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Demand-controlled ventilation: do different user groups require different CO_2-setpoints?

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Abstract. The aim of this study is to investigate whether children's bioeffluent generation rate is proportional to their carbon dioxide (CO_2) generation rate. Consequently, to assess if there is a need to differentiate the CO_2-setpoint for different user groups, focusing on children. Perceived air quality (PAQ) and odour intensity (OI) were assessed in three classrooms in Oslo, Norway. Two second-grade classes (7-8 years old) were compared with one eighth-grade class (13-14 years old). An untrained test panel consisting of 16 people visited each classroom twice and were asked to evaluate PAQ and OI upon entering the classrooms. The CO_2 levels in the classrooms were kept constant at either 600 ppm or 1100 ppm during each visitation. The results showed that average PAQ-score was significantly worse in the second-grade classrooms compared to the eighth-grade classroom. For perceived odour intensity, the average score indicated that the odour was stronger in the second-grade classrooms compared to the eighth-grade classroom, however, this difference in score was not significant. Our results indicate a need for differentiation of setpoints for CO_2-DCV based on user groups, especially for children.

1. Introduction

The increased focus on climate and energy use has resulted in demand-controlled ventilation (DCV) emerging as the dominating ventilation strategy in non-residential buildings in Norway. One of the most common methods for controlling such ventilation is by indoor carbon dioxide (CO_2) concentration level (CO_2-DCV) [1]. The current use of CO_2-DCV is based on the assumption that the CO_2 generation rate by people is proportional to their bioeffluent generation rate [2]. This allows the CO_2 level in a room to be used as an indication of the level of human contamination affecting the indoor air quality, which is further used to determine the required ventilation rates. The majority of the research which this assumption is based upon was carried out in the 80's using adult female or male students [3,4]. To the best of our knowledge, there is currently insufficient evidence to suggest that this relationship is valid for other user groups than adults.

Children are more vulnerable to air pollutants and research has shown their school related performance to be reduced by up to 30 % when the indoor air quality is reduced [5]. Children produce less CO_2 than adults, but recommendations for CO_2-DCV setpoints do not differentiate between user groups [6]. Consequently, children might receive a lower ventilation rate per person when CO_2-DCV is used in schools.

The aim of this paper is to investigate whether the relationship between children's bioeffluent generation rate and their rate of CO_2 generation is proportional. Consequently, to see if there is a need to differentiate the setpoints according to different user groups, focusing on children, when CO_2-DCV is used in schools.

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2. Methods

2.1. Study design

The study was carried out in three classrooms at a school in Oslo, Norway. The school has demand-controlled ventilation controlled by a combined CO_2 and temperature sensor. The classrooms had an average floor area of 60 m^2, height of 2.8 m and similar furnishings. One 8^{th} grade class (A) was compared with two 2^{nd} grade classes (B, C) at equal CO_2 levels. Each classroom was visited twice, first at a low CO_2 level (600 ppm) and then at a high CO_2 level (1100 ppm).

An untrained sensory panel of 16 people evaluated odour intensity (OI) and perceived air quality (PAQ) in the classrooms during the school day with pupils present. There was a gap of at least one hour between the two visitations. Each panelist received an assessment form for each round and were told to mark their responses on a PAQ scale and OI scale as shown in figure 1 [7].

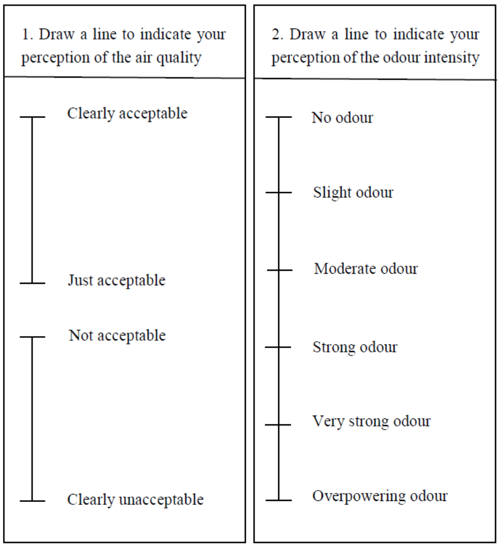

Figure 1. Scale used for assessment of PAQ (left) and odour intensity (right).

In order to achieve the desired CO_2 level, we used the new approach by Persily and de Jonge [6] to estimate CO_2 generation rates from building occupants. This approach takes into consideration gender, age, body mass and the level of physical activity by adding the basal metabolic rate (BMR) of the individuals of interest in the equation:

$$V_{CO_2} = \mathrm{RQ}\,\mathrm{BMR}\,M\left(\frac{T}{P}\right)0.000211 \quad (1)$$

Assuming the following values for the various parameters, where T (air temperature) = 294.15 K; *P* (pressure) = 101 kPa; RQ (respiratory quotient) = 0.85 and M (metabolic rate) = 1 met, eq. 1 can be expressed as:

$$V_{CO_2} = \mathrm{BMR}\ 0.000522 \quad (2)$$

The supply airflow rates for the classrooms were then calculated using eq. 3 [8]:

$$\dot{V}_{supply} = \frac{G_{CO_2}\cdot 10^6}{G_{i,CO_2} - C_{o,CO_2}}\cdot\frac{1}{\varepsilon_V} \quad (3)$$

where G_{CO2} is the estimated total generated CO_2 (l/s), $G_{i,CO2}$ is the required indoor CO_2 level (ppm), $C_{o,CO2}$ is the outdoor CO_2 level (400 ppm) and ε_V is the ventilation efficiency (set to 1). The calculated values are provided in table 1. These ventilation rates were then set as fixed airflow rates for the exhaust and supply air dampers during the experiments, overriding control signals from the building automation system.

Before the panelists entered the classrooms, we measured temperature, CO_2 concentration and relative humidity with a handheld Rotronic CP 11 (Rotronic AG, Bassers-dorf, Switzerland) with a declared accuracy of ±2.5 % RH, ±30 ppm ±5 % of the measured CO_2 value and ±0.3 K. Outdoor airflow rates were collected for each classroom by the Building Management system (BMS).

Table 1. Overview of the expected number of people, calculated outdoor air supply rate ($\dot{V}_{supply}$), and estimated total CO_2 generation rate (G_{CO_2}).

Classroom	N (pupils + teacher)	$\dot{V}_{supply}$ (m³/h)		G_{CO_2} (l/s)
		At 600 ppm	**At 1100 ppm**	
8A	18 + 1	1177	336	0.065
2B	23 + 1	1134	324	0.063
2C	23 + 1	1134	324	0.063

2.2. *Data analysis*

For data analysis, the PAQ acceptability scale and the OI scale were converted into numbers. The PAQ acceptability scale was divided in two parts and coded as following: 1 = "Clearly acceptable", and -1= "Clearly unacceptable", while the OI scale was coded as 0 ("No odour") to 5 ("Overpowering odour"). The scores were then used to calculate the percentage dissatisfied (PD) with air quality [9].

The paired sample t-test was used to examine whether there is a significant difference in PAQ and OI-scores between the 8th grade classroom and the two 2nd grade classrooms at constant CO_2 levels. The results were considered statistically significant when $P<0.05$. Statistical analyses were performed with SPSS version 24 (SPSS Inc, Chicago, USA).

Table 2. Overview of the actual number of people, calculated and actual ventilation rate per person ($\dot{V}_{pers}$), room temperature (T), CO_2, relative humidity (RH) and calculated enthalpy.

Classroom	CO_2 (ppm)	N	Estimated $\dot{V}_{pers}$ (l/s)	Actual $\dot{V}_{pers}$ (l/s)	T (°C)	RH (%)	Enthalpy (kJ/kg)
At low CO_2 level (600 ppm)							
8A	755	18+2	17.2	16.4	21.7	27.9	33.2
2B	668	17+1	13.1	17.5	22.7	25.2	33.7
2C	698	18+2	13.1	15.8	22.1	27.3	33.6
At high CO_2 level (1100 ppm)							
8A	932	13+1*	4.9	6.7*	22.2	28.1	34.1
2B	970	19+1	3.8	4.5	23.0	27.7	35.3
2C	1013	19+1	3.8	4.5	22.1	30.5	35.0

*several pupils left the classroom right before the visitation.

3. Results

The measured indoor climate parameters during the visitations at low and high CO_2 levels are shown in table 2. In general, there are not many variations in temperature and relative humidity in the three classrooms during each visitation. The actual number of people in the classrooms deviated from the estimated number, especially for the classroom with 8th graders, which when compared to the 2nd graders, resulted in higher CO_2 concentrations at low CO_2 level, and lower concentrations at high CO_2 level. The CO_2 levels were considered to be similar enough to be comparable.

3.1. PAQ

The variation of PAQ-scores for the three classrooms under different CO_2 levels are shown in figure 3. The test panel gave the highest PAQ-scores for the 8th grade classroom (low CO_2: median = 0.69, high CO_2: median = 0.65) with the lowest percentage dissatisfied (6.3 %). Classroom 2B received the lowest PAQ-scores (low CO_2: median = 0.26, high CO_2: median = 0.21) with more than 25 % dissatisfied with the air quality, especially at high CO_2 level (PD = 37.5 %).

We found significant differences in PAQ-scores between the 8th grade classroom with both 2nd grade classrooms at high CO_2 level. While at low CO_2 level, the average PAQ-score for the 8th grade classroom was only significantly higher when compared with 2B.

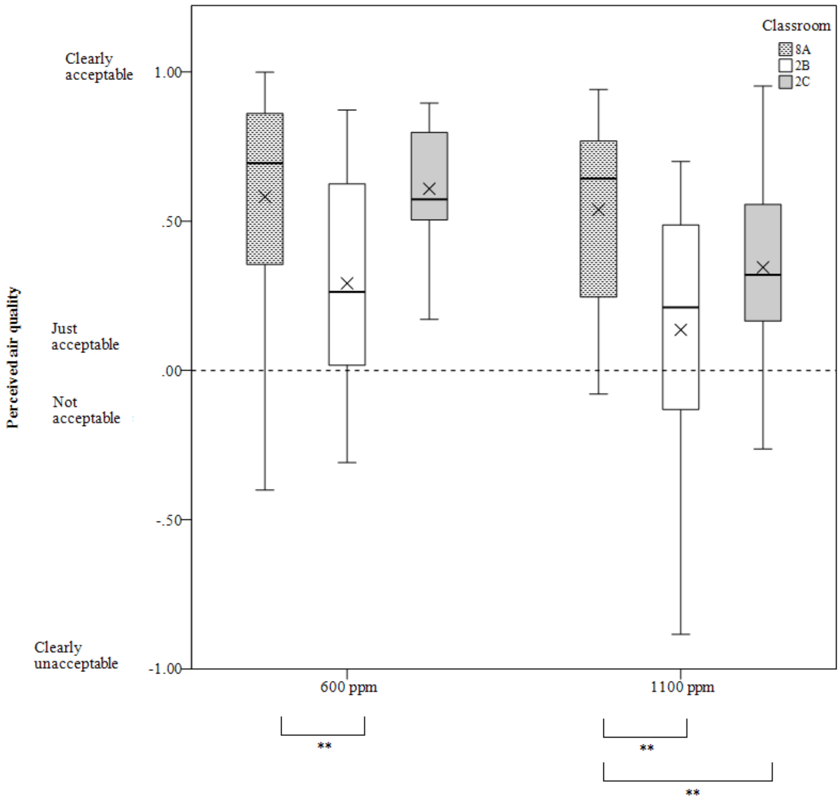

Figure 2. Boxplot of PAQ-scores by CO_2 level. The dotted line indicates just acceptable PAQ. The dark line in the middle of the boxes is the median, the X symbol is the mean. The top and bottom of the box are the 75th and 25th percentiles. Whiskers indicate the 10th and 90th percentiles. Asterisks indicate the level of statistical significance: **p<.05.

3.2. Odour intensity

Figure 3 shows the variation of odour intensity scores for the three classrooms at different CO_2 levels. Generally, the 2nd grade classrooms scored higher on the odour scale than the 8th grade classroom, especially at high CO_2 level (median = 1.8 for 2B and 2C). The percentage dissatisfied with odour was also highest for the two 2nd grade classrooms at high CO_2 level (PD = 37.5 %). At low CO_2 level, the 8th grade classroom, which had a higher ventilation rate per person, received a higher percentage dissatisfied with OI (PD = 25 %) than the two 2nd grade classrooms (PD = 12.5 – 18.8 %). We found that the OI-scores for the 8th grade classroom did not differ significantly from the OI-scores for the two 2nd grade classrooms.

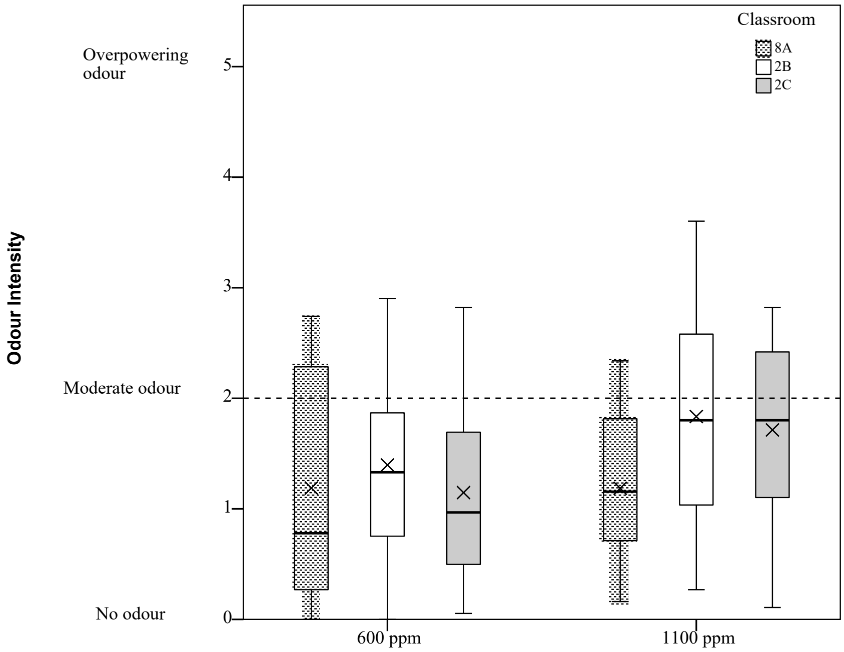

Figure 3. Boxplot of odour intensity by CO_2 level. The dotted line indicates acceptable odour intensity. The dark line in the middle of the boxes is the median, the X symbol is the mean. The top and bottom of the box are the 75th and 25th percentiles. Whiskers indicate the 10th and 90th percentiles.

4. Discussion

The aim of this study was to investigate whether the relationship between children's bioeffluent generation rate and their rate of CO_2 generation is proportional, and if there is a need to differentiate the setpoints for user groups such as children when CO_2-DCV is used in schools.

We found that the average PAQ-score in classrooms with children are significantly lower compared to a classroom of teenagers, at equal levels of CO_2 and similar temperature and RH. This indicates that the relationship between bioeffluent generation rate and CO_2 generation rate differs between children and teenagers. However, even small differences in enthalpy between the classrooms might have an effect on PAQ [10] as the largest difference in enthalpy (1.2 kJ/kg) resulted in the biggest difference in PAQ-score (difference of 0.35 between 8A and 2B at high CO_2 level). Nevertheless, the tendency of lower air quality in the classrooms with children is still visible when using ventilation rate per person as basis for comparison. The differences in PAQ and OI-score between the 2nd grade classrooms and the 8th grade classroom were generally more pronounced at high CO_2 level. Possibly due to the higher ventilation rates at the low CO_2 level (15 – 17 l/s per person), which are more than twice the recommended ventilation rate. This will presumably have removed most of the bioeffluents in the classrooms. Whereas at high CO_2 level with ventilation rates of 4.5 – 7 l/s per person, the variation in bioeffluents emitted from the pupils would have been more prominent. Yet, this could also be due to other factors than the bioeffluent generation rate, e.g. differences in hygiene, clothing or stored materials between the age groups. Further research is needed to test these hypotheses. Currently, our findings are not sufficient to fully describe a relationship between the bioeffluent generation rate and CO_2 generation rate.

Although it is not required to differentiate the setpoints according to user groups when using CO_2-DCV in Norway, it has been recommended to reduce the setpoint for children due to the CO_2 generation rate in children being 20 % lower than that of adults [11]. Based on the theoretical model by Persily and de Jonge [6], we found that the theoretical difference in CO_2 generation between children and adults can be as high as 38 %. Our findings thus also support the notion of lowering the CO_2-setpoints for children and teenagers. It is assumed that this will involve an increase in energy usage due to increased ventilation rates. However, the implications on energy usage and the technical challenges involved by introducing different setpoints according to user groups, e.g. children and teenagers, are not within the scope of this study.

As previous research within the field has been carried out using mostly adults, it would be of further interest to compare bioeffluent generation rate in children to that in adults. Also, it would be of interest to compare whether there are also differences in how the pupils themselves rate the air quality in the classroom they occupy.

5. Conclusion

Our results indicate that there might be a need to differentiate the setpoints for different user groups based on age when using CO_2-DCV, especially for children. Further research, such as an updated sensory pollution load according to age groups, would be useful to provide precise recommendations on CO_2-setpoints and ventilation rates at minimum occupancy.

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