Balancing indoor CO_2 concentration levels and thermal comfort: Actions in primary school classrooms

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Abstract

Current climate emergency context requires urgent action to reduce energy consumption in buildings while maintaining healthy indoor environment. Promoting good indoor environments, in particular increasing ventilation, has been a prominent strategy to mitigate the risk of COVID-19 transmission indoors. However, this strategy could be detrimental to thermal comfort, particularly in the heating season in temperate climate zones. This paper presents the findings from a pilot project conducted in 2 primary schools in South Wales (UK) monitoring the indoor environmental conditions in a small number of classrooms that implemented operational guidance issued post-COVID-19. The study measured CO_2, temperature and relative humidity. It explored the perceptions of indoor environment by pupils and teachers, with focus on thermal comfort and freshness of air. This paper presents the results of the monitoring study and discusses the behavioural adaptation strategies enacted in the primary schools to balance the requirement of reducing CO_2 concentration levels while promoting thermal comfort.

1. INTRODUCTION

Climate emergency and health concerns associated to poorly ventilated indoor environments call for urgent action to maintain healthy comfortable indoor spaces in energy efficient ways. The COVID-19 pandemic has highlighted the importance to promote healthy and safe indoor built environments for occupants (Awada et al, 2021). Research has found associations between the quality of the built environment (temperature, CO_2 as measured in buildings) and health and productivity outcomes of building occupants in terms of incidence of illnesses, absenteeism risks, effect on concentration and learning attainment; for example, Allen J and Macomber JD, 2020; Van Dijken et al 2006 to cite few. Children spent a significant proportion of their daily time in schools. Hence, it is important to promote healthy and comfortable classrooms where children can learn and play. Due to their physiology, children have different physical responses than adults to indoor environmental conditions (Teli et al, 2012). In order to promote adequate indoor environmental conditions in schools; schools are to follow ventilation, thermal comfort and indoor CO_2 recommendations set by guidance such as Building Bulletin 101. Building Bulletin 101 (2018) suggests that CO_2 <1000ppm indicate good indoor air quality; between 1200-1500ppm is acceptable level and >1750ppm flag out additional ventilation needs. In the wake-up to COVID-19 pandemic, schools in Wales are to comply with health and safety guidance and put in place proportionate control measures to mitigate COVID-19 risks.

‘Operational guidance for schools and settings to support limited attendance’[1] encourages schools to measure CO_2 levels. In October 2021, Welsh Government started to distribute CO_2 monitors for educational settings with the guidance on ‘Carbon dioxide monitors in educational settings’[2]. The guidance uses a traffic light system to classify CO_2 levels: green light for 400-800ppm adequate ventilation; amber light for 800-1500ppm inadequate ventilation (needs improvement) and red light for >1500ppm poor ventilation (action is needed) (Welsh Government, 2021). Buildings in temperate climates, including schools, have reduced their ventilation rates to prevent heat losses and reduce energy use associated to heating (Persily and Emmerich, 2012) due to energy conservation concerns. This strategy is problematic in the light of COVID-19 requirement to increase ventilation. This research explored the indoor environmental conditions post COVID-19 pandemic in 2 primary schools located in South Wales, UK. The study monitored the CO_2 levels, temperature and relative humidity in a small number of classrooms and undertook user studies to identify (1) teachers’ and pupils’ satisfaction levels with ventilation and thermal conditions and (2) actions and behavioural adaptations adopted to enhance the ventilation in the classrooms. The results reported in this paper are part of a broader project where the monitoring data was deployed to engage in learning with children and teachers about ways to maintain healthy well ventilated classrooms in energy efficient ways.

2. RESEARCH ON THERMAL COMFORT AND CO_2 IN SCHOOLS

There are three main elements explored by this research in relation to the notion of comfortable well ventilated classrooms post-COVID-19: (1) measured and perceived thermal conditions (2) measured CO_2 levels in classrooms; and (3) people’s experience and adaptations in classrooms. In relation to the first aspect, thermal comfort, research has focused on young people’s thermal experience in schools; for example, looking at thermal comfort in relation to monitoring data (Bako-Biro et al, 2012); exploring differences between children and adults thermal comfort experience (te Kulve et al, 2022). Teli et al (2012) investigated the thermal perceptions and preferences of school children aged 7-11 using questionnaires in relation to overheating risk in schools and in (Teli et al, 2017) the differences between children and adults’ thermal needs were compared. Questionnaires are a predominant research method used in thermal comfort research but they can be problematic for subjective thermal comfort responses (Schweiker et al, 2020). Research has suggested advice to design children’s questionnaires to evaluate thermal comfort (Haddad et al., 2012; Fabbri, 2015). Research has also applied participatory methodologies to explore young people’s experience in buildings in addition to questionnaire responses (Dominguez-Amarillo et al, 2020). There is an increased recognition that qualitative methods are valuable to gain richer insights into human dimension of building use (Bavaresco et al, 2020). This work applies a mixed method research design to explore the perceptions and experiences of teachers and pupils. The second aspect explored in this research is CO_2 concentration levels. Research shows that high CO_2 concentrations have a detrimental impact on people’s health

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[1] Operational guidance for schools and settings to support limited attendance, Available at https://gov.wales/operational-guidance-schools-and-settings-support-limited-attendance-html (Last accessed in February 2021)

[2] Carbon dioxide monitors in educational settings, Available at https://gov.wales/carbon-dioxide-monitors-education-settings (Last accessed in November 2021)

and cognitive performance (Mendell and Heath, 2005; Bluyssen, 2009 and Holgate et al, 2020). Research on CO_2 concentration levels in schools find that CO_2 above 1000ppm is associated to decreased attendance (Gaihre et al, 2014); increased dry cough and rhinitis among school children (Simoni et al, 2010). CO_2 levels above 1500ppm can result in more errors in performance tests compared to 900ppm (Petersen et al, 2016l) and are associated to difficulties in concentration (Madureira et al, 2009), decreased in annual school attendance (Shendell et al, 2004). CO_2 studies in schools post COVID-19 compare indoor conditions in schools in Spain pre and post COVID-19 (Monge-Barrio et al, 2022) while Vouriot et al (2021) use CO_2 data for statistical analysis of seasonal risk of airborne transmission diseases. This work monitors the CO_2 levels in classrooms in 2 primary schools in South Wales reporting on data gathered in the heating season post COVID-19 pandemic where guidance require schools to increase ventilation in classrooms. Finally, the last aspect this work explores is the children's and teachers' thermal (comfort) experience in the classroom and the actions adopted in schools in response to COVID-19 pandemic. Post COVID-19, research has looked at architectural design and built environment to prevent disease transmission risk; for example, Megahed and Ghoneim (2020) discuss safe built-environment; Emmanuel et al (2020) analyse health-care facilities design, Anisa et al (2021) explore home adaptations. This works explores actions and behavioural adaptations in schools in response to COVID-19.

3. RESEARCH DESIGN AND METHODOLOGY

Two primary schools located in South Wales were included in the study. School A opened in 2001, it is a one story building with an area of 1600m^2 and an Energy Performance certificate D and approximately 200 students. School B opened in 2010, it is one story building with an area of 1744m^2 , DEC D and 250 students. The research included (1) Monitoring studies to explore the indoor environmental conditions, with focus on temperature, relative humidity and CO_2 in classrooms; to identify the existing conditions and characterise typical conditions in autumn and in winter; and, (2) Qualitative user studies with teachers and pupils, to explore adaptations in response to COVID-19 and satisfaction levels in relation to thermal comfort conditions and ventilation in classrooms.

3.1 Monitoring studies

The monitoring studies included the long-term measurement of CO_2, temperature and relative humidity of 3 classrooms and at least one communal space in each of the primary schools. The monitored classrooms included different age groups and located in different orientations within the school building in each of the 2 primary schools (x6 classrooms in total). The monitoring study included (1) Indoor Temperature & Relative Humidity (T/RH): long term monitoring of three classrooms and one communal space in each school using two types of sensors per classroom (ALTA wireless Coin cell power sensor); (2) CO_2 concentration levels: long term monitoring using one sensor in each one of the three classrooms per school (ALTA wireless AA battery power sensor). In terms of accuracy, the ALTA temperature and humidity sensor has an accuracy of +/- 2% RH (reading rage 0-100%RH) and +/- 0.5^oC (reading rage 0-100^oC). The ALTA CO_2 sensor has a measuring are on 0 to 10,000 ppm, with an accuracy of =/- 45ppm +3% of reading. The CO_2 sensors are designed for applications on ordinary built environments where temperature ranges 0-50°C and humidity 0-95%RH. The capability and accuracy of instruments has been used to investigate healthy conditions in schools in the context of COVID-19, for example in Gil-Baez et al, 2021. The sensors were installed in July 2021. The monitoring study aimed to measure the indoor environmental conditions in classrooms during the academic year 2021/22 (from September 2021 to July 2022). This paper reports the data captured between Monday 6th of September 2021 to Friday 18th of February 2022 (last day of school before half term). The data analysis focuses on weekday occupied hours. Weekend data, data outside occupied hours and school holidays data is not reported.

3.2. Qualitative user studies with teachers and pupils

User studies with teachers and pupils were undertaken to explore their satisfaction levels with the indoor environment and the actions adopted to promote well ventilated classrooms. The research methods with teachers included two questionnaires (1) to identify their comfort perceptions related indoor environmental conditions and (2) to explore actions and adaptations in response COVID-19. The comfort perception questionnaire collected teachers' responses of their experience in different seasons using 5 point Likert scale. The questions focused on thermal conditions and ventilation in the classroom and actions taken to change the conditions in different seasons. This questionnaire was informed by standardised POE surveys such as the Building User Survey. A second questionnaire was administered to identify the adaptations enacted in schools. It included a mix of multiple-choice and open-ended questions. It explored changes in the use of the school buildings including spatial adaptation in classrooms and changes in everyday operation and use of building controls in classrooms; changes in use of school/classroom as response to COVID-19; provision of guidance. It prompted teachers to provide examples of actions adopted and to identify opportunities for flexible use of teaching spaces in classroom and outside classroom. The design of the questionnaires were informed by social science research principles (Bryman 2016). The questionnaires were piloted before being administered to teachers as a paper-based format. The research instruments with pupils comprised (1) drawings to express their perception of the indoor environment in their classrooms and actions to modify the thermal experience (used by all pupils participating in the study aged 7-11); and, (2) questionnaires to children aged 9-11 using traditional thermal comfort surveys adjusted to this age group (~100pupils in 4 classrooms). The design of research instruments with children considered recommendations by Christensen and James, 2017 and were informed by research on children's thermal experience in classrooms (Teli et alt, 2013; Dominguez-Amarillo et al, 2020). Teachers provided feedback to the forms used for children's drawings. The children's instruments explored how they felt in the classroom terms of temperature, humidity and air freshness 'right here right now'. The questionnaires were paper-based. Children's instruments were administered by the research team during workshops in the schools under teachers' supervision. The project was approved by the Ethics Committee. A package with information and consent forms was distributed to Headteacher, teachers and pupils' to ensure informed participation and consent. The research team explained the study to children during workshops. No personal data from pupils or teachers were collected.

4. RESULTS

4.1. Monitoring studies

As expected, the air temperature in the classrooms is correlated to the outdoor ambient air temperature given the guidance to maintain windows and external doors of classrooms open during teaching times. Figures 1 and 2. show the temperature daily profile for 3 monitored classrooms in School A in autumn and winter. The data illustrates temperature during occupied hours in relation to CIBSE Guide A and BB 101 (between 19-21°C). In autumn, Classroom 3's temperature profile is within CIBSE Guide A recommendations. Classroom 1 is slightly colder in the morning. Classroom 1 is colder during occupied hours (between mid 17 °C and mid 18 °C). In winter, all classrooms in School A are between 16-18 °C. The difference in the average hourly temperature within a single classroom is between autumn and winter is about 2 °C. Fig 3 summarises the temperature profile for 3 classrooms in School A for the monitoring period between September 2021 and February 2022. It illustrates minimum, maximum and average temperatures recorded per hour during occupied hours weekdays. It can be noticed that the minimum temperature recorded is approximately 14°C at 9am and the maximum temperature is approximately 24°C at 3pm.

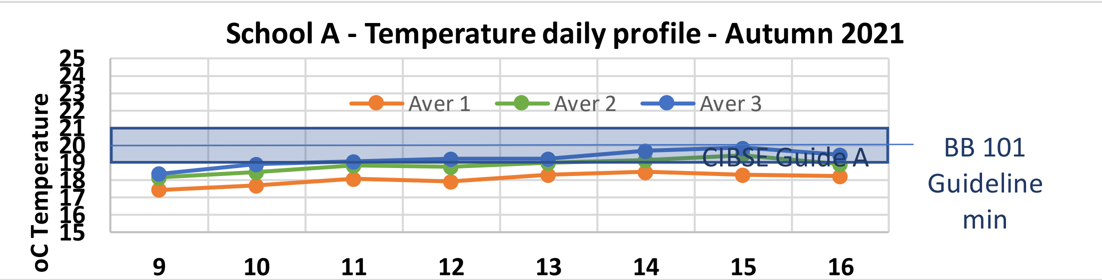

Figure 1. School A average temperature, hourly daily profile Autumn

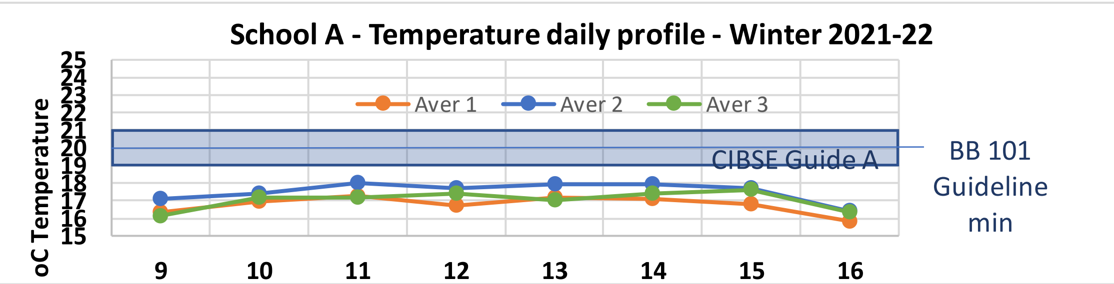

Figure 2. School A average temperature, hourly daily profile Winter

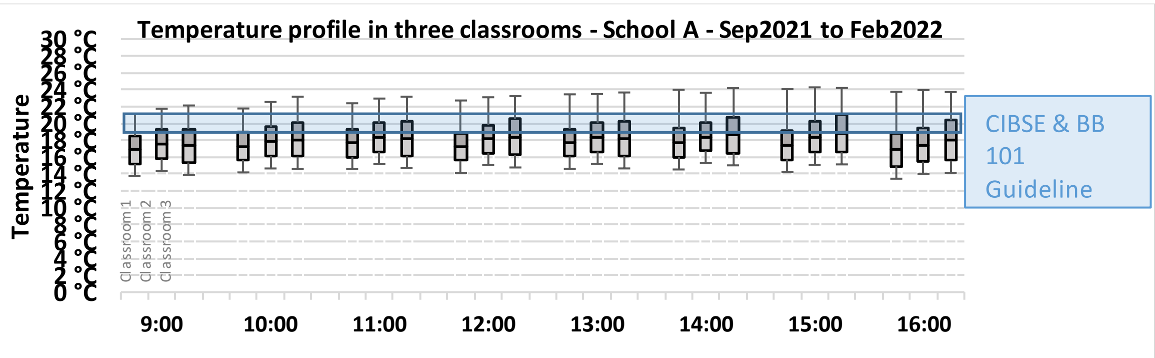

Fig 3. School A: Temperature profile for 3 classrooms showing min, max, average temperatures

Data of School B shows that in autumn (Fig 4), the temperature daily profile in Classrooms 1 and 2 within CIBSE Guide A recommendations (19-21ºC) while Classroom 3 is slightly colder (18 ºC) during times that classrooms are occupied. In winter (Fig 5), classrooms 2 and 3's average temperatures are slightly below the CIBSE Guide A recommendation while Classroom 1 maintains its average temperature within CIBSE Guide A recommendation at 19 ºC. The difference in the average hourly temperature within a single classroom is between autumn and winter is about 1 ºC in School B. Fig 6 summarises the temperature profile for 3 classrooms in School B for the monitoring period between September 2021 and February 2022. It illustrates minimum, maximum and average temperatures recorded per hour during occupied hours weekdays. It can be noticed that the minimum temperature recorded is approximately 14ºC at 9am and the maximum temperature recorded is approximately 25ºC at 4pm.

In terms of relative humidity, the average hourly readings for the 6 monitored classrooms in the 2 schools show that the levels remain within CIBSE A recommendations of 40-60% relative humidity in autumn and winter seasons.

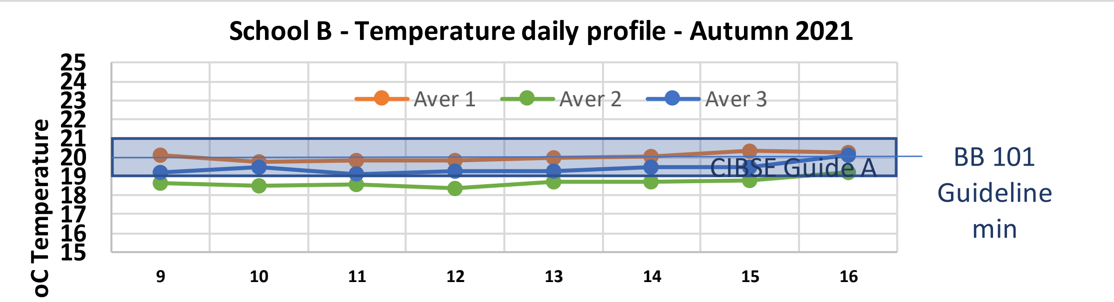

Figure 4. School B average temperature, hourly daily profile Autumn

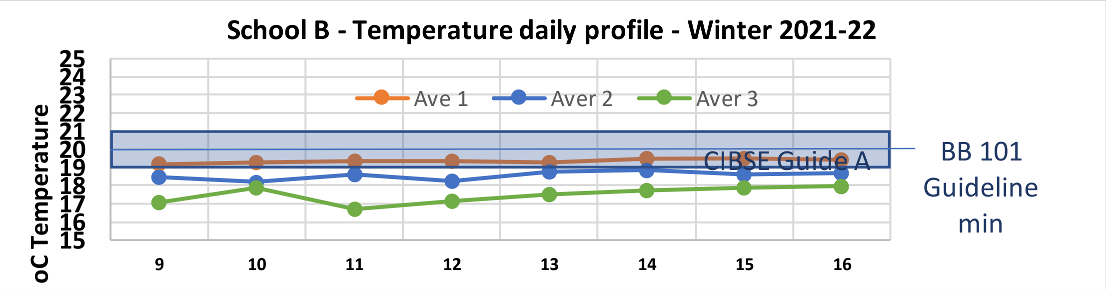

Figure 5. School B average temperature, hourly daily profile Winter

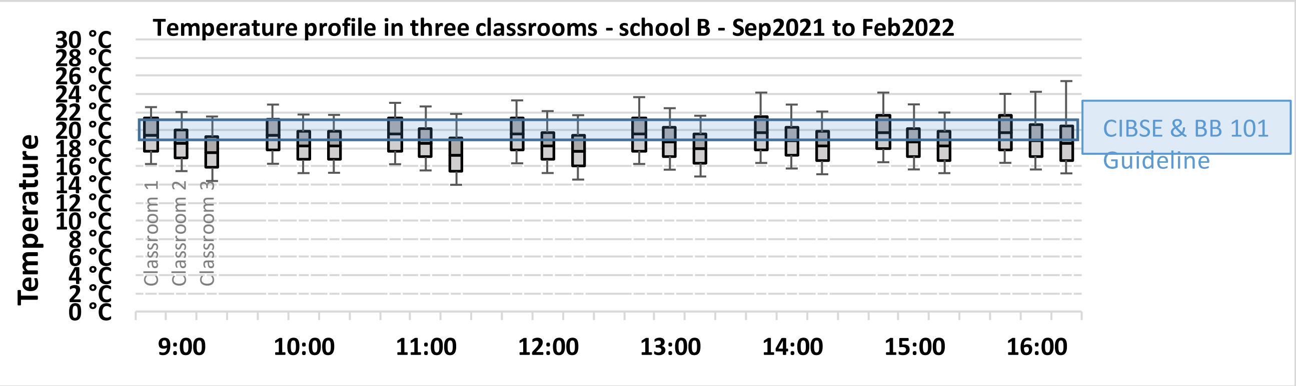

Fig 6. School B: Temperature profile for 3 classrooms showing min, max, average temperatures

In terms of CO_2 concentration levels, the average CO_2 levels in autumn in School A classrooms tend to be in the amber zone as per Welsh Government Guidance for occupied hours with readings below 1200ppm. In winter, classrooms 2 and 3's CO_2 levels remain under 1200ppm and classroom 1 has average CO_2 levels between 1000 and 1400ppm, with a high reading of 1500ppm at around 10am. This profile may reflect the window opening/closing regime where windows are open before pupils go to the classrooms and during breaks, with additional opening if CO_2 concentration levels rise based on feedback received from CO_2 monitors installed in the classrooms. Fig 8 summarises the CO_2 profile for 3 classrooms in School A for the monitoring period between September 2021 and February 2022. It illustrates minimum, maximum and average temperatures recorded from 7am to 4pm. It can be noticed that there are high CO_2 levels recorded during occupied hours, with a maximum of 3900ppm at 10am in classroom 3 Classroom 3 tends to have the highest CO_2 concentration levels among the monitored classrooms in School A.

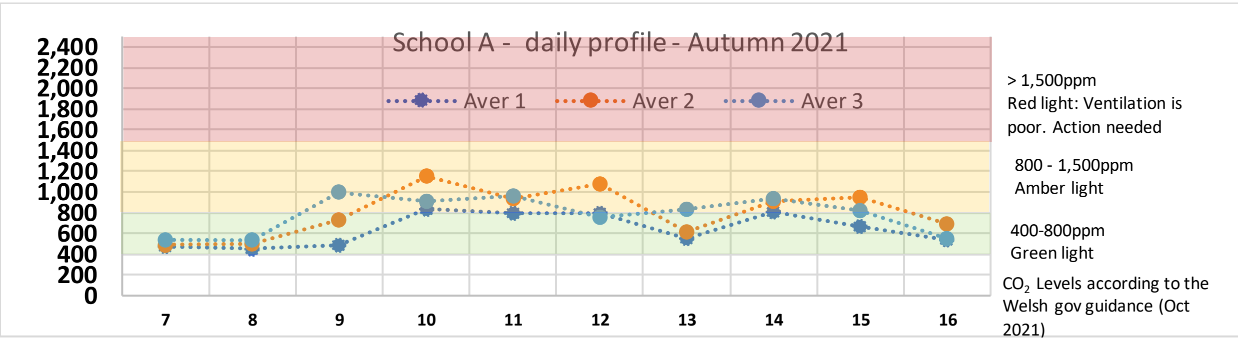

Figure 6. School A average CO_2 concentration (ppm) per classroom in autumn (weekdays 7am-4pm)

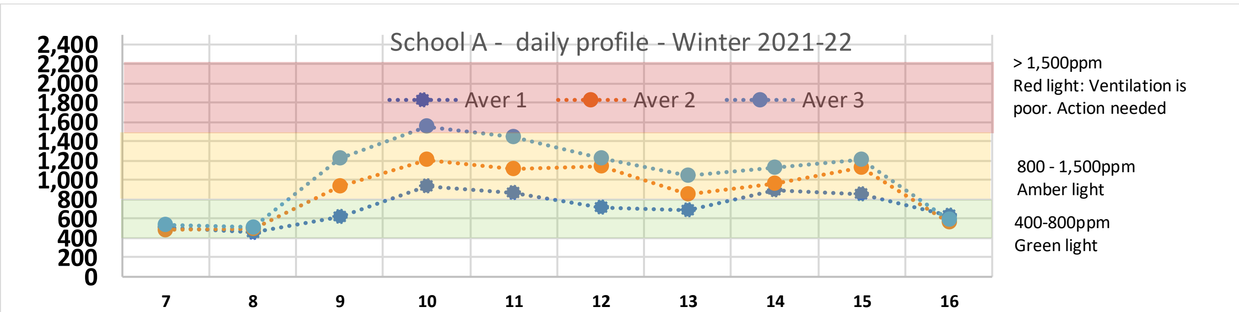

Figure 7. School A average CO_2 concentration (ppm) per classroom in winter (weekdays 7am-4pm)

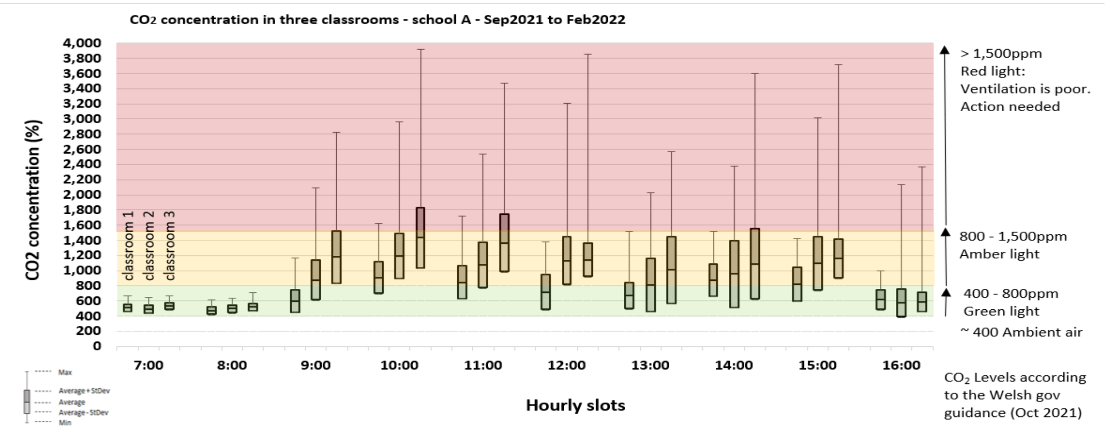

Figure 8. School A: min, max and average CO_2 (ppm) per classroom

The average CO_2 levels in autumn in School B classrooms tend to be in the green zone as per Welsh Government Guidance for occupied hours with readings predominantly between 450-650ppm. In winter, classrooms 2 and 3's CO_2 levels are in the amber zone, with levels remaining under 1200ppm and classroom 1 has average CO_2 levels between 600 and 80ppm. Fig 11 summarises the CO_2 profile for 3 classrooms in School B for the monitoring period between September 2021 and February 2022. It illustrates minimum, maximum and average temperatures recorded from 7am to 4pm. It can be noticed that there are high CO_2 levels recorded during occupied hours, with a maximum of 2600ppm at 2pm in Classroom 2.

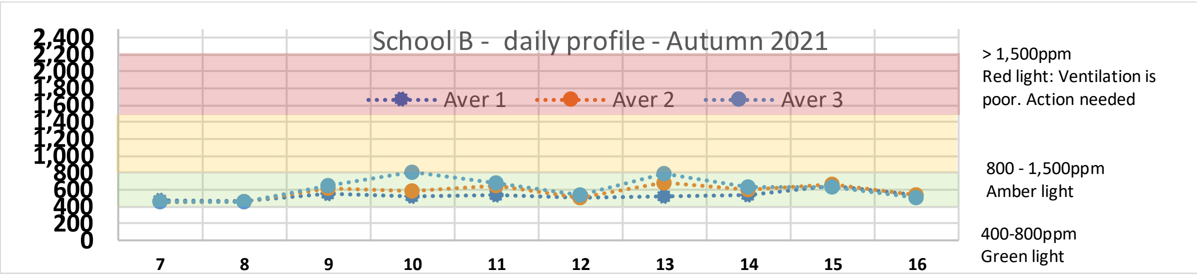

Figure 9. School B average CO_2 concentration (ppm) per classroom in autumn (weekdays 7am-4pm)

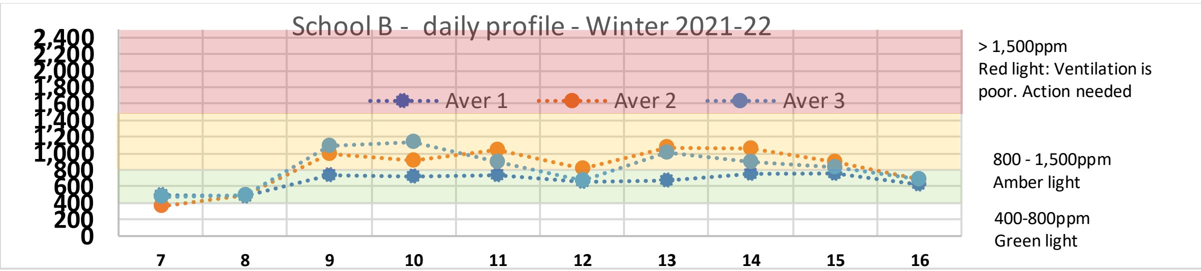

Figure 10. School B average CO_2 concentration (ppm) per classroom in winter (weekdays 7am-4pm)

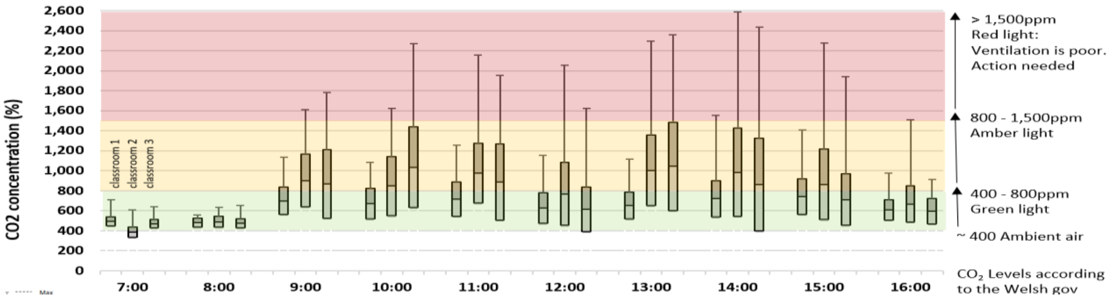

Fig 11.

Fig11. School B: min, max and average CO_2 (ppm) per classroom

4.2. Qualitative studies with teachers and pupils

Teachers reported that the main strategy adopted to foster ventilated classrooms was increasing the number of hours that windows and doors connecting to the outdoors were open during school time. However, this strategy is problematic in winter as it leads to discomfort due to low temperatures indoors. In order to minimise cold indoor temperatures during occupied hours, windows and doors are open during times when pupils are not in the classroom (ie. during breaks and during outdoor learning time). The CO_2 monitors help teachers to identify times to operate windows to maintain CO_2 concentration within recommended levels. In some instances, teachers reported new layouts and space configuration in the classrooms were they primary teach; for example, distances between desks and working stations, zoning of activities inside the classrooms. In younger year groups, teachers reported that learning activities are promoting more hours of outdoor learning, using covered areas connecting classrooms and to the outdoor open spaces. Teachers consider that there are opportunities to use flexibly outdoor spaces and spaces outside the classroom for younger year groups in alignment with pedagogical needs. Communal spaces used for breaks of for flexible learning by different year groups have been time-tabled more systematically to avoid mix of year groups. Teachers reported that advice has been provided in relation to mitigation risk for COVID-19. This advice has focused on cleaning, hygiene and social distancing. Other strategies included staggered drop-off and collecting times, designated access for different year groups using different access points to the school, one way circulation systems. In terms of thermal experience in the monitored classrooms, the study undertook studies of thermal comfort and perception of air freshness among pupils in December. All pupils used drawings to reflect about their thermal experience in the classroom and actions taken to achieve thermal comfort. Questionnaires were administered to pupils older than 9 years old to rate their perceptions of temperature and air freshness in their classrooms. Younger children were able to express concepts related to their thermal experience using drawings; however, it is unclear if their responses were a reflection of their perceived experience “right here, right now”. Typically drawings by younger children involved responses about their thermal experiences inside and outside the classroom, including their home environment. Younger children were able to identify a broad range of actions they can take to improve their thermal comfort, referring primarily to personal adaptation actions such as changing clothing levels (extra layers when cold). Drawings by older children (>9 years old) who also completed questionnaires showed a good understanding of concepts related to thermal experience but there seemed to be less clarity in relation to the understanding of concepts related to air freshness and ventilation. It was noticed that the general trends expressed in relation to thermal experience via drawings and the responses in questionnaires were aligned for data collected among older children through different instruments (drawings and questionnaires). Older children were able to express visually their thermal experience in the classroom. Actions to modify their thermal experience included examples of actions taken in the classroom setting as well as outside the classroom in other environments such as their home and the playground. This could be explained by the limited agency of children to take action to modify the thermal environment in their classroom and a wider recognition of typical thermal experiences in the different settings. The results in School A show that in terms of temperature perception, 26% of pupils felt very cold, 67% felt comfortable and 7% felt very hot. In relation to pupil’s reported perception of air freshness, 71% considered the air in the classroom to be fresh, 7% considered the air to be unfresh and 22% thought the air was neither fresh or unfresh. The results in School B show that in terms of temperature perception, 34% of pupils felt very cold, 26% felt comfortable and 40% felt very hot. In relation to pupil’s reported perception of air freshness, 30% considered the air in the classroom to be fresh, 30% considered the air to be unfresh and 40% thought the air was neither fresh or unfresh. Responses have not been disaggregated by gender as potential differences in gender-based responses are likely to be irrelevant for the context of this study (Zomorodian et al, 2016) or by age given the small variation in the age of questionnaire respondents (aged 9-11).

5. DISCUSSION

The data suggests that the participating schools have been implementing guidance to promote fresh air and ventilation by keeping windows and doors open during occupied hours. This strategy, however, has been adapted in relation to the needs to maintain thermal comfort in different seasons. During winter season, when outdoor temperature drops, window opening times have concentrated, whenever possibly, to times when pupils are not in the classroom to avoid discomfort due to cold temperature in the classroom. For example, windows and external doors in classrooms are open before the start of the school day, during lunch breaks and outdoor play times and after the end of the school day. The patterns of CO_2 concentration suggest trends around opening and closing windows and doors to promote ventilation. The monitored classrooms show that CO_2 concentration levels tend to be within green and amber light zone as per Welsh Government guideline in autumn and in winter. The classrooms monitored in this study show general trends that are aligned with the study of Monge-Barrio et al (2022) were CO_2 levels were measured in classrooms in Northern Spain post COVID-19 in the heating season and show that most of occupied hours CO_2 levels remain between 500 and 1500ppm. This study shows, however, instances where CO_2 values recorded exceed 1500ppm at different times of the day during occupied hours (Fig 8 and 11). These results are not surprising considering the frequency that high CO_2 levels are measured in classrooms (Holgate et al, 2020; Pereira et al, 2014).Considering seasonal differences, Deng and Lau (2019) surveyed 220 classrooms in Midwest USA and found that CO_2 levels were below 1000ppm only in 96 classrooms in autumn and 70 classrooms in winter; exposures to CO2 >1000pm is not unusual in schools. Vouriot et al (2021) suggest that the risk of airborne infection of COVID-19 doubles in January compared with July which is problematic in the context of balancing thermal comfort, ventilation and energy demands due to heating. The qualitative studies exploring the thermal experience and the perception of air freshness in classrooms show mix results. Pupils from School A where monitoring data in winter shows that classrooms are between 16-18°C show a good satisfaction levels with the temperature of their classrooms (67% of pupils reporting to feel comfortable). There is, however, a significant proportion of pupils in this school (26%) who felt very cold. In School B where the monitoring data suggest winter temperatures between 17-19°C there were mix responses both in terms of temperature and air freshness in the classroom without a clear majority of pupils reporting any predominant perception trend.

6. CONCLUSIONS

Schools have made significant efforts to adapt the school environment and their practices to ensure that children can learn in safe healthy environments in response to COVID-19. The predominant response to date has relied on behavioural change and adaptations to increase ventilation which may be detrimental to thermal comfort in classrooms. This pilot study has monitored the temperature and CO_2 levels in a small number of classrooms and engaged with pupils and teachers in 2 Primary schools to identify the strategies and actions they have adopted to promote ventilation while maintaining thermal comfort. The work included qualitative studies to identify the perceptions of comfort in terms of temperature and fresh air as experienced by pupils in their classrooms and offers some insights into early responses by schools in relation to COVID-19 guidance for educational settings. Future work will investigate architectural characteristics of the classrooms that affect the balance between CO_2 concentrations and comfortable thermal environment; integrating monitoring data and perceived satisfaction levels with indoor environmental conditions by pupils and teachers; in particular relating temperature and air freshness to monitoring data.

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