Application strategies and effectiveness of CO_2 signal lights for improving indoor air quality in classrooms

Simon Beck*[1], Gabriel Rojas[1]

1 University of Innsbruck and Digital Science Center
Innrain 52
6020 Innsbruck, Austria
**Corresponding author: simon.beck@uibk.ac.at*

ABSTRACT

Improving air quality in existing classrooms can be difficult if retrofitting a mechanical ventilation system is considered too expensive or cannot be implemented due to other reasons, e.g., heritage protection. Especially in the cold winter months, window airing initiated by pupils or teachers is often not sufficient. To address this issue, a possible approach involves the incorporation of CO_2 feedback devices (or CO_2 traffic lights) into classrooms, which serve to visually and sometimes acoustically alert occupants when CO_2 concentrations get too high, signalling the need for a higher outdoor air change rate. Different types of CO_2 feedback devices and strategies are investigated, looking at threshold values, the CO_2 sensors used, and their precision within existing studies, standards, and commercially available devices. In the scope of an ongoing Citizen Science project in ten Austrian schools, a typical CO_2 sensor light application strategy is tested in a subset of the investigated classrooms and evaluated under real-world conditions by monitoring CO_2 concentrations before and after its implementation, as well as a comparison to a control group. Analysis is done by comparing CO_2 levels at different outside temperatures and applying statistical tests such as the Welch t-Test and Mann-Whitney-U-Test. Covariances are investigated using the ANCOVA test. The comparison of CO_2 levels under different outdoor temperatures shows improvements after implementation of the visual feedback at lower ambient temperatures, suggesting that CO_2 traffic lights can be a valid intervention for classrooms. This is partly supported by the comparison to the control group, which showed unchanged air quality up to 9°C outdoor temperature when looking at a hypothetical intervention. The study concludes that the visual feedback system appears to be effective in reducing CO_2 levels in classrooms during colder periods, although long-term effects and potential behavioural changes require further investigation, including the effect on thermal comfort and energy use. Limitations include potential habituation to the equipment and the late intervention date, which affect interpretation due to seasonal differences in weather or behaviour. Future research could explore the removal of the CO_2 traffic lights after prolonged use to observe changes in behaviour in a reverse manner.

KEYWORDS

Indoor Air Quality, Schools, CO_2 Traffic Light, Ventilation, Intervention

1 INTRODUCTION

Window airing in educational buildings might not ensure optimal indoor air quality (IAQ) due to the trade-off between maintaining thermal comfort and indoor air quality, particularly in the colder seasons. This problem is still widespread in Austrian schools (Beck et al., 2023; Brandl et al., 2001; Hohenblum et al., 2008; Humhal, 2014; Knotzer & Venus, 2013), since there is a reluctance to install mechanical ventilation systems in schools, mainly because of the high cost or heritage protection of the buildings. As a result, alternative measures such as CO_2 traffic lights have gained attraction as a cost-effective and minimally invasive solution to this challenge. The effectiveness of such air quality feedback devices has merely been investigated, and reported results are inconclusive (Heebøll et al., 2018; Wargocki & Da Silva, 2015), probably because their effectiveness is dependent on the particular users to ensure proper

window operation. There is also the question of whether such devices will become less effective over time when the "novelty" effect has vanished.
Recognising that poor air quality can have a significant impact on student wellbeing and academic performance (e.g., Simons et al., 2010; Wargocki, 2015), there is growing interest in implementing real-time feedback mechanisms to monitor and improve IAQ. Since many indoor air contaminants cannot be reliably detected with human senses, the use of low-cost sensors might help with identifying ventilation needs. CO_2 concentration serves as an indicator for assessing contamination with bio-effluents and is therefore often used as a tool to evaluate ventilation (ASHRAE, 2022). By providing visual or acoustic signals based on CO_2 levels, these systems prompt occupants to sufficiently ventilate spaces, thereby helping to mitigate potential health risks associated with prolonged exposure to harmful indoor pollutants.
However, the lack of standardised guidelines for such feedback devices, together with variations in acceptable CO_2 thresholds within applicable standards (e.g., EN 16798-1, 2024; ÖNORM H 6039, 2023), underlines the need for systematic investigation of their effectiveness. To fill this gap, this study examines the effects of a specific variant of CO_2 traffic lights installed in 19 classrooms across Tyrol, Austria. These classrooms have been subject to continuous monitoring for approximately three months before the intervention (March 2024) and one month after the intervention. Within this longitudinal experiment, changes within classrooms using visual CO_2 feedback were analysed and compared to classrooms without such devices.
This research is part of the DIGIdat (2022) project, which focuses on assessing air quality in ten schools in Tyrol, Austria. Five of those schools that rely on window airing as the main ventilation method were chosen to implement the CO_2 traffic lights into their daily use. As part of the citizen science nature of the DIGIdat project, sensor maintenance was carried out by students in the classrooms studied. In addition, educational materials, including posters and instructional videos, were provided to support the effective use of the CO_2 traffic lights. In previous measurements, CO_2 concentrations of up to 5000 ppm were found in classrooms with window airing. (Beck et al., 2023)

1.1 Existing Studies

The literature search included databases such as Google Scholar, ScienceDirect, ResearchGate, Wiley Online Library, and Taylor & Francis Online. Different synonyms, such as "CO2 signal lights", "CO2 traffic lights", and "visual air quality feedback" were used. The search focused primarily on the school context. Only a small number of studies were found, and some of them were mostly of descriptive nature, considering the possibility of intervention for public buildings in general (Dunst, 2022) or the development of a do-it-yourself CO_2 traffic light (Dey et al., 2021; Wejner & Wilke, 2023) as well as a description of the underlying physics (Höfner & Schütze, 2021).
As a more general approach, a red warning light was introduced in the experiments of Geelen et al. (2008) in combination with advice on how to handle the signals. In this study, the feedback device was installed for one week, where it showed a reduction of the average CO_2 concentrations in the classroom, whereas it was stated that the long-term effect might not be given. The effect of a visual feedback device was evaluated in the work of Wargocki & Da Silva (2015), where they found that the window opening behaviour was affected and the CO_2 concentrations were reduced with the interventions, as it also increased the energy consumption of the school in the heating season. A similar intervention was researched in the study of Heebøll et al. (2018). They found that while the feedback device led to the windows being opened for a longer period of time during classroom usage, it did not significantly reduce the CO_2 levels. A different signal light, which displayed the feedback in a nine-step colour transition (green to yellow to red), was used in the work of Toftum et al. (2016). There the

"visual CO_2 display" helped to reduce the time in the classroom with concentrations over 1000 ppm by 40 - 60%. Another air quality feedback signal was tested by Avella et al. (2021), which in addition to CO_2 levels, also considers temperature and humidity as relevant inputs for the signal colour. The AI-based algorithm that decides if the light should be green, yellow, or red was not further described. They found that the effect of the visual feedback is heavily dependent on users, and the device has the best effect in mild temperatures with higher willingness for window airing. An overview of these studies and the applied CO_2 concentration for the visual feedback signal colours is displayed in Table 1.

Table 1: CO_2 Limits for signal light colour and sensor information

Source	**Feedback**	**Limit [ppm]**		**CO_2 Sensor**	
		Green - Yellow	Yellow - Red	Name	Accuracy
(Geelen et al., 2008)	Visual		1200*	Atal ATV-8002	± 75ppm
(Wargocki & Da Silva, 2015)	Visual	1000	1600	Vaisala GM20D	± 30ppm+2%
(Toftum et al., 2016)	Visual	1000	1600	Vaisala GMW22	± 100ppm+2%
(Heebøll et al., 2018)	Visual	1000	1600	Vaisala GMW22	± 100ppm+2%
(Avella et al., 2021)	Visual			Senseair K30	± 30ppm+3%
(Dey et al., 2021)	Visual	800	1200	Sensirion SCD30	± 30ppm+3%
(Höfner & Schütze, 2021)	Vis./Acoustic	750	1000	Sensirion SCD30	± 30ppm+3%
(Dunst, 2022)	Visual	1000	2000		
(Wejner & Wilke, 2023)	Visual			Winsen MS-Z14A	± 50ppm+5%

* Only red warning light

There is no consensus on the limits of the different warning signals in the existing studies. Based on the three levels of warning, the limit from green to yellow is between 750 and 1000 ppm, which should indicate that additional ventilation would now be beneficial, and the limit from yellow to red is between 1000 and 2000 ppm, which should prompt the immediate opening of windows.

1.2 Applicable standards

No standards or guidelines addressing air quality feedback systems as an airing aid are known to the authors. To decide on the most suitable limits for the warning signals, the applicable norms for CO_2 concentration limits in classrooms are investigated - here with focus on Austria. In general, the European standard for the energy performance of buildings, EN 16798-1 (2024), states input parameters for classrooms for the maximum CO_2 concentration at a value of 500 ppm above outdoor levels, which with today's outdoor levels is calculated to be 900 to 1000 ppm inside. The Austrian standard, ÖNORM H 6039 (2023), covering ventilation systems specifically for school and educational buildings, sets an upper limit for classrooms at 1000 ppm and for other spaces in schools at 1400 ppm, both calculated as the arithmetic mean over the duration of one lesson (usually 50 min). These limits are similar to ISO 16000-1 (2004). The so-called MAK value (maximum workplace concentration), the legally binding threshold limit value (TLV) for occupational exposure in Austria, is set at 5000 ppm for CO_2 and is therefore not relevant for evaluating ventilation requirements.
Outside of Austria, the lower threshold for appropriate air quality in schools is set similarly. In Germany, the recommendation of the German Federal Environmental Agency is as well at 1000 ppm absolute CO_2 concentration (UBA, 2017). Older versions of the ASHRAE Standard 62.1 (2018) display that a concentration in indoor spaces of less than 700 ppm above outdoor levels will likely satisfy the majority of occupants with respect to human bio-effluents, which was removed in more recent versions of the standard. The UK states for non-dwellings that an absolute CO_2 concentration of 1500 ppm is a sign of poor ventilation (The Building

Regulations 2010 Part F, 2022), and in China, the absolute CO_2 concentration is limited to 1000 ppm (GB/T 18883, 2023) as an average over eight hours.
For the CO_2 traffic light used in this study, the thresholds of the warning signals are chosen to be in accordance with the guidelines for the assessment of indoor air of the Federal Ministry in Austria, which set the limit for rooms with cognitive activities at 1000 ppm and the limit for rooms with permanent stay at 1400 ppm (Tappler, 2024).

1.3 Market analysis

To compare research and standards with commercially available CO_2 traffic lights, 26 devices were looked at, and their datasheet specifications were analysed. Of the given devices, ten have connectivity features that enable the use of IOT (internet of things) functions, and eight of them have a display to show the CO_2 measurements in addition to the warning signal light. Twelve devices have an extra acoustic signal when the concentrations surpass certain limits. In general, sensing is based on the NDIR (non-dispersive infrared) principle, and the available devices specify accuracies in the range of ±30 ppm+3% to ±50 ppm+5%. The calibration of the sensors follows mostly some auto-calibration algorithm or a manual method, where the devices must be (regularly) exposed to outdoor air. At least two of the traffic light devices measure other indoor air pollutants, such as fine particulate matter, nitrogen oxides, or volatile organic compounds. A summary of the data collected within the extended Google search is displayed in Table 2.

Table 2: Summary of 26 commercially available CO_2 feedback devices (March 2024)

Parameter	**Price [€]**	**CO_2 threshold [ppm]**			**Max. CO_2 sensor reading [ppm]**
		Good	Tolerable	Bad	
Minimum	55.00	750	1000	1200	2000
Mean	176.73	911	1552	2400	
Median	179.67	1000	1500	2650	5000
Maximum	309.00	1000	2000	3000	40000

2 METHOD

The primary objective of this study is to evaluate the effectiveness of CO_2 feedback devices in improving indoor air quality in classrooms with window airing as the sole ventilation method. To compare the non-randomised subject classrooms this study uses a quasi-experimental design and was carried out over a period of five months. The primary hypothesis is that classrooms equipped with these devices will be ventilated more sufficiently and therefore maintain lower CO_2 levels over the occupation period.
Within the project DIGIdat, five Tyrolean (Austria) schools were chosen to implement CO_2 traffic lights as an intervention to improve indoor air quality. The other five schools that participate in the project did not activate any feedback signals and only took part in the awareness campaign. The Tyrolean climate can be classified as warm-summer humid continental climate (Dfb) according to Köppen & Geiger, and therefore the given school buildings usually deal with an extended heating season from October to April. Altogether, 61 classrooms are equipped with sensor kits, which measure air quality and thermal comfort parameters in 60 s intervals over multiple months. Within each classroom, ca. three sensor kits that were built using the platform senseBox (2023) measure temperature, humidity, carbon dioxide, fine particulate matter, and volatile organic compounds and send their data via Wi-Fi to the online database for environmental measurements called openSenseMap (OpenSenseLab, 2023).

The measurements for the school year 2023/24 started in November/December 2023 and are still ongoing. Around the beginning of March (approx. after three months of measurements), the sensor kits in sixteen classrooms were upgraded to include visual feedback depending on the current CO_2 concentration. The upgrade was implemented by activating the LED included in the senseBox MCU. The programming was partially done by the pupils within a 2-hour workshop as part of the DIGIdat project. The code was verified and complemented by the scientific team to ensure its proper function. Apart from the project given devices, one school additionally installed their own CO_2 traffic lights in three classrooms, which the IT teacher had designed, assembled, and programmed with his students. Their self-made devices follow a very similar colour control strategy as the provided ones, with slightly lower threshold values (600 ppm and 1300 ppm) as anchors for the colour mapping and an additional purple colour for very high CO_2 levels.
The measurements after the intervention are still ongoing, but the data for the herein presented analysis ends on April 19, 2024, after one and a half months of measurements. The intervention is supported by a video on air quality and the usage of CO_2 traffic lights, as well as complementary posters in the investigated classrooms. All devices are maintained by the students of one particular class per school, which has had a programming workshop as part of the citizen science of project DIGIdat. A list of the subset of all classrooms which are supported by CO_2 traffic lights is given in Table 3. Only classrooms with window-airing as their sole ventilation method were chosen for the following analysis. The pupils in the given classrooms are approximately 12 to 16 years old and in most cases one teacher is present in the classrooms during lessons.

Table 3: List of rooms that are supported by CO_2 feedback devices

Room		Type	Active Kits	Standard Ventilation	Measurement Start	Intervention Date	Volume [m³]	Operable windows	Max N° of pupils
SC01	EG-07	classroom	3	window-airing	10.11.2023	07.03.2024	253	6	23
	EDV-2	informatics	2	window-airing	23.11.2023	07.03.2024	330	1	27
	EG-14	classroom	3	window-airing	10.11.2023	07.03.2024	166	2	18
	TW-2	handicraft	2	window-airing	23.11.2023	07.03.2024	107	2	11
	EG-04	classroom	3	window-airing	10.11.2023	07.03.2024	182	6	20
SC02*	105	classroom	3	window-airing	06.12.2023	04.03.2024	172	9	21
	201	classroom	3	window-airing	06.12.2023	22.02.2024	192	9	25
	NG106	classroom	3	window-airing	06.12.2023	06.03.2024	173	3	24
SC03	OG1011	classroom	5	window-airing	22.11.2023	29.02.2024	127	6	-
	OG1007	classroom	4	mechanical	22.11.2023	29.02.2024	239	8	-
SC04	R2.05	classroom	3	window-airing	11.12.2023	06.03.2024	248	3	30
	R2.19	classroom	3	mechanical	15.01.2024	06.03.2024	257	3	26
	R1.22	classroom	3	mechanical	11.12.2023	06.03.2024	245	2	27
	R3.08	classroom	3	window-airing	11.12.2023	06.03.2024	225	3	27
	WER2	handicraft	1	window-airing	11.12.2023	06.03.2024	173	5	15
SC05	EG08	classroom	3	overflow	28.11.2023	06.03.2024	206	4	-
	R2.3	classroom	3	window-airing	28.11.2023	06.03.2024	214	4	-
	R2.13	classroom	3	window-airing	28.11.2023	06.03.2024	214	4	-
	Sal29	classroom	3	mechanical	28.11.2023	06.03.2024	176	1	-

* installed their own CO_2 traffic lights

2.1 Control strategy of warning signal

Due to variations in threshold values among CO_2 feedback devices on the market, a new control strategy is introduced to represent the market average while also adhering to relevant standards and guidelines. The chosen threshold aligns with the guideline for assessing indoor air provided by the Austrian Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (Tappler, 2024). The feedback signal used within this investigation is a small LED, which shows a colour range from green over yellow to red. A mathematical dependency of the underlying RGB values of the LED was found for the measured CO_2 concentration on the device. The functions for the red and green parts of the RGB value are based on the limit for spaces with cognitive tasks at 1000 ppm and the limit for spaces with permanent stay at 1400 ppm (see formulas for β_1 and β_2). The formulas for the RGB values, with red, green, and blue values in the number range from 0 to 255 and the CO_2 concentration in parts per million (ppm), are the following:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0 \leq (\alpha \times CO_2 - \beta_1) \leq 255 \\ 0 \leq (-\alpha \times CO_2 + \beta_2) \leq 255 \\ 0 \end{bmatrix} \text{with } \alpha = 0.25$$

The constants are defined by $\beta_1 = 255 - 1400 \times \alpha$ and $\beta_2 = 255 + 1000 \times \alpha$. This results in a gradient from RGB (5,255,0) at 400 ppm to RGB (255,5,0) at 2000 ppm. The full colour range with the according values is displayed in Figure 1.

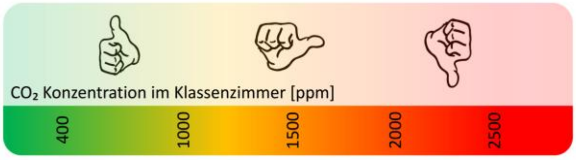

Figure 1: Colour range of CO_2 feedback signal

2.2 Positioning and housing

The sensor kits in each classroom, which are also used as CO_2 traffic lights, are mounted at a height of approx. 110 cm above the floor and positioned in the front (next to blackboard), the back (opposite side of blackboard) and the interior side wall (typically opposite the exterior wall with windows). The sensor height is matched with the breathing level of the students, and the positioning considers appropriate distance to windows, doors, and sources of pollution according to ISO 16000-1 (2004).

To protect the sensor kit from shocks and other environmental influences except from the air in the classroom, it is enclosed in a 3D-printed housing that has a separate chamber for the air quality and temperature sensors to reduce the heat flux from the processing unit. Despite this effort, the readings of the temperature sensors are inconsistently higher (up to 1° Celsius) than reference measurements. Three different CO_2 concentrations and their corresponding warning light are shown in Figure 2.

Figure 2: Example of the feedback colours at three different CO_2 levels of the used device

2.3 Sensor specifications and error adjustment

The sensor kits include, next to other air quality sensors, the SCD30 (Sensirion, 2020) for the CO_2 measurements (range: 0 – 10000 ppm, accuracy: ±30 ppm +3%) and the BME680 (Bosch Sensortec, 2022) for temperature (range: -40 – 85 °C, accuracy: ±1 °C). In fall 2023, the sensors were tested and compared before installation using high-grade reference measurement devices for CO_2 and temperature. Additionally, the CO_2 sensors were calibrated at a pressure of 950 hPa and temperature of 22°C at 1012 ppm using a calibration gas (synthetic air with specific carbon dioxide concentration). The auto-calibration function of the SCD30 was deactivated, and the data was pressure corrected in post-processing according to the school location's height. Measurement redundancy was provided by three measurement devices per classroom, and the readings are averaged within each timestep to weaken potential effects stemming from drifting of single sensors or unrealistic spikes, e.g. from "interested" students breathing directly onto the sensor.

2.4 Data Handling

Since the large amount of data is saved wirelessly via the openSenseMap (OpenSenseLab, 2023), the measurements were not disturbed during operation. One day at the beginning of the measurement campaign and around the intervention date were excluded from the dataset used in this paper so that boundary artefacts can be prevented. To complement missing data readings from the external sensors positioned within the DIGIdat project, ambient air temperature data from the nearest official weather station was retrieved from the GeoSphere Austria Data Hub (2024). Holidays and weekends were also omitted from the analysis. Data handling and statistical analysis were conducted using Python.

3 RESULTS OF STATISTICAL ANALYSIS

For evaluating the effect of the CO_2 traffic lights, two methods of comparison were employed. The focus of this analysis is the CO_2 concentration in each classroom between 9:00 to 12:00 on each school day, and since the air quality measurements from previous project phases showed a strong dependency of the CO_2 levels on the outside temperature, the data was categorised into 2 °C temperature bins. The two methods of comparison include:

- Pre- and post-intervention for CO_2 distribution within the studied classrooms
- Intervention and control group for CO_2 distribution with hypothetical intervention

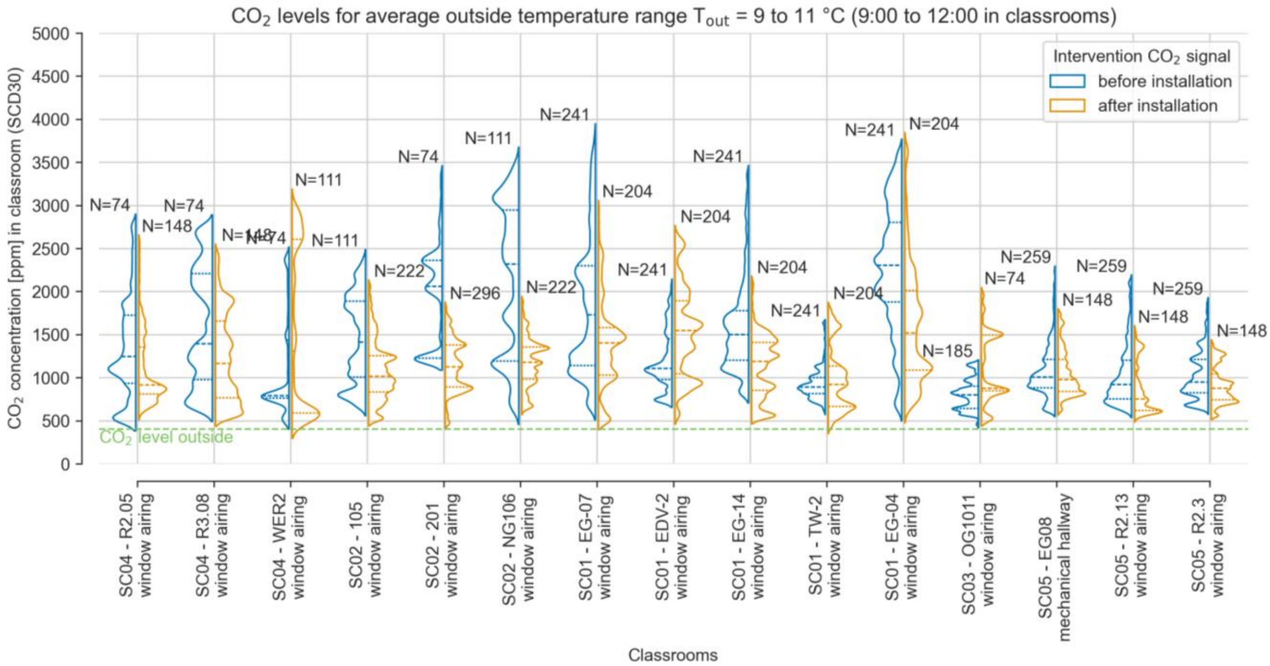

Figure 3: CO_2 concentrations from 9:00 to 12:00 before and after installation of the visual feedback device

As an example of the datasets for each classroom, Figure 3 shows the pre- and post-intervention (CO_2 traffic light installation) violin plots for temperature bin [9, 11] °C. A data point corresponds to the average of all sensors within a classroom over 5 minutes, which represents up to fifteen sensor readings for CO_2 and temperature. As the information on classroom occupancy was not complete up to this point, only readings from 9:00 to 12:00 were considered, chosen because this is the time when classrooms are most likely to be occupied.

3.1 Temperature dependency

To check for a difference between the dependency on the outside temperature before and after the intervention, CO_2 concentrations of all classrooms with their corresponding outside temperature are plotted (Figure 4) with a regression line and mean root square error (RMSE). Those datapoints represent the mean values for all measurements from 9:00 to 12:00 of each day and classroom.

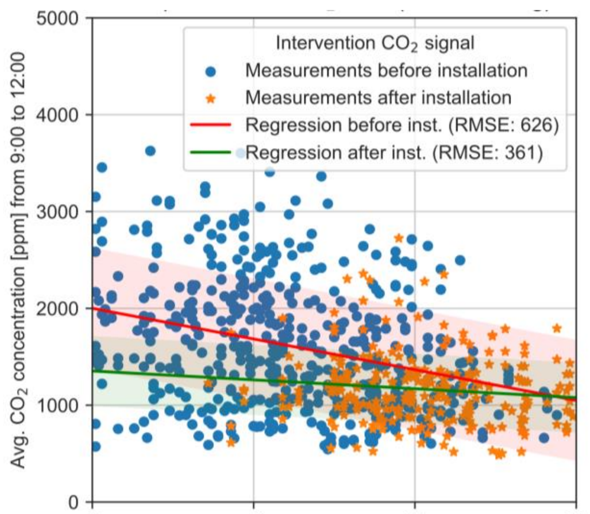

Figure 4: Correlation of outside temperature and inside CO_2 concentrations for classrooms with window airing

Similar to the previous study (Beck et al., 2023), the plot shows a strong temperature dependency of the average CO_2 levels in the classrooms without intervention. After installation of the device, the data shows a smaller dependency on outside temperatures. This is supported by the Spearman test, in which the null hypothesis states that the underlying data is not correlated. The resulting p-values are ca. 8e-12 before intervention and 0.047 after intervention. The regression lines only include data with outside temperatures from 0 to 15 °C, as this was the range with a reasonable amount of data points. Therefore, the results must be interpreted with caution, as the dataset after the intervention is smaller and within only a subset of the temperature range. According to the Shapiro-Wilk-Test, both datasets (before and after) are not normally distributed but follow a fitted Weibull distribution best. The p-values for the Kolmogorov-Smirnov test hypothesis, that the data is drawn from the Weibull distribution (determining the goodness of fit), are 0.79 (before intervention) and 0.09 (after intervention). The authors are not aware of a widely accepted test to compare the regression lines pre- and post-intervention with Weibull-distributed data; therefore, the ANCOVA (analysis of covariance) test was performed. The results of the ANCOVA test are shown in Table 4.

Table 4: Main results of ANCOVA to test the intervention effect

Parameter	**Sum of squares**	**F-value**	**p-value (uncorrected)**
Intervention	6.8e+06	22.34	2.70e-06
Avg. T_{out}	2.4e+07	79.44	2.90e-18

The data indicates a significant effect of the intervention but an even stronger effect of outside temperature on the CO_2 concentrations in the classrooms, with p-values well below a significance level of $\alpha = 0.01$.
To support this, the data was again summarised and plotted within the temperature bins, and their differences were checked using Welch's t-test (on ranked datapoints, RWT) and the Mann-Whitney-U-Test (MWU). Those tests were chosen because of the non-normality of the data distribution. The null hypothesis of both tests is that the CO_2 concentration after the intervention is not significantly smaller than before. Figure 5 shows the violin distribution curves before and after the installation of the CO_2 traffic lights in different temperature bins, which had enough data points to be statistically meaningful. The threshold of statistical significance due to the nature of the one-sided test is set at $\alpha = 0.005$.

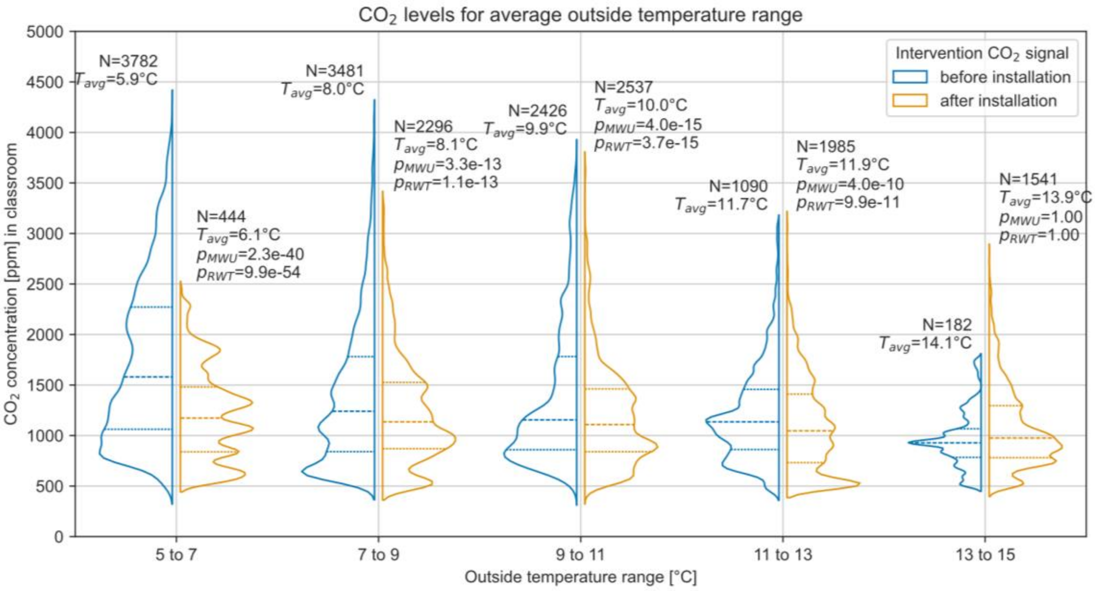

Figure 5: CO_2 concentration distribution for different outside temperature ranges

The p-values as shown in Figure 5 show a significantly smaller CO_2 concentration in classrooms in all temperature bins except for the bin from 13 to 15 °C.

3.2 Comparison to control group

To assess if the results are biased due to differing weather characteristics, in particular ambient temperature, the dataset is compared to a control group, which had the same awareness campaign but no visual feedback devices available. In this comparison, the control group was assigned a hypothetical intervention around a similar date, when the CO_2 traffic lights were installed in the intervention classrooms, namely at the beginning of March. The correlation between outside temperatures and inside CO_2 levels is shown in Figure 6. No major difference can be interpreted by visual inspection before and after the hypothetical intervention. Analysis using the Spearman test results in correlation coefficients of -0.29 (p: 6e-6) before and -0.27 (p: 0.0026) after the reference date, indicating a significant correlation between CO_2 concentration and ambient temperature for both periods. The ANCOVA test shows a similar picture (see Table 5). The given uncorrected p-value and F-value show a significant difference before and after the intervention date. However, it must be mentioned that this analysis does not quantify the magnitude and direction in which the correlation coefficients differ and that the observed difference in magnitude is small.

Table 5: Main results of ANCOVA to test control group with hypothetical intervention

Parameter	Sum of squares	F-value	p-value (uncorrected)
Hypothetical intervention	3.3e+06	12.41	4.79e-04
Avg. T_{out}	8.3e+07	31.11	4.58e-08

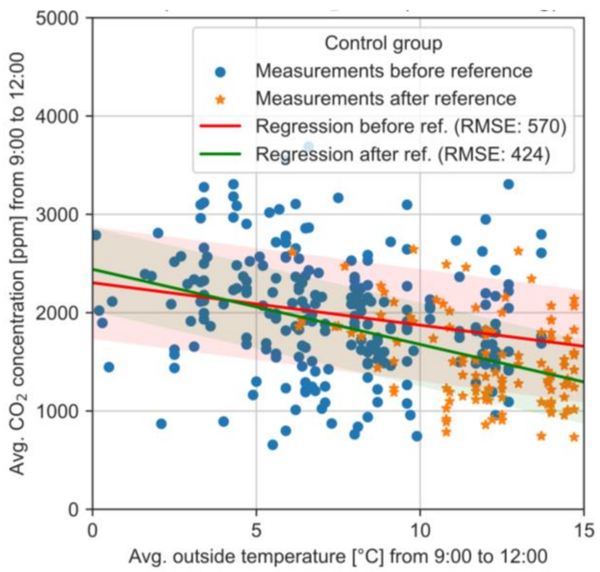

Figure 6: Correlation of outside temperature and inside CO_2 concentrations for classrooms (control group)

Violin plots for the control group (see Figure 7) in the different outside temperature ranges show that the CO_2 levels after reference are not lower during periods with lower ambient temperatures. The given p-values for the control group indicate that significantly lower CO_2 values after the reference date occur only in temperature bins with temperatures above 9 °C.

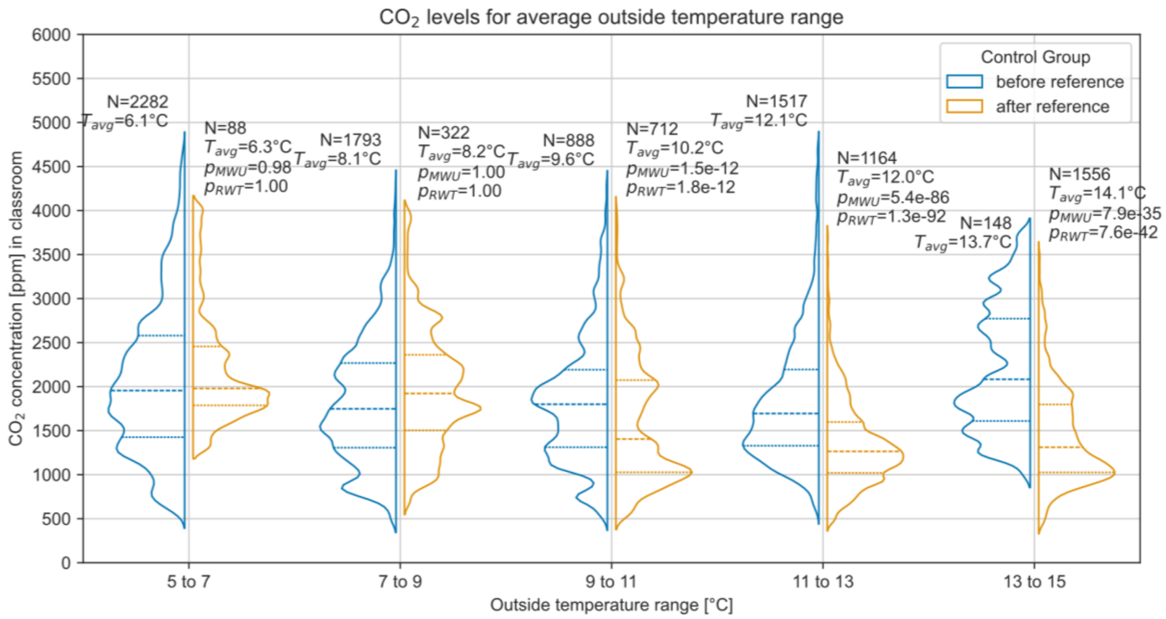

Figure 7: CO_2 concentration distribution for different outside temperature ranges (control group)

4 DISCUSSION AND CONCLUSION

This paper investigates whether there is a positive effect of CO_2 traffic lights on reducing CO_2 levels in the subject classrooms. The statistical analysis shows, according to two different comparison approaches, that the ventilation strategy using visual feedback improves the CO_2 levels in the classrooms under the given circumstances.

1) The difference between classrooms with or without CO_2 feedback signals is statistically significant at lower ambient temperatures (below 9 °C) when comparing before and after the intervention and shows no difference in the control group. At higher

ambient temperatures, these differences become small and/or are not significant. The question is, however, whether this effect will be visible over a longer period of time as pupils and teachers get used to the presence of such equipment. Other limiting factors of this study are the late date of the intervention, with generally warmer ambient temperatures after the intervention, and the fact that only schools with a presumable interest in air quality are taking part in this citizen science project. Five of the fifteen herein analysed classrooms have the additional bias of being actively involved in programming the feedback devices. Therefore, the willingness to ventilate according to the CO_2 traffic light might be higher than in other classrooms. It is also important to mention that the intervention has to be seen in the context of an awareness campaign, which was necessary to show affected teachers and students how to deal with the visual feedback. Another experiment should investigate the effect of visual feedback without proper information about its use.

2) A review of existing studies, standards, and the market shows that there are several approaches to the design of CO_2 traffic lights and thresholds for warning signals (usually green, yellow, and red). Therefore, a mathematical approach was considered to link the colour scheme to the thresholds given by the regulations in Austria.

As the measurement campaign is still ongoing, the long-term effect of the CO_2 traffic lights will be monitored and analysed with a more complete data set. Another interesting approach would be to test the difference of removing an active CO_2 traffic light after a longer period of use to see if there is a change in behaviour after this "negative" intervention. Based on the current data, the visual feedback system seems to be a valid approach to reducing CO_2 levels in classrooms.

Despite the effect, it must be considered, that the energy consumption for heating is probably higher due to a higher air change rate using the traffic light system. This trade-off between good air quality and the energy efficiency of the school building itself was not evaluated in this work and requires further investigation. E.g., mechanical ventilation systems with heat recovery might be able to alleviate this trade-off.

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