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Real-time monitoring of personal exposures to carbon dioxide

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Abstract

Elevated indoor CO_2 levels are indicative of insufficient ventilation in occupied spaces and correlate with elevated concentrations of pollutants of indoor origin. Adverse health and well-being outcomes associated with elevated indoor CO_2 levels are based on CO2 as a proxy, although some emerging evidence suggests CO_2 itself may impact human cognition. Using portable monitors, we conducted an exposure study with 16 subjects in Singapore to understand the levels, dynamics and influencing factors of personal exposure to CO_2. Participants carried a CO_2 monitor continuously for 7-day periods recording their exposure levels at 1-min intervals. A recall diary was maintained of time-microenvironment-activity budget. We found that the mode of bedroom ventilation was a major determinant of CO_2 exposure. Approximately half of the participants slept in bedrooms employing ductless split air-conditioners (group "AC"); half slept in bedrooms naturally ventilated through operable windows (group "NV"). Median CO_2 exposure levels for AC vs. NV groups are significantly different ($\tilde{x}_{AC}$ = 650 ppm vs. $\tilde{x}_{NV}$ = 550 ppm, $p < 0.001$). Mean daily integrated exposures for group AC were statistically higher than for group NV: 22,800 ppm h/d vs. 16,000 ppm h/d ($p < 0.005$). Exposure events associated with potential adverse cognitive implications (duration > 2.5 h, average CO_2 mixing ratio > 1000 ppm) occurred, on average, at frequencies of 0.5 d^{-1} across all participants, 0.6 d^{-1} for AC participants and 0.2 d^{-1} for NV participants. The majority of such events occurred in the home (86%), followed by work (9%) and transit (3%).

Keywords: indoor air pollution; ventilation; human cognition; wearable sensors; bioeffluents

1. Introduction

The mixing ratio of carbon dioxide (CO_2) in indoor air, a metric long-considered to be associated with the quality of indoor air [1], remains utilized in present guidelines [2]. Because humans emit CO_2 as a result of their metabolism, indoor CO_2 levels are used as a proxy to assess of the sufficiency of outdoor air ventilation in relation to occupancy and activity [3]. Indoor CO_2 levels, or estimates of metabolic CO_2 emission rates, are also used in demand controlled ventilation systems [4]. In cases such as these, elevated levels of CO_2 are not assumed to be directly problematic, but rather are taken to be indicative of insufficient dilution of indoor air with outdoor air, enabling air pollutants with indoor sources to accumulate, including bioeffluents other than CO_2 [3,5]. It is under this concept that CO_2 levels in indoor air are considered in guidelines such as ASHRAE 62.1, which includes an appendix with an example calculation showing an indoor CO_2 level of 700 ppm above outdoors results in satisfaction with respect to levels of human bioeffluents in a substantial majority of occupants [6].

By contrast, it is to protect against adverse direct health consequences that a personal exposure limit (PEL) has been established in the United States, limiting occupational CO_2 exposure to a maximum of 5000 ppm as an 8-h time weighted average [7]. This PEL is based on studies conducted at CO_2 levels ranging from 10,000 ppm to 30,000 ppm that show adverse outcomes including electrolyte imbalances, metabolic changes, and non-narcotic central nervous system effects [8].

As routinely encountered in nonindustrial buildings, elevated CO_2 has been empirically associated with a variety of adverse outcomes including symptoms of sick building syndrome and influenza [9], declines in rates of student attendance in schools [10], and increases in sick leave at a large manufacturing employer [11]. In these studies, CO_2 was not thought to act as a causative agent, but rather as an indicator. However, emerging evidence suggests that CO_2 itself may adversely affect human cognition and decision-making performance at levels that are elevated, but still commonly encountered indoors. Studies investigating the impact of CO_2 on cognition in the range of 600-5000 ppm were conducted with a cohort of ten participants in a controlled, office-type chamber [12–14]. These studies concluded that several hours exposure to 3000 ppm or 4000 ppm CO_2 results in decreased cognitive performance as observed via decrements in performance on a proofreading exercise. Satish et al. [15] exposed a cohort of 22 participants to 600, 1000, and 2500 ppm CO_2 for 2.5-h periods. At 1000 ppm, statistically significant, moderate reductions were observed in 7 of 9 metrics of decision making relative to 600 ppm; at 2500 ppm, statistically significant and more substantial reductions were observed in 8 of 9 metrics of decision making. A recent study largely substantiates those findings. Allen et al. [16] exposed 24 participants to CO_2 levels of 550 ppm, 945 ppm or 1400 ppm for "full work days" (~8 h), and found that cognitive function scores were 15% and 50% lower, respectively, for the days with 945 ppm and 1400 ppm as compared with 550 ppm.

On the other hand, other recent studies implicate bioeffluents or possibly the combination of CO_2 and bioeffluents as the agent(s) adversely affecting human cognitive performance. Zhang et al. [17, 18] reported measures of cognitive impacts and physiological responses to elevated CO_2 exposures lasting 255 min resulting from either injection of pure CO_2 or via reduced ventilation in relation to human metabolic emissions. During experiments in which CO_2 was injected, Zhang et al. [17] report no statistically significant effects on perceptions of air quality, acute health symptoms, or cognitive impacts. Only when reduced ventilation rates led to increased levels of metabolic CO_2 plus associated bioeffluents were deleterious effects observed. Maddalena et al. [19] found that 4-h exposures to 1800 ppm CO_2 and increased bioeffluent levels (reported as TVOC and noted to also include room sources) resulted in significant reductions in cognitive performance relative to a 900 ppm condition. They found similar reductions in cognitive performance across conditions where TVOC increased but CO_2 remained constant at ~900 ppm. Strøm-Tejsen et al. [20] reported reductions in objectively measured sleep quality as well as reduced measures of ability to concentrate and perform effectively on a test of logical thinking after subjects slept in bedrooms with elevated CO_2 levels owing to reduced ventilation.

A large body of prior work confirms that CO_2 levels used in the aforementioned cognitive studies are often observed in the building stock. In a sample of 100 office buildings in the United States (the BASE study), Erdmann and Apte [21] report an average ΔCO_2 ($CO_{2,indoor} - CO_{2,outdoor}$) of 260 ppm with a standard deviation of 130 ppm, indicating that the majority of offices in this sample are below the CO_2 level (700 ppm above outdoors) shown in the example provided in Appendix C of ASHRAE 62.1. However, as noted by Allen et al. [16], the highest 8-h time-weighted-average CO_2 mixing ratio was 1400 ppm in the BASE study. Classrooms, an indoor environment where cognitive performance is of central importance, are commonly susceptible to elevated indoor CO_2 [22]. Shendell et al. [10] reported that 45% of 434 US school classrooms had short-term (< 5-min) average CO_2 levels above 1000 ppm. Santamouris et al. [23] reported that 52% of 62 classrooms in naturally ventilated schools in Greece had average CO_2 mixing ratios greater than 1000 ppm.

There are also reports of the occurrence of elevated CO_2 levels in dwellings, especially in regions with substantial building heating or cooling loads. Bekö et al. [24] report that only 32% of 500 Danish children's bedrooms sustained average CO_2 levels below 1000 ppm during measured night-time periods, with 23% of rooms experiencing a twenty-minute period above 2000 ppm. In the constantly warm and humid climate of Singapore, studies have shown an accumulation of CO_2 in bedrooms (>1000 ppm) that are served by air-conditioning (typically a ductless split system) rather than being ventilated with open windows and operating fans [25, 26].

While a large body of building-associated CO_2 monitoring data have been reported, the levels of CO_2 are almost always reported for a particular building or indoor space of interest. Given the historical acknowledgement of CO_2 as a proxy of exposure to air pollutants with indoor sources, combined with emerging evidence for cognitive implications associated with CO_2 exposures per se, complementary studies are warranted to directly measure personal exposures to CO_2. Such studies are enabled by the recent development of portable, lightweight monitors that can be easily carried and that provide real-time measurement of an individual's personal CO_2 mixing ratio through time. We are aware of only one recent study of this type. That effort targeted a cohort of school-aged children who wore the sensor only during school hours [27]. In the study described here, we report a novel dataset that measured continuous (24 h/d over week-long periods), personal CO_2 mixing ratios with complementary time-microenvironment-activity budgets for 16 participants in Singapore. Part of the inspiration for this work was the observation of high overnight CO_2 levels in air-conditioned bedrooms of members of our research team in Singapore. That observation led us to explore the CO_2 exposure consequences of bedroom ventilation style for this tropical climate. Data generated by real-time personal CO_2 exposure studies can be used to identify the time and place of problematic exposures to air pollutants with indoor sources (i.e., by using CO_2 as a proxy). Real-time, personal CO_2 levels can also provide context for emerging studies of cognitive implications of human exposures to CO_2.

2. Methods

Study participants were recruited from a convenience sample of university students and professionals; all participants had a primary working environment of a typical cubicle-based office space. All participants were requested not to alter behavior from their normal day-to-day activities when engaged in the study. Because we anticipated sleeping environments to play an important role influencing CO_2 exposures in Singapore, subjects were recruited with the intent of creating equal sized groups within the sample population based on bedroom ventilation mode: either air-conditioned bedrooms served by a mini-split ductless air-conditioning systems (group "AC") or naturally ventilated (group "NV") bedrooms with operable windows (typically kept open when occupied) and operating fans.

In all, 16 subjects participated in the study; seven met the criteria for group AC, six for group NV, and three exhibited mixed bedroom ventilation characteristics (alternating AC and NV) and were assigned to group "MX". Of the 16 participants, six were female, ten male, and the age range was 20-39 y. Where noted, anonymized participant identifications reflect bedroom ventilation mode and gender followed by a numeric identifier, e.g., AC-M-02 is the 2nd male participant in the AC sleeping microenvironment category. Participants each responded to a demographic questionnaire to obtain relevant personal data. Demographic details of subjects participating in the study, including the participant's height, weight, marital status, a calculation of individual CO_2 generation rate (ranging from 15-22 L/h across the 16 participants), a description of air-conditioner usage, number of individuals living in each participant's home, and approximate number of coworkers in each participant's workplace, can be found in Table S1 of the Supporting Information (SI).

Participants were asked to complete a recall-based time-microenvironment-activity budget diary for each day engaged in the study. Participants recorded the time of entry and exit for each microenvironment, a broad descriptor of the type of environment (home, office, transit mode, outdoor, etc.), a broad descriptor of the nature of their activity (working, sleeping, eating, etc.), air-conditioning status (on/off), and window opening status (open/closed). For this manuscript, microenvironments are grouped into five categories: home, work, transit, other indoor, and outdoor (see SI for additional details). The 'other indoor' microenvironment includes all time spent indoors but not at home or work.

Participants wore, carried, or otherwise kept in close proximity to their person a portable, battery-operated sensor (CM-0018, CO2Meter Inc.) that measured and stored records of date, time, temperature (°C), relative humidity (%), and CO_2 mixing ratio (ppm) at 1-minute intervals. Participants were asked to use the sensor to monitor their exposures for 24 hours per day, for a target total of seven continuous days per person. In the event of sensor failure or user error, participants were asked to continue their participation to create a cumulative seven-day log, which resulted in a non-continuous record for some participants. All logs included at least two weekend days, to account for differences that may result from working vs. non-working activity patterns. Prior to use in the study, sensors were either factory calibrated or calibrated to a 3-point standard by placing the sensor in a 10-L stainless steel chamber (CTH-24, Eagle Stainless) and diluting a flow of food-grade (99%+) CO_2 with a stream of CO_2-free air passed through a CO_2 sorbent (Sodasorb, Grace Chemical) to reach the desired CO_2 mixing ratio in the chamber. Reference CO_2 mixing ratios were determined from flow rate measurements made with a primary air flow calibrator (Gilian Gilibrator 2, Sensidyne LP). Sensors used in the study were calibrated a minimum of once every two months.

Personal CO_2 measurements were made between 19 May and 9 December 2015. All subjects were residing in Singapore during participation in the study. Because of the year-round warm and humid climate of Singapore, no seasonal differences exist across the study's duration. Four subjects participated during the 2015 haze period, spanning September 2015 to November 2015 when outdoor air pollution frequently reached hazardous levels. The haze period may have influenced individuals' activity patterns and/or preference for enclosed, air-conditioned indoor spaces; however, no systematically elevated CO_2 exposures were observed for those subjects participating during haze periods compared to non-haze periods.

All statistical analyses described in this paper were conducted in Matlab (R2012a, The Mathworks, Inc.). Statistical significance testing and consequent *p*-values were determined with the Wilcoxon rank sum test. All participants signed informed consent documents and were compensated S$10/d for their participation in this study. The methods described here were reviewed and approved by the Institutional Review Board of Nanyang Technological University (IRB-2015-04-010).

3. Results and Discussion

3.1. Characterizing personal CO_2 mixing ratios

The 16 participants were engaged in the study for a total of 108 days, yielding an aggregate total of 2600 hours of continuous, personal CO_2 monitoring. The 1-min personal CO_2 mixing ratios from two participants are shown in Figure 1, one each from the AC and NV groups. A feature common to both participants (AC-F-01 and NV-M-02) are short-duration peaks in personal CO_2 mixing ratio. These peaks generally correspond with time spent in air-conditioned public transit vehicles; the median CO_2 mixing ratio in 'transit' environments was 1300 ppm across all subjects (Figure S1 of the SI). However, notwithstanding the elevated CO_2 mixing ratios in transit, as we will see in §3.2, the impact of transit environments on integrated exposure is modest owing to the relatively small contribution of this activity to total time-microenvironment budgets. In this sample, subjects spent an average of 7.2% of their time in transit.

Time series personal CO_2 mixing ratios are reported for participant AC-F-01 in the upper panel of Figure 1. Subject AC-F-01 reported that she was on holiday and spent the nights of 21-23 August in a hotel, returning to sleep in her normal air-conditioned bedroom on the nights of 23-26 August. The difference in the CO_2 profile between the two nights of 21-23 August and the three nights of 23-26 August result from sleeping in microenvironments with different modes of ventilation. On average, participant AC-F-01's integrated CO_2 exposure in the sleeping microenvironment was 25,000 ppm-h per sleeping period for 23-26 Aug compared to an average of 6800 ppm-h per sleeping period for 21-23 Aug. These differences are largely explained by a 3× higher average CO_2 mixing ratio (2370 ppm vs. 800 ppm) between these two sleeping microenvironments. This example illustrates the importance of the CO_2 mixing ratio in sleeping microenvironments, where individuals spend a substantial portion of their daily time budget. Sleeping microenvironments are also likely to be characterized by smaller volumes than other microenvironments, enabling accumulation of CO_2, particularly if measures are taken to limit outdoor air exchange to reduce total cooling demand (or heating demand, in cold climates). Integrated exposures are explored in §3.2.

As can be observed in the lower panel of Figure 1, sleeping periods are not as clearly apparent from CO_2 mixing ratios for participant NV-M-02, who slept exclusively in bedrooms ventilated with open windows and operating fans. The result is a flatter diurnal CO_2 profile for NV-M-02 than for AC-F-02, largely because CO_2 mixing ratios in the sleeping microenvironment with open windows are nearer to outdoor levels.

Summary statistics of 1-h averaged personal exposure mixing ratios for all participants across the duration of their engagement in the study are shown in Table 1; summary statistics of the raw 1-min personal exposure mixing ratios are shown in Table S2 of the SI. Personal CO_2 mixing ratios are neither normally nor lognormally distributed, as determined by inspection of Q-Q plots of 1-min mixing ratios and log-transformed 1-min mixing ratios for linearity. Mean 1-h exposure mixing ratios are substantially higher for AC participants than NV participants, primarily a result of higher personal CO_2 mixing ratios at the 75^{th} percentiles and above for AC participants.

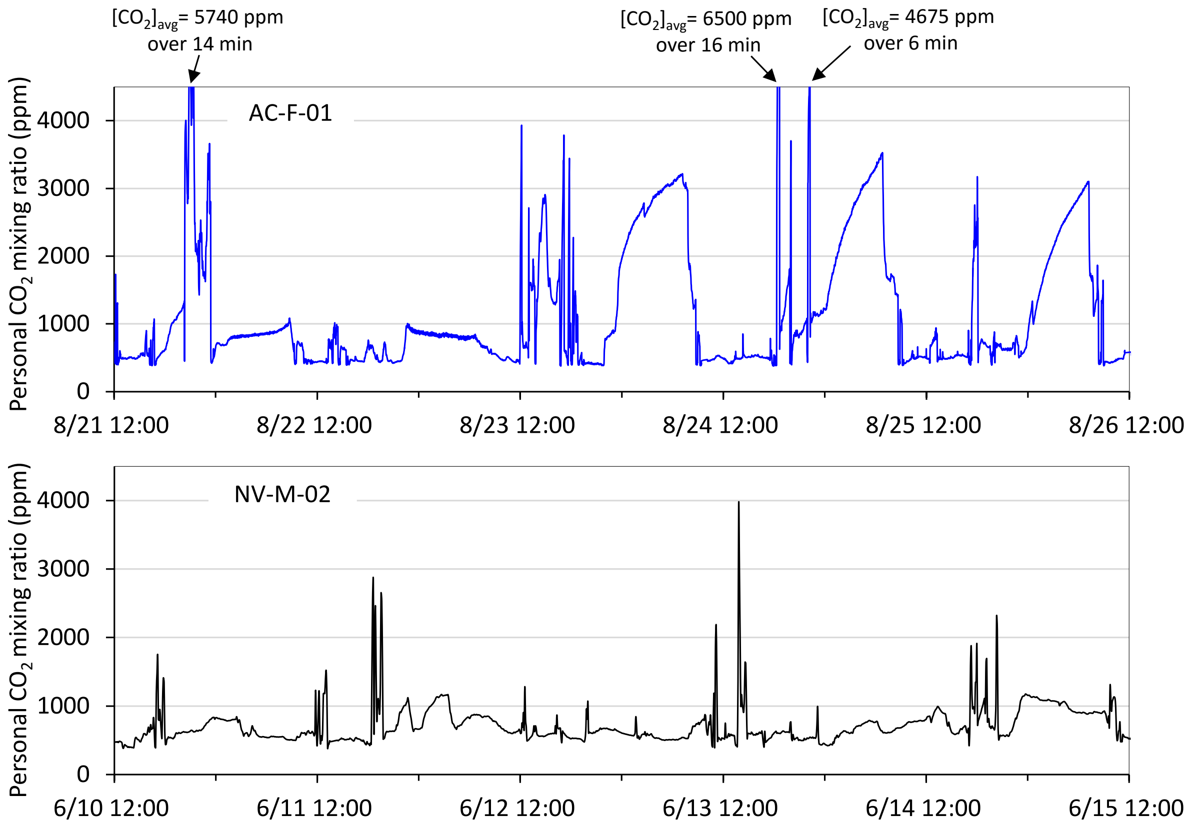

Figure 1. Example of continuous record of personal carbon dioxide mixing ratios for two participants: top panel (AC-F-01) and bottom panel (NV-M-02). Annotations to AC-F-01 correspond to elevated CO_2 in transit microenvironments.

The distributions in Table 1 reveal that all participants, regardless of sleeping microenvironment, spend a meaningful fraction of a typical day at elevated personal CO_2 levels. For AC participants, 95th percentile values (corresponding to 1.2 h/d) average 2200 ppm; all 95th percentile values are higher than 1100 ppm (700 ppm above a nominal outdoor background of 400 ppm, as shown in Appendix C of ASHRAE 62.1 and described previously). For NV and MX participants, the 95th percentile values are lower than for AC participants, averaging 1220 ppm and 1470 ppm, respectively

Cumulative distributions of 1-min personal CO_2 mixing ratios are shown in Figure 2. Exposure mixing ratios appear similar for AC and NV groups until approximately the 40th percentile, when values diverge. This is a result of AC and NV participants, spending, on average, a similar fraction of each day at or near ambient levels (< 500 ppm). The data shown in Figure 2 do not reflect any temporal patterns of exposure, that is, while AC and NV groups have similar 40th percentile exposure mixing ratios, the location or time of those exposures may differ between AC and NV groups.

Table 1. Summary of descriptive statistics of hourly averaged personal CO_2 mixing ratios (ppm) across all participants. [a,b]

Participant	Nights AC	Mean	Std. Dev.	Skew	Percentile 25	50	75	90	95
AC-M-01	7/7	860	640	1.5	450	510	1190	1950	2370
AC-F-01	6/7	1230	880	1.1	520	830	1760	2760	3010
AC-F-02	7/7	1020	720	1.1	390	780	1480	2110	2490
AC-M-02	7/7	740	240	1.8	570	710	840	950	1270
AC-M-03	7/7	830	490	3.1	550	710	840	1330	1780
AC-M-04	7/7	760	260	0.6	510	740	980	1090	1160
AC-M-05	5/6[c]	1190	1070	1.3	480	530	1890	2970	3430
NV-M-01	0/7	640	180	2.3	540	630	710	780	880
NV-M-02	0/7	710	190	1.4	570	670	830	920	1070
NV-F-01	0/7	610	310	6.1	500	540	580	770	1060
NV-M-03	1/7	660	400	2.1	440	480	660	1330	1680
NV-M-04	0/7	650	280	1.1	460	520	860	1130	1270
NV-F-02	0/4	700	340	2.4	500	570	790	1020	1390
MX-F-01	5/9	830	370	1.1	550	720	1000	1400	1580
MX-M-01	4/7	690	310	0.7	440	510	1020	1170	1210
MX-F-02	3/7[d]	1120	300	1.1	890	1080	1270	1540	1620

[a] "Nights AC" refers to the number of nights the participant spent in an air-conditioned sleeping microenvironment out of the total number of nights engaged in the study.
[b] All values of CO_2 are rounded to nearest 10 ppm.
[c] Participant AC-M-05 generally slept in a bedroom with the air-conditioner off but with windows closed, resulting in a bedroom ventilation condition more similar to the "AC" group.
[d] Participant MX-F-02 reported that the when the air-conditioner was operating, the windows were kept partially open to provide ventilation to the room.

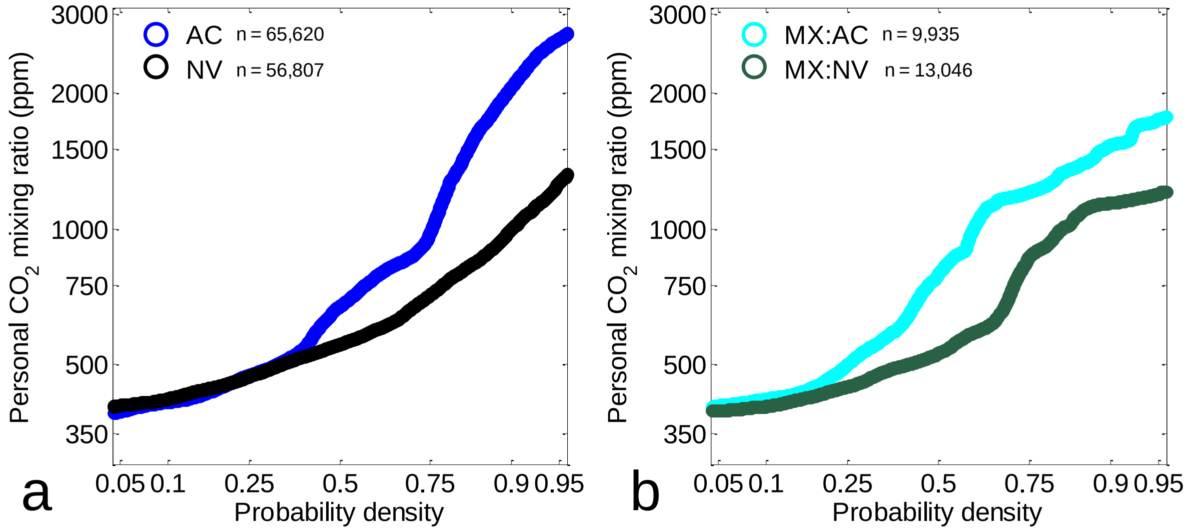

Figure 2. Grouped 1-min personal CO_2 mixing ratios for a) all participants in groups AC and NV and b) all participants in group MX split into the days MX participants slept in air conditioned bedrooms (MX:AC) and days MX participants slept in naturally ventilated bedrooms (MX:NV). Pairwise comparison of median values show differences that are statistically significant ($p < 0.0001$) for AC versus NV groups and for MX:AC versus MX:NV groups, as determined with the Wilcoxon rank sum test.

Median values of personal mixing ratios when grouped by sleeping environment are statistically significantly different when pooled for AC and NV participants ($p < 0.0001$). For the MX participants, we performed a similar analysis by subdividing the days when MX participants slept in AC conditions (MX:AC) from those sleeping in NV conditions (MX:NV), as shown in Figure 2b. Median values of personal CO_2 mixing ratios are again statistically significantly different ($p < 0.0001$) when comparing MX:AC and MX:NV. Further discussion of statistical testing of 1-min personal exposure mixing ratios can be found in the Supporting Information.

3.2. Estimates of time integrated CO_2 exposures and time activity budgets

Daily integrated CO_2 exposures are determined as the time-integral of personal CO_2 mixing ratios and calculated by summing over the day the product of a personal mixing ratio and the measurement time-step, similar in concept to the approach described by Burke et al. [28]. Average daily integrated exposures (ppm h/d) are summarized for groups of participants in Figure 3a. Time-microenvironment budgets across the five categories of microenvironment are summarized for groups of participants in Figure 3b. Apportionments of average daily integrated exposure and time-microenvironment budgets for individual participants are provided in Figures S2 and S3 of the SI. Average daily integrated exposure, when grouped by AC or NV, is significantly different ($\tilde{x}_{AC}$ = 22,800 ppm h/d vs. $\tilde{x}_{NV}$= 16,000 ppm h/d, $p <$ 0.005).

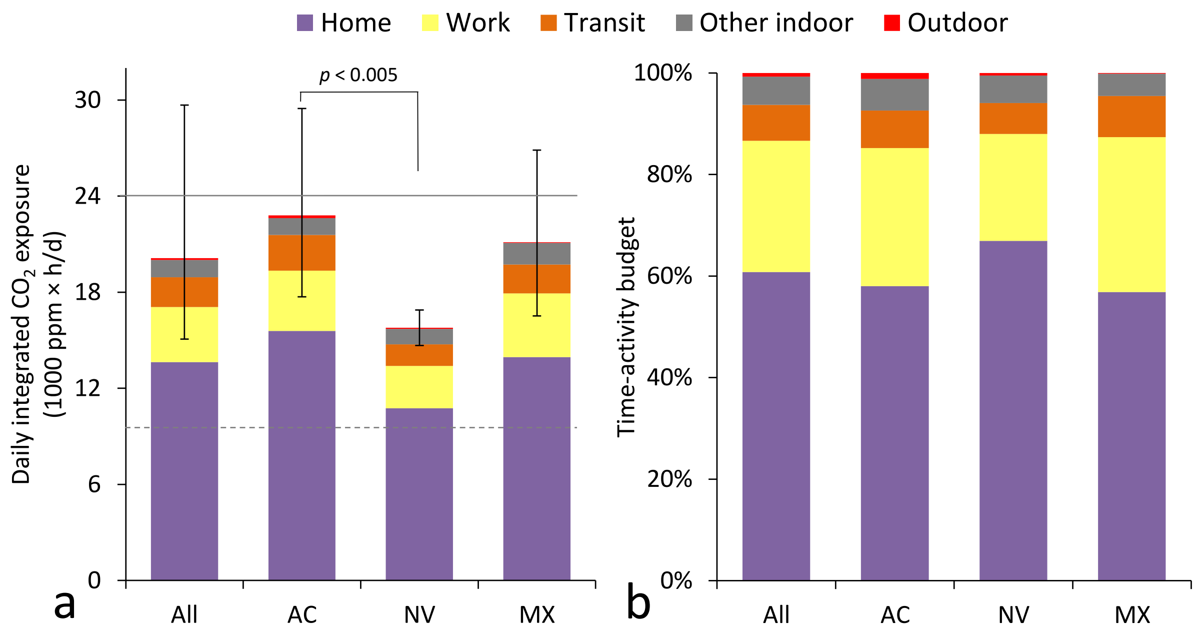

Figure 3. a) Average daily integrated CO_2 exposure and b) time-activity budget apportioned by category of microenvironment. Error bars shown in panel a) reflect the range of daily integrated exposures across individuals in the indicated group. Reported *p*-value is determined with the Wilcoxon rank sum test. Reference lines in panel a) are shown for comparison to a hypothetical equivalent daily integrated exposure from continuous exposure to an average CO_2 mixing ratio of 1000 ppm (solid) and 400 ppm (dashed) for a 24-h period.

Exposures in Figure 3 are presented in units of 1000 ppm h/d. A “baseline” hypothetical daily integrated exposure is shown on Figure 3 as a dashed line at 9,600 ppm h/d. This is the daily exposure that an individual would receive if average personal exposure mixing ratios were at outdoor ambient levels (400 ppm × 24 h/d). Analogously, the solid line at 24,000 ppm h/d represents the daily integrated exposure an individual would receive if personal exposure mixing ratios averaged 1000 ppm. This integrated mixing ratio implies periods of exposure both above and below 1000 ppm and is shown to provide context to the actual exposure data shown in Figure 3. Average daily integrated exposures across participants mostly occurred in the range 9600-24,000 ppm h/d, although as can be observed from the error bars in Figure 3, some individuals exceeded the 24,000 ppm h/d threshold (four AC participants and one MX participant; see Figure S2). Across all participants, the home microenvironment was the dominant contributor to daily integrated exposure, accounting for an average of 66% of daily integrated CO_2 exposure. The work microenvironment was the second largest contributor, averaging 18% for all participants, followed by transit (10%), 'other indoor' (5%), and 'outdoor' (0.5%).

While variability in daily integrated exposure is observed across participants in each group, on average, exposures reported Figure 3 follow the expected trend based on sleeping microenvironment ventilation mode. The AC group has the highest average daily integrated CO_2 exposure, followed by MX, and NV has the lowest. Inter-daily variability in exposures is also observed, with stronger variability for AC participants than for NV participants. An example of day-to-day variability for two illustrative participants is shown in Figure S4, where daily integrated exposures (ppm h/d) vary day-to-day by a factor of (max/min) 2.5 for AC-F-01, and only 1.4 for NV-M-02.

Exposure in any given microenvironment is the product of the average personal CO_2 mixing ratio encountered there and the duration of occupancy. Participants spent the large majority of their time in three microenvironment categories: 61% at home, 26% at work, 7% in transit, and spent only 1% outdoors. These time-activity budget values agree reasonably well with a recent modeling study of exposures to particulate matter and ozone in Singapore that reported 70%, 28%, 3.2%, and 4.5%, at home, at work, transit, and outdoors respectively [29]. Differences in daily integrated CO_2 exposures appear not to be driven by differences in behavior across groups as no statistically significant differences in comparisons of time-microenvironment-activity budgets are observed (see Table S3 in the SI). Instead, the major contributor to differences in exposure is levels of CO_2 in the home: median mixing ratios of CO_2 in AC vs. NV homes during times when the subjects were present are significantly different (883 vs. 656 ppm, $p < 0.01$).

3.3. Frequency, location, and duration of elevated exposure events

The high time resolution of CO_2 measurements, coupled with the detailed time-microenvironment budgets recorded by each subject enable an in-depth analysis of the nature of exposure 'events' when personal mixing ratios of CO_2 are elevated. In this study, we characterize elevated exposure events of the sample population in two ways. First, in §3.3.1, based on the exposure duration reported by Satish et al. [15], continuous 2.5-h rolling average personal exposure mixing ratios are determined for each subject for each day of participation. We extract the maximum 2.5-h rolling average for each day, resulting in approximately seven events for each of the 16 participants. In §3.3.2, exposure events are characterised as beginning when personal CO_2 crosses the threshold of 1000 ppm and ending when CO_2 falls below that same threshold. In both approaches, elevated exposure events are described by the average CO_2 mixing ratio during the event and cross-referenced to the time-microenvironment budget to determine the location in which the event occurred. If multiple microenvironments were occupied during an event, the location contributing the majority or plurality of the duration is reported.

Three categories of exposure events are considered: exposure level 0 (EL0) where mean personal CO_2 exceeds 1000 ppm for 0.5-2.5 h, exposure level of possible concern 1 (ELPC1) where mean personal CO_2 levels are 1000-2500 ppm for a duration exceeding 2.5 h, and exposure level of possible concern 2 (ELPC2) where CO_2 levels are above 2500 ppm for more than 2.5 h. These values are selected based on the work of Satish et al. [15]; selection of CO_2 level and duration endpoints from other studies would clearly affect the frequency of the categorized ELPC events. As our knowledge of the role of CO_2 influencing human cognition continues to develop, the original data could be re-evaluated to reflect a more detailed understanding of problematic CO_2 exposure levels. The approach of personal CO_2 monitoring also provides a means of identifying when and where problematic exposures to other air pollutants of indoor origin might occur. For example, Ramalho et al. [5] show that when average occupied CO_2 mixing ratios in dwellings increase from <750 ppm to between 1000-1500 ppm, the proportion of dwellings meeting a 2 $\mu g/m^3$ limit for benzene decreases from 60% to 46%, further decreasing to 31% when the average CO_2 level exceeds 2000 ppm. Also worth noting: because the occurrence of elevated CO_2 exposures is commonly a consequence of metabolic emissions, personal CO_2 exposure monitoring is a useful proxy for characterizing overall exposure to bioeffluents.

3.3.1. Maximum daily 2.5-h exposure mixing ratios

Statistics describing the distributions of daily maximum 2.5-h exposure mixing ratios are shown in Figure 4 for AC, NV, and MX participants. Median values of daily maximum 2.5-h mixing ratios follow expectations based on classification of sleeping microenvironment: the AC group exhibits the highest median value (1470 ppm), followed by MX (1270 ppm), and NV (1030 ppm). Pairwise comparisons of medians are significantly different for AC vs. NV ($p < 0.001$), AC vs. MX ($p < 0.05$), and MX vs. NV ($p < 0.05$). The distributions shown in Figure 4 reveal that ELPC1 is likely for all participants, representing the 18^{th}, 47^{th}, and 18^{th} percentile for groups AC, NV, and MX, respectively. Events meeting ELPC2 mixing ratio criteria (> 2500 ppm) correspond to the 70^{th} percentile of daily maximum 2.5-h averaged exposure mixing ratios for group AC; ELPC2 events are not experienced by NV and MX groups.

Daily maximum 2.5-h exposure mixing ratios are plotted as a function of time of day (plotted at the temporal midpoint of the 2.5-h period) and the corresponding classification of microenvironment in Figure 5. Across all subjects, the majority of daily maximum 2.5-h exposure mixing ratios occurred in the home (78%), followed by work (12%), transit (6%) and ‘other indoor’ locations (3%). Higher CO_2 levels in the homes of the AC group resulted in 88% of daily maximum 2.5-h exposure mixing ratios occurring in the home for this group. Elevated household levels also contributed to the relative dearth of occurrences of daily maximum exposures for AC participants in the timeframe 10:00-21:00. Data for group AC are clustered and elevated in the early morning (06:00-08:00), a result of overnight accumulation of CO_2 in an enclosed bedroom. In contrast, NV and MX participants’ daily maximum 2.5-h events occurred more uniformly throughout the day and in a broader diversity of microenvironments: 69% in the home, 13% at work, 11% in transit, and 7% in ‘other indoor’ locations.

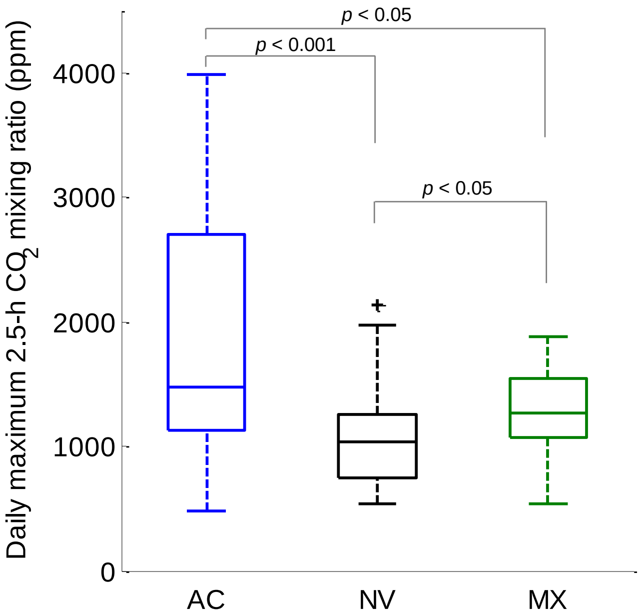

Figure 4. Distributions of daily maximum 2.5-h CO_2 mixing ratios for each category of participants: AC (n = 52), NV (n = 45), and MX (n = 26). In each box, the central mark is the median, the edges denote 25th and 75th percentiles, and whiskers extend to the data points not considered outliers while outliers are plotted individually. Median values across groups are significantly different as determined with a Wilcoxon rank sum test.

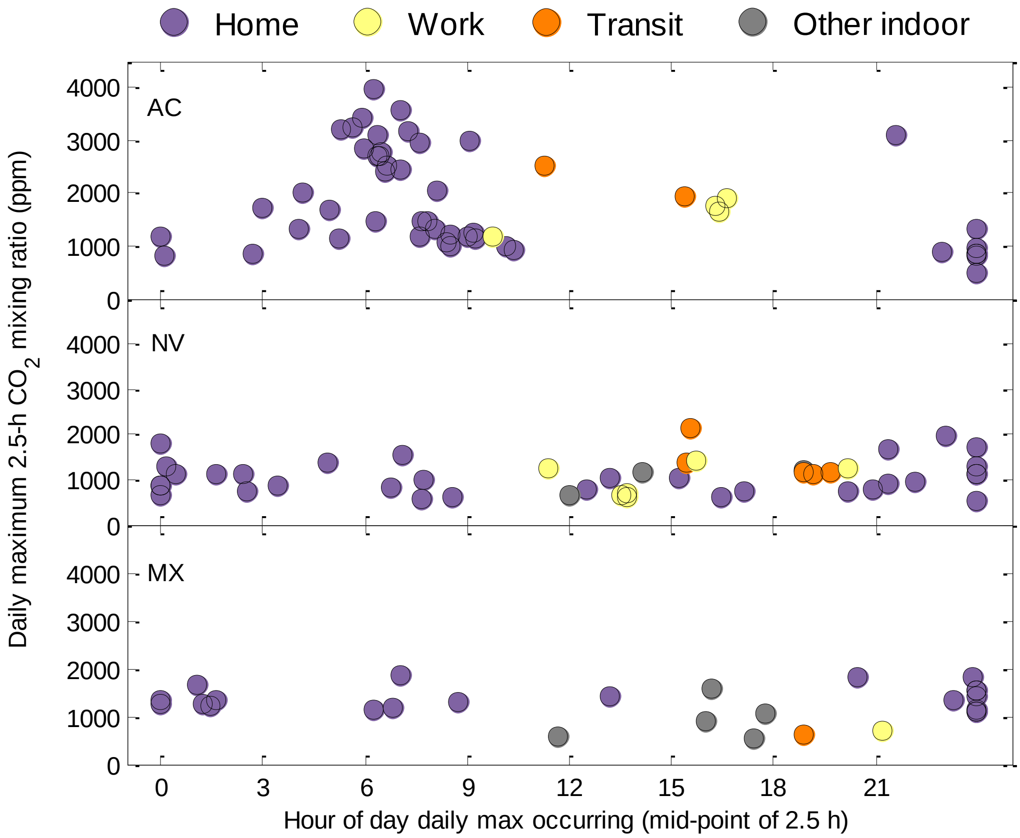

Figure 5. Diurnal distributions of daily maximum 2.5-h CO_2 exposure mixing ratios. For data points where more than one microenvironment contributed to the exposure during the 2.5-h period, the microenvironment that contributed the majority or plurality of exposure is the identified category.

3.3.2. Characterizing elevated exposure events (above 1000 ppm and for longer than 0.5 h)

A summary of the frequency and location of elevated events is provided in Table 2. These data are reported in greater detail in Tables S4-S7 of the SI, with six bins of average CO_2 level and six bins of duration. In aggregate, the sum of conditions ELPC1 and ELPC2 occur often, roughly once every second day when averaged across all participants. Events in the ELPC clusters occur more frequently for AC and MX participants than for NV subjects.

Exposure events meeting the ELPC criteria occur almost exclusively in the home microenvironment (Table 2): averaged across all participants 86% of events occurred in the home, while only 9% occurred in the work microenvironment. In this context, it is worth noting that the majority of cognitive studies of CO_2 [14–17,19] have focused on office-type microenvironments. Further studies exploring implications of elevated CO_2 exposures in homes and sleeping microenvironments, with attention to the next-day effects of CO_2 exposures during sleeping periods (e.g., [20]), are warranted.

Systematic investigations of the mechanisms of action for CO_2 alone and CO_2 plus bioeffluents to affect cognition at levels encountered in buildings are only beginning to emerge. Vehviläinen et al. [30] report that exposures to elevated CO_2 result in higher concentrations of CO_2 in body tissues, changes in heart rate variation, and increases in peripheral blood circulation in subjects. These changes coincided with increases in subjective assessments of sleepiness and incidence of headache. However, as CO_2 was not independently controlled in this study, impacts cannot be exclusively attributed to CO_2 exposure. Zhang et al. [18] report that exposures to elevated CO_2 and accompanying bioeffluents resulted in increases in diastolic blood pressure and salivary α-amylase. They propose a model that these increases are indicative of higher arousal/stress, in turn reducing human cognitive performance.

Table 2. Summary of the frequency and location for exposure events with CO_2 levels exceeding 1000 ppm for a duration of greater than 0.5 h.

	Frequency of indicated exposure event (per d) for group:			
Exposure category [a]	**All**	**AC**	**NV**	**MX**
EL0	0.75	0.64	0.71	1.0
ELPC1	0.46	0.47	0.18	0.97
ELPC2	0.05	0.12	0	0
	Fraction of ELPC events by location for group:			
Location	**All**	**AC**	**NV**	**MX**
Home	86%	85%	100%	86%
Work	9%	9%	0%	11%
Transit	3%	6%	0%	0%
Other indoor	1%	0%	0%	4%

[a] Designation of exposure categories by average CO_2 level across the duration of exposure event. EL0 is exposure level 0, for which the average CO_2 level exceeded 1000 ppm for a duration in the range 0.5-2.5 h. ELPC1 is exposure level of possible concern 1, for which the average CO_2 level was in the range 1000 - 2500 ppm for a duration exceeding 2.5 h. ELPC2 is exposure level of possible concern 2, for which the average CO_2 level exceeded 2500 ppm for a duration exceeding 2.5 h. Any ELPC event is the aggregate sum of events characterized by ELPC1 and ELPC2.

3.4. Study limitations and implications

The sample population in this study represents a limited sample from a narrow strata of the Singapore population, and is not statistically representative. While we observed the mode of bedroom ventilation to be an important determinant of personal CO_2 exposure, subsequent studies should confirm the findings of this work in larger sample populations with greater statistical power. Furthermore, there are many variables that combine to impact personal CO_2 exposures, including microenvironment volume, ventilation rates, and occupant densities that were not fully explored in this investigation. While data describing these variables are challenging to collect in real-time and in diverse populations, subsequent studies could investigate these factors via quantitative or qualitative criteria to elucidate the influence of other factors in addition to ventilation mode that are known to affect indoor CO_2 levels and personal exposures.

Notwithstanding the limitations, the data collected in this study illustrate the potential for frequent, elevated exposures to CO_2 and should motivate larger scale investigations of continuous, personal CO_2 exposures. Such investigations should expand the sample size of the present study of personal CO_2 exposures in populations residing in tropical regions as well as extend to other regions where outdoor air ventilation may be suppressed, for example, in regions with substantial building heating loads. Several long-term trends in built environments can motivate such studies. First, as airtightness of the building stock increases to help meet energy-efficiency goals, air pollutants with indoor sources, including CO_2, may accumulate to higher indoor levels. Secondly, a warming climate may induce building owners and occupants to install more ductless air-conditioning systems, as used in the AC group in this study, to improve thermal comfort. Such ductless systems do not generally include a provision for outdoor air ventilation, and therefore may substantially reduce outdoor air exchange in environments previously ventilated by open doors and windows.

Exposure monitoring in this study was conducted for a period of seven days per person, a practical upper-limit of individual participation duration based on informal subject feedback. Developments in CO_2 sensing and data logging to enable smaller device footprints, lighter weight, longer battery life, and simple, reliable data transfer would facilitate efforts to scale up exposure studies, either in individual duration or in numbers of participants.

Generally, indoor CO_2 levels are controlled through provision of adequate outdoor air ventilation for occupied spaces. Although ventilation contributes substantially to building energy consumption [31], the financial cost of providing adequate or even substantial ventilation rates (as much as 25 L/s/person) is minor compared to the typical wages of an office worker in an advanced economy [32]. Financial benefits from energy savings owing to reduced ventilation may thus be offset by elevated indoor CO_2 even if only relatively modest adverse effects on cognitive performance occur in practice. However, there is little research on the combined effects of thermal comfort and elevated exposure to CO_2 and other indoor air pollutants on human cognition. Such combined investigations are warranted given the available evidence that lower temperatures can improve work performance [33], and that temperature, ventilation mode, and air-exchange rate are likely to be interdependent. If cognitive consequences of excessive CO_2 exposure are further substantiated, opportunities for capture and/or sequestration of CO_2 in buildings, with dual-benefits for building sustainability and indoor environmental quality may become warranted to develop [34]. Several research efforts describe the application of CO_2 capture technologies to indoor environments [35,36]. Solid sorbents are beginning to be integrated into HVAC systems to remove CO_2 from recirculation air in commercial buildings [37].

4. Conclusions

Potential adverse outcomes associated with personal exposures to elevated indoor CO_2 include 1) exposures to coincident indoor-sourced air pollution for which CO_2 is an indicator and 2) possible decrements in cognitive performance. In this study, we report continuous, personal, highly time-resolved measurements of CO_2 for a cohort of 16 subjects in Singapore over week-long sampling periods. Nearly all participants spent a meaningful portion (1.2 h, or the 95th percentile) of a typical day with personal CO_2 mixing ratios elevated above 1100 ppm. We observed that the mode of bedroom ventilation was a major determinant of exposure, a result of the substantial time spent in the home (61% of each day) and the potential for CO_2 to accumulate in small, enclosed bedroom volumes. Exposure levels of possible concern (ELPC) with respect to adverse cognitive impacts occurred frequently in this sample population. Averaged across all participants, approximately one ELPC occurred every two days, with greater frequencies for the AC and MX groups than NV group. The majority (86%) of ELPC occurred in the home, followed by work (9%), transit (3%) and 'other indoor' locations (1.4%). Only the AC group experienced exposure events (ELPC2) for which substantial decrements in cognitive performance were observed in previous studies. These data inform our understanding of personal exposures to CO_2, motivating expanded studies to more thoroughly quantify personal CO_2 exposure and to inform studies of cognitive implications with data describing the extent, location, and drivers of elevated, personal CO_2 exposures.

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Supporting Information
Supplementary data related to this article can be found online.

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