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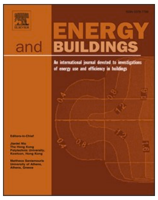

The impact of real-time carbon dioxide awareness on occupant behavior and ventilation rates in student dwellings

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ABSTRACT

Although existing standards typically prescribe fixed ventilation rates, a large portion of the building stock lacks mechanical ventilation systems. Such buildings obtain outdoor air through unintentional infiltration, open windows, and the operation of exhaust fans, which are mainly dependent on user awareness and behavior. This study investigates whether the presence of a simple CO_2 meter display can alter user behavior and improve indoor air quality (IAQ) in dwellings. We conducted a two-week monitoring of CO_2 concentration, air temperature, and relative humidity in 60 student dwellings (bedrooms and living rooms) in Denmark and Switzerland. During the first week, the CO_2 display was concealed, and occupants adhered to their usual routines. In the second week, occupants used the display's visual feedback to enhance IAQ when necessary. Results revealed that over 95% of dwellings witnessed a reduction in median CO_2 levels during the second week, both overall and in individual rooms. Furthermore, a descriptive analysis of CO_2 concentration step changes exceeding the thresholds of "normal variation" showed an increase in the number of negative step changes, indicating a shift in user behavior. These findings underscore the efficacy ofa display interface providing information on the indoor environment in triggering behavior changes and improving IAQ in dwellings.

1. Introduction

On average, the respiratory flow rate in humans is 8.8 l/min [1]. Considering that the majority of individuals in modern societies spend more than 90 % of their time indoors it can be inferred that average person will inhale more than 3 million liters of indoor air throughout their lifetime. Thus, it is not unexpected that the quality of the indoor air we breathe significantly impacts human health[2].

Then, how much outdoor air do buildings require to ensure appropriate indoor air quality? Although there are standards that prescribe various outdoor ventilation rates for different building types and activities, e.g. the ASHRAE Standard 62.1[3], there is still ambiguity to this question. Some studies have found significant productivity improvements[4,5]and sleep quality [6] when subjects are exposed to higher airflow rates than those prescribed in international and national standards, indicating that a revision of the existing standards is necessary to improve public health.

On the other hand, although various standards prescribe fixed limits for ventilation rates, a large part of developed countries' building stock, especially for domestic use, does not have continuous mechanical ventilation systems. The Danish building code BR2015[7]specifies a minimum outdoor air supply of 0.3 l/s per m^2 for residential buildings at each room and the whole building while allowing single-family houses to be naturally ventilated. The air change rate of these buildings depends mostly on user behavior and awareness, and it was shown that energy-efficiency concerns and financial reasons prevent many building owners from ventilating their buildings adequately[8].

Buildings equipped with a continuous mechanical ventilation system are more likely to comply with Indoor Air Quality (IAQ) performance

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Nomenclature

ACH	Air Changes per Hour
BMR	basal metabolic rate
C_R	CO_2 concentration of replacement air (ppm)
C_t	Room CO_2 concentration at time t (ppm)
DT_{out}	difference between week 1 and week 2 outdoor weekly mean temperature (K)
DRH_{out}	difference between week 1 and week 2 outdoor weekly mean relative humidity (%)
E_{CO2}	total CO_2 emission rate (l/min)
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
M	metabolic rate (met)
P	pressure (kPa)
Q	ventilation rate (m^3/h)
RQ	respiration quotient
SBS	Sick Building Syndrome
SFH	Single Family House
T	air temperature (K)
V	room volume (m^3)

standards[9,10], but the mere presence of a mechanical ventilation system is far from guaranteeing that airflow rates prescribed by standards are achieved. Numerous issues can and often do negatively affect the performance of ventilation systems, such as i) incorrectly designed flow rate; ii) improper installation; iii) olfactory contamination [11], iv) noise issues or controls that inhibit intuitive use[12]and, thus, occupants shut them off or set them at the minimum setting[13].

Even green-certified buildings do not automatically guarantee occupant comfort and well-being[15–16,14]. Al horr et al. [14] argue that designing for a good Indoor Environmental Quality (IEQ) is not sufficient and that building performance must be monitored during operation. Barthelmes et al. [17] reported that user awareness of environmental and energy-related behaviors is crucial to provide energy-efficient but also healthy and comfortable buildings. Real-time feedback based on IEQ or, specifically, CO_2 monitoring and visualization has been demonstrated to be an effective strategy for the improvement of IAQ in educational [18]and office buildings[19].

There is an increased interest in occupant behavior and its influence on the energy consumption and indoor environment[20,21]. There is also an increased interest in smart homes with most initiatives having the premiss that monitoring can reduce the energy consumption and improve IAQ, usually without considering the additional energy consumption of the devices used (including the energy consumption of the cloud) and with little consideration to data security and the potential health effects of increasing exposure to wireless radiation. To date, only a few initiatives have analysed different ways to interact with building occupants in order to promote the desired behaviors and energy/IAQ outcome[22,23]. Most studies use monitoring to characterize user behavior, but not how monitoring itself impact user behavior. There is a lack of studies addressing directly the impact of CO_2 monitoring on occupant behavior and IAQ. In addition, an increased in teleworking has been observed since 2020, which increases the need to study and improve IAQ in residential buildings.

In this view, this paper presents experimental data characterizing the IAQ in student residences and examines the parameters impacting the IAQ and ventilation rates, with the goal to capture the influence of the act of IAQ monitoring on user behavior and IAQ. The data was recorded over a period of two weeks in 60 student dwellings at two locations: 1) bedrooms and 2) living rooms. Effective ventilation rates were estimated from CO_2 measurements. Only during the second week, the users had visual access to the monitored data. The impact of CO_2 meters on home user behavior and indoor air quality is discussed, and recommendations are provided.

Therefore, the purpose of the study is to assess the effectiveness of acknowledged IAQ visual feedback strategies in residential buildings, which is poorly addressed in the literature. As noted above, student residences are often inadequately ventilated owing to economic and energy-related factors. In this view, the main research question that this paper seeks to address is: can a CO_2 meter display alter the user window opening behavior and improve IAQ in student dwellings? This research question will be answered by determining whether there is a significant difference in CO_2 concentration levels between the first and second week in the monitored dwellings.

2. Research background

In this study, the indoor air temperature, relative humidity, and CO_2 concentration were monitored in students' dwellings in 2 different countries, i.e., Denmark and Switzerland, to study occupant behavior change based on real-time IAQ feedback. Abundant research has already been performed on CO_2 and its impact on human health; this is a key pollutant characterizing IAQ and occupation. Relative humidity was also selected since it has a large influence on many other parameters affecting health [24]. Temperature is another key parameter that was selected because of its impact on thermal comfort and perceived air quality [25].

2.1. Carbon dioxide

For many scientists, CO_2 was long considered harmless at low indoor concentrations rates [26]. However, elevated indoor CO_2 levels have been associated with undesirable symptoms in many studies. Back in 1996, Myhrvold et al. [27] monitored CO_2 levels in 5 Norwegian schools and administered health symptom questionnaires and performance tests to 550 students. They found a statistically significant association between elevated CO_2 levels (1500——4000 ppm) compared to the limit of 1500 ppm with reduced performance and symptoms of headaches, dizziness, heavy-headedness, tiredness, and difficulty concentrating.

Although the research community debates the impact of carbon dioxide on human health, it has been largely accepted that carbon dioxide levels are a useful proxy of the quality of air and the likelihood of the existence of other pollutants in the air[28]. As stressed out by ASHRAE in their 2022 position document on indoor carbon dioxide, indoor CO_2 levels are a useful tool in IAQ assessments when users properly understand the associated limitations, but they do not provide an overall indication of IAQ since these emissions are not related to other contaminants that are not linked to occupancy, such as building materials and furniture [29].

2.2. Air temperature and relative humidity

Air temperature and relative humidity are among the parameters primarily affecting human comfort and well-being, and they are used to assess the IEQ mainly for the thermal environment[30]. Besides the noticeable impact of air temperature on thermal comfort, a significant relationship was demonstrated also between occupants' IAQ perception of health symptoms and air temperature. This is associated explicitly with the prioritized natural ventilation control based on hygrothermal conditions rather than on air quality conditions[31]. Moreover, reduced air quality perception was reported in warm environments[32,33]. However, IAQ appears to be more closely correlated to thermal comfort than temperature since air quality was demonstrated to be acceptable if thermal comfort is maintained[33]. Fang et al. [34] confirmed the impact of thermal conditions on perceived air quality in a working environment. Pigliautile et al. [35] obtained a negligible correlation between thermal and air quality sensation votes in summer and winter conditions when correlating thermal and air quality perception. Nevertheless, the existing literature clearly stresses the need to consider the interaction with thermal comfort when assessing IAQ conditions.

Other studies researched the inter-dependencies between occupants' perceived IEQ and many indoor environmental design conditions [36–39]. More specifically, Fang et al. [34] found that the impact of decreasing the ventilation rate on perceived air quality can be counteracted by a decrease in relative humidity. The authors argued that the air is perceived as acceptable when its relative humidity is low. At the same time, warm and humid air is always perceived as stuffy and unacceptable, even if the air is clean. Berglund [40] studied the relationship between air freshness and indoor air humidity and found that when indoor relative humidity increases to a certain level, the air is perceived as bad, regardless of whether it is clean or contaminated. Even further, He et al. [41] investigated the acceptability of indoor air quality under temperatures of 26 to 30 °C and RH of 60 % to 80 %; the authors confirmed a significant increase in dissatisfaction levels at higher humidity.

2.3. *Observed ventilation rates in buildings and IAQ*

A log-linear dose–response relationship between perceived air quality and ventilation rates was observed by Fanger [26]. Many studies have found a significant positive association between higher ventilation rates and reduced prevalence of SBS symptoms[42–44]. This has been confirmed in a *meta*-analysis in 2006[45]. In parallel, many studies did not find any significant association[42,46–49]. These inconsistencies may stem from the fact that the ventilation rates were adjusted with existing HVAC systems, which are a significant contamination source if they are not adequately maintained (Bluyssen, 1989; [50].

Bekö et al. [51] estimated that the yearly average bedroom air change rate at night for five houses in Denmark in all seasons was 0.67 ACH when using active tracer gas measurements and 1.45 with CO_2 measurements. The state of the opening of the bedroom door, relevant to understanding the degree of interzonal air mixing, was not reported in their data. A cross-sectional cohort study of 500 children revealed that air change rates were insufficient in most homes, with 56 % below 0.5 ACH [52].

2.4. *CO_2-based methods for evaluating ventilation rates in buildings*

The monitoring of CO_2 distribution indoors has proven to be effective for assessing ventilation strategies [53]. A review of CO_2-based methods for estimating ventilation rates is presented by Batterman [54]. The reviewed methods are classified as 1) steady-state, 2) decay, 3) build-up, and 4) transient mass balance method. All these methods are based on a fully mixed mass balance model. In a study reporting ventilation rates of 37 US schools, the authors argue that steady-state, decay, and build-up methods have severe limitations and biases. In contrast, the transient mass balance method better matches the conditions and minimizes biases (Batterman et al., 2017). Transient mass balance method is accurate as long as the occupancy and metabolic activity of the occupants remain the same. The transient mass balance method is very flexible as it does not require steady-state conditions. Batterman [54] notes that the method has less sensitivity to the time window selected compared to the buildup method and that any time interval can be used.

A study compared ventilation measurement techniques and the accuracy of three different methods: active tracer gas, occupant-generated CO_2, and long-term passive tracer gas [55]. Their results confirm that the CO_2 balance method yield a higher air change rate since both the outdoor air supply and interzonal airflow are captured with this method, while with active tracer gas, a constant gas concentration is maintained in all rooms. Thus, it can effectively measure only the outdoor air supply rates. Data from five Danish buildings revealed that while the ratio of CO_2-calculated air change rate to active tracer gas-calculated air change rate can reach 20, it is still relatively precise when internal doors are closed.

3. Methods

3.1. *Study site and student participants*

This study is an initiative to support research-based teaching at undergraduate and graduate university programs to enhance knowledge of residential air quality and human behavior. We recruited 60 students (Table 1) — thirty-eight from the University of Southern Denmark (SDU) in Odense, Denmark (ID 1–26; 32–43), and twenty-two (12 male and 10 female) from the École Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland (ID 27–31; 44–60).

These 60 residences included apartments (35), single-family houses (SFH) (21), and dormitories (4). Each residence differed by construction year (from 1860 to 2019), renovation status, ventilation system, and occupancy density. Characteristics of each residence are summarized in Table S1. While most residences were situated in urban areas of Odense and Lausanne, several residences were in semi-rural areas.

3.2. *Experimental design*

The air temperature, relative humidity, and concentration of CO_2 were continuously monitored and recorded in the investigated residences for two consecutive weeks. Outdoor weather conditions were derived from local weather stations[56]. It included outdoor daily mean temperature (T_{out}) (^{o}C), outdoor daily mean relative humidity (RH_{out}) (%) and daily mean wind speed (Ws) (km/h). The measurements were performed during four consecutive spring semesters, between 13 February and 15 May 2019 (ID 1–18), between 5 March and 24 April 2020 (ID 19–31), between 23 February and 28 April 2021 (ID 32–51), and between 14 March and 28 March 2022 (ID 52–60). To investigate the role of human behavior on indoor air quality and ventilation rates, we adopted a key variable — the visibility of a display screen on the measuring device. In the first week, the students had to fully cover the display and carry out their regular home routines without thinking about the CO_2 data logger. In the second week, the students were asked to uncover the display and use the real-time CO_2 reading to introduce actions for improving the IAQ. In addition to CO_2, each device displayed air temperature and relative humidity information. After the end of the second week, students were asked to fill out an Excel-based questionnaire for sharing their observations characterizing the measures' effectiveness (see Fig. 1 for the graphical summary of data collection process).

Each student received a pair of measurement devices. One device was always located in the bedrooms, while the second was typically in the living room. The students were asked to position the second device in the kitchen in residences with no living room. In bedrooms, the measuring device was positioned within 0.6–1.1 m height above the floor corresponding to typical breathing zone height; at least 1 m away from the breathing zone, walls, doors, windows, and air supply/exhaust elements. Potential stagnant zones with low-air mixings, such as room corners or space between furniture, were avoided. The criteria for

Table 1
Summary of studied residences by country and building type.

Country	Year	Apartment	Dormitory	SFH	Subtotal
Denmark	2019	10	NA	8	18
	2020	3	NA	5	8
	2021	8	NA	4	12
	Subtotal	21	0	17	38
Switzerland	2020	3	1	1	5
	2021	5	1	2	8
	2022	6	2	1	9
	Subtotal	14	4	4	22
	Total	**35**	**4**	**21**	**60**

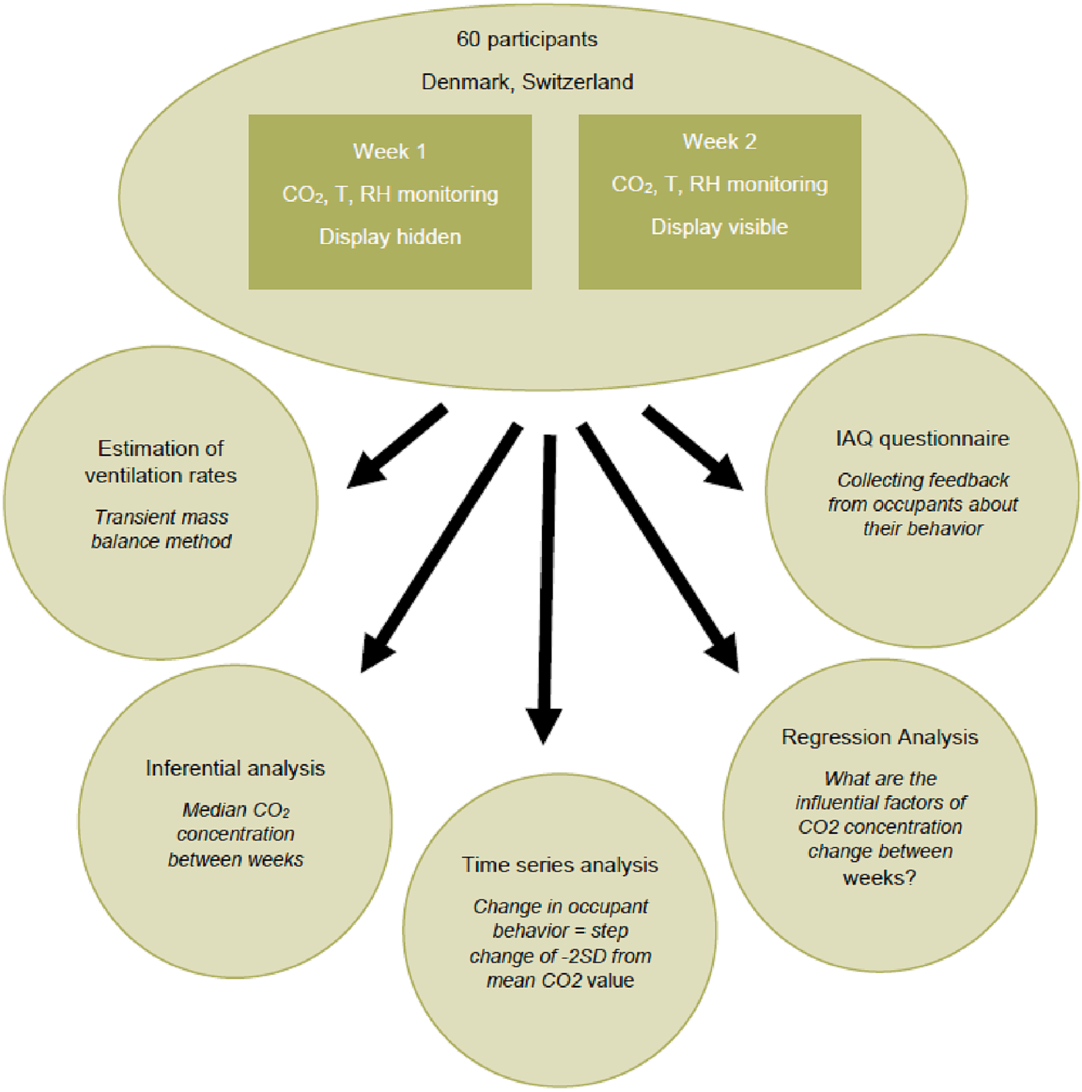

Fig. 1. Illustrative summary of the data collection and data analysis methods employed in this study.

positioning the second instrument were similar, except for the positioning height within 1.1–1.7 m, assuming that occupants in other rooms were predominantly sitting or standing.

3.3. Experimental equipment

The selection of instruments for CO_2 concentration measurements was based on the requirement that devices have high accuracy and can display real-time data on a visible screen. We selected two models of non-dispersive infrared CO_2 absorption monitors and data loggers. The device used in Danish residences in 2019 was the XT-10 CO_2 meter (CO2Meter, FL, USA) with a manufacturer-specified accuracy of ± 70 ppm and ± 3 % of the reading value (at < 5000 ppm) and a response time of 2 min. In 2020, the meters were replaced with another CO_2 meter (BZ30, Trotec) with a manufacturer-specified accuracy of ± 75 ppm and ± 5 % of the measuring value (at < 10′000 ppm) and a response time of 1 s. The device used in Switzerland was HOBO MX1102 (Onset Computer Corporation, MA, USA) with a reported accuracy of ± 50 ppm and ± 5 % of reading and a response time of 1 min. None of the devices had the alarm function activated, meaning that occupants were not informed about potentially high CO_2 concentrations. Along with CO_2 measurements, all devices also recorded indoor air temperature and relative humidity with an accuracy of ± 0.3 °C and ± 3 % (XT-10 CO_2), ±1°C and ± 5 % (BZ30), and ± 0.21 °C and ± 1 % (HOBO MX1102). During the study, the measurement interval was set at 3 min. For the HOBO MX1102 sensors, the measurement interval was set at 1 min, after which the results were averaged at a 3 min interval. The CO_2 instruments used in this study were newly calibrated by the manufacturers. Before each student cohort's field measurements, the instruments' performance was confirmed by placing them indoors side-by-side and comparing a week-long data record. Because the device at EPFL has a self-calibration option, the students were asked to perform a self-calibration outdoors at the end of the first week of measurements. The discrepancy among instruments was small, within manufacturer-specified uncertainty limits.

3.4. Questionnaire surveys

A questionnaire survey was distributed to each student, and we received the maximum response rate. The students were asked to assess the following list of variables – once for each week of measurements: 1) perception of indoor air quality, 2) frequency of experiencing any SBS symptoms, 3) frequency and time of window and door opening, 4) status of window and door opening during the night selected for calculating ventilation rate, 5) average time spent at home during weekdays. The students were also asked to describe their building characteristics, including information about the type of building (apartment, single-family house, or dormitory room), construction and renovation years, ventilation system type, and the number of adult and children occupants. Results from these questionnaires are provided in the supplementary data file (Tables S2 and S3).

3.5. Data analysis

Each household record had data covering a minimum of 6 days (timestamp, T, RH, and CO_2) for each space for each week. The data were initially sorted by household ID, room type, daytime, and descriptive statistics were used in combination with data visualizations to identify any outliers due to sensor drift or misplacement of the sensor. In general, the sensors performed well; rare cases of missing data (~1% of total dataset) were omitted from the dataset and not replaced. All statistical treatments were performed in software R[57]. The individual analysis performed in this study corresponds to (1) estimation of ventilation rates, (2) inferential analysis, (3) time series description, and (4) regression analysis and are described in the following subsections, as illustrated in Fig. 1.

3.5.1. Estimation of ventilation rates

For the final dataset, the night-time measurements of CO_2 in student bedrooms were used to calculate the ventilation rates. Among the four typical methods used for estimating bedroom ventilation rates described in the prior section, we adopted the transient mass balance method as the most accurate, owing to its independence of the steady-state conditions and the time interval selection [54]. The transient mass balance method is based on performing a single-zone mass balance for CO_2 during a specific time interval, as shown in the Equation 1:

$$C_{t+1} = \frac{610^4 \times E_{CO2}}{Q}\left(1 - e^{-\frac{Q}{V}\Delta t}\right) + (C_t - C_R)e^{-\frac{Q}{V}\Delta t} + C_R \qquad 1$$

Where C_{t+1} is the room CO_2 concentration at time t + 1 (ppm), E_{CO2} is the total CO_2 generation rate (l/min), Q is the ventilation rate (m^3/h), V is the room volume (m^3), C_t is the room CO_2 concentration at time t (ppm), t is the time (h), C_R is the CO_2 concentration of replacement air (assumed 400 ppm). The first term expresses the CO_2 emissions from indoor sources, while the second describes the dilution due to ventilation. The above equation must be solved numerically for Q, as obtaining an analytical solution is not possible.

A limitation of the adopted approach, which is expected regardless of the calculation method, is the assumption of well-mixed bedroom air volume and the assumption of constant outdoor CO_2 concentration, bedroom CO_2 generation rate, and ventilation rate. Additionally, estimated ventilation rates are not solely caused by the air change with outdoors but also include interzonal air mixing through bedroom doors. Ignoring interzonal airflows could lead to increased uncertainties in estimating ventilation rates[55,58,59].

To estimate the CO_2 generation rate of bedroom occupants, we adopted the ASTM D 6245 method [60]:

$$E_{CO2} = RQ \times BMR \times M \times \frac{T}{P} \times 0.000211 \qquad 2$$

Where RQ is the respiration quotient with a value of 0.85 as recommended in the standard, BMR is the basal metabolic rate, M is the metabolic rate (Met), T is the air temperature (K), and P is the pressure (kPa). The BMR calculation followed the procedure in ASTM D 6234 [60]; the students were asked to provide their ages, sex, and weight. While the ASHRAE 55 defines the metabolic rate value while sleeping at 0.7 Met, a value of 1 Met was selected for all students. Since the selected measurement window corresponded to when the subject stayed in the bedroom for a long uninterrupted segment usually at night, it is obvious that the subject was not always sleeping during this period. A higher metabolic activity early and late in the measurement period is common, and sometimes also at random moments. Therefore, a value of 1 Met was judged representative of the average metabolic rate during the selected measurement window. The students selected one night that corresponded to their usual sleeping behavior, which had a smooth CO_2 concentration profile for each of the two measurement weeks, at least 5 h of night-time data for data analysis, and ventilation rate calculations. The students were also asked to report the number of bedroom occupants and whether the doors and windows were closed, partially, or fully open. Finally, the bedroom volume was used to calculate the air change rate.

3.5.2. Inferential analysis

Data records of 58 participants were used for the supplementary inferential analysis as there was missing data in one of the two monitoring periods for two participants. The four following variables were used in the analysis: (1) dwelling ID; (2) 'period' as a record of the week during which the measurement took place week; (3) room in which the measurement was undertaken; and (4) CO_2 concentration level in ppm.

The first analysis consisted of two steps: (1) a review of the variables to determine the inferential test to apply, and (2) the application of inferential tests. The CO_2 concentration data was aggregated by dwelling ID, room and period to review CO_2 difference between weeks. On this dataset, inferential tests were performed for three levels: a) the entire dwelling (n = 58), b) the living room (n = 47), and c) the bedroom (n = 56). The sample sizes varied between levels as there were dwellings with no record in living rooms or in bedrooms. The CO_2 concentration was non-normally distributed (Kolmogorov-Smirnov test, $p < 0.05$). The samples were then paired into two groups (Week 1 and Week 2) for the first and second weeks of data collected during the study. As the data was non-parametric, paired and with independent observations, the Wilcoxon test was applied to address the research question. To follow this analysis, median CO_2 concentration within each dwelling was computed between weeks.

3.5.3. Time series analysis

The time series analysis aims to investigate if the decrease in CO_2 concentration between the first and the second week in bedrooms and living rooms could be associated with changes in occupants' behaviour. For instance, occupant behaviour could be an intentional increase in the room's ventilation when observing that the CO_2 concentration is above the recommended threshold. In this study, in order to consider the reduction in CO_2 concentration as an intentional change of behaviour, the step change in the time series should be a negative outlier in the order of −2SD from the mean value of the time series for each case study. On the other hand, a positive outlier would correspond to a sudden increase in CO_2 concentration that could mainly be associated with the specific activities and occupancy of each studied room. To be the best of the authors knowledge, the proposed methodological approach has not been previously used to infer occupants' behaviour.

Data records from 58 participants collected in bedrooms and data collected from 48 participants in living rooms were used in the time series analysis. The variables used in this analysis are: participant ID, room (i.e. bedroom, living room), measurement period (week 1 and week 2), CO_2 concentration, CO_2 step change (difference between the current and previous reading), CO_2_upper boundary (+2SD per Participant ID and Room), CO_2_lower boundary (-2SD per participant ID and room), and daytime. The time step of the data collected was 3 min. Due to anomalies in the data, values from the first and the last 30 min (~first and last 10 records) of monitoring were discarded.

The time analysis was conducted as follows: (1) changes in CO_2 concentrations were classified as "normal", "positive", and "negative" according to the magnitude and direction. Normal changes in CO_2 concentration levels correspond to the ones within two standard distributions, where the standard deviation was calculated individually for each case student (ID) and room type. A "positive" step changes are all the changes above the upper CO_2 boundary (+2SD), and the "negative" step changes are all the ones below the lower CO_2 boundary (-2SD); (2)

In the second step, the number of negative outliers observed during the first and the second weeks were calculated. Whenever the negative outliers during the second week exceeded the ones from the first week, it is concluded that users' behavior changed between the first and the second week through increased interventions (e.g., window opening) to reduce the CO_2 levels. Finally, (3) To quantify the number of interventions, the ratio between the number of negative outliers between the first and the second weeks was calculated. For instance, if the observed ratio is 1 to 2, it means that the number of negative outliers during the second week is between 1.1 and 2 times higher than the observed ones in the first week.

3.5.4. Regression analysis

Data records of 58 participants were used in the regression analysis. One binary dependent variable was used in this analysis. Two groups were determined from the inferential analysis: group 1 - dwellings with observed difference in median CO_2 concentration levels between the first and the second week (n = 52), and group 2 – dwellings with little observed difference in median CO_2 concentration levels between the first and second week (n = 6). These observed differences in CO_2 concentration levels may be occurring either in the bedroom, living room, or the entire dwelling.

Continuous and discrete independent variables were used in this analysis. The two continuous variables included are indoor air temperature and indoor relative humidity. The 20 discrete variables included in the regression analysis are as follows: the university which undertook the data collection (SDU or EPFL), the year during which the data collection took place (2019 to 2022), the country in which the data collection took place (DK or CH), the city in which the data collection took place, the building type (apartment, dormitory room, and single-family house), the year of construction of the building (ranging from 1870 to 2019), the year of renovation of the building (ranging from 1930 to 2019), the building level in which the data collection was undertaken (ground floor to 9th floor), the room in which the data collection was undertaken (living room, bedroom, dining room, kitchen, and office), the number of adults occupants (ranging from 1 to 10), the number of children occupants (ranging from 0 to 2), the type of ventilation for the building (mechanical or natural ventilation), for mechanical ventilation, presence of exhaust (yes or no), the type of ventilation for the room (mechanical and/or natural ventilation, none), the ventilation elements for the room (window and/or vent), the type of monitoring instruments, and the location of the monitoring instrument (at low, medium and high level).

The analysis procedure consisted of three steps as follows: (1) review of the relationships between the dependent variable and each continuous independent variable, using logistic regression analysis; (2) review of the relationships between the dependent variable and each discrete independent variable, using the chi-squared test and Fisher's exact test; (3) building a multinomial logistic regression analysis with the significant independent variables identified in the analysis above.

4. Results and discussion

4.1. Summary of descriptive data

First, the variation of CO_2 concentration, indoor air temperature, and air change rate were analyzed by each week, country, building type, and room type. Then, outdoor weather conditions were reviewed by each week and country.

Fig. 2 shows the variation of CO_2 concentration for the two meters for Switzerland and Denmark by week and type of building. In dormitory rooms (n = 4), there was a small variation (6 %) in average CO_2 concentration between the first and the second week (871 vs 816 ppm). A significant difference in CO_2 concentration was found in apartments and single-family houses (SFH). In particular, the highest difference was found in apartments (also the most numerous samples, n = 21), with an average reduction of 193 ppm of the mean CO_2 concentration and a reduction of 157 ppm for the median. In the Danish sample, a greater reduction in the second week was observed, especially in apartments, while the improvement was reduced in single-family houses.

Fig. 3 reports the variation of CO_2 concentration for each country by week and type of room across all building types. In both countries and both types of rooms, differences were detected between the first and the second week, particularly in bedrooms. Nevertheless, in Switzerland, the variation between the two weeks was slightly higher, while the standard deviation among samples was lower.

The analysis of the variation of CO_2 concentration by week and building type for the entire sample (Table 2) shows that the mean and median CO_2 concentration were generally higher in apartments, followed by single-family houses, with dormitory rooms characterized by

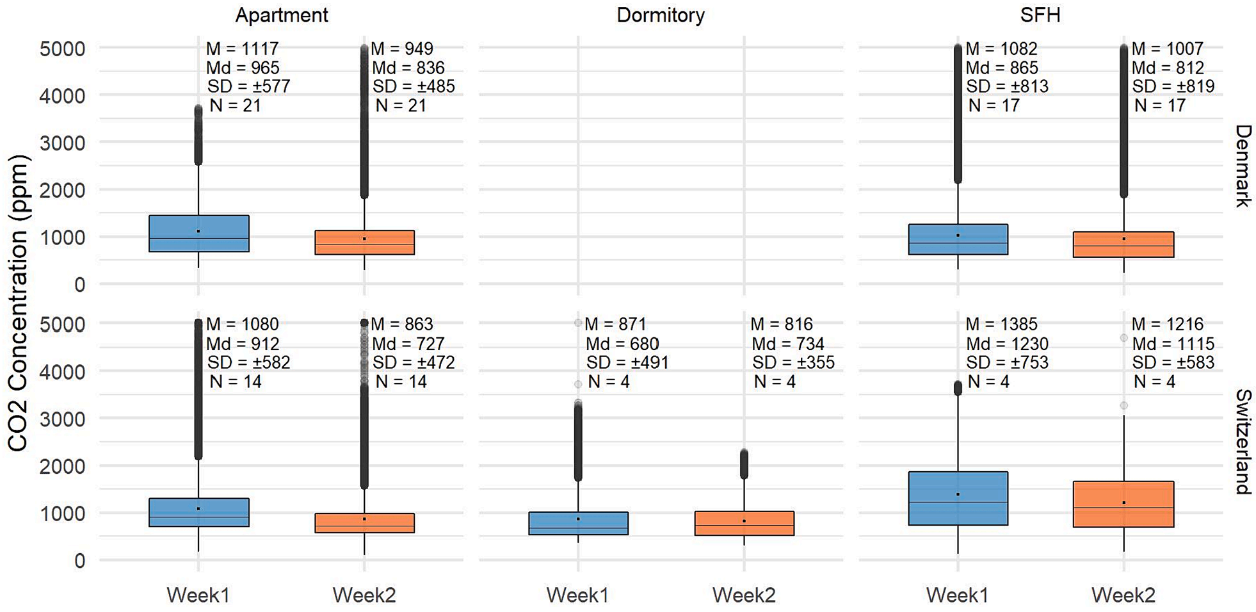

Fig. 2. CO_2 concentration recorded in Danish and Swiss dwellings by monitoring week and type of building. Box plots indicate the first quartile, mean (black dot), median, and third quartile values.

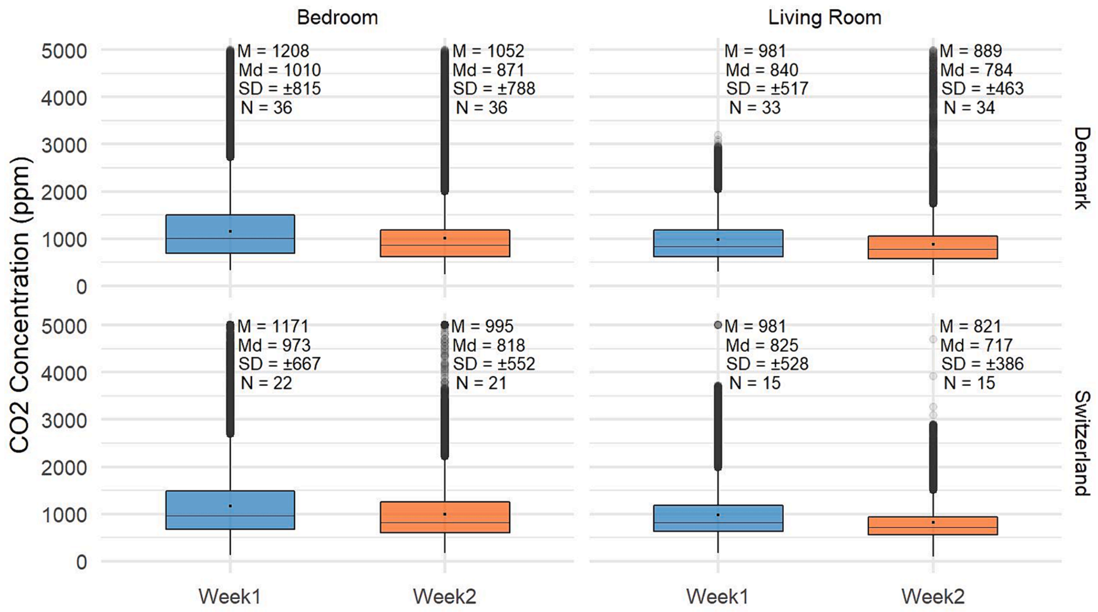

Fig. 3. CO2 concentration recorded in Danish and Swiss dwellings by monitoring week and room type. Box plots indicate the first quartile, mean (black dot), median, and third quartile values.

Table 2
CO_2 concentration (in ppm) per building type averaged across bedroom and living rooms for each case in Danish and Swiss dwellings.

Variable	Apartment		Dormitory		SFH	
Conditions	Week1	Week2	Week1	Week2	Week1	Week2
Sample	35	35	4	4	21	21
max	5000	5971	5000	2285	9497	9643
75 % quartile	1379	1070	1017	1025	1373	1228
Median	943	791	680	734	902	847
Mean	1103	916	871	816	1135	1047
25 % quartile	691	605	535	519	636	590
SD	579	482	491	355	811	784

The CO_2 concentration levels (in ppm) and the air change rate (ACH) for each investigated building type are summarized in Tables 2 and 3, respectively. The mean, median, standard deviation, 25% quartile, and 75% quartile values of both ACH and CO_2 levels are shown for the first and second week of the study. As seen in Table 3, the mean values of air change rate were higher in apartments, followed by family houses. The second week was characterized with higher air change rates especially with the case of apartments and single-family houses.

Table 3
Air change rate (ACH in h^{-1}) per building type for Danish and Swiss dwellings.

Variable	Apartment		Dorm		SFH	
Condition	Week1	Week2	Week1	Week2	Week1	Week2
Sample	33	33	4	4	21	21
Maximum	3.401	5.270	0.420	0.590	4.640	1.480
75 % quartile	0.480	0.990	0.275	0.568	0.560	0.980
Median	0.300	0.500	0.184	0.373	0.210	0.590
Mean	0.446	0.885	0.219	0.354	0.588	0.574
25 % quartile	0.150	0.290	0.128	0.159	0.160	0.170
Min	0.036	0.070	0.090	0.080	0.110	0.020
SD	0.589	1.079	0.145	0.259	0.996	0.431

the lower values. Almost all values appeared to be much lower in the second week with respect to the first week – especially in apartments – except for the median in dormitory rooms. Instead, the standard deviation was lower in dormitory rooms and much higher than the others in single-family houses, showing greater variability. Low CO_2 concentration in dormitory rooms along with low standard deviations could be attributed to low sample size (n = 4).

Fig. 4 depicts the variation of indoor air temperature in Switzerland and Denmark by week and building type. As might be expected, average and median indoor air temperatures were higher in dormitory rooms and lower in single-family houses. In the Swiss sample, a slight indoor air temperature reduction was detected in the dormitory rooms between the first and the second week, but differences were in general negligible both in terms of average and median. A similar result was obtained in the Danish sample, with slight indoor air temperature reduction noticed only in single-family houses. However, in this case, average and median indoor air temperatures were higher in the latter type of building. The negligible variation in indoor air temperature between the two weeks suggests a low correlation of this variable with the variation in CO_2 concentration.

The analysis of indoor air temperature variation for each country by week and type of room showed similar results, i.e., negligible differences between the first and the second week for both room types (data not shown).

Fig. 5 depicts the variation of air change rate for each country by week and type of building. Those were calculated from the CO_2 data in bedrooms for the most representative night of the first and second weeks. Overall, higher mean and median air change rates were observed across the three different buildings: apartments, dormitory rooms, and single-family houses. In the Swiss sample, higher mean air change rates were observed for apartments (38 %), dormitories (62 %), and single-family houses (67 %) in the second week compared to the first week. Regarding the Danish sample, the air change rate significantly increased in terms of mean value in apartment buildings but not in single-family houses in the second week compared to the first week. However, although relevant CO_2 concentration reduction was observed in single-family houses in the second week, they seemed not to be associated with an increase of air change rate in bedrooms in this building type.

In a certain way, the data is consistent with the results obtained for CO_2 concentrations. However, the magnitude of the calculated air change rate was not reflected in the decreased CO_2. One should note that the air change rate was calculated for a representative night while the CO_2 concentration corresponded to a whole week.

Finally, outdoor weather conditions were reviewed for each week and country. Results are summarised as follows; (1) the difference between week 1 and week 2 outdoor weekly mean temperature (DT_{out}) varied between 0 and 6 °C in Denmark and between 0.9 and 7.8 °C in

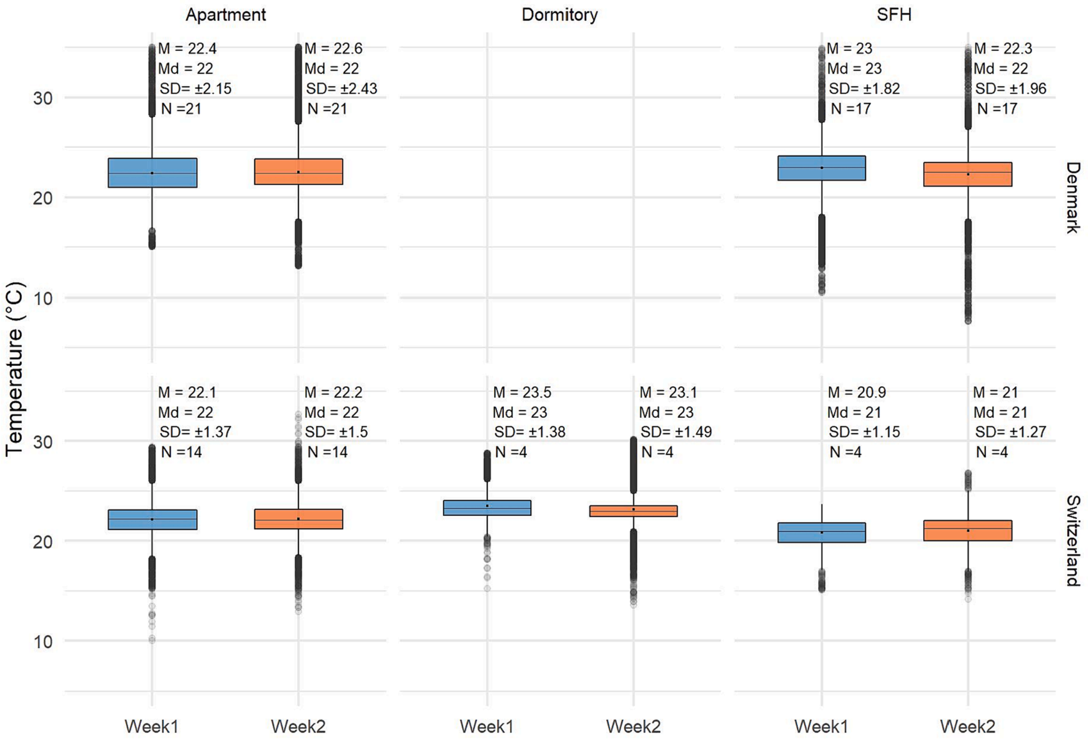

Fig. 4. Indoor air temperature recorded in Danish and Swiss dwellings by monitoring week and type of building.

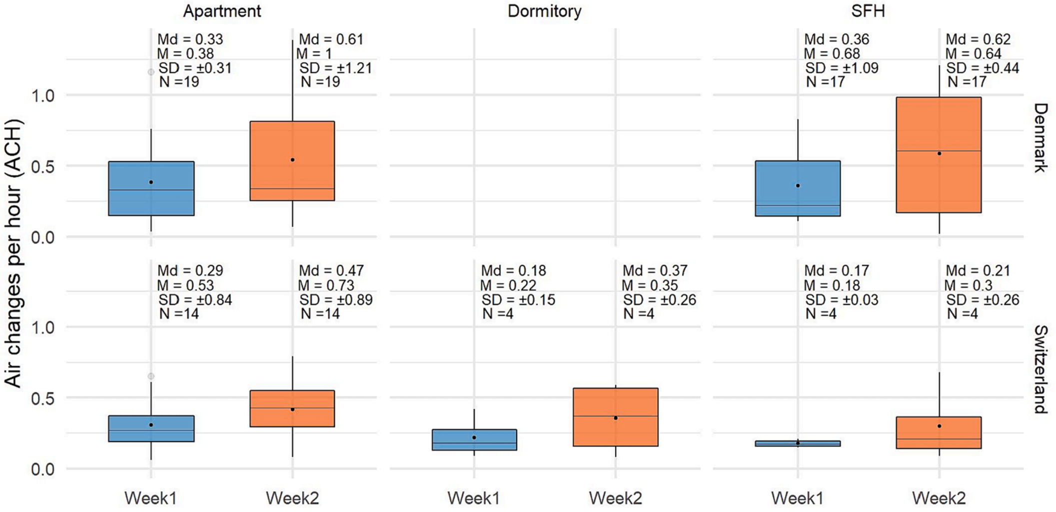

Fig. 5. Air change rate in bedrooms estimated for Danish and Swiss dwellings by monitoring week and type of building.

Switzerland; (2) the difference between week 1 and week 2 outdoor weekly mean relative humidity (DRH_{out}) varied between 0 and 8 % in Denmark and between 4 and 25 % in Switzerland; (3) the difference between week 1 and week 2 weekly mean wind speed (DWs) varied between 0 and 16.5 km/h in Denmark and between 0.3 and 8.2 km/h in Switzerland. For all three variables, the means (M) were lower than 12 (DT_{out} M = 1.8 °C in Denmark, DT_{out} M = 3.7 °C in Switzerland; DRH_{out} M = 3 % in Denmark, DRH_{out} M = 12 % in Switzerland; DWsM = 6.4 km/h in Denmark, DWs M = 3.9 km/h in Switzerland). For all three variables, the standard deviations (SD) were lower than 6 (DT_{out} SD = 1.8 °C in Denmark, DT_{out} SD = 2.1 °C in Switzerland; DRH_{out} SD = 2 % in Denmark, DRH_{out} SD = 6 % in Switzerland; DWs SD = 4.1 km/h in Denmark, DWs SD = 2 km/h in Switzerland). In conclusion, the variations in outdoor weather conditions between week 1 and week 2 were relatively small. This may be due to the two weeks being consecutive and in the same season.

4.2. *Results of inferential analysis*

The inferential analysis allowed addressing the research question: is there a significant difference in CO_2 concentration level between the first week and the second week within dwellings? As previously mentioned, three-room levels were assessed: the entire dwelling, the sole living room, and the sole bedroom.

For the analyzed dwellings (n = 58), the result of the Wilcoxon test indicated that CO_2 concentration in Week 1 (median = 1032 ppm) was significantly higher than in Week 2 (median = 864 ppm), $p < 0.05$. Based on the assessment of median CO_2 concentration within each dwelling, CO_2 was different between the first and the second week for most dwellings. Exceptions were noticed in three dwellings, all single-family homes: dwelling ID = 21, with a median CO_2 of ~ 860 ppm for both weeks; dwelling ID = 32, with a median CO_2 of ~ 520 ppm for both weeks; and dwelling ID = 45 with a median CO_2 of ~ 780 ppm for both weeks.

Fig. 6 depicts the cumulative proportion distribution of median and maximum CO_2 concentrations in the 58 dwellings in the two weeks. In the first week, the median CO_2 concentration ranged between 427 and 2055 ppm, while in the second week, it ranged between 425 and 1573 ppm. The difference in the median between the two weeks ranged from a decrease of 978 ppm to an increase of 472 ppm in the second week. The median of the median decreased by 112 ppm. In the first week, maximum CO_2 concentration ranged between 899 and 9497 ppm, while in the second week, it ranged between 812 and 9643 ppm. The difference in maximum between the two weeks ranged from a decrease of 3140 ppm to an increase of 3594 ppm in the second week, less than the median. During week 1, 40 % of the subjects encountered peaks of 2000 ppm or below, while in week 2, an equivalent percentage of students experienced peaks of 2500 ppm or lower. This suggests that the intervention was a little useful in reducing moderate peaks. Above a CO_2 concentration of 2800 ppm there are almost no difference in the cumulative proportion of maximum CO_2 levels, indicating that the intervention had limited impact on reducing the highest peaks.

In summary, at dwelling level, there was a significant difference in CO_2 concentration levels between the first and the second week, which was due to a decrease in CO_2 concentration levels for 76 % of the sample.

Regarding living rooms (n = 47), we observed similar results. The result of the Wilcoxon test indicated that CO_2 concentration in Week 1 in living rooms (median = 853 ppm) was significantly higher than in Week 2 (median = 794 ppm), $p < 0.05$. Within dwellings, for most living rooms, median CO_2 was different between the first and the second week ($p < 0.05$), except for two living rooms (ID = 30 and ID = 45). In the first week, median CO_2 concentration ranged between 408 and 2419 ppm, while in the second week, median CO_2 concentration ranged between 405 and 1812 ppm, namely up to about 600 ppm less for the top limit. The difference in the median between the two weeks ranged from a decrease of 1032 ppm to an increase of 405 ppm. Higher differences were observed, compared to the entire dwelling level, except for the median of the median, with a decrease of 67 ppm. Therefore, at living room level, there was a significant difference in CO_2 concentration level between the first and the second week, with a decrease in CO_2 concentration level for 74 % of the sample.

Finally, in bedrooms (n = 56), the result of the Wilcoxon test indicated that CO_2 concentration in Week 1 (median = 1155 ppm) was significantly higher than in Week 2 (median = 951 ppm), $p < 0.05$. Within dwelling, the bedroom median CO_2 level was different between the first and the second week for most of the bedrooms. Exceptions were found in two bedrooms (ID = 11 and ID = 13). In the first week, median CO_2 concentration ranged between 476 and 1945 ppm, while in the second week, median CO_2 concentration ranged between 493 and 1750 ppm, i.e., up to about 200 ppm less for the top limit. The difference in the median between the two weeks ranged from a decrease of 1062 ppm to an increase of 458 ppm, and the median of the median was a decrease of 118 ppm. The CO_2 concentration values in bedrooms were generally lower than in living rooms. In line with the previous two levels, at bedroom level, there was a significant difference in CO_2 concentration level between the first and the second week, with a decrease in CO_2 concentration level for 77 % of the sample.

Some subjects in naturally ventilated buildings reported difficulties in increasing ventilation because of the cold weather and the lack of flexibility in window opening positions (e.g. sometimes either 100 % closed or fully open, in between not possible) that resulted in discomfort. Other subjects in mechanically ventilated buildings reported not using the ventilation systems or only in the lowest setting because of noise issues.

Overall, this analysis demonstrated that, for most of the dwellings, there was a significant difference in CO_2 concentration level between the first and the second week, corresponding to a decrease in CO_2 concentration level. Therefore, using a display that shows an environmental index (e.g., CO_2 concentration level in our case) is suggested to have an influence on occupants' behaviors in optimizing the index towards better IAQ. This hypothesis, suggested by the obtained results, is further assessed in the following section.

4.3. Results of time series analysis

Following the results obtained in the previous analysis, the time series analysis presented in this section addresses the research question: could the observed differences in CO_2 concentration levels between the first and second weeks be attributed to occupants' behavior? Therefore, the analysis focused on calculating the negative outliers with respect to the standard CO2 concentration distribution observed during each week, which corresponds to a reduction in CO_2 concentration. If the

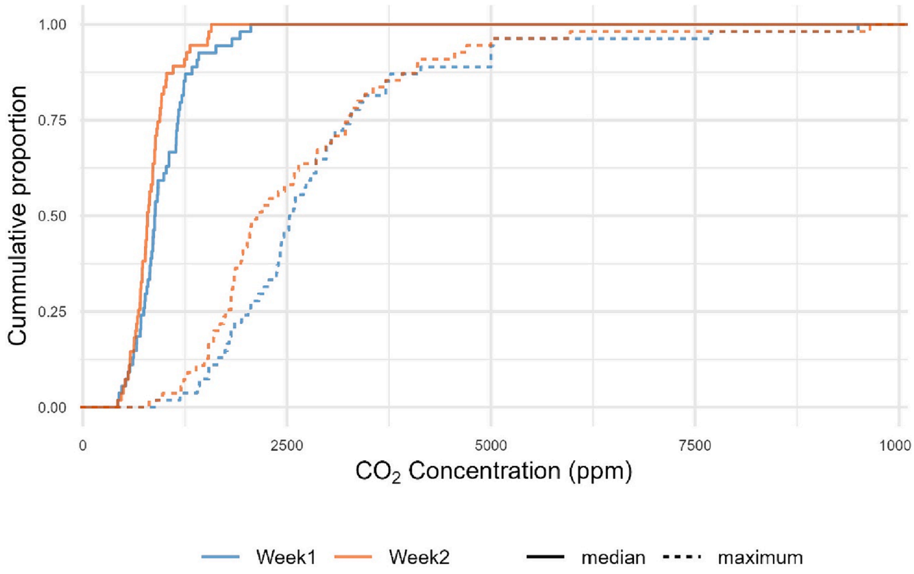

Fig. 6. Cumulative proportion distribution of median and maximum CO_2 concentrations in 58 dwellings recorded during the first and second week.

negative outliers during the second week exceed those during the first week, it could be interpreted as a change in user behavior between the two weeks in the form of taking actions in order to reduce CO_2. Fig. 7 and Fig. 8 show case studies where the CO_2 concentration levels between the first week and the second week were significantly different based on inferential analysis described in the previous section (Section 4.2). For instance, Fig. 7 shows the three-minute step change in CO_2 concentration between the first and the second week in living rooms for two case studies where the difference in CO_2 concentration was significantly different (ID = 25) and non-significantly different (ID = 30), respectively. The lower threshold - equal to two times the standard deviation for each case – allows identifying changes in CO_2 concentration that could be attributed to the user's behaviors aimed at reducing the CO_2 concentration, i.e., those that exceed the threshold. In living room ID = 25, the number of negative outliers during the second week is much higher (negative outliers = 53) than in the first week (negative outliers = 19), the ratio is 2.8 between weeks. Besides, the median CO_2 concentration of the negative step change in living room ID = 25 is –87 in the first week and –129 in the second week. On the contrary, in living room ID = 30, the negative outliers are comparable between the two weeks, as well as the median CO_2 concentration of the negative step changes. A total of 50 negative outliers were observed in the first week and 79 and a median CO2 concentration of the negative step changes of – 58.7 ppm. Whereas, in the second week even if a slight increase is noticed in the second week the count of negative outliers is only 71 and the median CO_2 concentration of the negative step changes is −68.7 ppm.

Similarly, Fig. 8 shows the step of change in CO_2 concentration between the first and the second week in bedrooms for two case studies where the difference in CO_2 concentration was found to be significantly different (ID = 25) and non-significantly different (ID = 13), respectively. The lower threshold highlights that the user of bedroom ID = 25 increased the number of actions that led to a negative outlier during the second week compared to the first week. In bedroom ID = 25, the count of negative outliers increased by 10 between first and the second week from 36 to 46 (ratio = 1.28). Besides the median negative step change in CO2 increased from −77.5 ppm in the first week to −146 ppm in the second week. On the contrary, in bedroom ID = 13, the negative outliers are much lower and similar in number between the two weeks, a total of 32 negative outliers are observed in the first week in relation to the 22 observed during the second week and median negative step change is almost the same –116 ppm in the first week and –104 in the second week.

Analyzing the data of all 59 bedrooms and 49 living rooms revealed a higher ratio of negative outliers in the second week in 25 (43 %) bedrooms and 24 (48 %) living rooms when comparing against the first week. The ratio of negative step changes (outliers) higher than 0 to 1 in 45 % of the bedrooms and 50 % of the living rooms between the first and the second week. Fig. 9 clearly shows that at least in half of the studied rooms, there was a higher number of negative outlier observations in relation to the week where sensor displays were covered (first week). Most interactions in both rooms were 1–2 × higher; in a few cases, the interaction increased up to 4–5 × compared to the first week. Overall, there was no observed difference in the number of negative outliers between rooms (bedrooms and living rooms), suggesting no behavior difference between the room types. These outliers indicate a sudden CO_2 reduction, which could be caused by intermittently opening a window/ door or fan. This could also be caused by occasional wind gusts through an open window or internal movement altering air mixing.

The heat map in Fig. 10 shows the ratio of negative step changes by time, day of the week, type of building and country. When looking into the ratio of negative step changes in bedrooms, one can notice that in general there are very few negative outliers between 01:00 and 07:00 am. A few negative outliers within this period, mainly observed in apartments and dormitories, could be associated with mechanical ventilation existing in some of the case studies. The highest ratio or negative step changes in bedrooms is observed in apartments between 08:00 and 13:00. It is important to notice that there are only four case

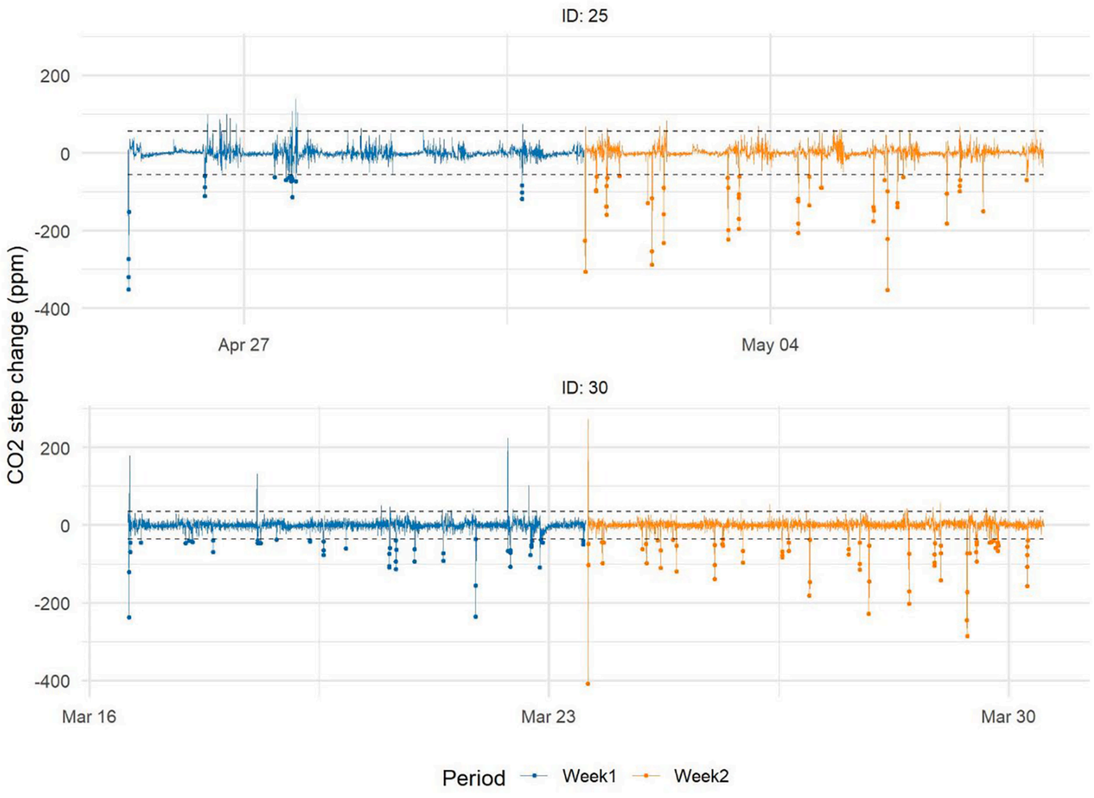

Fig. 7. A three-minute step change in CO_2 concentration per week for case studies ID = 25 (significant) and ID = 30 (non-significant) in living rooms.

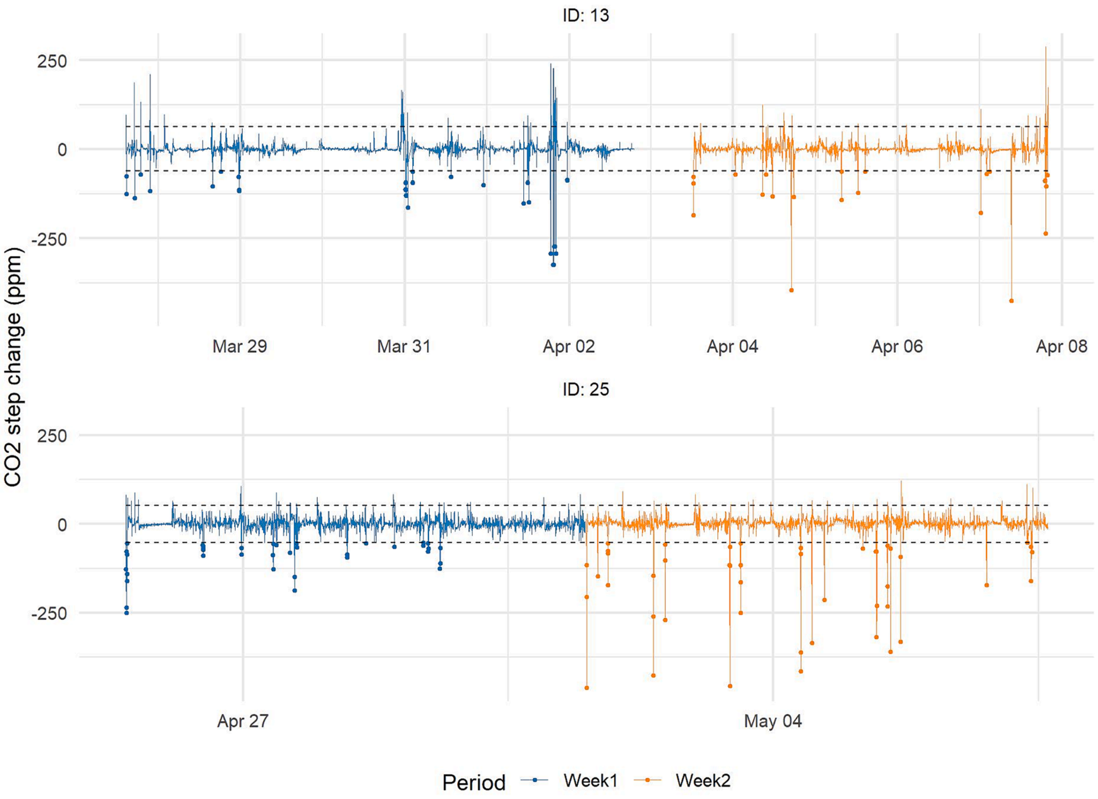

Fig. 8. A three-minute step change in CO_2 concentration per week for case studies ID = 13 (non-significant) and ID = 25 (significant) in bedrooms.

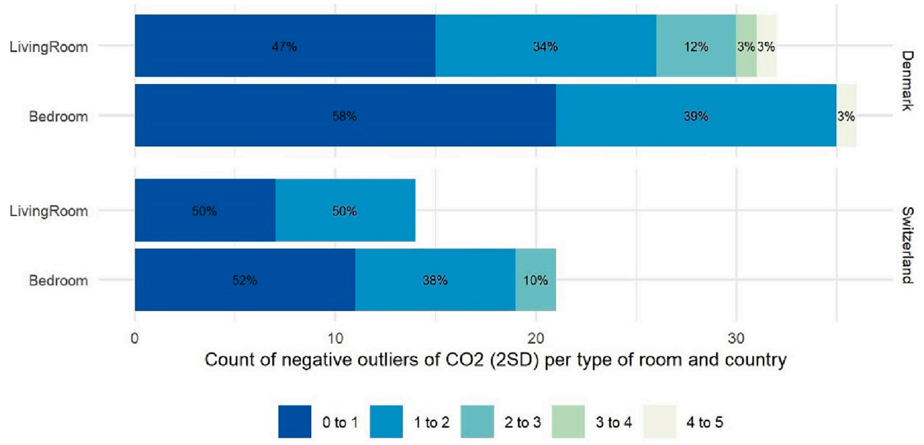

Fig. 9. Ratio count (x-axis) of negative outliers of CO_2 (2SD) and percentage of occurrences per room type and country type. (Dark blue 0–1 outlier, Mid blue 1–2 outliers, Turquoise 2–3 outliers, Green 3–4 outliers, Light green 4–5 outliers). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

studies for dormitory and single-family house (SFH) in Switzerland, thus the little number observed of negative step changes. However, a clear pattern of negative step changes is observed in SFH bedrooms between 09:00 and 10:00. This result was expected according to each specific room's principal time of use. Night-time was not among the times that showed a behavior change. Indeed, many students living in naturally ventilated buildings mentioned poor window operation as the main cause for compromised IAQ (e.g., windows that can be only opened at one fixed wide opening). Therefore, they were not able to open a window at night because of prevailing thermal comfort needs.

In terms of the living rooms, there is almost no observed ratio of negative step changes between 01:00 and 07:00 am and most of the negative step changes occurring consistently through the day from 08:00 onwards. When looking by type of living, one can notice that a higher ratio of negative step changes by type of building in living rooms is observed in single family homes.

Finally, Fig. 11 shows the results in terms of negative step changes for the case study, a bedroom (ID = 19), where the highest number of negative CO2 concentration outliers in the second week were compared to the first week. The heatmap in Fig. 11, reveals that during the first week very few negative outliers are observed mainly in the morning (07:00 to 11:00). Contrary to the second week, where the frequency of negative outliers is observed throughout the entire day between 07:00 until 23:00 in both rooms. This result suggests that, if properly understood and used, having access to a display that shows the IAQ conditions in the room can drive significant behavioral change in user-building

Fig. 10. Ratio of negative outliers of CO_2 concentration between the two weeks per building type, room type, and time of the day. (Dark blue 1–2 outlier, Mid blue 2–3 outliers, Turquoise 3–4 outliers, Green 4–5 outliers, Light green 5- >6 outliers). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interaction.

Therefore, this analysis revealed an increased interaction of the users to alter/change the CO_2 concentration in the case study rooms between the first and the second week by highlighting the increased number of CO_2 concentration step changes out of the thresholds of "normal variation". These results confirmed the hypothesis made from the inferential analysis that having a display interface providing information on the indoor environment is a positive trigger towards users' behavior change to improve IAQ.

Concerning strategies implemented to reduce the high CO_2 concentration levels detected by the monitoring system, the participants reported some actions but also some limitations to their implementation. For instance, in a bedroom with windows on two different facades, slightly cracking one window open only marginally increased the ventilation rate while cracking both windows open significantly increased the ventilation rate and the effect on IAQ improvement. In another natural ventilated dwelling, opening a bedroom window would prevent the heating system's operation. Therefore, keeping the window even slightly open was not an option because of the lack of heating and resulting thermal discomfort. In another case study, which was an apartment equipped with central exhaust and ventilation grilles in window frames, the participant reported having to close the ventilation grilles because of a high pitch noise resulting in acoustic discomfort. As reported in a single-family house bedroom, a successful strategy for reducing CO_2 levels during daytime occupancy was using a small desk fan positioned to blow air in the hallway. Finally, many students reported putting a plant in their bedroom during the second week to improve IAQ, but none of them could notice any difference caused by the plant.

4.4. Results of regression analysis

The regression analysis addressed the question: what are the predictors/influential factors of the observed difference in CO_2 concentration level between the first week and the second week within dwellings?

To follow the results of the inferential analysis, dwellings with very little difference in median CO_2 concentration between weeks were identified. The dependent variable was defined as a binary variable with

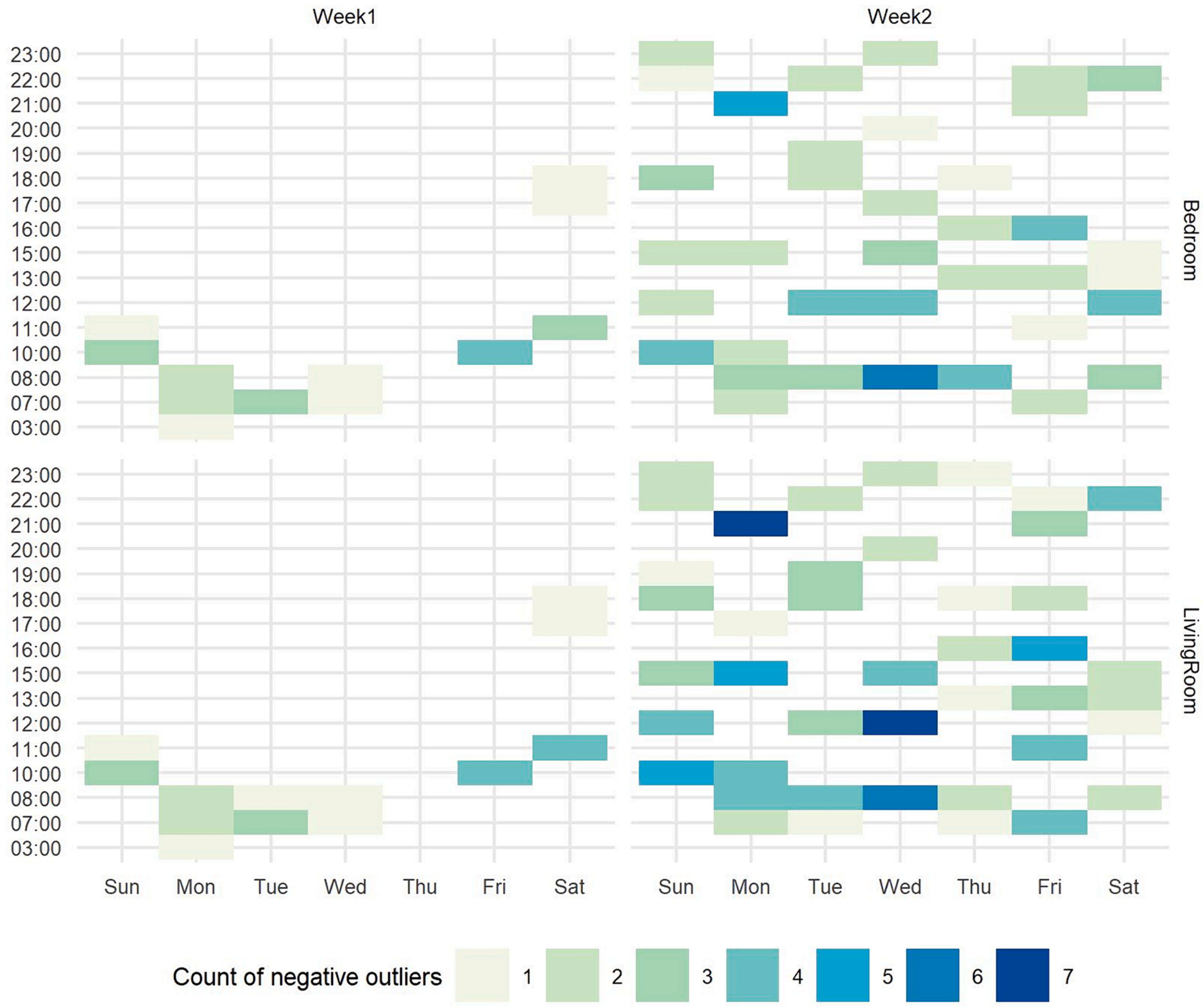

Fig. 11. CO_2 step change per week for case study ID = 19 in the bedroom: the one with the highest ratio changes between the two weeks.

"1″ for dwellings with observed difference in median CO_2 concentration level between weeks ($n = 52$), and "0" for dwellings with small observed difference in median CO_2 concentration level between weeks ($n = 6$). The first independent variables considered were indoor air temperature and relative humidity. Although both continuous independent variables were important predictors ($p < 0.05$), the models' fits were low. For temperature, the McFadden R^2 was 0.010, and for relative humidity, the McFadden R^2 was 0.016. These values indicate that indoor air temperature and relative humidity both had very low predictive power on the observed difference in CO_2 concentration level between the first and the second week – which confirms the results obtained in the descriptive analysis.

On the other hand, among the 20 discrete variables included in the analysis, three were found to be relevant: the building type (apartment, dormitory room, and single-family house), the type of ventilation for the room (mechanical and/or natural ventilation, none), and the location of the monitoring instrument within the room. In this case, there were significant differences between the first and the second week for the three discrete variables (two-tailed, $p < 0.05$): the building type (Chi-Square χ^2 (degrees of freedom = 2, sample size n = 226) = 10.52, $p < 0.05$), the type of ventilation for the room (χ^2 (2, n = 141) = 8.36, $p < 0.05$) and the location of the monitoring instrument (χ^2 (2, n = 141) = 14.41, $p < 0.05$). Therefore, when building a multinomial logistic regression including the three discrete variables above-mentioned, the model fit was good, with McFadden's $R^2 = 0.21$, and there was no multicollinearity (VIF < 5).

In summary, this analysis reviewed the predictors/influential factors of the observed difference in CO_2 concentration level between weeks. The results.

showed that indoor air temperature and relative humidity were both poor predictors of a difference in CO_2 concentration level between the two weeks and, therefore, of occupants' actions to improve IAQ. On the contrary, three discrete variables were found to be good predictors, namely the building type, the type of ventilation for the room, and the location of the monitoring and display instrument within the occupied room. The presence and, in case, the type of ventilation system available directly suggest the potential control of the occupants on IAQ. However, it is not obvious that they would use it properly. Moreover, certain building types can be subjected to restrictions on the use of those interfaces that control air changes and, therefore, e.g., dormitories. As for the location of the monitoring and display instrument, the visibility of the display interface affects the associated occupant's action. According to these outcomes, when designing visual interfaces that display the IAQ conditions, they should be in a position as visible as possible. This could appear obvious, but it is not. Moreover, building interfaces, e.g., natural/mechanical ventilation systems, should be easily accessible and controllable by the users or, if automatic, should ensure the required occupant-centric IAQ conditions.

4.5. *Results from IAQ questionnaires*

Participants were asked to assess to which extent using the visual display helps them a) identify IAQ-related issues at home they have not considered before and b) have used the visual display to monitor the IAQ and change their everyday activities and behaviour. For this purpose, the four-point scale used ranges from “Yes, definitely”, “Yes, to some extent”, “Slightly”, and “Not at all”.

In terms of identifying IAQ-related issues and activities that students have not thought before, 40 % out of 35 respondents voted for “Yes, definitely”, 46 % voted for “Yes, to some extend”, and only 11 % for “slightly”.

When asking the students about using the visual display to monitor and change their everyday activities and behaviour to improve/maintain IAQ at their home, 60 % out of 35 voted for “Yes, definitely”, 29 % for “Yes, to some extent” and 11 % voted for “Not at all”.

In this study, it was found that the following variables had a high impact on user behavior and IAQ: meteorological conditions, outside noise, schedule/time spent at home, type of activities (e.g., cooking, firing, candles), number of occupants, presence of a mechanical system (and its operation level vs. noise), window opening, use of recirculation and exhaust fan, presence of passive air inlets, the possibility of opening the window at a custom opening angle compared to a wide fixed angle.

5. Limitations

In interpreting study results, several limitations should be acknowledged. First, transient mass balance method was applied to estimate bedroom ventilation rates without considering interzonal airflow exchange through the bedroom doors. This could lead to substantial uncertainties[58]. Bekö et al. [59] estimated the error to be less than 30 %. Bekö et al. [55] found that air change measurements estimated from CO_2 generated by occupants may be relatively precise when interzonal flows are minimized by closing internal doors. However, status of bedroom doors was not controlled in our study because of the objective to capture the realistic and actual ventilation conditions. Although, the ventilation rates presented here are not entirely corresponding to outdoor ventilation rates, our results give an accurate assessment of total air change in the rooms.

The test subjects were engineering students enrolled in courses covering fundamental IAQ topics. Participation in this study was part of the course and was evaluated. Students reported a high level of appreciation for this learning activity. Although students were instructed for the first week to install the IAQ meter and carry on their activities as usual without making any change, the ‘Hawthorne effect’ could have occurred because of their awareness of the study, which may have altered their behavior[61,62]. However, this effect is not expected to be particularly significant as over complete week, it is unlikely that the subjects were continuously thinking about the meter among their normal daily activities. User behavior is a complex topic and the engineering students involved in this study likely had a higher motivation than conventional homeowners or tenants may not necessarily have. Therefore, the students who took part in this study may not be representative of the general student population without prior IAQ knowledge or awareness about the study. The study population has also a distinct profile regarding age, education and economic status which is not representative of the whole population.

In addition, this study’s short duration did not allow to identify whether the user behavior changes were temporary or permanent. This study shows that the subjects were able to increase their ventilation rates closer to target levels by providing them with a CO_2 meter and simple instructions. Additional longitudinal studies are needed to identify what is needed to favour long-lasting behavioral changes that can result in improves residential IAQ.

Further, monitoring of exterior temperature and wind speed as well as openings and closings of windows and doors inside the students’ dwellings should be included in the data analysis to draw correlation regarding changes in physical IAQ conditions, such as indoor CO_2 concentrations. Furthermore, the study focused on collecting indoor environmental data and general occupancy patterns. For future studies, an in-depth investigation could benefit from additional data collection such as detailed occupancy status and activities (e.g., operating of windows, doors and vents) to better understand changes in behaviour, indoor environment and impact of visual displays effect. Also, due to the nature of the study, we faced limitations in obtaining more comprehensive information about building and ventilation characteristics, thereby restricting our ability to assess their impact on indoor CO_2 levels.

Finally, the control group was represented by each subject during the first week. Even if the display of the CO_2 meter was covered and students were instructed not to alter their behavior, it is possible that consciously or not, the behavior of students was somewhat changed and not fully representative of their normal behavior.

Taking into consideration all these limitations, this study is valuable for showing that in the cases studies, approximately 50 % of the subjects could significantly increase the ventilation rate simply using an inexpensive CO_2 meter with real time display. The remaining half was not able to make significant improvements because of limitations and challenges linked to building characteristics and occupant behavior.

6. Conclusions

The main research question of this paper was: can the presence of a simple and low-cost CO_2 meter display influence user behavior, thus resulting in improved IAQ in student dwellings? To answer this question, CO_2 concentration, air temperature, and relative humidity data was collected from 60 student dwellings in Denmark and Switzerland over two-week period. The first week, when the meter display was covered, established a baseline for IAQ and user behavior. During the second week, students were instructed to use visual feedback from the meter display to proactively improve IAQ.

The first relevant outcome, obtained from the calculation of the negative outliers in CO_2 concentration distribution, indicates that for half of the monitored dwellings, there was a change in user behavior in both the bedroom and living room. However, this was calculated from the CO_2 step change between two-time steps, potentially overlooking some forms of user behavior, such as increasing the mechanical ventilation flow rates, which may not result in sudden and occasional CO_2 reduction but could contribute to lower CO_2 levels.

Specifically, a large proportion of dwellings had reduced median CO_2 levels during the second week, both in the dwelling as a whole and in individual rooms. In the majority of dwellings, ventilation rates doubled during the second week, with students explicitly attributing these changes to the visual display’s feedback on CO_2 concentrations. Importantly, students were able to identify issues related to their activities and IAQ through this display, even though it may not have been entirely effective in reducing peak concentrations. Factors such as mechanical system noise, indoor and outdoor environmental conditions, weather fluctuations, and inadequate window configurations posed challenges to further increasing ventilation rates. Nevertheless, the availability of the CO_2 meter display positively affected the participants’ behaviour and heightened their IAQ awareness, as evidenced by the median air change rate per hour in various types of dwellings, including dormitories, single-family homes, and apartments, all registering an increase during the intervention week.

Therefore, this study shows that a simple CO_2 meter with a display with low investment cost can effectively inform user behavior, prompting them to take actions to improve IAQ. However, due to the limitations of this study, further studies should consider enlarging the sample size and duration of measurements, aiming to investigate whether sustained behavior changes and improvement of IAQ can be observed in the general population over the long term. Additionally, investigating the influence of climatic and other contextual factors, such as different seasons, would be valuable in advancing our understanding of this process. Future studies should also strive to improve the accuracy of estimating ventilation rates by accounting for interzonal airflows. Finally, researchers are encouraged to collect a more comprehensive dataset on indoor air pollutants, outdoor environmental conditions, building characteristics, and occupants' activities and health status, which could be valuable for improved prediction and control of indoor air quality in student dwellings and beyond.

CRediT authorship contribution statement

Diane Bastien: Conceptualization, Data curation, Investigation, Methodology, Resources, Supervision, Writing – original draft. **Dusan Licina:** Conceptualization, Data curation, Investigation, Methodology, Resources, Supervision, Writing – original draft. **Leonidas Bourikas:** Formal analysis, Visualization, Data curation, Writing – original draft. **Sarah Crosby:** Formal analysis, Visualization, Data curation, Writing – original draft. **Stephanie Gauthier:** Formal analysis, Visualization, Data curation, Writing – original draft. **Isabel Mino-Rodriguez:** Formal analysis, Visualization, Data curation, Writing – original draft. **Cristina Piselli:** Formal analysis, Visualization, Data curation, Writing – original draft.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2024.114132.

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