Demand-controlled ventilation in schools: Influence of base ventilation rates on subjective symptoms, perceived indoor environment and young adults' learning performance

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ABSTRACT

The ventilation airflow rates in a demand-controlled ventilation strategy typically vary between a base (V_{min}) and a maximum ventilation rate (V_{max}). Classrooms have relatively short but intense hours of occupancy and a low V_{min} can result in high energy savings. Our study aims to examine how different V_{min} (1.1 versus 2.0 l/s per m^2) affect subjective symptoms, perceived indoor environment quality (IEQ), and performance for young adults.

Symptom intensity and perceived IEQ were recorded on a visual scale, and performance was examined by identifying three different letters in a nonsense text. Tests were done immediately after entering the classroom.

We found no significant effects of increasing V_{min} from 1.1 to 2.0 l/s per m^2 on learning performance, symptoms, or perceived IEQ.

INTRODUCTION

Demand-controlled ventilation (DCV) may significantly reduce the energy consumption of mechanically ventilates buildings by lowering the ventilation rate when spaces are unoccupied. The base ventilation rate, which is the minimum ventilation airflow rate in a DCV-control strategy, significantly affects these energy savings. Classrooms typically have relatively short but intense hours of occupancy. According to a study of schools in Oslo, the typical use of classrooms for normal school activities is on average four hours out of the 10 hours of ventilation operation. Thus energy savings of 38 - 51 % could be achieved by utilizing DCV compared to constant air volume ventilation (Mysen et al., 2005).

The base ventilation rate also affects the air quality upon entry, before increased ventilation rates during occupancy reduce pollutant levels to new steady-state levels. Several studies indicate that insufficient ventilation of educational facilities affects school performance and that sufficient ventilation would be cost-effective (Toftum et al., 2015; Wargocki & Wyon, 2017). Most studies, however, have focused on ventilation rates per person during occupancy (Maddalena et al., 2015). Emissions from building materials, furnishing, user equipment, and accumulated dust and debris will affect the air quality of classrooms (Smedje & Norbäck, 2000). The emissions might be diluted by the base ventilation, but little information is available on the effect of base ventilation rates on subjective symptoms, perceived indoor environment and performance, in classrooms with realistic pollution loads. We have previously assessed the effect of the base ventilation on PAQ in 18 unoccupied classrooms (Holøs et al., 2019). The present study aimed to examine the effects of two base ventilation rates on subjective symptoms and learning performance of young adults. The base ventilation rates were set to reflect the rate currently used in schools in Oslo, Norway, and a significantly reduced ventilation rate that is still well above recommended value in the current Norwegian Building Code.

METHODS

Study design

A repeated crossover experiment (low-high-high-low) was conducted in two similar small classrooms with a floor area of 30 m^2, a height of 2.6 m, and with standard furnishings for 11 pupils. The rooms were on the second and third floor. Additionally, we also introduced some pollutant sources. These include one uncapped whiteboard marker, 15 laptop computers in a closed but ventilated charging cupboard, and one open vacuum cleaner bag containing dust from vacuum cleaning of 60 m^2 floor area of a classroom after regular use.

17 healthy students (7 females and 10 males) from OsloMet were recruited to participate in the study. Compensation was paid for the participation. The participants were divided into two groups and participated in two sessions per day. At the morning session, one group was first exposed to a low (1.1 l/s per m2) base ventilation rate, while the other group was exposed to a high (2.0 l/s per m^2) base ventilation rate on the first test day. The two groups changed the test room after lunch. On the second day, the order of exposure to base ventilation rate was switched. Each participant served as their control as they were exposed to both low and high base ventilation twice. Not all students participated every day, thus the number of participants in each group varied between six and seven for each session.

Upon entering into each test room, and again after 75 minutes, the participants were asked to do the following tasks: 1) to assess perceived air quality (PAQ), 2) to respond to an online questionnaire about perceived indoor environment and subjective symptoms, and 3) to identify three different letters in a nonsense text (BOK-test). The total time required for completing these tasks was 11-14 minutes.

Before the morning session, the ventilation had been operating at the selected base ventilation rate for 18 hours. When the participants entered the rooms, the ventilation was manually adjusted to a high ventilation rate corresponding to 5.7 l/s per m^2. After the morning session, ventilation was run at the base ventilation rate for 90 minutes before the next test round. Relative humidity (RH), CO_2 and indoor temperature were logged in both test rooms.

Perceived air quality (PAQ)

PAQ was evaluated using a continuous acceptability scale divided into two parts (Fang et al., 2004). The PAQ-acceptability scale was coded as following: -1 = "Clearly Unacceptable", 0 = "Just unacceptable/Just acceptable" and +1= "Clearly Acceptable". It was not possible to score at the midpoint.

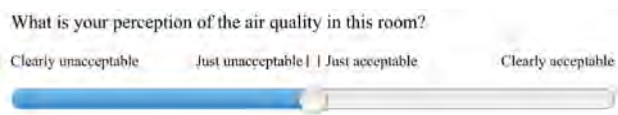


Figure 1 Screenshot of the PAQ acceptability scale.

Questionnaire

The online questionnaire is a modified version of the MM-questionnaire developed at the Department of Occupational and Environmental Medicine in Örebro, Sweden (Andersson 1998). The questionnaire consists of 25 questions related to the subjective assessment of general perceptions of the indoor environment, thermal comfort, and sick building syndrome (SBS) symptoms. A continuous scale slider was used to record the responses to the questions, where the response "No, not at all" was converted to a score of 0 and "Yes, very" to a score of 10. It was not possible to score at the midpoint.

Figure 2 Excerpt of the online questionnaire. Score 0 corresponds to "No, not at all" and 10 corresponds to "Yes, very".

BOK test

The BOK test is a modification of the "OK Tick Off Test"(Fostervold & Nersveen, 2008) with one extra letter (B) to be ticked off. The BOK test requires attention and speed and is a visual detection task designed to assess the ability of individuals to maintain cognitive alertness for an extended period. The test consists of identifying the letter b, o, k in a nonsense text for 10 minutes. Accuracy (percentage of correctly identified letters) and concentration performance (CP; defined as the number of correctly marked target characters minus incorrectly marked distractor characters) were measured.

Statistical analyses

Statistical analyses were performed with SPSS version 24 (SPSS Inc, Chicago, USA). Wilcoxon's signed-rank test was used to check for differences in responses at low and high base ventilation rates.

RESULTS

Table 1 shows an overview of the measured CO_2, indoor temperature and relative humidity in the test rooms during the different test rounds upon entering the test rooms. The average CO_2-level rises somewhat higher upon entry in room 1 than 2, as the dampers in this room reacted slower to the signal to increase the ventilation rate. Temperatures were higher in test room 2 than test room 1 during tests 2,3 and 4. RH was lower in both test rooms on the second day (test rounds 3 and 4). Otherwise, all parameters are comparable.

Table 1 Overview of logged indoor parameters. Derived from 5 minutes upon entry into the testrooms.

Test round	Test room	CO_2 (ppm)	Temp. (°C)	RH (%)	Air supply (l/s·m^2)	N
1	1	616	23.4	40.4	1.1	7
	2	454	23.6	38.6	2.0	7
2	1	606	23.5	39.3	1.1	7
	2	462	24.3	37.4	2.0	6
3	1	646	22.7	26.6	2.0	7
	2	556	24.4	24.8	1.1	5
4	1	540	23.2	27.0	2.0	6
	2	504	24.7	25.6	1.1	6

PAQ

The variations in PAQ-score given by the participants are seen in Figure 3. The average PAQ-score given immediately upon entry was higher at high base ventilation (0.66 ±0.33) than at low (0.42±0.47). Although this difference in PAQ-score was not statistically significant, there is a tendency that perceived air quality was more acceptable at a higher base ventilation rate.

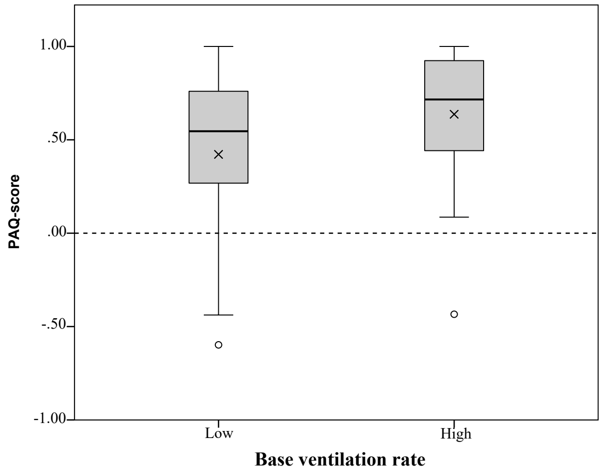


Figure 3 Boxplot of the PAQ acceptability scores (-1 = "Clearly unacceptable", 0 =" Just unacceptable/Just acceptable" and 1= "Clearly acceptable) by base ventilation rate. The dark line in the middle of the boxes is the median and the x-mark is the mean value. The top and bottom of the box are the 75th and 25th percentiles. Whiskers indicate the 10th and 90th percentiles and individual outliers are shown as points.

Questionnaire

The questionnaire was categorized into responses related to perceived indoor environmental factors, thermal comfort, general and specific SBS symptoms and are shown in Figures 4– 7.

Generally, the average scores of the perceived indoor environment factors were below 3, indicating that the participants were generally satisfied with the indoor climate. The base ventilation rate had no significant effect on these parameters.

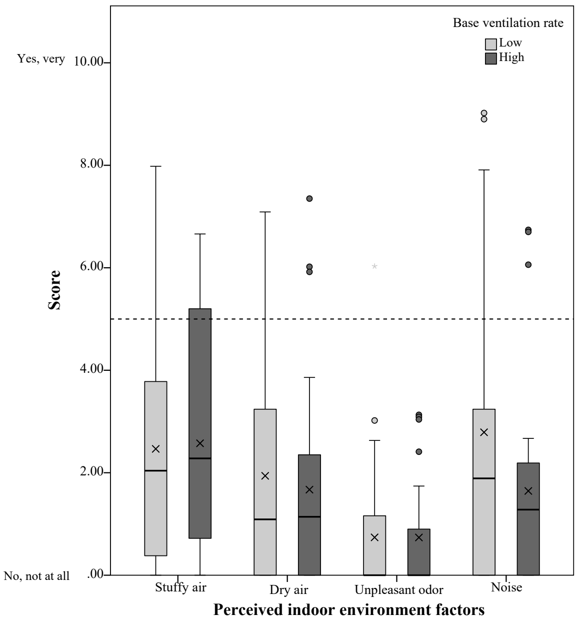


Figure 4 Boxplots of perceived indoor environment factors by base ventilation rate. The dark line in the middle of the boxes is the median and the x-mark is the mean value.

We also did not find any significant effect of the base ventilation rate on thermal comfort scores. As seen in Figure 5, the highest average score was related to the question about the test rooms being too warm.

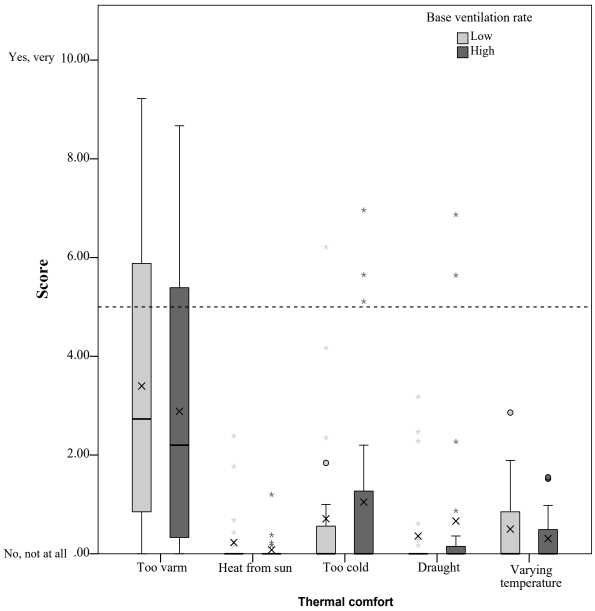


Figure 5 Boxplot of thermal comfort by base ventilation rate. The dark line in the middle of the boxes is the median and the x-mark is the mean.

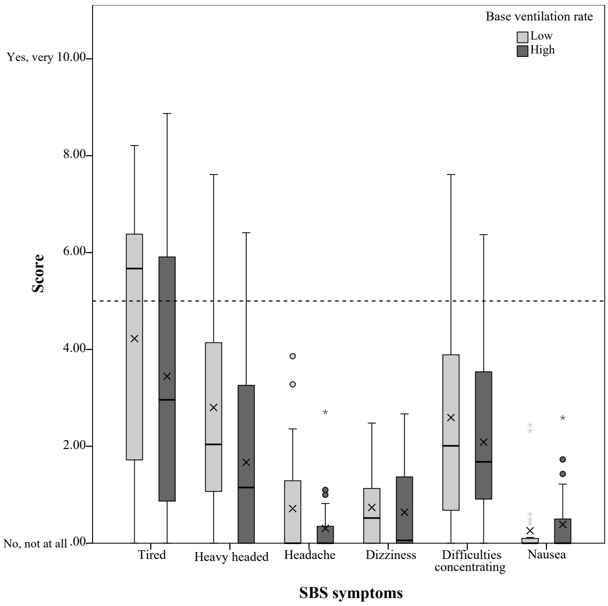


Figure 6 Boxplots of SBS symptoms. The dark line in the middle of the boxes is the median and the x-mark is the mean value.

Figure 6 presents the responses to the questions related to SBS-symptoms. Except for nausea, there is a tendency of higher symptom intensities at lower base ventilation rates. However, these differences in score were not significant. The most frequent symptoms were being "tired", "heavy headed" and "difficulties concentrating".

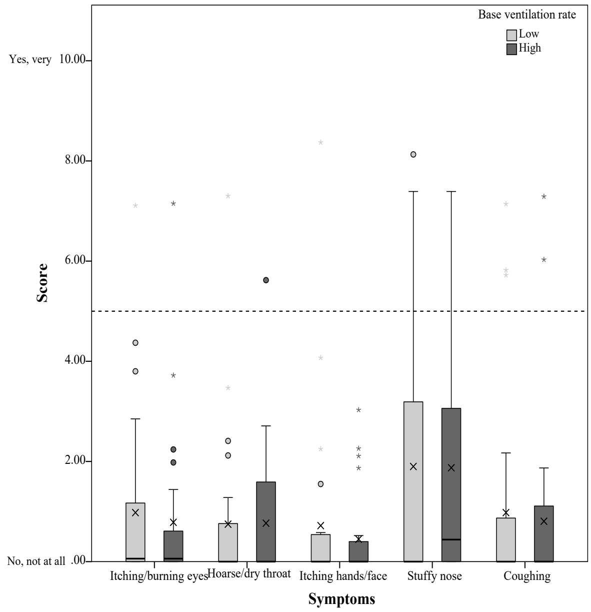


Figure 7 Boxplot of the responses to the questions about general symptoms. (0 = "No, not at all", 10 =" Yes, very") by base ventilation rate. The dark line in the middle of the boxes is the median and the x-mark is the mean value. The top and bottom of the box are the 75th and 25th percentiles. Whiskers indicate the 10th and 90th percentiles and individual outliers are shown as points.

The responses to the questions related to general symptoms are presented in Figure 7. Overall, there were few reported symptoms at both base ventilation rates. We also found no significant effects of increasing the base ventilation rate on general symptoms.

Results after the lecture.

The participants spent 1.5h in each test room, with a supply airflow rate of 5.7 l/s per m². The indoor climate parameters during the period 75-90 minutes after entry are provided in Table 2 a.

Table 2 Overview of logged indoor parameters. The supply airflow rate was set to 5.7 l/s per m² in both test rooms.

Test round	Test room	CO_2 (ppm)	Temperature (°C)	RH (%)	V_{min}	N
1	1	579	24.0	38.6	Low	7
	2	584	24.5	37.5	High	7
2	1	647	24.2	36.9	Low	7
	2	596	24.9	35.5	High	6
3	1	635	23.5	27.3	High	7
	2	599	25.1	24.7	Low	5
4	1	572	23.8	25.3	High	6
	2	559	25.3	23.7	Low	6

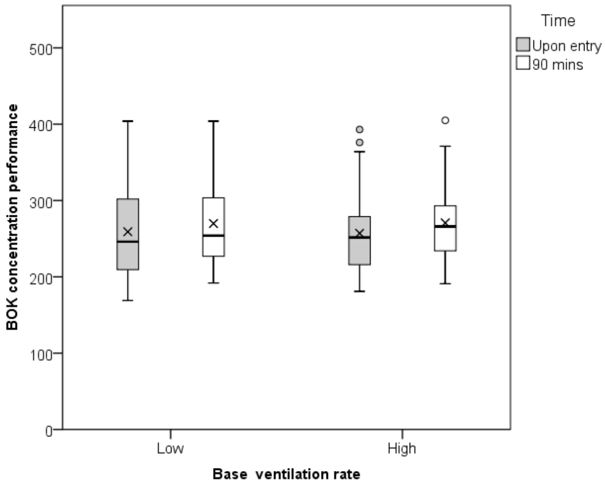
Table 3 shows an overview of the average scores given by the participants upon entry and after staying 75 minutes in the testrooms. Generally, the average scores for majority of responses of the questionnaire increased after 75 minutes, both at high and low V_{min}.

Table 3 Overview of the responses to the questionnaires (average ±standard deviation) upon entry and after staying 75 minutes in the testroom. 0 = no, not all, 10 = yes,very.

	Low V_{min}		High V_{min}	
	Upon entry	90 mins	Upon entry	90 mins
Tired	4.2±2.8	5.2±2.9	3.4±2.8	4.7±3
Heavy headed	2.8±2.4	4.5±2.8	1.7±1.9	3.7±2.3
Headache	0.7±1.1	1.3±1.9	0.3±0.6	0.7±1.4
Dizziness	0.7±0.8	1.6±2.1	0.6±0.9	1.3±1.4
Difficulties concentrating	2.6±2.4	4.3±3	2.1±1.9	4.3±2.9
Nausea	0.3±0.7	0.2±0.6	0.4±0.7	0.2±0.6
Itching/burning eyes	1±1.8	1.9±2.9	0.8±1.6	2.2±3.1
Hoarse/dry throat	0.7±1.6	1.3±2	0.8±1.3	1.4±2.1
Itching hands/face	0.7±1.8	0.5±0.9	0.4±0.9	1±2.1
Stuffy nose	1.9±2.8	2.4±3.3	1.9±2.5	1.7±2.5
Cough	1±2.1	0.8±1.9	0.8±1.9	1.2±2.2
Too warm	3.4±2.8	3.1±2.8	2.9±2.7	2.9±3
Heat from sun	0.2±0.6	0.2±0.5	0.1±0.3	0.2±0.6
Too cold	0.7±1.5	1.3±1.6	1±2	1.2±1.8
Draught	0.4±0.9	0.4±1.2	0.7±1.8	0.8±1.9
Varying temperature	0.5±0.8	1±1.9	0.3±0.5	1.2±2.3
Stuffy air	2.5±2.5	3.6±2.9	2.6±2.3	3.3±2.8
Dry air	1.9±2.3	1.9±2.1	1.7±2.1	2.5±2.7
Unpleasant odor	0.7±1.4	0.7±1.5	0.7±1.1	1.2±2
Noise	2.8±3.2	2±2.5	1.6±2	1.8±2.5

Performance test

The parameters related to the participants' learning performance are presented in figure 8. We did not find any significant effect of increasing the base ventilation rate on BOK concentration performance or the number of correctly identified letters, both upon entry and after 75 to 90 minutes.



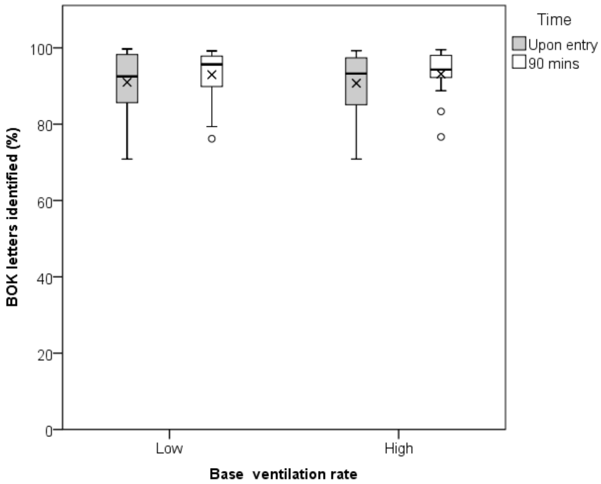


Figure 8 Concentration performance (above) and percentage correct identified letters (below) by base ventilation rate. The dark line in the middle of the boxes is the median and the x-mark is the mean value. The top and bottom of the box are the 75th and 25th percentiles. Whiskers indicate the 10th and 90th percentiles and individual outliers are shown as points.

DISCUSSIONS

The aim of this study was to assess the effect of the base ventilation rate on PAQ, indoor environmental factors, symptoms, and learning performance. These parameters were assessed when the participants entered the test rooms and after 90 minutes.

Energy-efficient demand control strategies

An optimal ventilation strategy should maximize benefits for users while minimizing costs and negative environmental or societal effects. For rooms with intermittent use and mixing ventilation, the main elements of the ventilation strategy are the base ventilation rate, the maximum ventilation rate, the controlling parameter(s), and the regulation of ventilation rate between the base and maximum ventilation. Provided the following assumptions are valid: 1) the control parameters represent the increased ventilation demand when users are present, 2) the ventilation rate is adjusted to this demand, and 3) the maximum ventilation rate is high compared to room volume and duration of occupancy, the pollutant levels during occupancy will depend more on the demand-adjusted ventilation rate than on the base ventilation rate. Accordingly, the base ventilation rate is of limited significance for the airborne exposure of occupants. In such situations, reducing the base ventilation rate is an efficient way to reduce energy demand and associated costs.

Possible effects of low base ventilation rate

The base ventilation rate should, at any rate, be sufficient to dilute pollutants from building materials, furniture, and stored user equipment to levels that are not harmful. However, for many buildings, including the case school of this study, concentrations of pollutants are often well below levels where health effects are considered likely. Still, the sensory impression is affected by the concentration of airborne contaminants and may vary between rooms with identical material usage (Holøs et al., 2019; Mysen et al., 2019).

The human olfactory senses are particularly sensitive to abrupt increases in pollutant concentration (Fanger, 1988), and therefore the effects of a sensory impression of perceived air quality upon entry into a room may be greater than expected from the fraction of the total exposure represented by this entry period. Negative olfactory impressions are associated with negative outcomes on stress level, cognition, mood and symptoms, according to a recent literature review (Dalton et al., 2020), and it has been shown that a belief that an odour has negative health effects could reduce cognitive performance (Nordin et al., 2013).

An earlier study on the effects of V_{min} on SBS-symptoms and performance was from the same school, found that increasing V_{min} from 1 l/s per m^2 to 2 l/s per m^2 did not have any impact on SBS-symptoms and performance (measured with OK-tick test) (Mysen et al., 2019). In our study, the ventilation rate during occupancy was kept constant at 5.7 l/s per m^2, while in the study by Mysen et al. (2019) the assessment was done in a regular classroom and with varying airflow rates (3 to 6 l/s per person) during occupancy. Our results indicate a statistically insignificant improvement of perceived air quality with increased base ventilation, but there was no indication of reduced performance. However, there is a slight but insignificant tendency of higher intensity of symptoms from the central nervous system (headache, tiredness, difficulty concentrating and feeling heavy headed) at the low base ventilation rate. As such symptoms could potentially affect performance, a further investigation of any effect on symptoms of the first impression upon entry is recommended.

CONCLUSIONS

No statistically significant effects were observed by increasing the base ventilation rates above 1.1 l/s.

Perceived air quality at this ventilation rate was good. However, a slight tendency of lower PAQ-scores and higher symptom intensity at the lower ventilation rate should be explored further.

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