Indoor CO₂ and Thermal Conditions in Twenty Scottish Primary School Classrooms with Different Ventilation Systems during the COVID-19 Pandemic

Natalie Bain-Reguis 1,*; Andrew Smith 1; Caroline Hollins Martin 2 and John Currie 1

Abstract: Healthy indoor environments influence the comfort, health and wellbeing of the occupants. Monitoring the indoor temperature, relative humidity and CO₂ levels in primary schools during the COVID-19 pandemic was mandated by a local authority in Scotland. The aim was to investigate the comfort and safety of the teachers and their pupils. This paper presents the measurements of indoor climate in 20 classrooms in four different primary schools in Scotland. The schools were of different architypes. The classrooms were of different sizes, orientations and occupancy, and had different ventilation systems. Ventilation was achieved either by manually opening the windows, or by a mechanical ventilation system. Indoor air temperature, relative humidity and carbon dioxide (CO₂) concentrations were continuously monitored for one week during the heating season 2020/21. Occupancy and opening of the windows were logged in by the teachers. The ventilation rates in the classrooms were estimated by measuring the CO₂ concentrations. On the 20 classrooms of the study, data of 19 were analysed. The results show that four of the five mechanically ventilated classrooms performed better than natural ventilation, which indicates that opening the windows depended on the customs and habits. Classrooms in naturally ventilated Victorian buildings have the worst average ventilation rate (4.38 L/s per person) compared to the other classrooms (5.8 L/s per person for the more recent naturally ventilated ones, and 6.08 L/s per person for the mechanically ventilated ones). The results of this preliminary study will be used as the basis to find ways to ensure adequate ventilation in natural ventilated classrooms.

Keywords: school; classroom; ventilation system type; indoor temperature; relative humidity; carbon dioxide; IEQ; IAQ

1. Introduction

The quality of the indoor environment (IEQ) has been shown to have an impact on the health and wellbeing of workers [1], who mostly complain about poor indoor air quality (IAQ) [2] and inadequate indoor temperature [3]. Schools are not exempt from these issues, being places where pupils and teachers spend hours in an overcrowded enclosed space, often with poor ventilation [4].

Multiple studies [4–15] have shown the importance of maintaining appropriate IAQ in classrooms for the comfort, health and wellbeing of both pupils and teachers. The World Green Building Council has published a factsheet about IAQ for schools, and how bad air affects children [16]. According to this report, a 1000 parts per million (ppm) increase above ambient levels of CO₂ has been linked to a 10%–20% increase in days away from school.

Keeping healthy IAQ in schools will help children stay healthier, more focused and more productive [8,17]; it will help reduce health and wellbeing issues among pupils [9,10,18,19] and
teachers [11,12,20–22] while maintaining a comfortable and healthy working environment to enhance pupils’ learning [6,7,13–15,23,24].

Furthermore, schools are known to be places where viruses can spread easily, from noroviruses to the seasonal flu [25], due to occupants being in close proximity to each other [26]. The SARS-COVID-19 virus is not different, being an airborne virus [27,28] and thriving in dark, dry and crowded places [29].

To evaluate the IAQ, an assessment of the ventilation rates of the rooms can be undertaken. Measuring metabolic respiration evolved carbon dioxide (CO$_2$) concentrations in occupied rooms has historically been shown to be a good proxy for ventilation assessment [30–32] and is proposed as part of ASHRAE Standards 62.2 [33] and the COVID-19 Education Recovery Group CERG (2020) guidance [34]. Since background (ambient) CO$_2$ level is relatively stable and indoor excess CO$_2$ is usually only from living beings’ exhalation, measurements of indoor CO$_2$ concentration by low-cost CO$_2$ sensors can often be good indicators of ventilation adequacy and thus suitable for mass deployment [35,36].

Keeping schools open is essential for the mental, social and physical development of the children, but cannot be to the detriment of their own health and wellbeing nor that of their teachers. While it is paramount to ensure good ventilation in schools, the comfort of the occupants is also important. It is therefore necessary to monitor the indoor climate of the classrooms, which includes indoor temperature and relative humidity (RH).

Thus, monitoring indoor temperature, RH and CO$_2$ concentrations have become the guidance to ensure a safe indoor environment [37].

In Scottish schools, the latest guidance suggests CO$_2$ levels should not exceed 1500 ppm in classrooms and 800 ppm in music rooms and gym halls [35]. The ASHRAE standard 62.2 [33] recommends that indoor CO$_2$ levels should not be higher than 700 ppm compared to outside. If outdoor CO$_2$ is assumed to be around 420 ppm, this would mean that ASHRAE recommends a maximum of 1120 ppm for indoor CO$_2$. Other regulations have imposed stricter limits, down to 800 ppm for some European Countries [38], like in France [39] or in Ireland [40]. The Chartered Institute of Building Services Engineers (CIBSE) has published a new guide stipulating that the ventilation rate should be 10 L/s/person minimum, which is equivalent to 2 air changes/h [41].

The indoor temperature in Scottish classrooms should be kept above 17 °C, according to current regulations [35].

There is a close physical relationship between air temperature and RH levels (psychrometry), which makes the control of humidity in naturally ventilated spaces difficult through simple ventilation measures alone, and in the UK lower levels of RH as a trade-off are often accepted. There is currently no mandatory legal requirement to control RH and the relative risk posed by this parameter alone has not yet been fully ascertained in research. However, some studies have identified an RH ‘sweet spot’ between 40% and 60%, adding that air that is too dry would allow viruses to thrive and be more active [42,43].

Therefore, the main objective of the present work was to evaluate the environmental conditions of Scottish schools by monitoring the indoor temperature, RH and CO$_2$ levels of their classrooms, from different building architypes, different sizes, orientations and occupancy and with different ventilation strategies.

2. Materials and Methods

The study was at the request of a Local Authority in Scotland during the heating season of the COVID-19 pandemic (winter 2020/21) to assess the CO$_2$ levels, ventilation rates and thermal comfort in their classrooms. The study was performed in four urban primary schools all chosen by the local authority after receiving the approval to participate from the headteachers. The 20 classrooms were selected by the business managers of the schools in which the study was performed. Overall, 15 of the 20 classrooms were naturally ventilated, whereas 5 used a mechanical ventilation system.

The typology of all classrooms is presented in Table 1.
Table 1. Classroom’s typology where the measurements were performed.

<table>
<thead>
<tr>
<th>School</th>
<th>Classroom</th>
<th>Storey</th>
<th>Ventilation System</th>
<th>Orientation</th>
<th>Space Volume (m³)</th>
<th>Space Area (m²)</th>
<th>Year Built/Last Renovation</th>
<th>Occupancy (Teachers and Pupils)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A1</td>
<td>Ground</td>
<td>Natural</td>
<td>SSE-E</td>
<td>71.8</td>
<td>28.0</td>
<td>1964</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>Ground</td>
<td>Natural</td>
<td>SSE</td>
<td>94.3</td>
<td>36.3</td>
<td>1964</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>Ground</td>
<td>Natural</td>
<td>SSE</td>
<td>116.8</td>
<td>38.9</td>
<td>1964</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>A4</td>
<td>1st</td>
<td>Natural</td>
<td>E-NNE</td>
<td>145.1</td>
<td>48.4</td>
<td>1964</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>A5</td>
<td>2nd (Top)</td>
<td>Natural</td>
<td>SSE</td>
<td>145.1</td>
<td>48.4</td>
<td>1964</td>
<td>19</td>
</tr>
<tr>
<td>B</td>
<td>B1</td>
<td>Ground</td>
<td>Mechanical</td>
<td>E-W</td>
<td>142.8</td>
<td>47.6</td>
<td>1968</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>2nd (Top)</td>
<td>Natural</td>
<td>NE-SW</td>
<td>148.1</td>
<td>51.9</td>
<td>1968</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>1st</td>
<td>Natural</td>
<td>NE-SW</td>
<td>61.2</td>
<td>23.5</td>
<td>1968</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td>Ground</td>
<td>Mechanical</td>
<td>NW</td>
<td>126.8</td>
<td>42.3</td>
<td>2013</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>B5</td>
<td>Ground</td>
<td>Mechanical</td>
<td>N-S-E-W</td>
<td>432.0</td>
<td>154.3</td>
<td>2017</td>
<td>47</td>
</tr>
<tr>
<td>C</td>
<td>C1</td>
<td>Ground</td>
<td>Natural</td>
<td>W</td>
<td>196.0</td>
<td>38.2</td>
<td>1891</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>2nd (Top)</td>
<td>Natural</td>
<td>SW-W</td>
<td>184.3</td>
<td>40.0</td>
<td>1891</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>2nd (Top)</td>
<td>Natural</td>
<td>W</td>
<td>173.4</td>
<td>38.2</td>
<td>1891</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>C4</td>
<td>2nd (Top)</td>
<td>Natural</td>
<td>NE</td>
<td>250.7</td>
<td>54.5</td>
<td>1891</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td>2nd (Top)</td>
<td>Natural</td>
<td>NE-W</td>
<td>250.6</td>
<td>54.5</td>
<td>1891</td>
<td>32</td>
</tr>
<tr>
<td>D</td>
<td>D1</td>
<td>Ground</td>
<td>Mechanical</td>
<td>W</td>
<td>168.0</td>
<td>42</td>
<td>2015</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>Ground</td>
<td>Natural</td>
<td>SW</td>
<td>210.0</td>
<td>42</td>
<td>1902</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>D3</td>
<td>1st</td>
<td>Natural</td>
<td>NE</td>
<td>192.0</td>
<td>48</td>
<td>1902</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>D4</td>
<td>2nd (Top)</td>
<td>Natural</td>
<td>SW</td>
<td>165.0</td>
<td>33</td>
<td>1902</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>D5</td>
<td>Ground</td>
<td>Mechanical</td>
<td>S</td>
<td>162.0</td>
<td>40.5</td>
<td>2007</td>
<td>23</td>
</tr>
</tbody>
</table>

School A, having been built in the early 1960s, is poorly insulated [44] and naturally ventilated, with classrooms on the ground floor having double doors opening directly into the playground.

Schools B and D are composed of different buildings built over the years with different ventilation systems.

School C is a typical Victorian school that is naturally ventilated.

Figures 1–17 show the locations and the floorplans of the schools (classrooms identified and devices localised by a red dot.) and illustrate the different architypes and ventilation systems of classrooms of the school buildings. Note: The floorplans are for illustration purpose and are not to scale.

Due to the emergency of the situation during the COVID-19 pandemic, the local authority granted access to each school buildings for a period of one week maximum over the heating season (November–December 2020), during which the measurements were performed (November–December 2020). They included the measurements of CO₂ concentration using TinyTag TGE-0010 and TGE-0011 loggers (accuracy ± 50 ppm, ±2% of reading). Other TinyTag TGU-4500 loggers recorded the indoor temperature (−25 to +85 °C) and RH (0% to 95%). All the data loggers were provided by the local authority.

Logging intervals were set to every minute with min, max and actual readings. Sample collection began by setting up all sensors for a fixed start time on their deployment date.

Once in the classrooms, the CO₂ monitors were plugged in to an available power socket and made safe with the logger mounted in the ‘occupied zone’ at approximately 1.5 m above floor level.

The temperature and RH sensors were located next to the CO₂ monitors, placed either on the teachers’ desks or on shelves (as shown on Figure 18). Both monitors were positioned away from direct sunlight, radiators, doors and windows.

At the end of the one week of monitoring, all monitors were retrieved, and the data were downloaded onto the Tinytag Explorer platform via a USB cable. The data were then output to Microsoft Excel for analysis.
Figure 1. School A.

Figure 2. Picture of school A.
**Figure 3.** Picture of classroom A2.

**Figure 4.** Cont.
As any indoor environment is impacted by outdoor climatic conditions, the outdoor temperature, RH, wind speed and direction were also studied alongside the internal measured elements. The purpose was to identify potential correlation between the variations of the indoor and the outdoor conditions. The outdoor climate was monitored through the website [https://www.wunderground.com/](https://www.wunderground.com/) (last accessed on the 20 November 2021) from different weather stations, located close to the schools monitored. Values were also
recorded from a centrally located weather station owned by Edinburgh Napier University, to validate the data from the Wunderground website.

Opening of the windows and doors and the occupancy were logged in by the teachers. The average of the peak values of CO\textsubscript{2} concentration measured during school hours was used to estimate the classrooms ventilation rates. Batterman recently reviewed different methods to assess the ventilation rates, using occupant-generated CO\textsubscript{2} [45]. He described four main methods: the steady-state method, the concentration decay, the built-up method and the transient mass balance equation method. Allen and colleagues published a quick five-step guide to evaluate the ventilation rates in classrooms [46], one of which follows the steady-state method described by Batterman.

Figure 7. Picture of classroom B3.

Figure 8. Picture of classroom B5.

Figure 9. Cont.
Figure 9. School C.
Logarithmic decay was used in early experiments in an attempt to evaluate room ventilation rates, but the transitory nature of occupancy experienced, combined with a limited range of concentration decay between occupancy events (flushing), gave inconsistent results. A method for mapping time integrated CO$_2$ evolution through resolving the first-order partial differential equation for a room ventilated at a specific rate was also undertaken but found to be very time intensive. It was thus decided to utilise time integrated metabolic CO$_2$ mass balancing to establish comparable metrics.

Considering the pros and cons of each method, and assuming the peak CO$_2$ is indicative of steady-state CO$_2$ concentration levels, it could therefore be used to estimate the minimum ventilation rate [41]. The CO$_2$ generation rate per pupil was assumed to be 0.004 L/s and 0.0054 L/s per teacher [47–49]. The outdoor CO$_2$ was assumed to be 420 ppm for the City of Edinburgh, considering the global average atmospheric CO$_2$ for 2020 was estimated to be 412.5 ppm (NOAA, 2021).
Figure 12. School D.
Figure 13. Picture of school D.

Figure 14. Picture of classroom D1.

Figure 15. Picture of classroom D3.

Figure 16. Picture of classroom D5.
3. Results

In the following paragraphs, the indoor temperature, the RH and the CO₂ concentrations measured during the monitored weeks as well as the ventilation rates are discussed. The patterned bars on the different graphs show the results for the classrooms with mechanical ventilation. The monitor in the classroom B3 was unplugged shortly after deployment. Therefore, no data were analysed for this classroom.

3.1. Link between Outdoor and Indoor Climate (Temperature and RH)

No evident correlation could be found between outdoor conditions recorded and indoor monitored data. Longer periods of sampling might be necessary to verify the trend.

From the returned log sheets and data recorded therein, it was difficult to quantify exactly how often and for how long the window apertures were opened. Mechanisms for automatically recording window opening and room occupancy should be considered for further studies of this nature.

3.2. Indoor Climate (Temperature and RH)

This section details the indoor temperature and RH in all the monitored classrooms, alongside the 17 °C temperature threshold and the 40%–60% ‘sweet spot’ of RH levels.

3.2.1. Indoor Temperature

To assess the indoor temperature of the classrooms according to the 17 °C threshold, the minimum and the average indoor temperature of each classroom are shown on Figure 19. It shows that school A, room A5 (16.4 °C) and school B, room B4 (16.9 °C) recorded an average indoor temperature below 17 °C.

Figure 17. Picture of classroom D5.

Figure 18. Monitors’ positioning sample.
Figure 19. Indoor temperature in the classrooms during school hours, with classrooms B1, B4, B5, D1 and D5 having mechanical ventilation.

To highlight the classrooms with lower than acceptable indoor temperatures, Figure 20 shows the classrooms having an indoor temperature below the 17 °C threshold by % of time and in hours.

Figure 20. Classrooms with indoor temperature below the 17 °C threshold, with classrooms B1, B4, B5, D1 and D5 having mechanical ventilation.

Studying Figures 19 and 20 alongside the information on Table 2 shows the following. A5 and B4 are either situated on the ground or the top floor, with less potential heat gain from the neighbouring classrooms.
Both A5 and B4 have lower occupancy compared to the other classrooms of the study: 22 and 25 persons (pupils and teachers), respectively, compared to 31 on average, with less heat gain from their occupants.

Table 2. Classrooms with orientation, location, occupancy and window surface areas.

<table>
<thead>
<tr>
<th>Classroom</th>
<th>Storey</th>
<th>Orientation</th>
<th>Windows Area (m²)</th>
<th>Occupancy (Teachers and Pupils)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min</td>
</tr>
<tr>
<td>A1</td>
<td>Ground</td>
<td>SSE-E</td>
<td>22.99</td>
<td>23</td>
</tr>
<tr>
<td>A2</td>
<td>Ground</td>
<td>SSE</td>
<td>41.47</td>
<td>11</td>
</tr>
<tr>
<td>A3</td>
<td>Ground</td>
<td>SSE</td>
<td>10.44</td>
<td>24</td>
</tr>
<tr>
<td>A4</td>
<td>1st</td>
<td>E-NNE</td>
<td>17.48</td>
<td>23</td>
</tr>
<tr>
<td>A5</td>
<td>2nd (Top)</td>
<td>SSE-W</td>
<td>33.70</td>
<td>19</td>
</tr>
<tr>
<td>B1</td>
<td>Ground</td>
<td>E-W</td>
<td>4.34</td>
<td>30</td>
</tr>
<tr>
<td>B2</td>
<td>2nd (Top)</td>
<td>NE-SW</td>
<td>9.63</td>
<td>27</td>
</tr>
<tr>
<td>B3</td>
<td>1st</td>
<td>NE-SW</td>
<td>2.10</td>
<td>22</td>
</tr>
<tr>
<td>B4</td>
<td>Ground</td>
<td>NW</td>
<td>12.87</td>
<td>23</td>
</tr>
<tr>
<td>B5</td>
<td>Ground</td>
<td>N-S-E-W</td>
<td>7.68</td>
<td>47</td>
</tr>
<tr>
<td>C1</td>
<td>Ground</td>
<td>W</td>
<td>5.21</td>
<td>22</td>
</tr>
<tr>
<td>C2</td>
<td>2nd (Top)</td>
<td>SW-W</td>
<td>8.83</td>
<td>33</td>
</tr>
<tr>
<td>C3</td>
<td>2nd (Top)</td>
<td>W</td>
<td>10.47</td>
<td>22</td>
</tr>
<tr>
<td>C4</td>
<td>2nd (Top)</td>
<td>NE</td>
<td>8.83</td>
<td>22</td>
</tr>
<tr>
<td>C5</td>
<td>2nd (Top)</td>
<td>NE-W</td>
<td>2.30</td>
<td>32</td>
</tr>
<tr>
<td>D1</td>
<td>Ground</td>
<td>W</td>
<td>4.00</td>
<td>24</td>
</tr>
<tr>
<td>D2</td>
<td>Ground</td>
<td>SW</td>
<td>5.00</td>
<td>30</td>
</tr>
<tr>
<td>D3</td>
<td>1st</td>
<td>NE</td>
<td>4.22</td>
<td>29</td>
</tr>
<tr>
<td>D4</td>
<td>2nd (Top)</td>
<td>SW</td>
<td>4.40</td>
<td>24</td>
</tr>
<tr>
<td>D5</td>
<td>Ground</td>
<td>S</td>
<td>22.99</td>
<td>23</td>
</tr>
</tbody>
</table>

A5 has one of the largest openable window areas of the study (33 m² compared to 11 m² on average) with more heat loss through the windows, while B4 is facing northwest (where the wind was predominantly blowing during the study week).

In addition to A5 and B4, three other classrooms had an indoor temperature below the 17 °C threshold for at least 10% of the time when pupils are in class: C1, C2 and A3, which are either on the ground or top floor and are facing West (C1 and C2).

To summarise, for this study, factors influencing the indoor temperature in classrooms are the occupancy and the openable surface areas of the windows, as well as their orientation (North and West) and the location (ground or top floor) in the buildings.

3.2.2. Indoor RH

Whereas there are no regulations for RH in Scottish schools, it has been shown in other indoor environments that levels below 40% are favourable for the spreading of viruses [42,43], and levels above 60% tend to increase the development of mould. Therefore, a threshold of 40%–60% was set for this study.

According to Figure 21, the classroom B1 from school B has average RH levels of less than 40% (39%RH), and room A5 from school A has an RH above 60% (60.9%).

The room B1 recorded lower RH values and had a higher average indoor temperature, above 20 °C as shown on Figure 19, with fewer windows recorded as being open compared to other classrooms in the same school. Depending on outside environmental conditions, lowering the room temperature through increased use of natural ventilation would generally increase relative humidity in these spaces.

Figure 22 shows for how long the RH is either less than 40% or more than 60%, while the pupils are in school.
Figure 21. Indoor relative humidity in the classrooms during school hours, with classrooms B1, B4, B5, D1 and D5 having mechanical ventilation.

Figure 22. Total time when RH out with threshold (in % and in hours), with classrooms B1, B4, B5, D1 and D5 having mechanical ventilation.

In total, 18 of the 20 classrooms monitored had an RH out of the 40%–60% threshold, either being lower or higher, with B4 and D5 having the highest number of hours performing out with the threshold, and both classrooms being mechanically ventilated.
3.3. CO₂ Concentration and Ventilation Rates

3.3.1. Carbon Dioxide Concentration

The recommended thresholds for room occupancy as provided by Scottish Government advice were 1500 ppm for normal teaching classrooms and 800 ppm for music, drama and gym [35]. Unsurprisingly, the maximum CO₂ levels occurred during school time, when the pupils were present in the class, as it has been shown in other studies [50].

Maximum CO₂ Levels and % of Time above Threshold

From Figure 23, 79% of the schools monitored demonstrated periods where the maximum recorded CO₂ concentrations exceeded threshold values identified above, except for school A:

- All the rooms at school B were between 1863 and 2810 ppm;
- Almost all the classrooms at school C (except room C2) were from 1560 to 1862 ppm;
- At school D, classrooms D2 (2001 ppm), D3 (1620 ppm) and D4 (1999 ppm) exceeded threshold values.

School A, where all classrooms have natural ventilation, has never recorded values going above the threshold, indicating adequate ventilation to achieve guideline levels.

Peak values going beyond the thresholds, and their duration at such levels, are an important consideration. However, when the CO₂ levels reach very high concentration for very short periods of time (less than 20 consecutive minutes), it might be assumed a change in the physical environment occurred, such as opening of more windows and doors, or changes in occupancy, such as pupils sent outside for breaks. When looking at data in more detail, most of these episodes evidenced CO₂ concentrations above the Scottish Government thresholds for only short periods of time and can be put into perspective when comparing these with classrooms that evidenced CO₂ concentrations above the threshold for more than 20 consecutive minutes (as per regulation in place).

The following school classrooms, representing 42% of all classrooms, were recorded with CO₂ concentrations above the threshold (1500 ppm for normal subjects and 800 ppm for music, drama and gym) for more than 20 consecutive minutes:
School B: rooms B1 (2% above 1500 ppm), B2 (18% of the time above 1500 ppm), B4 (2% of the time above 1500 ppm) and B5 (69% of the time above 1500 ppm);
− School C in rooms C1 (1%), C4 (9% of the time above 1500 ppm) and C5 (4%);
− School D in room D2 (22% of the time above 1500 ppm).

Figure 24 shows the classrooms that have CO₂ concentrations above the thresholds for more than 20 min, and how many hours that represents.

![Figure 24](image_url)

**Figure 24.** Classrooms with CO₂ concentrations above the threshold for more than 20 consecutives minutes.

Three classrooms (B2, B5 and D2) in two different schools had CO₂ levels above the threshold for more than 10% of the occupied time. B2 and D2 are naturally ventilated, while B5 is mechanically ventilated, which can suggest B5 ventilation system is not supplying enough fresh air (hypothesis will be confirmed in Section Analysis of the CO₂ Concentration for B5).

The following paragraphs analyse the potential reasons for these highest concentrations.

**Analysis of the CO₂ Concentration for B5**

The CO₂ concentration in B5 (illustrated in Figure 25) was concerning, considering the peak levels were not recorded due to the operating range of the CO₂ sensor installed (2000 ppm), assuming the accurate CO₂ levels were higher. The space is serviced by a recirculatory HVAC system serviced by a heat pump. When considering the ventilation openings recorded on that same day, it was shown that little to no adventitious ventilation support (through openable windows/louvers) was enabled in the room. The Council has since sent technical staff to the site to evaluate issues. In fact, the windows have full height opening sashes that open inwards and are free to swing once open with no restriction on how far it can open. The windows also have the capability to tilt. However, staff did not have keys to enable these functionalities and therefore relied only on the HVAC system. This issue was raised by the local authority directly with the school.
Analysis of the CO$_2$ Concentration for B2 and D2

Both classrooms are situated in a Victorian building and are naturally ventilated (Figure 26).

Figure 27 shows the temperature and CO$_2$ concentration monitored in B2 over the duration of the study while the school was open for the pupils, alongside the number of occupants and windows openings.

The number of pupils present was almost constant throughout the study days (minimum 26, maximum 27).

The teacher left the maximum windows open during two full days of the week, opening half of the windows for the remaining days.

It is noticeable the peaks of CO$_2$ concentrations build up throughout the week even though the CO$_2$ concentrations at the start of each day are the same: the levels are higher at
the end of the week than at the start, with a peak on the Friday. The lower levels correspond to a break when the children are leaving the classroom (either mid-morning, for lunch or at the end of the school day). This phenomenon may be caused by residual CO$_2$ from the other part of the building: corridors, halls, etc., where the ventilation strategies are unknown.

Figure 26. Classroom B2 on first floor of school B.

Figure 27. Temperature and CO$_2$ in B2 over the study week (pupils in school: 6 h 30 min per day Monday to Thursday and 4 h 30 min on Fridays).
Having more windows open impacts the CO₂ concentration in two ways: the level decreases quicker and takes longer to increase.

Considering the number of pupils in the classroom is almost constant, pupils leaving the classroom has a direct impact on the CO₂ levels: less occupancy implies lower CO₂ levels.

Figure 28 shows the CO₂ concentrations and the indoor temperature over the study week for the classroom D2. However, the openings and occupancy were reported accurately for this classroom, which is a limitation, and therefore will not be discussed.

![Figure 28. Temperature and CO₂ concentrations in D2 over the four days study week.](image)

The variation in the CO₂ concentrations is more important for this classroom. It is assumed no pupils came in class on day 4, as very low levels were recorded.

When the classroom is occupied consecutively for full days, the same observation as for B2 can be made: the CO₂ concentrations are getting higher over the days, but when the classroom is empty for a longer period, the concentrations tend to be lower.

### 3.3.2. Ventilation Rates

As detailed in paragraph 2, the ventilation rate calculation technique does not rely on the decay method. Table 3 shows the average ventilation rates in the classrooms, estimated using the measured peak CO₂ concentrations during school hours.

In total, 80% of the mechanically ventilated classrooms had an ACH above the recommended 2 h⁻¹, compared to 71% of the naturally ventilated ones. Mechanically ventilated classrooms had a higher ACH except for B5, due to the issue with the HVAC. The high ACH in school A is likely to be a result of the archtype of the school building (as detailed in Table 1). It can be assumed the classrooms with mechanical ventilation relied only on the system when the naturally ventilated classrooms had the instructions to open windows and doors as much as possible during the pandemic. This can explain high ACH in some of the naturally ventilated classrooms.

Only the classroom D5 had ventilation rates above the threshold of 10 L/s per person, which suggests that windows and doors should have been open more often.

Except for classroom B5, ventilation rates were lowest where the classrooms were naturally ventilated (average of 4.9 L/s per person) and the highest in the classrooms with a mechanical ventilation system (average of 6.08 L/s per person).

For naturally ventilated buildings, the average of the ventilation rates of Victorian buildings was lower (4.38 L/s per person) compared to more recent ones (5.8 L/s per person).
Table 3. Peak CO₂ concentration and the estimated ventilation rates in classrooms with different ventilation systems.

<table>
<thead>
<tr>
<th>Class Number</th>
<th>Naturally Ventilated Classrooms</th>
<th>Mechanically Ventilated Classrooms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
<td>A2</td>
</tr>
<tr>
<td>Average Peak CO₂ (ppm)</td>
<td>945</td>
<td>1186</td>
</tr>
<tr>
<td>ACH (h⁻¹)</td>
<td>10.2</td>
<td>5.4</td>
</tr>
<tr>
<td>Ventilation rate per person (l/s/pers.)</td>
<td>7.54</td>
<td>5.44</td>
</tr>
<tr>
<td>average ACH</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>average Ventilation rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Victorian buildings only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average ACH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Victorian only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average Ventilation rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>newer buildings only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average ACH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>newer only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average Ventilation rate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
It was assumed that the mechanical ventilation in room B5 underperformed as discussed in Section Maximum CO\textsubscript{2} Levels and % of Time above Threshold.

4. Discussion

Of the 20 school classrooms monitored and studied, 19 were studied, as 1 had its monitors unplugged.

On the 19 primary classrooms analysed, this study shows that the peaks of CO\textsubscript{2} concentrations are shown to increase during the day and over the week: the later in the day, the higher the peak CO\textsubscript{2} concentration recorded, and the later in the week, the higher the peak concentrations recorded in classrooms.

As previously anticipated and shown in Section 3.3.2, older Victorian naturally ventilated classrooms (in school C and classrooms D2 to D4) have the lowest ventilation rates. As discussed in Section 3.2, the location and orientation of the classrooms within the school building as well as the occupancy have a direct impact on the indoor temperature.

As expected, this study confirms that mechanically ventilated classrooms, if operated properly, perform better in terms of CO\textsubscript{2} concentrations than naturally ventilated ones [51,52].

Therefore, this study can imply some recommendations. Firstly, all mechanical heating and ventilation systems and manually operated windows servicing classrooms should be checked to ensure correct operation.

Secondly, flush the air by opening fully windows and doors at the start and at the end of the school days.

Thirdly, ensure adequate ventilation (windows and doors) during class time to stimulate cross-ventilation.

Fourthly, windows and doors should be open fully during break and lunch time when pupils are leaving the classroom.

Finally, try to reduce the number of occupants per classrooms or promote outdoor activities.

5. Limitations and Further Work

5.1. Limitations

Some limitations apply to this study and can be divided into three categories.

First, the limitations are related to human behaviour. The equipment was unplugged for short periods of time or for the whole week. Some teachers did not engage in the study or gave imprecise/ incomplete information, including classroom D2.

Secondly, the limitations related to the length of the study and the monitors used. The short period of monitoring and of the memory of the data loggers at high resolution enabled only a snapshot of the data. No remote access to the data implied the need to go onsite to upload the results and we only noticed potential issues once they were uploaded.

Finally, due to the transitory nature of occupancy experienced, combined with a limited range of concentration decay between occupancy events (flushing), the often used decay method to calculate ventilation rates gave inconsistent results. Therefore, an adaptation of the steady-state method was adopted.

5.2. Further Development

Following this study, some further development should be envisaged.

More research studies on the impact of RH in schools should be considered.

Primary school classrooms of Victorian buildings have been shown to have the lowest ventilation rates. A longer and more in-depth study targeting these schools would help confirm the trends found during this study.

Measuring the CO\textsubscript{2} concentrations levels alongside the tVOCs may confirm a correlation already noticed during other studies performed in naturally ventilated classrooms [53].

In that context, raising awareness of the importance of IAQ in schools, to teachers, pupils, headteachers and janitorial staff should enable them to grasp the importance of good indoor air quality. In addition, providing each classroom with visual feedback from
monitors for occupants to have the option to act could empower them to feel more in charge of their indoor environment. The use of wireless sensors with remotely accessible data will enable the monitoring to solve any issues as soon as they arise.

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**References**


