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The effects of bedroom air quality on sleep and next-day performance

Abstract The effects of bedroom air quality on sleep and next-day performance were examined in two field-intervention experiments in single-occupancy student dormitory rooms. The occupants, half of them women, could adjust an electric heater to maintain thermal comfort but they experienced two bedroom ventilation conditions, each maintained for 1 week, in balanced order. In the initial pilot experiment (N = 14), bedroom ventilation was changed by opening a window (the resulting average CO_2 level was 2585 or 660 ppm). In the second experiment (N = 16), an inaudible fan in the air intake vent was either disabled or operated whenever CO_2 levels exceeded 900 ppm (the resulting average CO_2 level was 2395 or 835 ppm). Bedroom air temperatures varied over a wide range but did not differ between ventilation conditions. Sleep was assessed from movement data recorded on wristwatch-type actigraphs and subjects reported their perceptions and their well-being each morning using online questionnaires. Two tests of next-day mental performance were applied. Objectively measured sleep quality and the perceived freshness of bedroom air improved significantly when the CO_2 level was lower, as did next-day reported sleepiness and ability to concentrate and the subjects' performance of a test of logical thinking.

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Practical Implications

It is often possible to select bedroom air temperature at will, but in bedrooms with the window closed for energy conservation and the internal door closed for privacy, the effective ventilation rate is often so poor that CO_2 levels routinely exceed 2500 ppm. This occurs in cold or temperate regions and certainly also in air-conditioned bedrooms in hot-humid regions. This field experiment was the first to examine how bedroom air quality affects sleep and next-day performance. It was shown that both can be significantly improved by increasing the clean outdoor air supply rate in bedrooms. In cold and temperate regions, this could be achieved at low energy cost and with no loss of privacy by installing outdoor air inlets with counter-flow heat exchange in each bedroom, the air exchange being controlled by the CO_2 level in the exhaust flow. However, it should be remembered that in some areas noise attenuation and pollution removal technology might then become necessary and that in such areas, the simpler solution of opening a window might have a negative effect on sleep.

Introduction

People spend one-third of their life sleeping, 12–14 h/day during infancy and 7–8 h/day during adulthood, so this may well be essential to human health and well-being. Preferred bedroom temperatures vary widely as a function of sleepwear, bedcover insulation and drape, and mattress insulation, with a trade-off between what is thermally comfortable for sleep and for other activities in the bedroom while not asleep. However, bedrooms with the doors and windows closed for acoustic privacy and energy conservation are often very poorly ventilated indeed, and according to the association Sleep America (2004), 43% of school-age children under 10 have a TV set in their bedroom, and 11% have a computer. Both have been shown to contribute air pollution to indoor air (Bakó-Biró et al., 2002; Nakagawa et al., 2003). Bekö et al. (2010) recently reported that the outdoor air supply rate in 57% of the bedrooms of Danish children was lower than the minimum ventilation requirements stipulated in EN 15251:2007(E) for dwellings in general, and in a study of typical Belgian houses by Laverge and Janssens (2011), it was estimated that exposure to poor air quality is up to 16 times higher in the bedroom. If bedroom air quality affects sleep, there might be negative effects on next-day performance, as studies by Tynjälä et al. (1999) and Meijer et al. (2000) among children in Finland and Holland, respectively, showed a strong correlation between sleep quality and the ability to concentrate the next day.

Laverge et al. (2012) asked 22 students to sleep in their dormitory room either with the window open (high ventilation rate) or with the window closed (low ventilation rate). CO_2 concentration, air temperature, and relative humidity were measured throughout. Sleep duration and quality were assessed using actigraphy, and the subjects completed a questionnaire every morning to report their sleep quality. Sleep efficiency (proportion of time in bed spent asleep) tended to be less when windows were open, which is an unexpected result, but neither this nor any other effect of the intervention on the actigraphy data reached significance and as subjects were aware that the window was open, the reported effects on subjectively perceived sleep quality could have been due to expectation. In laboratory experiments in which a small flow of outdoor air was supplied directly to the breathing zone (personal ventilation), Lan et al. (2013) found that this reduced the time it took elderly subjects to fall asleep, and Zhou et al. (2014) found that heart-rate variability during sleep was reduced, from which they concluded that subjects slept more soundly. In their review of the literature on IAQ effects on sleep, Urlaub et al. (2015) concluded that no other studies of IAQ effects on sleep had been reported. The present field study was undertaken to investigate the effect of bedroom air quality on sleep and next-day performance, using an approach that was very similar to that used by Laverge et al. (2012).

Methods

Facilities and subjects

Two different experiments were performed in the identical rooms of the Campus Village at the Technical University of Denmark (DTU), which is situated in a temperate region. 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. It is situated in a quiet area with clean ambient air. The rooms are furnished with a sofa/bed, a wardrobe, a desk, and sometimes additional private furniture. Each housing unit has common toilet, bath, and kitchen facilities with mechanical exhaust, creating a negative pressure in the corridor. There is normally a small air vent in the outside wall of each room, but this was manipulated in each experiment. An equal number of males and females took part in each experiment. They were reminded that they could adjust the electric heater below the window to achieve their preferred thermal condition for sleeping, and were asked to maintain their normal life style, although with restricted alcohol and caffeine consumption. They were therefore free to choose their preferred sleeping attire and bedcover insulation and neither bedtime nor sleeping duration was stipulated, in strong contrast to what is imposed in most laboratory experiments on sleep. Any occupant suffering from asthma, allergy, sensitive skin, or sleeping disorders, and those who either smoked or used medication were excluded, based on 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 and whether the subject had experienced anything unexpected or traumatic that might be expected to affect sleep. No subject was excluded on the basis of their replies to these questions, and each experimental period was in the middle of term with no examinations pending.

Experimental design

Pilot experiment. Twenty dormitory occupants from 10 nations participated in a pilot experiment, although usable data were obtained from only 14 subjects: data from two subjects were excluded because they included nights in which one subject did not return to the dormitory until the small hours and one subject did not always sleep alone; data from the other four subjects were missing because they forgot to complete the morning questionnaire on the computer or the computer malfunctioned or because CO_2 data were not obtained when power to both sensors had been unintentionally switched off. The air vents in the outside wall were sealed, and each subject was exposed to two experimental conditions, open and closed window, in balanced order of exposure, each condition lasting 1 week. Balanced order of exposure in this context means that half of the subjects, randomly selected, experienced the open-window condition first. In the 'open-window condition' one window sash was held open at night by a 10-cm-long plastic window stay. In the daytime, the subjects could close or open the window according to their preferences. The experiment was performed in September to December 2012 when outdoor minimum air temperatures varied between −7 and 11°C. The experimental condition in the rooms was changed on Saturdays. Data from the four nights between Monday and Friday were used in the analysis.

Main experiment. Sixteen dormitory occupants from 12 nations participated in the main experiment. The air vent in the outer wall was removed and the hole in the wall was used to supply outdoor air mechanically, using an ultra-low noise computer fan controlled by a CO_2 sensor. The fan noise, usually 22 dBA, was further reduced by fitting a silencer. When questioned, some of the subjects reported hearing the fan occasionally, but none of them knew that it was being used to provide more outdoor air to the room. When conditions were changed, the fan was switched on or off from outside each room at a time when nobody was there. The subjects were thus blind to condition. Each subject was exposed to two experimental conditions, ventilation and no ventilation, in balanced order of exposure, each condition lasting 1 week. In the condition 'ventilation' the fan was turned on whenever the CO_2 concentration rose to approx. 900 ppm, while in the condition 'no ventilation' the fan was off and the air intake was sealed. The windows were closed at night but in the daytime the subjects could close or open the window according to their preferences. The experiment was performed in February to April 2014 when outdoor minimum air temperatures varied between −3 and 4°C. The experimental condition in the rooms was changed on Fridays. Data from the four nights between Monday and Friday were used in the analysis.

Physical measurements and questionnaires

Two measuring stations were used, one in the center of each side wall, to record the air temperature, relative humidity, and CO_2 concentration at 5-min intervals. No noise measurements were made inside or outside the room. A miniature data logger (HOBO U12-012) recorded the air temperature and relative humidity with an accuracy of ±0.35 K and ±2.5%, respectively, and the signal from a CO_2 sensor (Vaisala GM20), calibrated for the range 0–5000 ppm, with an accuracy of ±(2% of range + 2% of reading). The ventilation rates were calculated from the CO_2 concentration at steady-state and the CO_2 generation from each person, the latter based on an activity level of 0.7 MET (sleeping), a standard respiratory quotient of 0.83, and the DuBois body surface area of the subjects. The maximum CO_2 concentration during the night was used if no steady-state concentration was reached. Steady state was always reached in the better-ventilated condition but in the poorly ventilated condition it was reached only when the room had been occupied for some time before bedtime, with the door closed.

Fig. 1 Philips Actiwatch 2

During the two experimental weeks, the subjects agreed to wear a wrist-watch-type actigraph (Figure 1) on the non-preferred side (Philips Actiwatch). This is a well-established method for field studies of sleep (Kushida et al., 2001; Sadeh et al., 1995). The actigraph recorded arm movement in each 30-s period as a measure of gross motor activity. The software supplied with this instrument can distinguish between rest and waking.

Each morning, the subjects spent about 3 min completing an online questionnaire, starting within 10 min of waking up. Two online performance tests were then applied, the Tsai–Partington numbers test (Ammons, 1955), lasting about 3 min, then a Grammatical Reasoning Test (Baddeley, 1968) lasting about 4 min, the former applied in the three versions introduced by Wyon (1969). The questionnaire included fifteen questions from the Groningen Sleep Quality (GSQ) Scale (Mulder-Hajonides van der Meulen et al., 1980), asking about different aspects of good quality sleep, to be marked true or false. It also included visual analog scales shown in Table 1, on which subjects rated seven aspects of the sleep environment, including Perceived Air Quality (PAQ), 13 SBS symptoms, four aspects of perceived sleep quality, and two next-day symptoms. Additional questions asked about clothing worn dur-

Table 1 Visual analog scales used in the questionnaire

Variable	Scale endpoints	
Sleep environment		
Temperature	Too hot	Too cold
Air humidity	Too humid	Too dry
Freshness of air	Stuffy air	Fresh air
Draught	Draughty	Stagnant air
Noise	Quiet	Noisy
Illumination	Too bright	Too dark
Temperature of cover	Too warm	Too cold
Symptoms		
Nasal dryness	Nose dry	Nose running
Nose blocked	Nose blocked	Nose clear
Mouth dryness	Mouth dry	Mouth not dry
Skin dryness	Skin dry	Skin not dry
Eye dryness	Eyes dry	Eyes not dry
Eye clearness	Eyes clear	Eyes gummed up
Lip dryness	Lips not dry	Lips dry
Thirst	Very thirsty	Not thirsty at all
Headache	No headache	Severe headache
Mental state	Uptight, irritated	Relaxed, content
Alertness	Alert	Sleepy
Rested	Well rested	Tired out
Wellbeing	Good	Bad
Sleep symptoms		
Quality of sleep	Very poorly	Very well
Duration of sleep	More than enough	Very little
Lightness of sleep	Very deeply	Very lightly
Ability to fall asleep	Very easy	Very difficult
Next-day symptoms		
Sleepiness	Fresh	Sleepy
Ability to concentrate	Hard to concentrate	Easy to concentrate

ing 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.

Data processing

The measurements of air temperature, relative humidity, and CO_2 concentration were assumed to be normally distributed and are presented in the paper as average and SD values. Subjects were compared only with themselves, between conditions. 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 so the nonparametric Wilcoxon matched-pair signed-ranks test was used. The *P*-values reported in the Results section are for a two-tailed test of the difference between conditions in the 4-day mean values. Where a directional hypothesis was justified, the two experiments could be regarded as independent tests of the same hypothesis and the one-tail *P*-values were combined: Fisher (Winer, 1962) has shown that the sum of their natural logarithms is equal to $-0.5 \times$ chi-square, with 2 df for each experiment.

Results

Bedroom T

In the pilot experiment, bedroom air temperatures averaged 23.9°C with the window closed, 24.7°C when it was open (i.e. opening a window did not reduce air temperature). The nightly average value was calculated for the period when actigraph data indicated that the subject was asleep. The thermostat settings selected by each subject resulted in mean temperatures that varied widely between subjects (16.3-27.8°C) and were about 3 K higher for female subjects. In the main experiment, bedroom temperatures averaged 21.9°C without ventilation and 21.8°C with ventilation (i.e. no effect of fan operation) and ranged from 13.7–27.7°C. Female subjects again selected temperatures about 3 K higher on average. Mean and SD values for the four nightly average values measured for each subject in each experiment and condition are shown in Table 1, separately for male and female subjects. There were no significant differences in bedroom temperature between conditions in a within-subjects analysis of either experiment ($P \geq 0.10$).

Bedroom RH

In the pilot experiment, RH was 54% with windows closed, 40% with windows open, on average. In the main experiment, average RH was 52% without ventilation, 40% with ventilation. Bedroom RH was thus slightly lower in the better-ventilated conditions, as expected. Mean and SD values are shown in Table 2.

Bedroom CO_2

Pilot experiment. The average values of the CO_2 concentration in each room when subjects were sleeping are shown in Figure 2. They ranged from 1730 to 3900 ppm with the window closed and from 525 to 840 ppm with the window open. Some of the variation between subjects will have been due to differences in wind speed and direction affecting infiltration, but the main source of the variation was

Table 2 Mean temperature (°C) and relative humidity (%) for each experiment and condition

Experiment	Pilot experiment				Main experiment			
	Window closed		Window open		Ventilation off		Ventilation on	
Condition	Average	s.d.	Average	s.d.	Average	s.d.	Average	s.d.
Females								
Temperature	25.1	1.7	26.5	1.9	23.4	2.5	23.1	1.6
RH	52.5	6.9	36.2	8.1	50.2	9.1	37.7	2.6
Males								
Temperature	22.6	2.9	22.8	3.8	20.3	3.4	20.4	4.1
RH	55.5	10.2	44.2	9.8	54.7	8.9	41.8	7.8

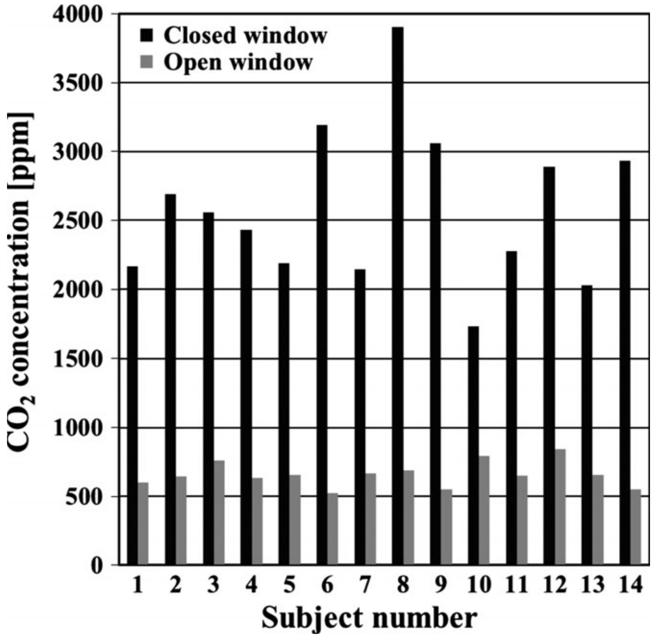

Fig. 2 Pilot experiment: comparison of the CO_2 concentration during night-time, each bar representing a 4-day average

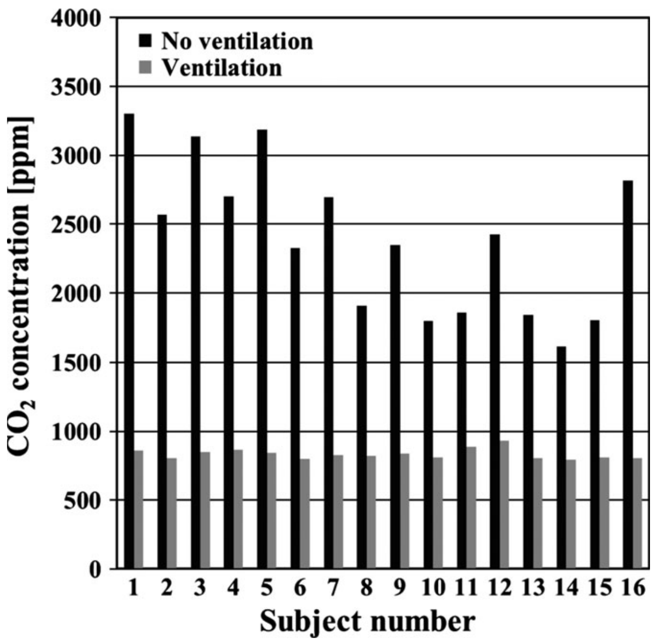

Fig. 3 Main experiment: comparison of the CO_2 concentration during night-time, each bar representing a 4-day average

the time for which the room had been occupied prior to bedtime. The average CO_2 concentration was 2585 ppm in the closed-window condition and 660 ppm in the open-window condition. The air exchange rate was 10 times greater with the window open: 0.17 ACH with closed window, 1.8 ACH with the window open, or 1.2 and 13 l/s/person.

Main experiment. Average values of the CO_2 concentration in each room during the period that each subject was asleep are shown in Figure 3. They ranged from 1620 to 3300 ppm without ventilation and from 795 to 935 ppm with ventilation. The average CO_2 concentration in each condition was 2395 ppm and 835 ppm, respectively. The difference in air exchange rate between the conditions was 4–5 times: 0.24 ACH without ventilation and 1.1 ACH with ventilation, or 1.7 and 7.9 l/s/person. The ventilation rate without ventilation was lower than the minimum for bedrooms stipulated in EN 15251:2007(E).

Morning questionnaire

Pilot experiment. When the window was open, subjects considered the bedroom air to be more fresh ($P < 0.0010$) and reported falling asleep more easily ($P < 0.0303$), although it should be remembered that they knew when the window was open. When it was, subjects reported less nasal dryness ($P < 0.0480$) and more lip dryness ($P < 0.0413$) and tended to report more air movement ($P < 0.0555$, NS). Using two-tail tests, no other subjective ratings differed significantly between conditions, but their ratings suggested that they tended to be less sleepy the morning after a night with the window open ($P < 0.0516$). The median and quartile values are shown in Table 3.

Main experiment. When the fan in the air intake was in operation, subjects reported that the air had been fresher ($P < 0.0052$), that they felt better in general ($P < 0.0174$), and that they felt more rested ($P < 0.0465$), although they also reported more mouth dryness ($P < 0.0386$) and more skin dryness ($P < 0.0299$) in this condition. Using two-tail tests, no other subjective ratings differed significantly between conditions, but subjects again tended to be less sleepy the morning after a night with the fan running ($P < 0.0703$). The median and quartile values are shown in Table 4.

Actigraph data

The actigraph data were analyzed in terms of sleep duration, the time spent sleeping, excluding intervening periods spent awake; sleep latency, the time required to fall asleep; snooze time, the time required to become active after finally awakening; and sleep efficiency, the percentage of time in bed spent asleep.

Pilot experiment. Sleep latency improved significantly ($P < 0.0480$); that is, subjects fell asleep more rapidly with the window open. There was a (non-significant) tendency for sleep efficiency to be better in this condition ($P < 0.0736$).

Table 3 Subjective assessments for all subjects from the pilot experiment

Variable Scale endpoint values	Freshness of air ($P < 0.0010$) 100: Fresh air 0: Stuffy air		Air movement ($P < 0.0555$) 100: Draughty 0: Stagnant		Ability to fall asleep ($P < 0.0303$) 100: Very easy 0: Very difficult		Next-day sleepiness ($P < 0.0516$) 100: Sleepy 0: Fresh		Nasal dryness ($P < 0.0480$) 100: Nose dry 0: Nose running		Lip dryness ($P < 0.0413$) 100: Lips dry 0: Lips not dry	
Condition	Window closed	Window open	Window closed	Window open	Window closed	Window open	Window closed	Window open	Window closed	Window open	Window closed	Window open
75% quartile	40.3	71.3	49.8	68.6	72.4	84.6	56.6	42.3	72.6	65.7	70.1	71.0
Median	34.5	67.5	46.3	54.0	60.5	74.8	45.4	38.9	66.5	55.6	61.0	66.5
25% quartile	27.1	58.6	34.6	49.6	51.8	61.8	30.9	28.4	58.4	50.8	49.7	60.2

Table 4 Subjective assessments for all subjects from the main experiment

Variable Scale endpoint values	Freshness of air ($P < 0.0052$) 100: Fresh air 0: Stuffy air		Mental state ($P < 0.0174$) 100: Uptight 0: Relaxed		Rested ($P < 0.0465$) 100: Well rested 0: Tired out		Next-day sleepiness ($P < 0.0703$) 100: Sleepy 0: Fresh		Mouth dryness ($P < 0.0386$) 100: Mouth dry 0: Mouth not dry		Skin dryness ($P < 0.0299$) 100: Skin dry 0: Skin not dry	
Condition	Ventilation off	Ventilation on	Ventilation off	Ventilation on	Ventilation off	Ventilation on	Ventilation off	Ventilation on	Ventilation off	Ventilation on	Ventilation off	Ventilation on
75% quartile	51.9	65.4	57.6	50.8	61.0	62.6	59.1	54.1	72.4	79.7	59.2	70.4
Median	47.0	53.5	48.9	42.6	48.8	55.1	50.1	43.8	61.0	68.0	49.9	50.1
25% quartile	36.1	48.6	37.4	30.5	43.6	51.7	42.1	35.7	42.4	50.1	37.8	43.3

Main experiment. Sleep efficiency was significantly better when the fan was in operation ($P < 0.0494$); that is, subjects spent a greater percentage of their time in bed asleep. The two experiments can be regarded as independent tests of the same directional hypothesis, namely that sleep efficiency improved with outdoor air supply rate. Combining the one-tail P-values by Fisher's method yields chi-square on 4df = 14.01 ($P < 0.01$). The (non-significant) tendency reported by Laverge et al. (2012, op.cit.) was in the opposite direction, but is likely to have been either due to chance or to noise from outside the building having had a more disturbing effect on sleep with the window open.

Table 5 Baddeley's test of grammatical reasoning (unit correctly completed)

Experiment Condition	Pilot experiment ($P < 0.1579$)		Main experiment ($P < 0.0736$)	
	Window closed	Window open	Ventilation off	Ventilation on
75% quartile	14.0	14.0	14.9	15.4
Median	13.0	13.4	14.0	14.3
25% quartile	12.0	12.8	13.1	13.6

Groningen Sleep Quality Scale (GSQ)

The GSQ values obtained did not differ significantly between conditions in either experiment (two-tail P-values were 0.1080 and 0.0664, respectively), but the tendency was in the same direction in each case. The two experiments can be regarded as independent tests of the same directional hypothesis, namely that sleep quality is better when bedroom IAQ is better, and the one-tail P-values can then be combined. This yields chi-square on 4df = 12.65 ($P < 0.02$), confirming the significant effects on subjectively assessed sleep that were reported by Laverge et al. (2012).

Reproducibility of the subjective findings

Although some reported sensations of dryness did apparently differ between conditions in both experiments, none did so consistently in both and so should probably be discounted, but it is logical that increased air movement would be reported only when a window was open. Given the objective actigraph findings, it is logical that subjects should report falling asleep more quickly only when they did (in the open-window condition) and should report feeling more rested and generally better only in the main experiment (with the window closed to decrease external noise) in which sleep efficiency increased. As the results for next-day sleepiness and ability to concentrate were reproducible, they can be re-examined even though they did not reach significance in either experiment. The two experiments can be regarded as independent tests of the same directional hypotheses, namely that subjects felt less sleepy and better able to concentrate after sleeping under conditions in which their sleep efficiency improved. Combining P-values given above for next-day sleepiness yields chi-square on 4df = 14.01 ($P < 0.01$). A similar analysis of the reported ability to concentrate (for which two-tail P-values of 0.0806 and 0.3520 were obtained, respectively) yields chi-square on 4df = 9.90 ($P < 0.05$).

Next-day performance

Logical thinking. Using two-tail tests, there were no formally significant effects of condition on Baddeley's test of grammatical reasoning in either experiment. However, combining these P-values (0.1579 and 0.0736, respectively) to estimate the probability that the ability to think logically was better after sleeping under conditions in which sleep efficiency improved yields chi-square on 4df = 11.68 ($P < 0.02$). The median and quartile values of the performance units correctly completed out of 16 possible are shown in Table 5.

Tsai–Partington. There were no significant differences between conditions on this test of cue utilization.

Discussion

In two independent field-intervention experiments, bedroom air quality was improved and the effects of the interventions on sleep, next-day questionnaire responses, and next-day performance were assessed. Opening a window in the pilot experiment will have allowed noise from outside the building to disturb sleep rather more than in the closed-window condition and will have allowed any wind to increase draughts, but these changes would be expected to reduce the beneficial effect of improved air quality on sleep, so the beneficial effects observed in the open-window condition can be attributed to the change in bedroom air quality. In the main experiment, bedroom air quality was improved covertly, with no perceptible change in bedroom noise or draught, so any differences between conditions may confidently be attributed to improved bedroom air quality. There is no doubt that both interventions did improve bedroom air quality – the effective outdoor air supply rate was found to be greater by a factor of at least 10 if the window was open and by a factor of at least four if an air supply fan was covertly operated whenever the CO_2 concentration was above 900 ppm. This led to a significant improvement in the subjects' own ratings of perceived air quality (PAQ). Improving bedroom air quality was hypothesized to improve sleep, and objective measures of sleep obtained by analyzing actigraph data confirmed this hypothesis, extending the findings of Lan et al. (2013 op.cit.) and Zhou et al. (2014 op.cit.) from personal ventilation to bedroom ventilation. It was possible to show that responses to the well-established Groningen Sleep Quality scale indicated that sleep quality improved with bedroom air quality and that the subjects' own rating of next-day sleepiness and ability to concentrate differed significantly between conditions in the expected direction. Given these findings, it is reasonable to hypothesize that next-day performance would be better after sleeping in the conditions that provided better bedroom air quality. It was possible to show that this was the case, apparently for the first time. The size of the IAQ effect was about 3%. However, considerably more research is required before this preliminary finding in a quiet area with clean air can be generalized from students to the general population and to other climatic regions.

There were no significant differences between conditions in perceived T or RH, yet in both experiments, subjects reported significantly more symptoms that are normally attributed to dry air in the better-ventilated condition. In the open-window experiment, there was an almost significant tendency for subjects to report more air movement (two-tail $P < 0.0555$), but this was not found in the experiment in which a small fan was operated intermittently, nor would it be expected, so air movement is not an adequate explanation. Objectively measured RH did not fall below 40% in either condition, so it seems unlikely that the decrease from 52% or 54% caused by the intervention could have been responsible for the associated increase in reported skin, lip, and mouth dryness. As increasing the outdoor air supply rate undoubtedly increased the concentration of whatever pollutants were present in outdoor air, including ozone, this may have been the cause of these symptoms. It should be remembered that bedroom air temperatures varied widely between subjects but did not differ between conditions and that symptoms attributed to air dryness can often be alleviated by reducing the air temperature.

Conclusions

It has been shown that when bedroom air quality was improved in these experiments:

- Subjects reported that the bedroom air was fresher.
- Sleep quality improved.
- Responses on the Groningen Sleep Quality scale improved.
- Subjects felt better next day, less sleepy, and more able to concentrate.
- Subjects' performance of a test of logical thinking improved.

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References

Ammons, C.H. (1955) Task for the study of perceptual learning and performance variables, *Percept. Mot. Skills*, **5**, 11–1.

Baddeley, A.D. (1968) A 3-min reasoning test based on grammatical transformation, *Psychon. Sci.*, **10**, 341–342.

Bakó-Biró, Zs., Wargocki, P., Weschler, C.J. and Fanger, P.O. (2002) Personal computers pollute indoor air: effects on perceived air quality, SBS symptoms and productivity in offices. In: Proceedings of Indoor Air 2002, Monterey, Vol 2, pp. 249–254.

Bekö, G., Lund, T., Nors, F., Toftum, J. and Clausen, G. (2010) Ventilation rates in the bedrooms of 500 Danish children, *Build. Environ.*, **45**, 2289–2295.

Buysse, D.J., Reynolds, C.F. III, Monk, T.H., Berman, S.R. and Kupfer, D.J. (1989) The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research, *J. Psychiatr. Res.*, **28**, 193–213.

EN 15251:2007(E). *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. CEN, Brussels.

Mulder-Hajonides van der Meulen, W.R.E.H., Wijnberg, J.R., Hollander, J.J., De Diana, I.P.F. and van den Hoofdakker, R.H. (1980) Measurement of subjective sleep quality, *Eur. Sleep Res. Soc. Abstr.*, **5**, 98.

Kushida, C.A., Chang, A., Gadkary, C., Guilleminault, C., Carrillo, O. and Dement, W.C. (2001) Comparison of actigraphic, polysomnographic and subjective assessment of sleep parameters in sleep-disordered patients, *Sleep Med.*, **2**, 389–396.

Lan, L., Lian, Z., Zhou, X., Sun, C., Huang, H., Lin, Y. and Zhao, J. (2013) Pilot study on the application of bedside personalized ventilation to sleeping people, *Build. Environ.*, **67**, 160–166.

Laverge, J. and Janssens, A. (2011) IAQ exposure of sleeping occupants under different residential ventilation configurations. In: Proceedings of Roomvent 2011, Trondheim, Paper 125.

Laverge, J., Novoselac, A., Corsi, R. and Janssens, A. (2012) Experimental assessment of ventilation in the bedroom: physiological response to ventilation and impact of position on rebreathing. In: Proceedings of the 5th IBPC, Kyoto, Japan, May 28–31.

Meijer, A.M., Habekothé, H.T. and van den Wittenboer, G.L. (2000) Time in bed, quality of sleep and school functioning of children, *J. Sleep Res.*, **9**, 145–153.

Nakagawa, T., Wargocki, P., Tanabe, S., Weschler, C.J., Baginska, S., Bakó-Biró, Zs. and Fanger, P.O. (2003) Chemical emission rates from personal computer. In: Proceedings of Healthy Buildings 2003, Singapore, Vol 1, pp. 468–473.

Sadeh, A., Hauri, P.J., Kripke, D.F. and Lavie, P. (1995) The role of actigraphy in the evaluation of sleep disorders, *Sleep*, **18**, 288–302.

Sleep America (2004) *Survey of Children's Sleeping Habits and Arrangements*, USA, National Sleep Foundation.

Strøm-Tejsen, P., Wargocki, P., Wyon, D.P. and Kondracka, A. (2014a) The effect of air quality on sleep. In: Proceedings of Indoor Air 2014, Hong Kong, Paper HP0506.

Strøm-Tejsen, P., Wargocki, P., Wyon, D.P. and Zukowska, D. (2014b) The effect of CO_2 controlled bedroom ventilation on sleep and next-day performance. In: Proceedings of Roomvent 2014, Sao Paulo, Brazil, Paper 148.

Tynjälä, J., Kannas, L., Levälahti, E. and Välimaa, R. (1999) Perceived sleep quality and its precursors in adolescents, *Health Promot. Int.*, **14**, 155–166.

Urlaub, S., Grün, G., Foldbjerg, P. and Sedlbauer, K. (2015) The influence of the indoor environment on sleep quality. In: Proceedings of Healthy Buildings Europe 2015, Eindhoven, NL, Paper 650.

Winer, B.J. (1962) *Statistical Principles in Experimental Design*, New York, NY, McGraw-Hill.

Wyon, D.P. (1969) *The effects of moderate heat stress on the mental performance of children*. National Swedish Institute for Building Research, Document D8/69, 83p.

Zhou, X., Lian, Z. and Lan, L. (2014) Experimental study on a bedside personalized ventilation system for improving sleep comfort and quality, *Indoor Built Environ.*, **23**, 313–323.