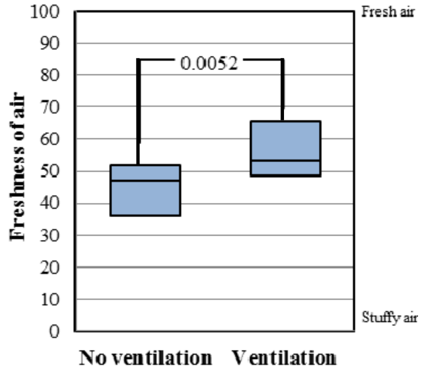

Figure 4: Ratings of freshness of air

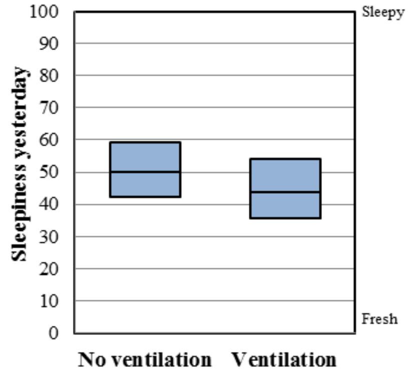

Figure 5: Ratings of next-day sleepiness

In the **SBS symptoms** section, there were statistically significant differences between the two conditions for two out of 13 symptoms – **Mouth dryness** ($P<0.0386$) and **Skin dryness** ($P<0.0299$), see Figures 6 and 7. The subjects felt both their mouth and skin to be drier with ventilation, which may be due to the slightly but consistently lower relative humidity in this condition.

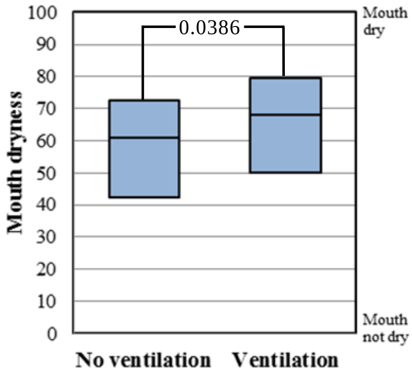

Figure 6: Ratings of mouth dryness

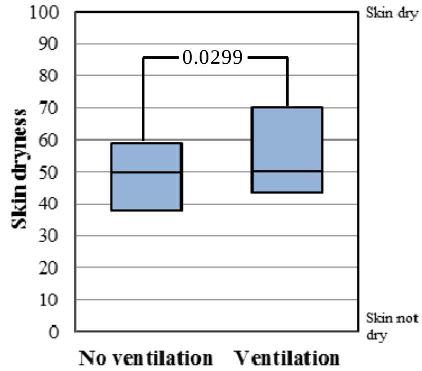

Figure 7: Ratings of skin dryness

The subjects reported their **Mental state** ($P<0.0174$) to be better and they felt more **Rested** ($P<0.0465$) in the condition with ventilation, see Figures 8 and 9. Although not statistically significant ($P<0.0703$), there was a tendency for better **Well-being** in the condition with ventilation (Figure 10).

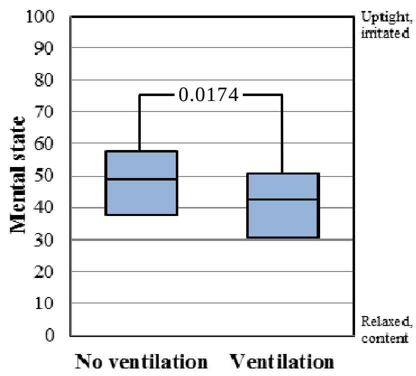

Figure 8: Ratings of mental state

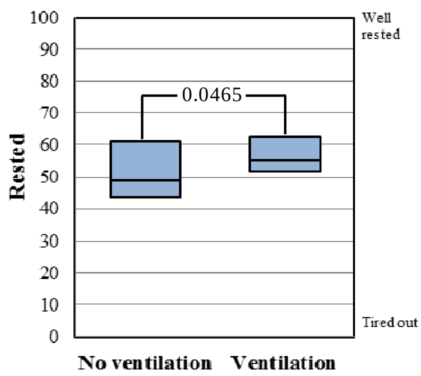

Figure 9: Ratings of being rested

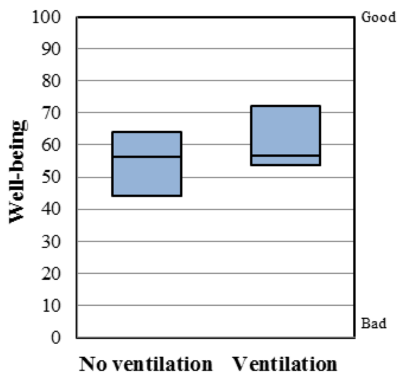

Figure 10: Ratings of well-being

The statistical analysis of Baddeley's Grammatical Reasoning Test showed that there was a significant tendency for the subjects to perform better (P<0.0368, 1-tail test), as expected, the day after sleeping with improved ventilation. There was no effect of the intervention on the Tsai-Partington Test, and no trends were apparent in the quartile graph (not shown).

3.3 Actigraph data

The results from the statistical analysis of the actigraph data are shown in Table 2, where sleep duration is the time spent sleeping, excluding intervening periods spent awake; sleep latency is the time required to fall asleep; snooze time is the time required to become active after finally awakening; sleep efficiency is the percentage of time in bed spent asleep. It was not possible to predict how sleep would be improved by ventilation, so all the tests are 2-tailed.

Table 2*: P-values obtained from the Wilcoxon Signed-Rank Test for the actigraph data*

Variable	P-value	Comments
ACTIWATCH DATA		
Sleep duration	0.8971	
Sleep latency	0.2553	
Snooze time	0.9382	
Sleep efficiency	**0.0494**	**Efficient when ventilation**
No. of awakenings	0.1627	

All P-values are 2-tailed. Bold: P<0.05.

The results show a significant improvement for **Sleep efficiency** (P<0.0494). Having established subjectively that the subjects felt more rested and objectively that sleep efficiency was improved by having the ventilation running, it is reasonable to expect less next-day sleepiness. It is then appropriate to use a 1-tail P-value as an estimate of the probability of the observed change, in which case a significant improvement was found for next-day sleepiness (P<0.0368).

3.4 Experimental design

The study was performed in the normal sleeping environment of the subjects. This was made possible by using actigraphy and online questionnaires. Although this added to the realism of the study, the physical parameters of the sleep environment were not fully controlled. Confounding occurred because the higher ventilation rate provided by such a simple system affects the relative humidity as well as the air quality. Although no significant difference was found for Noise or Draught between the two conditions, there is no guarantee that the subjects had not noticed any noise from the fan or become aware of the increased air movement. It can therefore not be assumed that the subjects were fully blinded to the intervention. This study was of the effects of a simple intervention, one that can be made in most bedrooms, namely adding a fan controlled by a CO_2 sensor.

Any bias caused by variables such as the outdoor noise level, and indoor and outdoor pollution sources was reduced by using identical student dormitory rooms and a within-subject design. The rooms were designed for single occupancy so there was no disturbance from other people in the rooms. However, the student lifestyle, with no regular schedule during the week, will have increased individual variation and thus reduced the probability of obtaining significant results.

4 Conclusion

The measurements of CO_2 concentration in the rooms showed a marked difference between the two conditions – a night-time average of 2395 ppm in the condition without ventilation and 835 ppm with ventilation, with no difference for the measured indoor air temperature, so the objective of the intervention was achieved.

Supplying air using a CO_2 controlled fan had a significant positive effect on the assessed freshness of air. The lower relative humidity in the ventilation condition resulted in more mouth and skin dryness.

The subjectively assessed mental state and the subjects' feeling of being rested were significantly greater in the condition with ventilation. The Groningen Sleep Quality Scale showed a tendency for the subjects to sleep better with ventilation, a result supported by the actigraphy data.

The subjects also reported feeling less sleepy the day after sleeping with the ventilation running, and their objectively measured performance of a logical reasoning task improved.

5 Acknowledgement

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