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Impact of cognitive tasks on CO_2 and isoprene emissions from humans

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1. Abstract

The human body emits a wide range of chemicals, including CO_2 and isoprene. To examine the impact of cognitive tasks on human emission rates of CO_2 and isoprene, we conducted an across subjects, counterbalanced study in a controlled chamber involving 16 adults. The chamber replicated an office environment. In groups of four, participants engaged in 30 minutes each of cognitive tasks (stressed activity) and watching nature documentaries (relaxed activity). Measured biomarkers indicated higher stress levels were achieved during the stressed activity. Per-person CO_2 emission rates were greater for stressed than relaxed activity (30.3 ± 2.1 vs. 27.0 ± 1.7 g/h/p, p = 0.0044, mean ± standard deviation). Isoprene emission rates were also elevated under stressed vs. relaxed activity (154 ± 25 µg/h/p vs. 116 ± 20 µg/h/p, p = 0.041). Chamber temperature was held constant at 26.2 ± 0.49 ◦C; incidental variation in temperature did not explain variance in emission rates. Isoprene emission rates increased linearly with salivary-alpha amylase levels (r^2 = 0.6, p = 0.02). These results imply the possibility of considering cognitive tasks when determining building ventilation rates. They also present the possibility of monitoring indicators of cognitive tasks of occupants through measurement of air quality.

Keywords: human emissions; bioeffluents; stress biomarkers; CO_2; isoprene

2. Introduction

Human chemical emissions of gaseous or particle-phase compounds associated with human metabolism include carbon dioxide,[1] volatile organic compounds (VOCs),[2] and bioaerosols.[3,4] These compounds, emitted via human breath and skin, impact indoor air chemistry and contribute to degraded indoor air quality.[5,6] Human chemical emissions, often indicated by proxy measurement of carbon dioxide (CO_2), are also a driver of the need to ventilate buildings, with prominent building ventilation standards like ASHRAE 62.1 and EN

16798 based on removing odorous human chemical emissions from the indoor environment.[7] Exposure to human chemical emissions may also impact human cognition.[8,9] Studies have implicated exposure to pure elevated CO_2 as impairing human cognition,[10,11] though there also exist studies that show no effect of CO_2 itself on cognition.[12,13] However, it is consistently shown that reduced outdoor air ventilation, leading to higher indoor concentration of human chemical emissions, is responsible for observed decrements in cognition or environment perception.[14–16]

A variety of factors beyond ventilation rate and occupant density impact the level of human chemical emissions in a given indoor space. There are methods for predicting the CO_2 generation rate per-occupant,[17,18] and they consider body surface area, body composition, metabolic rate (related to type of activity), air temperature, and a respiratory quotient, which is largely a function of diet.[19] There are many studies in the literature quantifying type and quantity of emissions of endogenous and exogenous volatile organic compounds,[20–23] often in pursuit of understanding the human "volatilome" for diagnosis of disease.[24] Enabled by analytical methods that can measure VOCs with high time resolution, studies have estimated average, per-person emission rates of carbon dioxide and VOCs in a variety of field settings including classrooms,[2,25,26] a museum,[27] and a movie theater[28]; these studies have substantially expanded our knowledge of the magnitudes and type of human chemical emissions. However, comparatively fewer studies investigate factors in healthy humans that may influence human chemical emissions, including traits like age, sex, or smoking status,[29–31] and their biochemical mechanisms.[32] Recent studies, conducted in controlled chambers, measured human emissions under varying "human factors" including type of clothing worn and age, as well as environmental factors, including temperature.[33,34]

The impact of psychological factors on human chemical emissions is not well-studied or understood. In a 1975 field study of human bioeffluent emissions, Wang et al.[35] measured volatile emissions from students in a University classroom used for lectures and examinations. They found twelve organic compounds were elevated during lecture periods, and estimate per-person production rates. In that study, the researchers identified and separated examination periods as a condition where occupants experienced increased stress relative to lecture. They reported a 43% increase in CO_2 emission rate when comparing examination to lecture conditions; the authors suggest that this was due to elevated metabolism. More recently, Williams et al.[36], investigated the role of audiovisual stimuli to influence human chemical emissions using a high time-resolution proton transfer reaction - time of flight - mass spectrometer installed in the heating, ventilation and air-conditioning system of a movie theater. By annotating films with scene content labels, the researchers ascertained whether a scene label could predict variation of the measured human chemical emissions. Carbon dioxide and isoprene exhibited high correlations with scene labels, indicating emissions of these compounds may be associated with biochemical pathways induced by emotional responses to the movie scene. Isoprene emissions and variability have also been studied as a potential marker for age-appropriateness of film content,[37] and may serve as an indicator for several metabolic processes in the human body, including lipid metabolism and physiological state.[38]

Better understanding of factors influencing human chemical emission, including stimuli such as cognitive tasks and audiovisual experience, will advance our understanding of metabolic and biochemical pathways that may be initiated as a result of cognitive processes. Such knowledge could be applied to improve ventilation strategies in buildings by, for

example, tailoring ventilation strategies to the psychological experience and/or commitments of the occupants. Conversely, monitoring levels of human chemical emissions in buildings could be used to gauge occupant cognitive engagement. To date, studies advancing our knowledge of factors influencing human chemical emissions have generally occurred in uncontrolled field environments (movie theaters, classrooms, museums). We use a state-of-the-art controlled test chamber to engage sixteen subjects in an across subjects, counterbalanced study, to explore how cognitive tasks may influence human chemical emission rates of isoprene and carbon dioxide. To our knowledge, this is the first controlled study of the effect of cognitive tasks on human chemical emission rates.

3. Methods and materials

3.1 Test chamber and subjects

We conducted studies in a room-scale test chamber to measure the influence of cognitive tasks on CO_2 and isoprene emitted by humans. The test chamber is located within the Singapore-Berkeley Building Efficiency for Sustainability in the Tropics facility (Figure S1, Supporting Information). The test bed consists of four climatic chambers, each 5.6×4.3×2.7 m. Our tests were conducted in one of the four chambers mocked up as a typical office environment with desks and computer workstations. Four participants and one researcher were present during test periods, shown in Figure 1 (a) and (b). An experimental timeline, post-occupancy by test subjects, is shown in Figure 1 (c). The test chamber was served by a single-pass, mixing ventilation forced air heating, ventilation, and air-conditioning (HVAC) system that includes supply air cleaning, with MERV8 and pleated activated carbon (International Filtration, Carbon Pleated Interfold). Supply air is drawn into the chamber HVAC system from the surrounding indoor space, which is a laboratory environment. A ceiling fan with transparent blades (diameter = 1.47 m, Artemis Minka-Aire F803L-TL model,

Minka Group, USA) was kept operational during the study sessions to improve mixing of the chamber air with low distractions. Experimental and outdoor conditions during each test are shown in Table S1 and Table S2 of the Supporting Information.

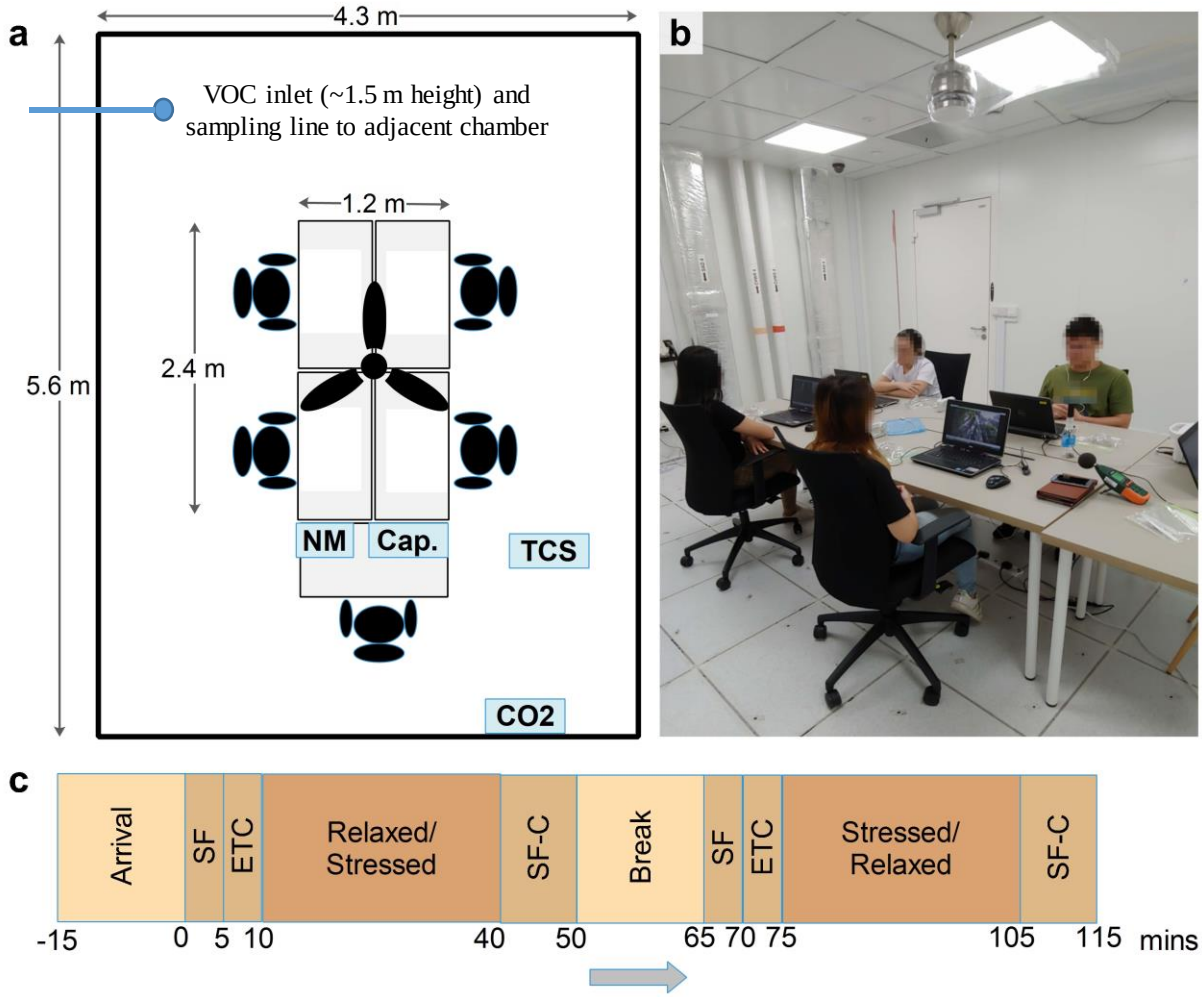

Figure 1. Overview of experimental set-up (a) and (b) and time-line of experiments post-occupancy (c). SF = subjective feedback, ETC = eye tracker calibration, SF-C = subjective feedback & capnometer, TCS = thermal comfort monitoring station, CO_2 = Wall mounted CO_2 sensor, NM = noise meter, Cap. = capnometer.

3.2 Measurement of participant stress levels

Our test protocol recruited participants to engage in an experiment where human chemical emissions were measured while engaged in two activities: a "relaxed" activity where the participants viewed a 30-minute nature documentary (two clips of nature documentaries, 15 min each, the first a "tour" of redwood forests and the second a hummingbird documentary

narrated by Sir David Attenborough) and a "stressed" activity where the participants engaged in a 30-min series of cognitive tasks. We selected five cognitive tasks covering the executive functions: working memory, inhibition, and cognitive flexibility/task switching.[39] The tasks were administered through the PEBL platform.[40] Prior studies suggest that audiovisual stimuli can alter stress state, observable by biomarkers like cortisol and salivary alpha amylase,[41,42] with viewing of stressful or soothing videos of ~30 min in length.[42,43] We include further details of cognitive tests used in the Supporting Information. In total, we tested sixteen participants in groups of four, with the order of exposure to the relaxed and stressed activities alternating over the four days of testing to achieve a counterbalanced design. Participant characteristics are shown in Table S3 of Supporting Information. The test protocol was approved by the University of California Berkeley Ethics Committee (Protocol #IRB2019-07-12403). Participants were briefed on the study in a one-hour familiarization session conducted for each participant prior to the experiments.

We measured objective and subjective indicators of occupant stress and perceptions of the test-chamber's indoor environment. Participants arrived 15 minutes prior to the start of the session and were outfitted with a heart rate sensor (Polar H10, Polar, Finland). During the session, each participant sat at a workstation with a laptop. Each laptop had an eye tracker installed (Tobii Pro Nano, Tobii Pro, Sweden) to measure pupil dilation. Upon completion of the relaxed and stressed activities, we measured salivary alpha amylase (Cocoro Meter, Nipro Corporation, Japan) and end tidal CO_2 ($etCO_2$) level (CO_2 monitor, OLG-3800, Nihon Kohden, Japan). We also collected subjective feedback concerning indoor environmental quality and mental effort; further details are provided in the Supporting Information. After the

session was complete, we measured participants' weight and body composition using a bioelectrical impedance based monitor (RD-545IM, Tanita, Japan).

3.3 Human chemical emission measurement

Human chemical emissions evaluated in this study include carbon dioxide and isoprene. Human chemical emissions were measured during a 30-min baseline period, occurring prior to the arrival of occupants, and during the two 30-min periods during occupancy, coinciding with relaxed or stressed activity (Figure 1 (c), baseline not shown). In 1-min intervals, measurements of CO_2 were made in the chamber supply air and in bulk air in the test chamber (GMW84, Vaisala, Finland, Range 0-2000 ppm, uncertainty: larger of 30 ppm and 3%). Time-integrated measurements of volatile organic compounds were made during baseline and occupied periods via sampling with sorbent tubes packed with 100 mg of Tenax TA and 180 mg of Carbograph 1, based on a method developed previously,[44] modified for target compounds, sampling times, and sampling flowrate (~130 mL/min, total sample volume = 4 L). One portable sampling pump (PCXR4, SKC, USA) drew sample air through perfluoroalkoxy (PFA) tubing connected to the room supply air duct and another sampling pump did the same from the bulk room air. Both sampling pumps had ~2 m of 0.635" OD tubing placed upstream of the sorbent cartridge. Bulk room air samples were made in duplicate using a flow splitter. Sorbent cartridges were analyzed with thermal desorption – gas chromatography – mass spectrometry (TD-GC-MS, TurboMatrix 650, PerkinElmer, USA connected to a gas chromatograph, Model 7890 A, Agilent Technologies, USA). We quantified VOCs by generating calibration curves from a calibration mixture that included isoprene and acetone. We do not report acetone levels or emission rates due to uncertainty in quantification, apparent in high variability across duplicate samples: the mean relative percent difference (RPD) across all duplicate isoprene concentrations measured was 10.9% while the

RPD for acetone duplicates was 66.8%. Since acetone is emitted by humans with high source strength, we suspect the method is not suitable for robust acetone quantification at the levels present in the chamber. Further details of the sampling and analysis method are provided in the Supporting Information and in Figure S2. To return chamber bioeffluent levels to near-background levels, during the break between the two activities the room was flushed with a fan (flowrate = 62 m^3/min, IBF300, Aman, India) providing ~10 turnovers of air during the 15-min break.

Chamber temperature and relative humidity were measured continuously in 1-min intervals (ThermCondSys 5500, Sensor, Poland) and ozone levels were monitored (Model 205, 2BTech, USA) once per day, prior to the arrival of occupants, to ensure near-zero ozone levels; ozone was consistently <2 ppb, the stated uncertainty of the instrument. Light levels at each workstation ranged between 931 and 957 lux, which is within normal ranges of typical office work environments. The chamber windows were blacked out to ensure consistent lighting levels and avoid variations due to outside lights. We determined the air-exchange rate in the chamber from measurements of air flow rates in the supply duct as well as tracer decay tests conducted following the conclusion of the experiments for the day (excepting day 1) (see Table S1). The chamber is well-mixed, confirmed via measurements of temperature and airflow gradients, as well as high r^2 (>0.99) when applying a well-mixed model to CO_2 tracer decay periods. The sorbent tubes and sampling pumps were located in a chamber adjacent to the experimental test chamber, and were not visible or audible to participants (instruments were in Chamber III, participants in Chamber IV, Figure S1 of Supporting Information).

3.4 Data analysis

3.4.1 Calculation of CO_2 emission rates

Time-series measurements of CO_2 were used to estimate emission rates of CO_2 for the baseline and 30-minute periods during which participants were engaged in either relaxed or stressed activity. We used a non-linear curve-fit applied to the analytical solution of a mass-balance equation that included air-exchange and CO_2 emissions from occupants, shown in equation 1:

$$C_{CO2,t} = \left(C_{CO2,o} + \frac{S_{CO2}}{\lambda V}\right)\left(1 - e^{-\lambda t}\right) + C_{CO2,t=0}e^{-\lambda t} \quad (1)$$

where, $C_{CO2,t}$is the concentration of CO_2 in the chamber at time *t* within the 30-min period of a "relaxed" or "stressed" activity (g m^{-3}), $C_{CO2,o}$ is the time-averaged concentration in supply air over the 30-min period (g m^{-3}), S_{CO2} is the chamber CO_2 source strength due to occupancy (g h^{-1}), λ is the air-exchange rate due to ventilation of the chamber (h^{-1}), V is the volume of the chamber (m^3), *t* is time since the start of the 30-min test period (h), and $C_{CO2,t=0}$ is the CO_2 level in the chamber at the start of the 30-min test period (g m^{-3}).

A best-fit value of S_{CO2} over the 30-min period was determined using the "fit" function in MATLAB R2019a, with the fit type specified as eq. 1. The chamber was occupied by five persons during all occupied test conditions; we report CO_2 source strengths on a per-person basis by dividing the best-fit S_{CO2} from eq. 1 by five. Note that one of the occupants was always the same researcher, present in the chamber as per IRB protocol requirement. He maintained a similar diet, exercise level, and sleep schedule during the week of testing, and endeavored to maintain similar during-test activity level across all tests.

3.4.2 Calculation of isoprene emission rates

Isoprene was measured over three 30-min periods: baseline (unoccupied), stressed and relaxed activity (both occupied by five persons). Measured isoprene levels are time-integrated over these 30-min periods. In the case of the baseline period, the chamber was previously

unoccupied and operated at constant air-exchange for ~18 hours, and we assume the chamber has reached steady-state. For unoccupied conditions we calculate the isoprene emission rate according to equation 2:

$$S_{isoprene,baseline} = \lambda\left(C_{i,chamber} - C_{i,o}\right)V \quad (2)$$

where $S_{isoprene,baseline}$ is the source or sink strength of isoprene (μg h^{-1}) under baseline conditions, λ is the air-exchange rate due to ventilation of the chamber (h^{-1}), C_i is the concentration of isoprene in chamber air (μg m^{-3}), $C_{i,o}$ is the concentration of isoprene in supply air (μg m^{-3}) and V is the volume of the chamber (m^3). Measurements of isoprene were corrected for the field blank, converted from mass to concentration using the sample volume for the specific sampling event.

For periods of occupancy, we developed a method for estimating the isoprene source strength using a mass-balance model as in equation 1, written for isoprene. Because our measurement of isoprene was time-integrated, we integrated the mass-balance model over the 30-min period of relaxed or stressed condition, in 1-min time-step, for either relaxed or stressed activity period to determine the area under the concentration-time curve. Note that the relaxed or stressed condition began 10 min following occupancy (Figure 1c). This area calculation was established as the objective function, and the source strength of isoprene over the 30-min period was varied until the modeled area is equal to that of the concentration-time area known from the time-integrated measurement, as shown in equation 3:

$$\sum_{t=10}^{40\ min} C_{i,model,t} \times \Delta t_{model} = C_{i,measured} \times \Delta t_{measured} \quad (3)$$

where $C_{i,model,t}$ is the modeled chamber concentration of isoprene, calculated in 1-min intervals using a mass-balance as shown in equation S1 of the Supporting Information (μg m^{-3}), Δt_{model} is the time resolution of the discrete integration of the model concentration-time

curve (1 min), $C_{i,measured}$ is the time-integrated measurement of isoprene in the chamber, taken as the average of duplicate measurements of isoprene and corrected for field blank (µg m^{-3}), and $\Delta t_{measured}$ is the time duration of the measured isoprene level in the chamber (30-min).

A detailed example of the method employed for determining isoprene emission rates is provided in the supporting information in Table S4, with a graphical presentation Figure S3, present in the Supporting Information.

3.4.3 Statistical tests

As shown in Table S1 of the Supporting Information, we conducted tests over four days where CO_2 and isoprene source or sink strengths were measured for baseline, relaxed, and stressed activity, with order of relaxed and stressed activity alternating each day. To determine if the test conditions resulted in statistically significant changes in CO_2 or isoprene source or sink strength in the chamber, we used analysis of variance (ANOVA) across three groups (baseline, relaxed, stressed), similar to a method described previously.[45] Briefly, if the three-group comparison resulted in $\alpha < 0.05$, we then made direct comparisons across groups (i.e., baseline vs. relaxed, baseline vs. stressed, and relaxed vs. stressed) using Tukey's honest significant difference test (Tukey test). We included the baseline (unoccupied) conditions in ANOVA to evaluate whether source or sink strengths during occupied conditions were significantly different from unoccupied conditions. All statistical analyses were performed using MATLAB 2019a.

Measurements of biomarkers (HRV, SAA, pupil dilation, and end tidal CO_2) of stress were analyzed using either parametric (t-tests) or non-parametric tests (Wilcoxon rank sum tests) depending on if the data was normally distributed or not. Significance level was taken at

0.05 except for the HRV parameters, where, due to the large number of comparisons, Benjamini–Hochberg procedure (false discovery rate taken as 10%) was used. All comparisons were paired and two tailed.

Data and analysis scripts/functions are publicly available and can be downloaded from the Dryad repository: https://doi.org/10.5061/dryad.gb5mkkwmk.

4. Results and Discussion

4.1 Objective and subjective indicators of occupant stress

Objective measured stress biomarkers shown in Figure 2 indicate that the cognitive tests (stressed activity) induced a state of occupant stress compared to watching nature documentaries (relaxed activity). While most of the physiological parameters examined should increase with stress levels, the inverse is true for some parameters, specifically the Mean RR interval (the interval between heart beats) and fraction of power of heart beats in the lower frequency bands. To create a simpler visual presentation, we present these parameters multiplied by -1 for plots. This ensures that all the plotted parameters are low when stress is low and are high when stress is high.

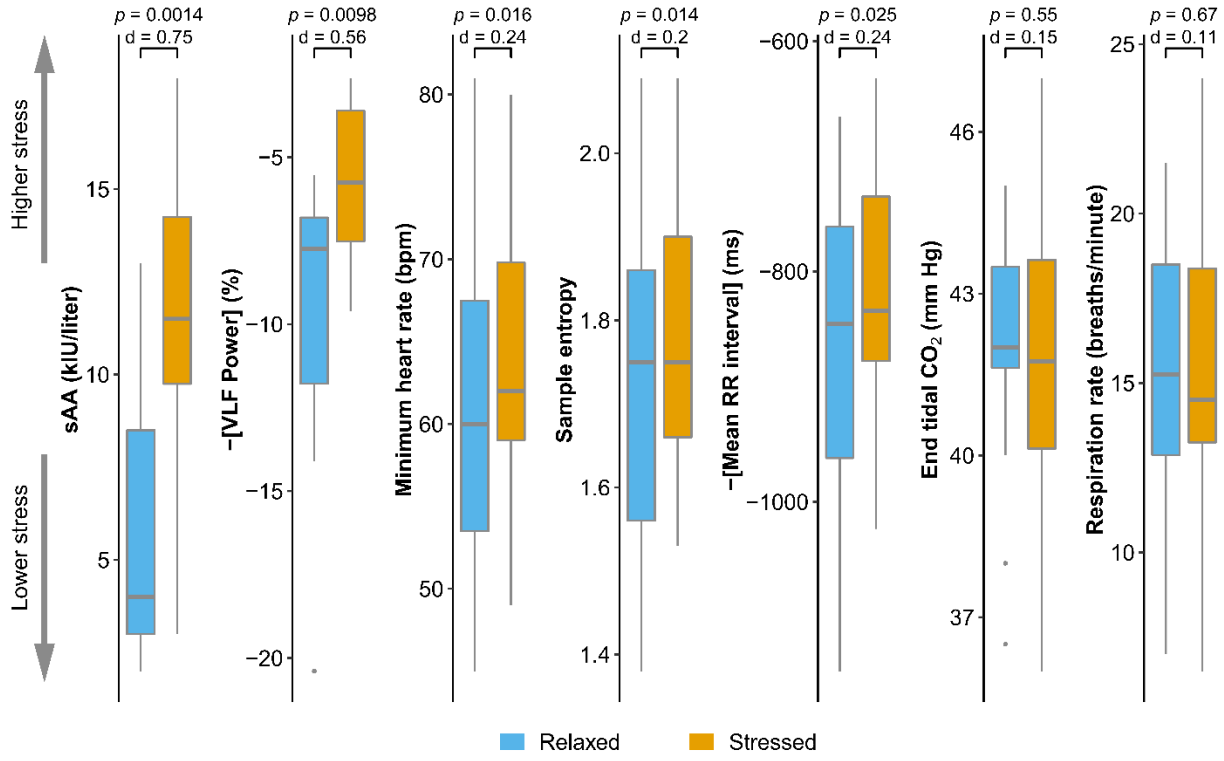

Figure 2. End tidal CO_2, salivary alpha amylase (sAA), respiration rate and summary of key indicators of heart rate variability data: fraction of power in the very low frequency (VLF) band, minimum heart rate, sample entropy and mean of the RR interval (interval between heart beats) measured in the relaxed and stressed activity.

Salivary alpha amylase levels are elevated during stressed activity compared to relaxed activity (*p*-value = 0.0014, d = 0.75, a medium to large size effect). Salivary alpha amylase levels are known to follow a diurnal course, and prior studies recommend controlling for time of day;[46] our design had occupants entering the chamber at ~14:00 (Table S1) each day and the relaxed/stressed activities occurred over a period of ~120 min. Nevertheless, the study was counterbalanced, which will address the potential for confounding due to diurnal changes in salivary alpha amylase that may have occurred over this 120-min period, though we expect this effect to be small based on the diurnal profiles presented by Nater et al.[46]. We analyzed 51 parameters of heart rate variability; as noted from previous studies,[47] not all parameters are expected to yield a significant difference when stress is imposed on people. Note that one participant's data was lost on day 3; subsequent analysis used data from fifteen participants. In

Figure 2 are four metrics showing differences due to external stress, evident due to statistically significant differences from the relaxed to stressed activity in the nonparametric statistical tests and Cohen's D. The VLF power is the percentage of power in the Very Low Frequency band ($0.003 \leq f < 0.04$ Hz) of the frequency domain transformation (Fast Fourier Transform) of the time domain RR (interval between heart beats) interval data ($p = 0.0098$, $d = 0.56$, a medium size effect). The degree of heart rate variability (HRV) in terms of VLF power is expected to reduce as activity intensity increases,[48] an effect observed in our data. The minimum heart rate was lower during relaxed activity ($p = 0.016$, $d = 0.24$, a small size effect). Sample entropy, which indicates randomness of the data (lack of regularity in heart rate), was higher for the stressed activity ($p=0.014$, $d = 0.2$, a small size effect). Finally, the mean RR was significantly higher during the relaxed activity, indicating greater heart rate variability and hence less stress ($p = 0.025$, $d = 0.2$, a small size effect). Results of subjective feedback assessments (sleepiness, thermal preference) and pupil dilation data are provided in the Supporting Information. Mean and median pupil size were significantly larger during stressed than relaxed activity, shown in Figure S4 of the Supporting Information, another objective indicator associated with stress.[49] Collectively, these objective indicators demonstrate that cognitive testing vs. nature documentary was effective in causing a relative increase in participants' stress.

The end-tidal CO_2 ($etCO_2$) and respiration rate data did not show significant difference between relaxed and stressed activity periods ($p > 0.7$), determined using a t-test since distributions were normal. This finding was somewhat unexpected given that emission rates of CO_2 calculated from chamber air during occupied periods (Section 4.3) are elevated during stressed compared to relaxed activity. Importantly, $etCO_2$ was measured post-testing, over a

period of ~10 minutes following completion of relaxed or stressed activity while bioeffluent CO_2 emission rates are calculated with data collected during the 30-min of relaxed or stressed activity. No significant changes in $etCO_2$ implies body CO_2 levels were similar at the end of the two periods. As respiration rates are also similar, in conjunction with $etCO_2$ values, this indicates that the body is able to effectively ventilate the additional CO_2 being generated during the test period, possibly through breathing in greater volumes of air.

4.2 Human emissions of CO_2 and isoprene

Representative experimental results from one of the four days of controlled testing of human chemical emissions are shown in Figure 3. An abbreviated experimental protocol is shown: measurement of levels of chemical emissions occurred during a baseline (unoccupied) period and two subsequent occupied periods. Also shown in Figure 3 is example TD-GC-MS data for isoprene, which is time-integrated. The x-direction bars on the plot indicate the period of time over which the sample was taken while the y-direction error bars show the range across duplicate samples taken in chamber air.

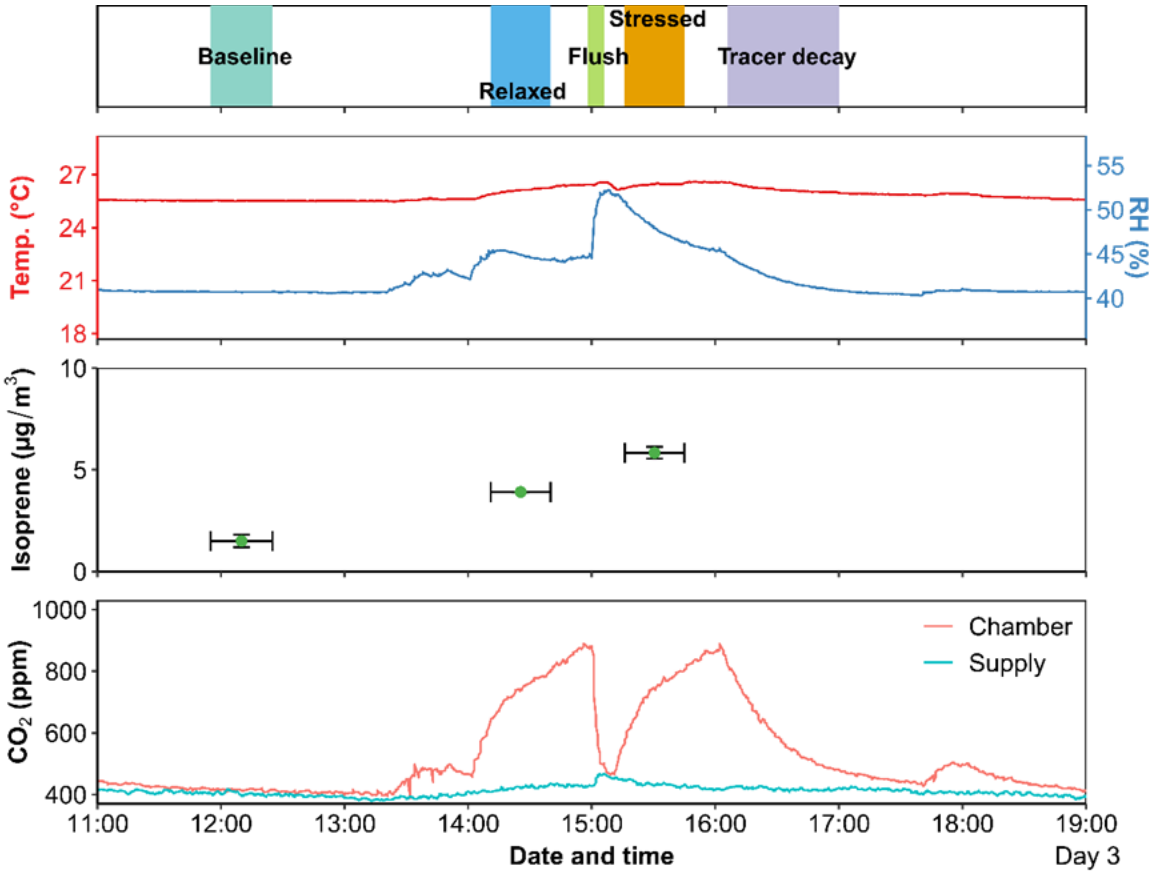

Figure 3. Representative experimental results for chamber dry-bulb air temperature, relative humidity, isoprene levels during baseline and occupied periods and time-series measurements of carbon dioxide.

The effect of occupancy on CO_2 levels and the flushing of the chamber in between the two occupied periods is apparent in Figure 3, the flushing due to a temporarily placed fan that evacuated air from the chamber, replacing with ambient laboratory air and reducing to near-background levels of CO_2 prior to the initiation of the second test activity. The test chamber CO_2 level was monitored and observable in real-time, and was used to ensure the second test activity of each day occurred with initial CO_2 conditions similar to that of the first test. The short duration for flushing the chamber between occupied activities is one reason for limiting analysis of chemical emissions to CO_2 and isoprene, both compounds that are predominantly present in the gas-phase. There existed no aqueous water present in the chamber and surfaces were impermeable, hard surfaces. CO_2 sorption to surfaces indoors is typically taken as

negligible. Isoprene is considered a very volatile organic compound, or VVOC, with vapor pressure 7.2×10^4 Pa.[50] A recently published model of partitioning of organics indoors shows isoprene is expected to be predominantly present in the gas-phase across a range of indoor surface reservoir conditions, though experimentally determined response times indicate dynamic partitioning does occur.[51] We expect that error introduced for isoprene from surface partitioning is likely small, based on calculations of emission rates into the chamber under unoccupied conditions vs. occupied conditions (13 µg/h vs. 675 µg/h). Furthermore, uncertainty due to the impact of isoprene surface interactions on comparisons of emission magnitudes across stressed and relaxed activities is addressed, at least partially, in the counterbalanced design.

We calculated source strengths during baseline, relaxed and stressed activities for CO_2 and isoprene. Results of the source strength calculation are shown in Table 1 for isoprene and CO_2, which met the three-group comparison ANOVA criteria of $\alpha < 0.05$.

Table 1. Chamber conditions and magnitudes of carbon dioxide and isoprene emissions across baseline, relaxed, and stressed activities.

Day		Temp	RH	O_3	CO_2 inlet*	CO_2 chamber*	Isoprene inlet%	Isoprene chamber%		CO_2 emission rate	Isoprene emission rate
		◦C	%	ppb	ppm	ppm	µg/m³	µg/m³		g/h/p	µg/h/p
								rep1	rep2		
1	Baseline#	26.9	38	<2	415	420	2.1	1.5	2.1	0.32	8.03
	Relaxed	26.9	43		441	784	2.4	4.9	5.4	27.8	144.2
	Stressed	27.1	48		467	768	2.8	5.6	5.7	30.5	154.9
2	Baseline#	25.6	41	<2	411	435	1.8	1.9	1.9	0.65	-2.72
	Stressed	26.2	46		406	774	1.9	4.8	3.9	32.3	119.3
	Relaxed	26.5	47		441	722	1.9	4.5	4.0	27.7	115.6
3	Baseline#	25.5	41	<2	403	415	1.6	1.7	1.4	0.58	2.84
	Relaxed	26.1	45		421	733	2.0	3.9	3.9	25.4	102.5
	Stressed	26.4	48		435	721	2.6	5.7	6.0	28.9	176.4
4	Baseline#	25.5	40	<2	403	418	2.2	2.5	2.2	0.69	2.75
	Stressed	26.2	45		420	780	2.6	5.8	6.1	29.7	165.9
	Relaxed	26.5	47		430	712	2.1	4.1	4.5	27.3	100.0

*CO_2 levels were measured in 1-min interval in the inlet and room, averages over the 30-min test periods are reported here for brevity. See Figure S5 for full time-series analysis of CO_2 data.
baseline CO_2 and isoprene emission rates are presented on a per-person normalized basis, though no humans were present in the chamber during baseline conditions, to enable comparisons to the occupied (relaxed and stressed activities). All per-person normalizations were made by dividing the total emission rate into the chamber by five, four participants plus the experimenter.
% isoprene levels were corrected for field blanks in calculations of isoprene source strength (field blanks were 0.27, 0.27, 0.27, and 0.45 μg/m^3 on days, 1, 2, 3 and 4, respectively)

Emission rates calculated from mass-balance models during accumulation of CO_2 in the test chamber (28.7 g/h/p averaged across all participants and conditions) are in agreement with prior estimates of per-person CO_2 generation rates. Values reported here are consistent with estimates for adults in residences and bedrooms, and slightly lower than values typically assumed for office environments.[1,18] Per-person CO_2 emission rates reported here are similar to those reported by Stönner et al.[28] for adults (30 g/h/p) and Wang[35] for students (27 g/h/p during lecture, 38 g/h/p during exam). Our results are somewhat higher than the average reported by Tang et al. [2] in an occupied college classroom (21 g/h/p). Our per-person emission rate for isoprene is 135 μg/h/p across all occupied conditions (132 μg/h/p if the aforementioned baseline emission is accounted for), are in general agreement with prior studies. Three independent prior studies reporting per-person isoprene emission rates for adults are 105, 162, and 166 μg/h/p.[2,27,28] Our estimate for per-person isoprene emission rate is near the average of these prior studies.

4.3 Impact of cognitive tasks on isoprene and CO_2 emission rate

Full results across the four days of repeated testing are shown in Figure 4 for carbon dioxide and isoprene. Per-person CO_2 emission rates were greater for stressed than relaxed conditions (30.3 ± 2.1 vs. 27.0 ± 1.7 g/h/p, p = 0.0044, mean ± standard deviation) and

isoprene emission rates were also elevated under stressed vs. relaxed conditions (154 ± 25 µg/h/p vs. 116 ± 20 µg/h/p, $p = 0.041$)

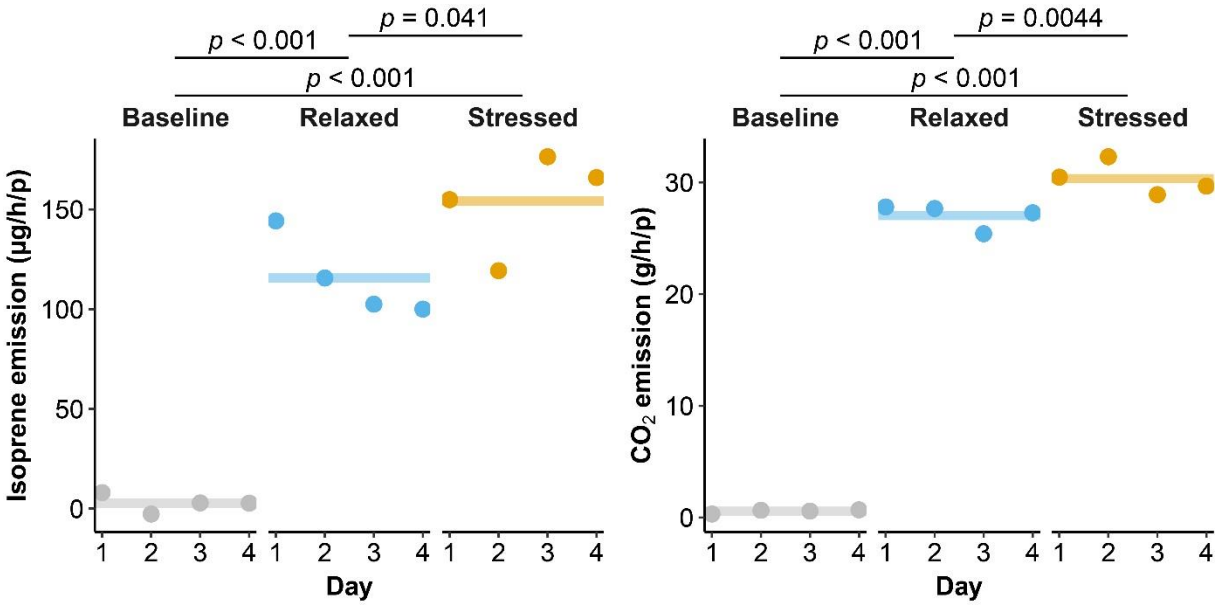

Figure 4. Per-person emission rates of carbon dioxide and isoprene. The horizontal bar is the average across all days of testing, each dot shows the measurement for a particular day. Values of emission rates shown for occupied condition emissions (i.e., relaxed and stressed activities) do not subtract unoccupied (baseline) estimates of emissions.

Shown in Figure 4 is that carbon dioxide emission rates are consistently higher (12%) during stressed activity than relaxed activity for all repeated trials of the study; regressions used to estimate emission rates from dynamic CO_2 data each day of testing are shown in Figure S5 of the Supporting Information. Because the study was counterbalanced, consistently elevated CO_2 emissions imply that it is the stressed activity that caused the elevated CO_2 emission, rather than the order of tests conducted. Inspection of isoprene emission rates also reveals elevated emission rate under stressed activity; isoprene emissions were 33% higher than the relaxed activity. The finding of greater relative increases in isoprene vs. CO_2 emission rate is interesting given that demand-controlled ventilation systems are typically based on CO_2 levels; results here indicate isoprene may be a useful additional parameter for designing building ventilation systems with sensitivity to cognitive tasks.

As presented in Section 4.1, we measured objective indicators of occupant stress, including biomarkers of salivary alpha amylase and metrics associated with participant's heart rate variability and pupil dilation. We also measured chamber temperature and relative humidity conditions. To explore the utility of these objective biomarkers and environmental conditions as possible predictors of the observed elevation in bioeffluent emission rates, we performed regression to observe relationships to variance and change in CO_2 and isoprene emission rates. Full results of this analysis are shown in Figure S6 of Supporting Information for biomarkers observed to be statistically significantly different between stressed and relaxed activity and temperature and RH. Note that since bioeffluent emission rates are the average per-person emission for individuals present in the chamber, we regress these emission rates against biomarkers averaged for those same individuals. The sAA data here includes that of the experimenter who was inside the chamber, was not subject to the same research protocol, but nevertheless contributed to CO_2 and isoprene emissions. However, since the experimenter did not wear an HRV monitor, the HRV related markers do not have his information.

We found that of biomarkers measured, only subject salivary alpha amylase (Figure 5) is significantly related to isoprene emission rates (p-value = 0.02), and that a substantial portion of the variance in observed isoprene emission rates is explained ($R^2 = 0.60$). This result is interesting considering a prior study identifies isoprene as a marker associated with emotional stress arising from moviegoers' interaction with audiovisual stimuli during films.[36] Stönner et al.[37] suggest that isoprene emission and variability in isoprene level could be useful as an objective indicator for recommending age-appropriateness of different films. Isoprene is thought to be generated during cholesterolgenesis[52] and some studies suggest measurement of breath isoprene levels may be useful as a non-invasive method for assessing blood cholesterol

levels.[53] Williams et al.[36] suggest isoprene production is related to cortisol production via the cholesterol production pathway; this link appears based on their empirical findings, as no biological pathway is mentioned. If isoprene and cortisol production are related, this may explain the observed correlation here between isoprene emission and salivary alpha amylase, since studies show responses of both salivary alpha amylase and cortisol follow stressful events with salivary alpha amylase levels responding more rapidly than cortisol levels.[54] However, it should be cautioned that linking the production of an endogenously generated compound like isoprene to external stimuli is challenging, as per-person differences in isoprene production as measured by human breath may result from interactions between the metabolic pathways with the circulatory (heart rate) and pulmonary systems (breathing rate).[53]

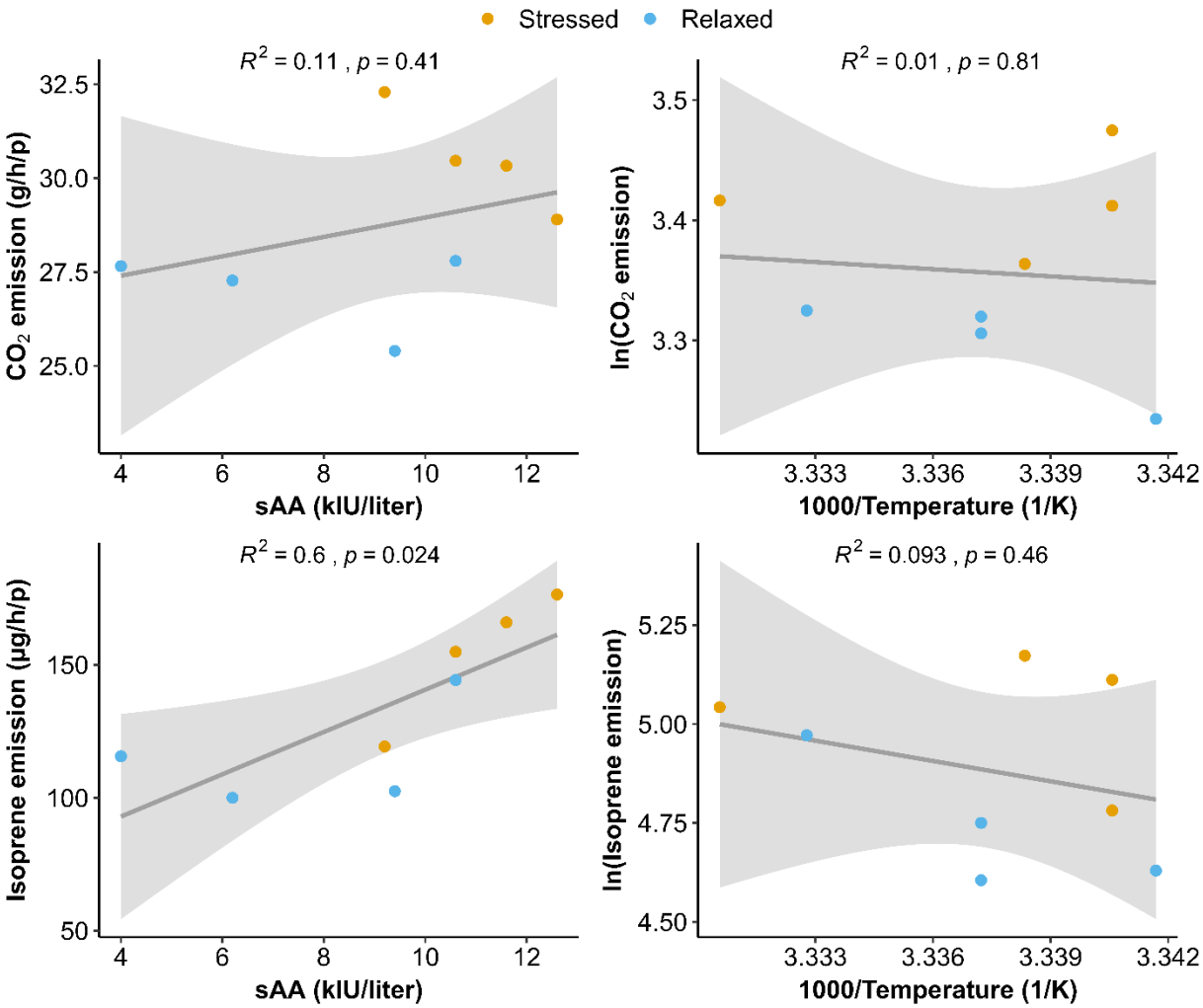

Figure 5. Regression of isoprene and CO_2 emission rates vs. salivary alpha amylase and chamber air temperature. Shown above each plot are the r-squared and *p*-value associated with the linear regression slope. Curves around each linear regression are the 95% confidence interval. Note that the target chamber temperature was constant at 26 ◦C; the above plot investigates whether incidental variation in temperature is related to observed changes in in emission rates of isoprene and CO_2.

Changes in salivary alpha amylase were not significantly associated with changes in per-person CO_2 production rates. It is possible that CO_2 production was elevated due to temporary increase in metabolism during the stressed activity, but was not correlated with endogenous production of salivary alpha amylase. Other biomarkers measured associated with heart rate did not appear to have statistically significant correlation with changes in isoprene or CO_2 emission rate or explain variance in observed CO_2 or isoprene emission rates. From

Figure S6 in the Supporting Information, we do observe that the relation between isoprene emission rates and three of the four HRV related markers are in the expected directions, that is, human chemical emission of isoprene increases with increases in stress markers, though not statistically significantly.

Prior studies have explored the relationship between cognitive tests and other factors on human VOC emissions. Santos et al.[55], with a study design that employed a cognitive test to elicit stress in a cohort of 14 individuals, identified possible VOCs that are indicative of stress. Their study identified benzaldehyde, ethyl acetate, and 2-propanol as indicators of stress, compounds we found in the chamber at measurable levels in TD-GC-MS samples. Santos et al.[55] employed a prototype sampling device and analysis via GC-IMS. The GC-IMS method is noted as subject to uncertainty in identification of compounds. We do not here speculate concerning the possible relationship of these compounds to cognitive tasks, since these compounds were not present in our calibration mixture.

A recent study explored the relationship between temperature and human chemical emissions, finding increases in ammonia emissions from humans with increasing temperature.[34] Our study design aimed to hold temperature constant; temperature averaged 26.2 ± 0.49 ◦C (mean ± standard deviation). Given the known association between air temperature and human CO_2 emissions[18] and recent observation of temperature dependence on ammonia emissions, Figure 5 includes a regression of CO_2 and isoprene emission rates as a function of chamber air temperature, plotted as the natural log of emission rate vs. the inverse of temperature. While slopes are in the expected direction (i.e., a negative slope, implying higher temperature yields higher emission rate), the regression statistics indicate the

468 relationship is not significant. A linear regression of emission rate vs. relative humidity also
469 resulted in no significant correlation (Figure S6 of Supporting Information).
470 In this study, we limit our analysis to isoprene and CO_2 as robust quantification of
471 other VOCs is limited by the calibration standard and TD-GC-MS method applied to this
472 chamber study. One further limitation is that our dynamic analysis of isoprene emission rates
473 was constrained by time-integrated sampling in the chamber and inlet air. We believe the
474 method for estimating per-person isoprene emission rates developed is robust; empty chamber
475 isoprene emission rates were near zero while occupied chamber emission rates are in close
476 agreement with prior estimates. However, there exists uncertainty associated with the initial
477 conditions required for the solution, that is, the level of isoprene was assumed to be that of the
478 baseline conditions at the start of an occupied chamber experiment. Sensitivity analyses
479 indicate the solution is relatively insensitive to this input; model runs show a 20% change to
480 the initial condition in the chamber results in a ~5% change in the calculated isoprene
481 emission rate. As discussed, surface adsorption/desorption of isoprene may impact the second
482 occupied test of each day, though we believe the effect is likely small based on the high
483 volatility of isoprene, our observation of near-zero isoprene emission rates in the unoccupied
484 (baseline) test chamber, and counterbalanced design.
485 Subsequent chamber studies should employ additional analytical instrumentation, e.g.,
486 real-time chemical ionization mass spectrometry, to further elucidate the chemical complexity
487 of human chemical emissions impacted by cognitive task. These instruments would greatly
488 expand the classes of compounds that can be measured and improve robustness of source
489 strength calculations with dynamic measurements. Future studies should also be conducted
490 on larger sample populations, with different cognitive tasks, and examine potential for

compounding interactions with other indoor environmental quality variables, e.g., varying temperature and RH condition.

Supporting Information

The Supporting Information contains additional information concerning the test bed facility, experimental conditions, details of cognitive tests used for the "stressed" activity, characteristics of participants, and additional details of indicators of participant stress and feedback. Further information is provided concerning the measurement of isoprene and resulting calculation of isoprene emission rates. Additional data is reported from the subjective feedback and pupillometry, analysis of CO_2 regressions to determine CO_2 emission rates, and full results of regression of CO_2 and isoprene emission rates with stress indicators and chamber temperature and RH conditions.

Author Contributions

ETG led study design, analysis, and writing, AM contributed to study design, analysis and writing, JL contributed to study design, analysis and data visualization, SS contributed to study design, writing, and editing, AL contributed to data analysis and editing. All authors have given approval to the final version of the manuscript.

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