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# Temperature-dependent ventilation rates might improve perceived air quality in a demand-controlled ventilation strategy

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ABSTRACT

The aim of the Best Vent project was to find the optimal control strategy for demand-controlled ventilation (DCV) without compromising on indoor air quality. In this paper, we discuss control strategies that would ensure acceptable perceived air quality for unadapted users.

This study is a part of a series of field studies where sensory panels of untrained persons visited classrooms at a school. The sensory panel visited classrooms occupied by different user groups, at different ventilation rates and temperatures, and in empty classrooms at different ventilation rates, and with different pollutant loads. This study aims to assess whether it would be reasonable to control the supply airflow rate towards a higher $CO_2$ setpoint at low air temperature, and still maintain the same perceived indoor air quality upon entry. The results indicate that the perception of indoor air quality does not deteriorate at higher $CO_2$ concentrations when the air temperature is kept at 21 °C as opposed to at 24 °C. Furthermore, an increase in air temperature yielded poorer perceived air quality scores at similar $CO_2$ concentrations in the classrooms.

Our results indicate that a DCV-control strategy with a higher $CO_2$ setpoint in classrooms at low temperatures would not compromise perceived air quality. Further research would be needed to assess whether the same is true for indoor climate-related symptoms or performance.

## 1. Introduction

In Norway as well as other Nordic countries, demand-controlled ventilation (DCV) is the dominating ventilation strategy. This is motivated by the national and EU requirements to reduce greenhouse gasses and profitability in terms of energy savings. In buildings with varying occupancies, such as schools and office buildings, DCV systems can significantly lower energy use [1,2]. Energy reductions can be achieved not only because less air needs heating, cooling and transport in the HVAC systems, but also due to the higher heat recovery rate and lower specific fan power of many systems when the airflow is lower than maximum capacity [3]. DCV systems vary the ventilation rates between a maximum ($V_{max}$) and minimum ($V_{min}$) supply airflow rate, based on the signal from one or more room sensors. The choice of these two airflows and the regulation between these two values can potentially have a large impact on indoor air quality and energy usage.

One of the most common parameters used to control the supply airflow rate is the indoor carbon dioxide ($CO_2$) concentration [4]. The current use of $CO_2$-DCV assumes that the rate of $CO_2$ production is proportional to the bioeffluent generation rate, and thus the $CO_2$ level in a room can 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. This relation is usually assumed to be valid for all user groups, and ventilation requirements are often given as a recommended $CO_2$ concentration or $CO_2$ concentration above outdoor concentrations. The Norwegian Institute for Public Health recommends 1000 ppm absolute concentration as a guideline limit [5].

Children produce less $CO_2$ than adults, but recommendations for $CO_2$-DCV setpoints do not differentiate between user groups [6]. Consequently, children receive a lower ventilation rate per person compared to adults when $CO_2$-DCV is used in schools. 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 [7].

Several studies have shown that cool and dry air is perceived as more acceptable than warm and humid air of identical composition, implying a potential for reducing airflow rates at lower enthalpy [8,9]. This insight, however, is not implemented in the operation of buildings we

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have studied. To ensure that the occupants achieve thermal comfort, temperature sensors are often used to control heating and cooling. Temperature control often includes increasing airflow rates. Currently, the control system of $CO_2$ and temperature sensors is often based on fixed independent set points for these two parameters, and the parameter that exceeds its setpoint first becomes the controlling parameter. To avoid complaints about indoor air quality, $CO_2$ setpoints are often significantly lower than necessary to comply with regulations or recommendations in Norway. As an example, the building used in this study had a $CO_2$ setpoint of 550 ppm in normal operation. A combined $CO_2$ and temperature control strategy could potentially provide a further reduction in energy use while maintaining a satisfactory indoor air quality and thermal comfort [10,11]. The principle is to decrease and increase the supply airflow rates according to the room air temperature. A lower supply airflow rate at low room air temperatures would reduce energy use.

To assess whether the perceived air quality level is satisfactory or not, sensory evaluation using human observers is commonly used to obtain the required ventilation rates [12,13]. EN 16798 [14] recommends an airflow of 7 l/s per non-adapted person to dilute bioeffluents from people for different categories This would correspond to an expected dissatisfied percentage of 20. ASHRAE 62.1 recommends a ventilation rate in the breathing zone in classrooms of minimum 5 l/s per person [15]. The minimum airflow rate during occupancy is recommended to never be below 4 l/s per person due to health reasons [16]. This study is part of several studies undertaken in a research project to define robust strategies for DCV-systems in schools to maximise air quality in occupied spaces and minimize energy use for ventilating empty spaces. Previously, we have investigated the effect of varying $V_{min}$ on perceived air quality in empty classrooms with varying pollution loads [17,18], and the effect of ventilation rate on perceived air quality and odour intensity for different user groups [19,20]. In the study by Mysen et al. [17], to gather more knowledge about $V_{min}$ in a DCV control strategy, perceived air quality was assessed in 20 unoccupied classrooms of which two had extra pollution sources. They found that increasing $V_{min}$ above 1.0 l/s per $m^2$ had little effect on perceived air quality for the unoccupied classrooms, but did have a positive effect on perceived air quality in the classrooms where extra pollution sources were introduced. This finding was further verified in a similar study by Holøs et al. [18] where the perceived air quality in 18 unoccupied classrooms with different pollution loads was assessed. For the classrooms which were not cleaned or had extra pollution sources, a $V_{min}$ of 2.0 l/s per $m^2$ was deemed insufficient.

To optimize DCV control strategies, it is also of interest to determine ventilation rates in occupied spaces without compromising on indoor air quality. This study aims to investigate whether it would be reasonable to control the supply airflow rate towards a higher $CO_2$ setpoint at low room air temperature, and still maintain the same perceived indoor air quality upon entering the room. Moreover, the results of this study will be reviewed along with the results from our previous studies undertaken at the same school to provide recommendations regarding the optimal DCV strategy for best perceived air quality in schools.

## 2. Methods

### 2.1. Study site

Most of our studies took place in a relatively newly built primary school in Oslo which was taken into use in August 2016. The school was built after Norwegian passive-house standards, and the building materials and paints used were either M1-classified or low-emitting. The school is L-shaped and consists of three floors plus a basement with the classrooms distributed over the second and third floor. The classrooms are similar in size and furnishing, with an average floor area of 60 $m^2$ and a height of 2.8 m. The classrooms are designed for 31 occupants including the teacher(s). The ventilation system is operational between 06:00–17:00 during weekdays and off during the weekends.

The classrooms are equipped with balanced supply and exhaust ventilation with a rotating heat exchanger and the ventilation airflow rate is demand-controlled with a $CO_2$- and temperature sensor in each classroom. The airflow rate is regulated by adjustable ventilation dampers (VAV units) and provides a minimum airflow rate ($V_{min}$) of 430–440 $m^3/h$ when the indoor $CO_2$ concentration and room air temperature is below a certain setpoint. The setpoint for $CO_2$ varies between 500 and 550 ppm, while the setpoint for the room air temperature is 22 °C. When one of the setpoint values is exceeded, the airflow rate is increased to 1250 $m^3/h$ ($V_{max}$). In practice, during occupied hours, the maximum ventilation airflow rate is provided to the classrooms.

### 2.2. Study design

The study was carried out at the same time as Haugland et al. [20] in February 2018 in two classrooms situated on the second floor. The two classrooms were occupied by 8th graders. To minimize the influence of other factors on perceived air quality, the selected classrooms were adjacent to each other, with similar furnishings and occupied by users from the same age group with similar usage. Moreover, the classrooms should not face south to minimize the influence of solar radiation.

One of the classrooms was preheated using a heating element to 24 °C (classroom B), while the other one was kept as it was at a nominal room air temperature of 21 °C (classroom A). The teachers were asked to keep the door closed during class and breaks to ensure that the conditions of the classrooms were kept as they were.

The supply airflow rates required to reach the desired $CO_2$ levels of 600 and 1100 ppm in the respective classrooms was calculated based on the expected number of pupils and teacher in the classroom using the proposed method by Persily & de Jonge [6]. In short, this method of estimating $CO_2$ generation rate ($V_{CO2}$ in l/s) considers the basal metabolic rate (BMR) of the individual of interest in addition to the level of physical activity. BMR is calculated based on gender, age group and body mass.

$$V_{CO2} = RQ \cdot BMR \cdot M \cdot (T/P) \cdot 0.000211 \tag{1}$$

With the assumptions that $RQ$ (respiratory quotient) = 0.85, $T$ is the room air temperature (294.15 K or 297.15 K); $P$ (pressure) = 101 kPa, $M$ (metabolic rate) = 1 met and $BMR$ in units of MJ/day.

The supply airflow rates required to get the desired $CO_2$ levels can be calculated as follows:

$$\dot{V}_{supply} = \frac{G_{CO_2} \cdot 10^6}{V_{i,\,CO_2} - C_{o,\,CO_2}} \cdot \frac{1}{\varepsilon_v} \tag{2}$$

Where $G_{CO2}$ is the estimated total generated $CO_2$ (l/s), $V_{i,CO2}$ is the required indoor $CO_2$ level (600 or 1100 ppm), $C_{o,CO2}$ is the outdoor $CO_2$ level (400 ppm) and $\epsilon_V$ is the ventilation efficiency (set to 1). The exhaust and supply air dampers were then set to the fixed airflow rates derived from equation (2) to achieve the desired $CO_2$ levels in the classroom, overriding control signals from the building automation system.

### 2.3. Sensory panel and assessment questionnaires

A sensory panel of untrained persons consisting of students from Oslo Metropolitan University were recruited to assess perceived air quality, odour intensity and thermal comfort in the two classrooms upon entry. The panellists consisted of 12 males and 4 females aged 22–30 years (three participants did not want to state their age) and the majority of the panellists were ethnical Norwegians. Each visitation took place at least 30 min after the start of the class to ensure close to steady-state conditions. The panellists entered the classrooms at the same time and were asked to give their assessment within 30–60 s to counteract sensory adaption. The sensory panellists were told in advance to evenly distribute themselves in the classrooms while giving their ratings. The classrooms were visited first at low $CO_2$ level, then at high $CO_2$ level with an hour between the two visits. In between the visitations, panellists spent their time in a fully ventilated auditorium. Each panellist received a paper assessment form for each round and was asked to mark their responses using a pen. The questions were related to the perception of the indoor air quality and thermal environment, and the scales used are shown in Fig. 1. The participants were also asked some general questions and whether they wanted to adjust the room temperature.

The Building Management system (BMS) provided data on room air temperature, $CO_2$ concentrations and airflow rates. In addition, before each classroom visitation, we measured room air temperature, $CO_2$ concentration and relative humidity with a calibrated 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 of the temperature. The measurement was done in the middle of the classroom, at a height of approximately 1.6 m.

The dataset was tested for normal distribution using the Shapiro-Wilk test. Paired sample *t*-test was used to examine whether there is a significant difference in scores at different $CO_2$ levels and room air temperatures. The results were considered statistically significant when $P < 0.05$. Statistical analyses were performed with SPSS version 24 (SPSS Inc, Chicago, USA).

## 3. Results

### 3.1. Indoor climate parameters

Table 1 shows an overview of the measured indoor climate parameters during the two visits. The room air temperature in the classroom with high temperature (B) was well within the intended level. The room air temperature in the classroom with low temperature (A) was a bit higher than intended. Right before the second visit, several students left the classroom (A2) which resulted in lower $CO_2$ levels than the desired value.

**Table 1**
Overview of the actual number of people, temperature (T), $CO_2$, supply airflow rate ($V_{supply}$), estimated and actual ventilation rate per person ($V_{pers}$), relative humidity (RH) and calculated enthalpy. Classroom A had low air temperature and the experimental conditions A1 with low $CO_2$ level and A2 with high $CO_2$ level. Classroom B had high air temperature and the experimental conditions B1 with low $CO_2$ level and B2 with high $CO_2$ level.

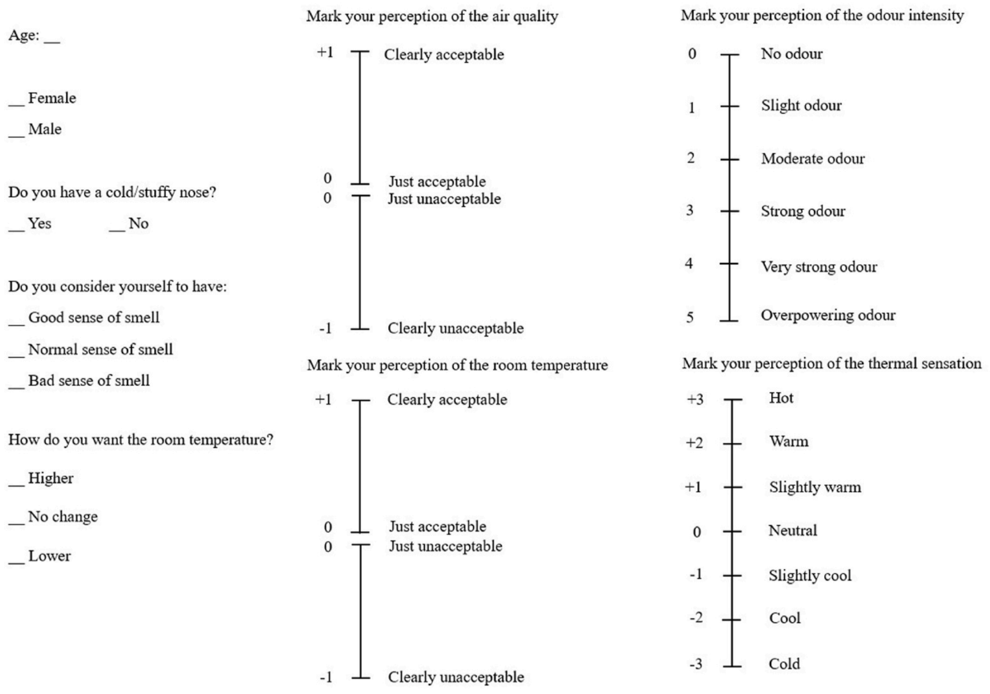
| Classroom | A1 | B1 (high T) | A2 | B2 (high T) |
|---|---|---|---|---|
| Visit | 1 | 1 | 2 | 2 |
| N | 18 + 2 | 18 + 1 | 13 + 2* | 18 + 1 |
| $CO_2$ (ppm) | 755 | 775 | 932 | 1192 |
| Temperature (°C) | 21.7 | 23.3 | 22.2 | 23.7 |
| $V_{supply}$ ($m^3/h$) | 1177 | 1247 | 336 | 356 |
| Estimated $V_{pers}$ (l/s) | 17.2 | 17.3 | 4.9 | 4.9 |
| Actual $V_{pers}$ (l/s) | 16.3 | 18.2 | 6.7 | 5.2 |
| RH (%) | 27.9 | 26.5 | 28.1 | 30.5 |
| Enthalpy (kJ/kg) | 33.2 | 35.4 | 34.2 | 38.0 |

*Unexpectedly, several pupils left the classroom right before the visitation.

### 3.2. Perceived air quality and odour intensity

Fig. 2 shows the variation in scores of perceived air quality in the two classrooms at different $CO_2$ levels and temperatures. Generally, the panellists found the air quality acceptable irrespective of temperature and $CO_2$ level. The highest average perceived air quality score was given for the classroom with low temperature and increasing the $CO_2$ level did not have a significant effect on the perceived air quality score. The percentage dissatisfied also remained at 6 % even with increased $CO_2$ levels. The lowest average perceived air quality scores were given for the classroom with high temperature and increasing the $CO_2$ level significantly lowered the average perceived air quality score. The percentage dissatisfied also increased from 19 % to 36 %. Increasing the temperature had a larger effect on the perceived air quality score than increased $CO_2$ levels.

Fig. 3 shows the variations of odour intensity scores where a score of 2 which corresponds to "moderate odour" indicates acceptable odour intensity. The average odour intensity score for the classrooms was generally around 1 which corresponds to "slight odour". In the classrooms with high $CO_2$ levels, slightly higher average odour intensity



Age: __

__ Female
__ Male

Do you have a cold/stuffy nose?
__ Yes __ No

Do you consider yourself to have:
__ Good sense of smell
__ Normal sense of smell
__ Bad sense of smell

How do you want the room temperature?
__ Higher
__ No change
__ Lower

Mark your perception of the air quality
+1 Clearly acceptable
0 Just acceptable
0 Just unacceptable
-1 Clearly unacceptable

Mark your perception of the room temperature
+1 Clearly acceptable
0 Just acceptable
0 Just unacceptable
-1 Clearly unacceptable

Mark your perception of the odour intensity
0 No odour
1 Slight odour
2 Moderate odour
3 Strong odour
4 Very strong odour
5 Overpowering odour

Mark your perception of the thermal sensation
+3 Hot
+2 Warm
+1 Slightly warm
0 Neutral
-1 Slightly cool
-2 Cool
-3 Cold

**Fig. 1.** Survey questionnaire.

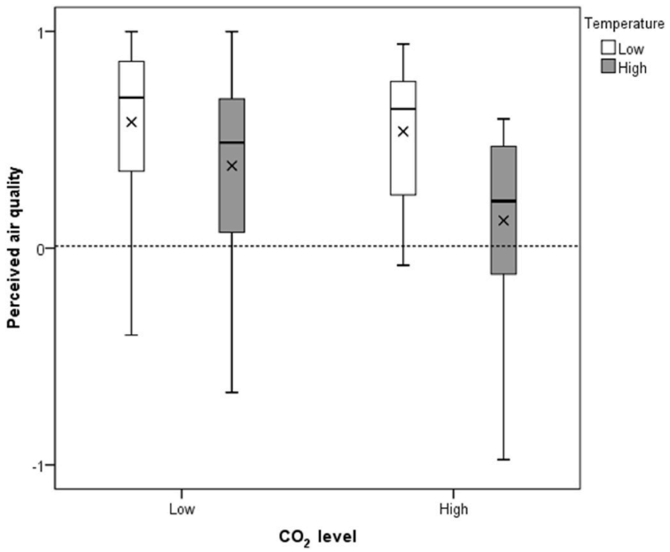


**Fig. 2.** Boxplot of the perceived air quality scores. The dotted line indicates just acceptable/unacceptable perceived air quality (score = 0.01). The dark line in the middle of the boxes is the median, x symbol is the mean. The top and bottom of the box are the 75th and 25th percentiles. Whiskers indicate the minimum and maximum values.

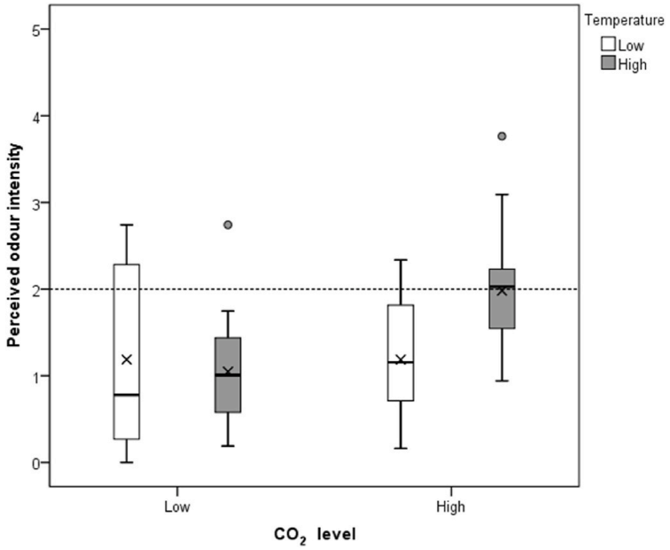


**Fig. 3.** Boxplot of perceived odour intensity (0 = No odour, 5 = overpowering odour). The dotted line indicates acceptable odour intensity (2 = moderate odour). The dark line in the middle of the boxes is the median, x symbol is the mean. The top and bottom of the box are the 75th and 25th percentiles. Whiskers indicate the minimum and maximum values. The circles indicate outliers.

scores were obtained. The highest odour intensity score was given for the classroom with high temperature (mean score = 1.98) with the highest percentage (50 %) dissatisfied with the odour. Surprisingly, the percentage dissatisfied was also high for the classroom at low temperature and low $CO_2$ level (25 %). Increasing the temperature did not have a significant effect on the odour intensity score at low $CO_2$ levels. Similarly, increased $CO_2$ levels did not have a significant effect on the odour intensity score at low temperature.

### 3.3. *Perceived thermal acceptability and thermal sensation*

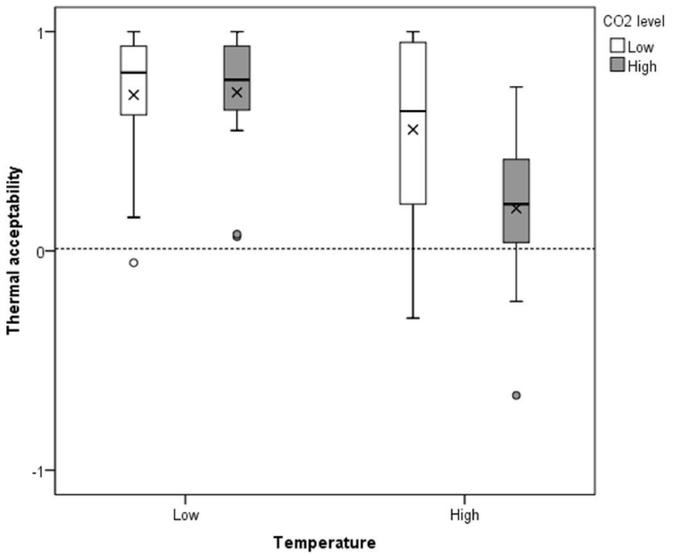


**Fig. 4.** Boxplot of thermal acceptability. The dotted line indicates just acceptable/unacceptable. The dark line in the middle of the boxes is the median, x symbol is the mean. The top and bottom of the box are the 75th and 25th percentiles. Whiskers indicate the minimum and maximum values. The circles indicate outliers.

Fig. 4 shows the distribution of thermal acceptability scores. At both high and low $CO_2$ levels, the classroom with low temperature received a higher perceived thermal acceptability score than the classroom with high temperature. However, at 24 °C, increasing the $CO_2$ levels significantly lowered the thermal acceptability score. At a low $CO_2$ level, increasing the temperature did not have a significant effect on perceived thermal acceptability.

Fig. 5 shows the thermal sensation of the panellists under different conditions. The majority felt neutral about the thermal environment upon entering the room at the low temperature and increasing the $CO_2$ level did not significantly influence their thermal sensation score. Only 5 % were dissatisfied at low temperature. At 24 °C, the scores for thermal sensation moved to slightly warm/warm and increasing the $CO_2$ levels increased the percentage thermally dissatisfied from 5 % to 50 %. 75 % of the panellists also stated that they would want a lower temperature. Fig. 6 shows that although the panellists indicated the thermal environment to be slightly warm/warm at high temperature, the majority found it to be thermally acceptable.

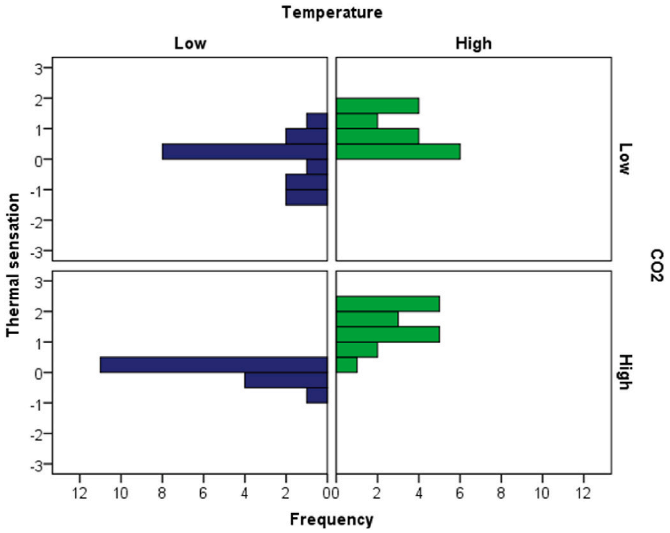


**Fig. 5.** Frequency distribution of the thermal sensation scores.

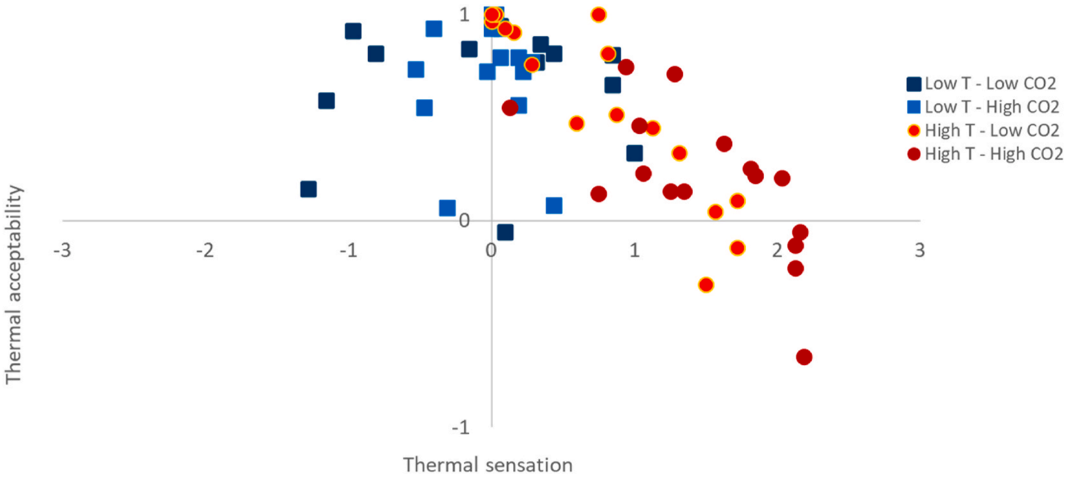


**Fig. 6.** Relation between thermal acceptability and thermal sensation. The square markers indicate low temperature, while the circular markers indicate high temperature.

## 4. Discussion

This study aims to assess whether it would be acceptable to control the supply airflow rate towards a higher $CO_2$ setpoint at low temperature, and still maintain the same perceived indoor air quality upon entering the room. This study is a part of a series of field experiments in classrooms where perceived air quality has been assessed under different conditions using sensory panels of untrained persons. The objective was to provide recommendations with regards to an optimal DCV control strategy. The method of sensory evaluation in classrooms during the normal operation was chosen to provide as realistic exposure as possible to the sensory panellists. On the other hand, this practical approach limits the number of cases studied, and there is a significant risk that uncontrolled factors related to activities in the class could affect the results. As an example, experiment A2 had fewer pupils present than the other experiments, which led to a lower $CO_2$ level than planned. In addition to causing the experimental setup less clear-cut, it is conceivable that a changed user group composition in the relevant classrooms could affect the relationship between $CO_2$ level and bioeffluents.

Previously, Cablé et al. [11] compared $CO_2$-DCV with a combined $CO_2$ and temperature DCV control strategy and their influence on perceived indoor climate in a classroom in Norway. The combined control strategy aimed at decreasing or increasing the ventilation rates depending on whether the room temperature was below or above 22.5 °C. Unlike our study, the indoor climate was assessed by the pupils in the classrooms after each class session. They found that the combined ventilation strategy resulted in a somewhat better perceived air quality and reduced the discomfort from too high variations of room temperature. However, as the measured indoor temperature did not go below 22 °C, they were not able to compare the effects of the two control strategies on perceived air quality at low indoor temperature and high $CO_2$ levels. Mysen et al. [10] provided examples of different control strategies with either linear or stepwise temperature-compensated $CO_2$ setpoints based on their field experiment in a primary school where draught and too low temperatures were issues. The authors suggested $CO_2$ setpoints of 1250 ppm for a room temperature of 18 °C and 800 ppm at 22 °C. This suggestion assumes an outdoor $CO_2$ concentration of 350 ppm, that the total pollution load is always dominated by pollution from the occupants and so reduced airflow rates would lead to a probably significant improvement of the thermal conditions.

We found that at a low room air temperature around ~22 °C, increasing the $CO_2$ level to ~1000 ppm would not significantly affect perceived indoor air quality, odour intensity, perceived thermal acceptability, and thermal sensation. The increase in room temperature at similar $CO_2$ concentrations yielded poorer perceived air quality scores, but not perceived odour intensity. This indicates that perceived air quality can be maintained by decreasing air temperature when the ventilation rates are reduced. Our findings are in line with the study by Wargocki and Wyon [21] where at low ventilation rates (180 $m^3/h$), reducing the air temperature from 24.9 °C to 21.6 °C significantly increased the acceptability of classroom air quality and the air was also perceived to be significantly fresher. However, unlike our study, the sensory panel visited the classrooms after the pupils had gone home and the average $CO_2$ measured in the classroom was much higher, at 1230 ± 325 ppm and 1462 ± 412 ppm for high and low air temperature, respectively. In the same study, it was also found that the performance of schoolwork by children improved by reducing the air temperature. Generally, decreasing the supply airflow rates might not be a preferred option as it could result in increased sick building syndrome symptoms and reductions in aspects of human performance [22,23], however, the supply airflow rates and the corresponding $CO_2$ levels used in our study were well within the bounds of the recommended values from recent studies [16,24,25].

Studies have demonstrated a strong correlation between enthalpy and perceived air quality and this was also confirmed in our study [26]. As seen in Fig. 7, our results also show a strong correlation. We have focused on temperature rather than enthalpy in our studies, as room and supply air temperatures typically can be quite well controlled, while tight control of humidity would require humidification or dehumidification, adding considerably to HVAC complexity and costs. The absolute humidity in a classroom is largely determined by the humidity of outdoor air, moisture production by occupants, and ventilation rate. The humidity of outdoor air is strongly correlated with outdoor temperatures, and moisture production by occupants correlates well with body size and metabolic rate, and thus $CO_2$ production in individuals close to thermal neutrality [27]. The option of using enthalpy to control ventilation rates might be relevant in certain situations. However, further studies would be required to determine if incorporating enthalpy is a better option than a simpler control strategy that increases ventilation rates as a function of indoor temperature in periods where indoor temperatures cannot be maintained below a set level of e.g., 21 °C.

Previously, to investigate whether children would require different ventilation rates compared to adults, perceived air quality and odour intensity in different classrooms (2. grade to 10. grade) at the same school as the present study were assessed [19,20]. Fig. 8 shows the results from those two studies along with the results from this study plotted as a function of $CO_2$ level and room air temperature. Generally, the average perceived air quality scores at high room air temperatures (>23 °C) and low $CO_2$ levels were comparable to those at lower temperatures and high $CO_2$ levels. The odour intensity scores vary between

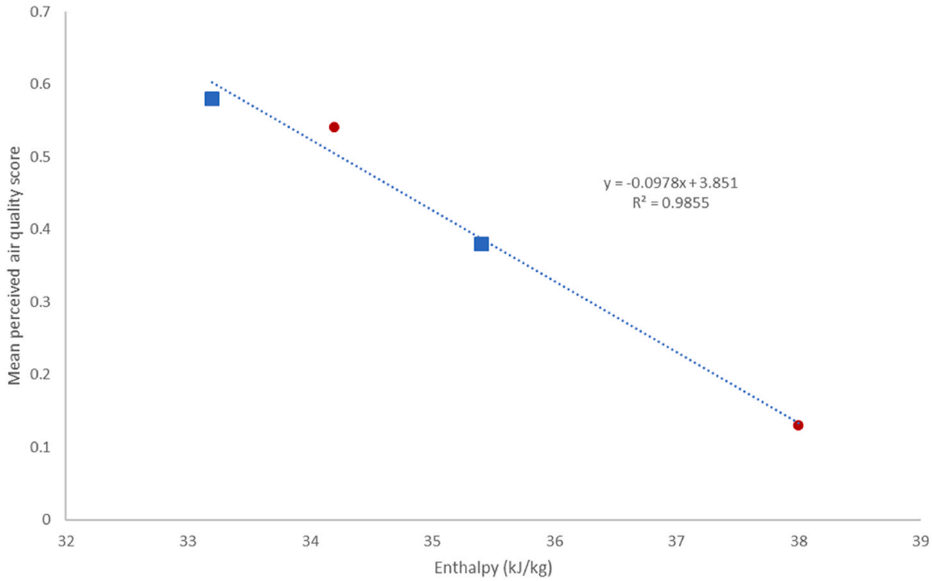


**Fig. 7.** Relation between mean perceived air quality score and enthalpy. The blue square markers indicate high $CO_2$ levels. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

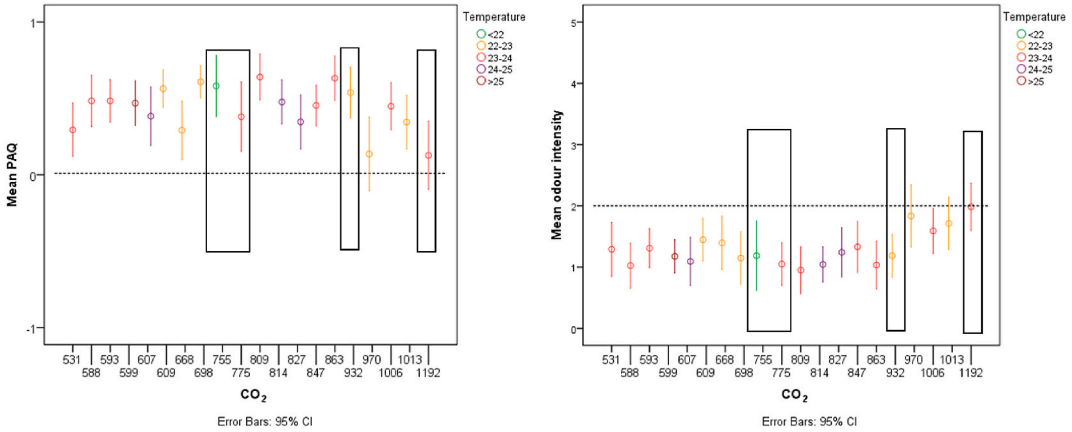


**Fig. 8.** Overview of perceived air quality scores (−1 = Clearly unacceptable, 1 = Clearly acceptable) and odour intensity scores (0 = no odour, 5 = overpowering odour) from this study and two previous studies [19,20]. The results inside the boxes are from this study. Error bars indicate 95 % CI.

1 ("slight odour") to 2 ("moderate odour"), where the highest average odour intensity scores were observed for the visitations with the highest $CO_2$ concentrations and the room air temperature were generally ≥ 23 °C. As seen in Table 2, the supply airflow rates in the three studies are in the range of 324–1247 $m^3/h$, which correspond to actual ventilation rates of 4.5–18.2 l/s per person, making it challenging to compare the

**Table 2**
Overview of perceived air quality and odour intensity scores from this study and two previous studies [19,20]. %PD is the calculated percentage dissatisfied. $V_{supply}$ is the supplied outdoor airflow rate, Vpers is the actual ventilation rate based on the number of people in the classroom.

| Grade | Perceived air quality | | | Odour intensity | | | $V_{supply}$ | $V_{pers}$ | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| | mean ± sd | median | %PD | mean ± sd | median | %PD | $m^3/h$ | (l/s) | |
| 5C | 0.43 ± 0.31 | 0.48 | 17–22 | 1.46 ± 0.79 | 1.40 | 0 | 685* | 7.3* | [19] |
| 6A | 0.64 ± 0.29 | 0.67 | 6–11 | 1.00 ± 0.79 | 0.85 | 0–6 | 570* | 9.0* | [19] |
| 8A | 0.57 ± 0.26 | 0.58 | 11–17 | 1.18 ± 0.78 | 1.10 | 0–11 | 409* | 6.7* | [19] |
| 10A | 0.55 ± 0.28 | 0.58 | 6–11 | 1.20 ± 0.72 | 1.10 | 0–11 | 614* | 7.3* | [19] |
| 8A | 0.58 ± 0.38 | 0.69 | 6 | 1.19 ± 1.06 | 0.78 | 25 | 1177 | 16.3 | This study, [20] |
| | 0.54 ± 0.32 | 0.64 | 6 | 1.19 ± 0.66 | 1.16 | 13 | 336 | 6.7 | |
| 8B | 0.38 ± 0.43 | 0.49 | 19 | 1.05 ± 0.66 | 1.01 | 6 | 1247 | 18.2 | This study |
| | 0.13 ± 0.42 | 0.22 | 38 | 1.98 ± 0.73 | 2.13 | 50 | 356 | 5.2 | |
| 2B | 0.29 ± 0.36 | 0.26 | 25 | 1.40 ± 0.82 | 1.33 | 25 | 1134 | 17.5 | [20] |
| | 0.14 ± 0.46 | 0.21 | 38 | 1.84 ± 0.96 | 1.80 | 38 | 324 | 4.5 | |
| 2C | 0.61 ± 0.20 | 0.57 | 0 | 1.15 ± 0.81 | 0.97 | 0 | 1134 | 15.8 | [20] |
| | 0.35 ± 0.33 | 0.32 | 13 | 1.71 ± 0.81 | 1.80 | 13 | 324 | 4.5 | |

*Average of three visitations in the same classroom.

results across the studies. At low $CO_2$ levels, the high ventilation rates (15–17 l/s per person) would have removed most of the generated bioeffluents in the classrooms. Nevertheless, the average odour intensity score was still higher than the investigated classrooms in Holand et al. [19], indicating that there is a possible influence of the age groups and/or stored materials in the different classrooms.

In the study by Mysen et al. [17], an intervention study was also done to assess two different control strategies. The $CO_2$ setpoint was set to 550 ppm or 1000 ppm, while the temperature setpoint was set to 28 °C. The temperature in the room during the eight test rounds varied between 19.9 and 22.4 °C and the temperature difference upon entry and after 60 min was less than 1.7 K, thus it was assumed that only the ventilation rate influenced the perceived air quality scores. No consistent or significant impact of the ventilation rate ($V_{min}$) on perceived air quality upon entry was observed. The variations in $CO_2$ concentrations upon entry could be explained by that it might have taken some minutes before the sensory panel (N = 15–22) provided their perceived air quality scores. As seen in Fig. 9, the ventilation rate had a larger impact on the average perceived air quality score after 60 min, with a decreasing tendency as the $CO_2$ concentration increased. After 60 min, the temperature increased by ~1K for each test session, but no associations between temperature and perceived air quality were observed.

Perceived air quality does not consider the health impacts of contaminants. Certain contaminants have health impacts below the odour and irritation thresholds, and thus, perceived air quality is not a reliable indicator for health risks. While our results are coherent with previous knowledge that $CO_2$ with occupants as the source is a useful indicator of bioeffluents reducing perceived air quality levels if corrections for air temperature and humidity are made, links between $CO_2$ and harmful concentrations of pollutants are in most cases unclear. A notable exception may be airborne infectious organisms, where the $CO_2$ level can be used as a marker for exhaled breath exposure and thus the concentration of airborne pathogen concentrations [28]. The outbreak of infectious respiratory diseases, particularly the COVID-19 pandemic, has reiterated the importance of ventilation in buildings. WHO has in its roadmap to improve and ensure good indoor ventilation in the context of COVID-19 recommended a minimum ventilation rate of 10 L/s per person for non-residential buildings [29]. For DCV-systems, REHVA has recommended a $CO_2$ setpoint of 550 ppm to maintain nominal speed and full ventilation during lower occupancy to reduce the risk of transmission of infectious diseases [30]. While these recommendations may be sound, we argue that the most relevant indicator for infection risk from aerosols is the dilution of exhaled breath in the breathing zone. It may make sense to ensure that operation strategy can be adapted to current infection risks in addition to climate and the other variable previously discussed.

Due to time and capacity constraints, we were only able to evaluate a limited number of classrooms under two different temperatures and ventilation conditions. This study was a part of several experiments performed at the same school where we assessed the effect of adjusting ventilation rates on perceived air quality. The indoor air quality in this study was assessed by a sensory panel and might therefore not be representative of the air quality perceived by the occupants. It would be of further interest to compare the perceived indoor air quality of the occupants to that of a sensory panel. Previous studies have indicated that women are more likely to express dissatisfaction with indoor environmental quality, particularly related to thermal comfort. Other individual confounding factors such as age, ethnicity, BMI and social class have also been suggested [31]. This study only examined the first impressions given by a test panel upon entering a classroom and it would be therefore of interest to examine the effect of a combined $CO_2$ and temperature control strategy over a longer period. It is well known that an increased outdoor air supply rate is a powerful remedial measure to improve indoor air quality but comes at the expense of energy consumption. Our previous findings do suggest that even in classrooms with low-emitting materials, a higher $V_{min}$ is needed for rooms with higher pollution loads, indicating that source control should be prioritized. Moreover, we also found indications of the need to adjust ventilation rates according to the users who occupied the various classrooms. Based on this study only, it is challenging to provide recommendations for an optimal DCV strategy. Our results do confirm previous findings that temperature significantly influences perceived air quality and indicate that a DCV control strategy with a higher $CO_2$ setpoint at low temperature can be recommended without compromising on perceived air quality upon entry.

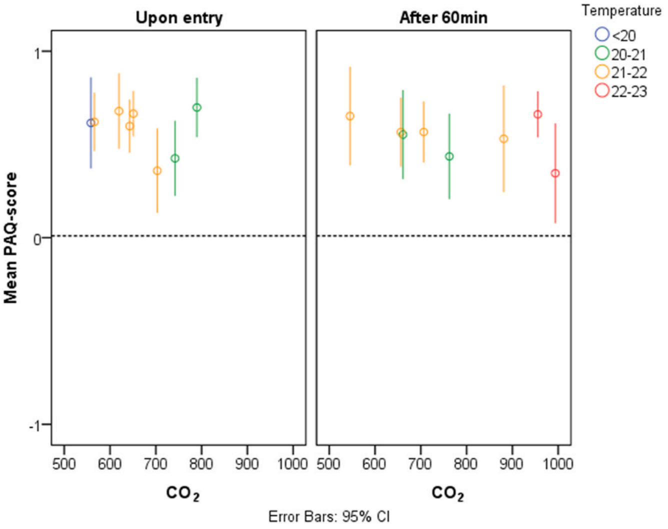


**Fig. 9.** Average perceived air quality scores for 8 test rounds with varying airflow rates, data upon entry from Mysen et al. [17] and after 60 min.

## 5. Conclusions

Our results indicate that a DCV-control strategy with a higher $CO_2$ setpoint in classrooms at low temperatures can be recommended, at least without compromising perceived air quality. Our results confirm the previous studies on the effect of temperature on perceived air quality, and is more relevant than ever, particularly in Nordic countries where DCV-ventilation systems are taken more and more into use in schools. Based on the field experiments done in this study and from previous studies at the same school, an optimal DCV strategy should allow individual modifications of $V_{min}$, $V_{max}$ or $CO_2$ and temperature setpoints according to actual needs. As we only assessed perceived air quality, further research on indoor climate-related symptoms is needed, where health symptoms and performance tests over time are examined. Moreover, it would also be of interest to compare the perceived air quality assessed by a sensory panel with that of the occupants in the relevant classrooms coupled with objective measurements of pollutants.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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