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1 Impact of cognitive tasks on CO₂ and isoprene 2 emissions from humans

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11 **1. Abstract**

12 The human body emits a wide range of chemicals, including CO₂ and isoprene. To examine
13 the impact of cognitive tasks on human emission rates of CO₂ and isoprene, we conducted an
14 across subjects, counterbalanced study in a controlled chamber involving 16 adults. The
15 chamber replicated an office environment. In groups of four, participants engaged in 30
16 minutes each of cognitive tasks (stressed activity) and watching nature documentaries (relaxed
17 activity). Measured biomarkers indicated higher stress levels were achieved during the
18 stressed activity. Per-person CO₂ emission rates were greater for stressed than relaxed activity
19 (30.3 ± 2.1 vs. 27.0 ± 1.7 g/h/p, $p = 0.0044$, mean \pm standard deviation). Isoprene emission
20 rates were also elevated under stressed vs. relaxed activity (154 ± 25 μ g/h/p vs. 116 ± 20
21 μ g/h/p, $p = 0.041$). Chamber temperature was held constant at 26.2 ± 0.49 °C; incidental
22 variation in temperature did not explain variance in emission rates. Isoprene emission rates
23 increased linearly with salivary-alpha amylase levels ($r^2 = 0.6$, $p = 0.02$). These results imply
24 the possibility of considering cognitive tasks when determining building ventilation rates.
25 They also present the possibility of monitoring indicators of cognitive tasks of occupants
26 through measurement of air quality.

27 **Keywords:** human emissions; bioeffluents; stress biomarkers; CO₂; isoprene

28 **2. Introduction**

29 Human chemical emissions of gaseous or particle-phase compounds associated with
30 human metabolism include carbon dioxide,¹ volatile organic compounds (VOCs),² and
31 bioaerosols.^{3,4} These compounds, emitted via human breath and skin, impact indoor air
32 chemistry and contribute to degraded indoor air quality.^{5,6} Human chemical emissions, often
33 indicated by proxy measurement of carbon dioxide (CO₂), are also a driver of the need to
34 ventilate buildings, with prominent building ventilation standards like ASHRAE 62.1 and EN

35 16798 based on removing odorous human chemical emissions from the indoor environment.⁷
36 Exposure to human chemical emissions may also impact human cognition.^{8,9} Studies have
37 implicated exposure to pure elevated CO₂ as impairing human cognition,^{10,11} though there also
38 exist studies that show no effect of CO₂ itself on cognition.^{12,13} However, it is consistently
39 shown that reduced outdoor air ventilation, leading to higher indoor concentration of human
40 chemical emissions, is responsible for observed decrements in cognition or environment
41 perception.¹⁴⁻¹⁶

42 A variety of factors beyond ventilation rate and occupant density impact the level of
43 human chemical emissions in a given indoor space. There are methods for predicting the CO₂
44 generation rate per-occupant,^{17,18} and they consider body surface area, body composition,
45 metabolic rate (related to type of activity), air temperature, and a respiratory quotient, which is
46 largely a function of diet.¹⁹ There are many studies in the literature quantifying type and
47 quantity of emissions of endogenous and exogenous volatile organic compounds,²⁰⁻²³ often in
48 pursuit of understanding the human “volatilome” for diagnosis of disease.²⁴ Enabled by
49 analytical methods that can measure VOCs with high time resolution, studies have estimated
50 average, per-person emission rates of carbon dioxide and VOCs in a variety of field settings
51 including classrooms,^{2,25,26} a museum,²⁷ and a movie theater²⁸; these studies have substantially
52 expanded our knowledge of the magnitudes and type of human chemical emissions. However,
53 comparatively fewer studies investigate factors in healthy humans that may influence human
54 chemical emissions, including traits like age, sex, or smoking status,²⁹⁻³¹ and their
55 biochemical mechanisms.³² Recent studies, conducted in controlled chambers, measured
56 human emissions under varying “human factors” including type of clothing worn and age, as
57 well as environmental factors, including temperature.^{33,34}

58 The impact of psychological factors on human chemical emissions is not well-studied
59 or understood. In a 1975 field study of human bioeffluent emissions, Wang et al.³⁵ measured
60 volatile emissions from students in a University classroom used for lectures and examinations.
61 They found twelve organic compounds were elevated during lecture periods, and estimate per-
62 person production rates. In that study, the researchers identified and separated examination
63 periods as a condition where occupants experienced increased stress relative to lecture. They
64 reported a 43% increase in CO₂ emission rate when comparing examination to lecture
65 conditions; the authors suggest that this was due to elevated metabolism. More recently,
66 Williams et al.³⁶, investigated the role of audiovisual stimuli to influence human chemical
67 emissions using a high time-resolution proton transfer reaction - time of flight - mass
68 spectrometer installed in the heating, ventilation and air-conditioning system of a movie
69 theater. By annotating films with scene content labels, the researchers ascertained whether a
70 scene label could predict variation of the measured human chemical emissions. Carbon
71 dioxide and isoprene exhibited high correlations with scene labels, indicating emissions of
72 these compounds may be associated with biochemical pathways induced by emotional
73 responses to the movie scene. Isoprene emissions and variability have also been studied as a
74 potential marker for age-appropriateness of film content,³⁷ and may serve as an indicator for
75 several metabolic processes in the human body, including lipid metabolism and physiological
76 state.³⁸

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

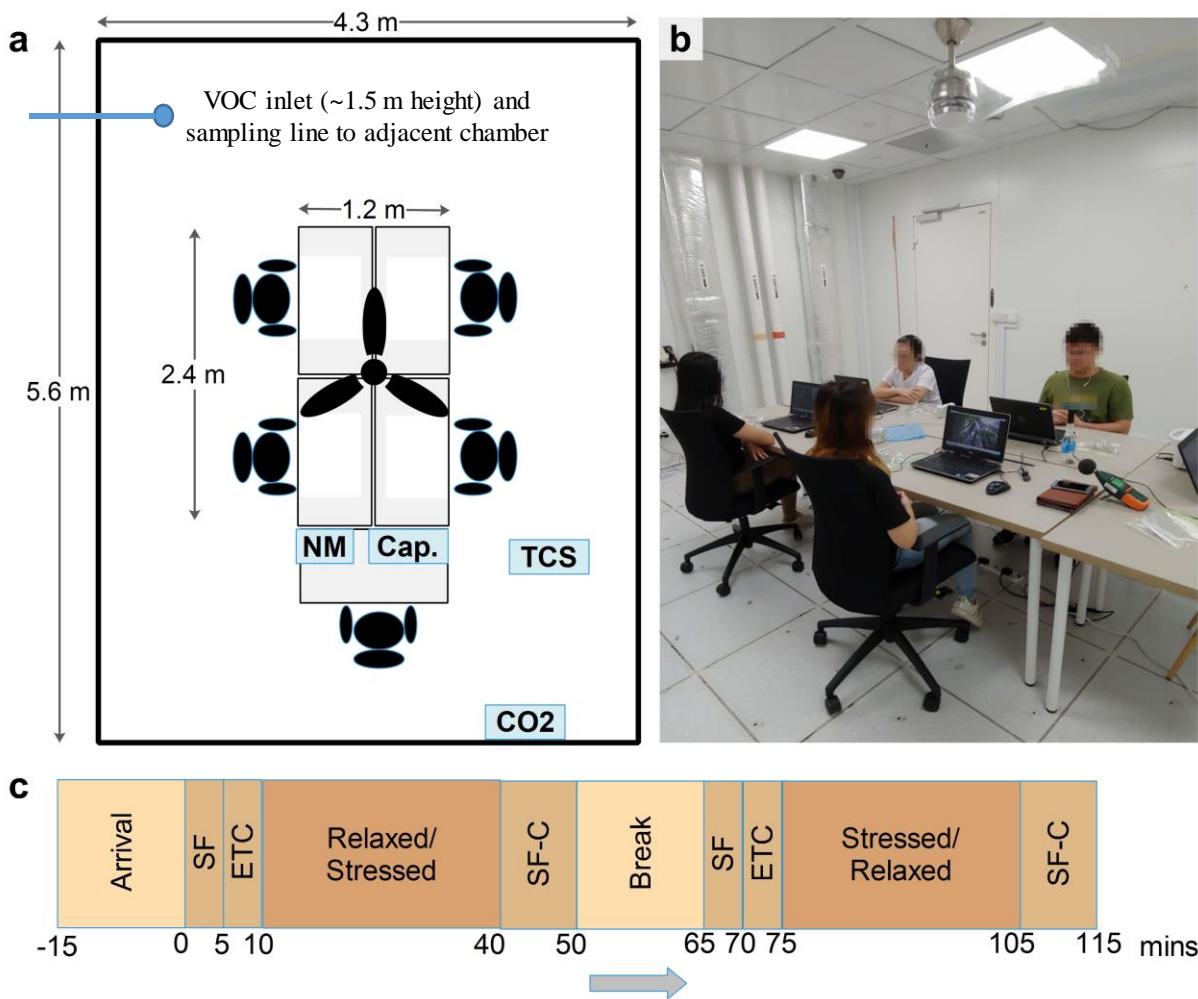
81 example, tailoring ventilation strategies to the psychological experience and/or commitments
82 of the occupants. Conversely, monitoring levels of human chemical emissions in buildings
83 could be used to gauge occupant cognitive engagement. To date, studies advancing our
84 knowledge of factors influencing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

90 **3. Methods and materials**

91 *3.1 Test chamber and subjects*

92 We conducted studies in a room-scale test chamber to measure the influence of
93 cognitive tasks on CO₂ and isoprene emitted by humans. The test chamber is located within
94 the Singapore-Berkeley Building Efficiency for Sustainability in the Tropics facility (Figure
95 S1, Supporting Information). The test bed consists of four climatic chambers, each
96 5.6×4.3×2.7 m. Our tests were conducted in one of the four chambers mocked up as a typical
97 office environment with desks and computer workstations. Four participants and one
98 researcher were present during test periods, shown in Figure 1 (a) and (b). An experimental
99 timeline, post-occupancy by test subjects, is shown in Figure 1 (c). The test chamber was
100 served by a single-pass, mixing ventilation forced air heating, ventilation, and air-conditioning
101 (HVAC) system that includes supply air cleaning, with MERV8 and pleated activated carbon
102 (International Filtration, Carbon Pleated Interfold). Supply air is drawn into the chamber
103 HVAC system from the surrounding indoor space, which is a laboratory environment. A
104 ceiling fan with transparent blades (diameter = 1.47 m, Artemis Minka-Aire F803L-TL model,

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



108 **Figure 1.** Overview of experimental set-up (a) and (b) and time-line of experiments post-
 109 occupancy (c). SF = subjective feedback, ETC = eye tracker calibration, SF-C = subjective
 110 feedback & capnometer, TCS = thermal comfort monitoring station, CO₂ = Wall mounted
 111 CO₂ sensor, NM = noise meter, Cap. = capnometer.
 112

113
 114 *3.2 Measurement of participant stress levels*

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

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

132 We measured objective and subjective indicators of occupant stress and perceptions of
133 the test-chamber’s indoor environment. Participants arrived 15 minutes prior to the start of the
134 session and were outfitted with a heart rate sensor (Polar H10, Polar, Finland). During the
135 session, each participant sat at a workstation with a laptop. Each laptop had an eye tracker
136 installed (Tobii Pro Nano, Tobii Pro, Sweden) to measure pupil dilation. Upon completion of
137 the relaxed and stressed activities, we measured salivary alpha amylase (Cocoro Meter, Nipro
138 Corporation, Japan) and end tidal CO₂ (etCO₂) level (CO₂ monitor, OLG-3800, Nihon
139 Kohden, Japan). We also collected subjective feedback concerning indoor environmental
140 quality and mental effort; further details are provided in the Supporting Information. After the

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

143 *3.3 Human chemical emission measurement*

144 Human chemical emissions evaluated in this study include carbon dioxide and
145 isoprene. Human chemical emissions were measured during a 30-min baseline period,
146 occurring prior to the arrival of occupants, and during the two 30-min periods during
147 occupancy, coinciding with relaxed or stressed activity (Figure 1 (c), baseline not shown). In
148 1-min intervals, measurements of CO₂ were made in the chamber supply air and in bulk air in
149 the test chamber (GMW84, Vaisala, Finland, Range 0-2000 ppm, uncertainty: larger of 30
150 ppm and 3%). Time-integrated measurements of volatile organic compounds were made
151 during baseline and occupied periods via sampling with sorbent tubes packed with 100 mg of
152 Tenax TA and 180 mg of Carbograph 1, based on a method developed previously,⁴⁴ modified
153 for target compounds, sampling times, and sampling flowrate (~130 mL/min, total sample
154 volume = 4 L). One portable sampling pump (PCXR4, SKC, USA) drew sample air through
155 perfluoroalkoxy (PFA) tubing connected to the room supply air duct and another sampling
156 pump did the same from the bulk room air. Both sampling pumps had ~2 m of 0.635" OD
157 tubing placed upstream of the sorbent cartridge. Bulk room air samples were made in
158 duplicate using a flow splitter. Sorbent cartridges were analyzed with thermal desorption – gas
159 chromatography – mass spectrometry (TD-GC-MS, TurboMatrix 650, PerkinElmer, USA
160 connected to a gas chromatograph, Model 7890 A, Agilent Technologies, USA). We
161 quantified VOCs by generating calibration curves from a calibration mixture that included
162 isoprene and acetone. We do not report acetone levels or emission rates due to uncertainty in
163 quantification, apparent in high variability across duplicate samples: the mean relative percent
164 difference (RPD) across all duplicate isoprene concentrations measured was 10.9% while the

165 RPD for acetone duplicates was 66.8%. Since acetone is emitted by humans with high source
166 strength, we suspect the method is not suitable for robust acetone quantification at the levels
167 present in the chamber. Further details of the sampling and analysis method are provided in
168 the Supporting Information and in Figure S2. To return chamber bioeffluent levels to near-
169 background levels, during the break between the two activities the room was flushed with a
170 fan (flowrate = 62 m³/min, IBF300, Aman, India) providing ~10 turnovers of air during the
171 15-min break.

172 Chamber temperature and relative humidity were measured continuously in 1-min
173 intervals (ThermCondSys 5500, Sensor, Poland) and ozone levels were monitored (Model
174 205, 2BTech, USA) once per day, prior to the arrival of occupants, to ensure near-zero ozone
175 levels; ozone was consistently <2 ppb, the stated uncertainty of the instrument. Light levels at
176 each workstation ranged between 931 and 957 lux, which is within normal ranges of typical
177 office work environments. The chamber windows were blacked out to ensure consistent
178 lighting levels and avoid variations due to outside lights. We determined the air-exchange rate
179 in the chamber from measurements of air flow rates in the supply duct as well as tracer decay
180 tests conducted following the conclusion of the experiments for the day (excepting day 1) (see
181 Table S1). The chamber is well-mixed, confirmed via measurements of temperature and
182 airflow gradients, as well as high r^2 (>0.99) when applying a well-mixed model to CO₂ tracer
183 decay periods. The sorbent tubes and sampling pumps were located in a chamber adjacent to
184 the experimental test chamber, and were not visible or audible to participants (instruments
185 were in Chamber III, participants in Chamber IV, Figure S1 of Supporting Information).

186 *3.4 Data analysis*

187 *3.4.1 Calculation of CO₂ emission rates*

188 Time-series measurements of CO₂ were used to estimate emission rates of CO₂ for the
189 baseline and 30-minute periods during which participants were engaged in either relaxed or
190 stressed activity. We used a non-linear curve-fit applied to the analytical solution of a mass-
191 balance equation that included air-exchange and CO₂ emissions from occupants, shown in
192 equation 1:

$$C_{CO_2,t} = \left(C_{CO_2,o} + \frac{S_{CO_2}}{\lambda V} \right) (1 - e^{-\lambda t}) + C_{CO_2,t=0} e^{-\lambda t} \quad (1)$$

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

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

206 *3.4.2 Calculation of isoprene emission rates*

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

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

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

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

219 For periods of occupancy, we developed a method for estimating the isoprene source
 220 strength using a mass-balance model as in equation 1, written for isoprene. Because our
 221 measurement of isoprene was time-integrated, we integrated the mass-balance model over the
 222 30-min period of relaxed or stressed condition, in 1-min time-step, for either relaxed or
 223 stressed activity period to determine the area under the concentration-time curve. Note that the
 224 relaxed or stressed condition began 10 min following occupancy (Figure 1c). This area
 225 calculation was established as the objective function, and the source strength of isoprene over
 226 the 30-min period was varied until the modeled area is equal to that of the concentration-time
 227 area known from the time-integrated measurement, as shown in equation 3:

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

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

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

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

238 *3.4.3 Statistical tests*

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

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

254 0.05 except for the HRV parameters, where, due to the large number of comparisons,
255 Benjamini–Hochberg procedure (false discovery rate taken as 10%) was used. All
256 comparisons were paired and two tailed.

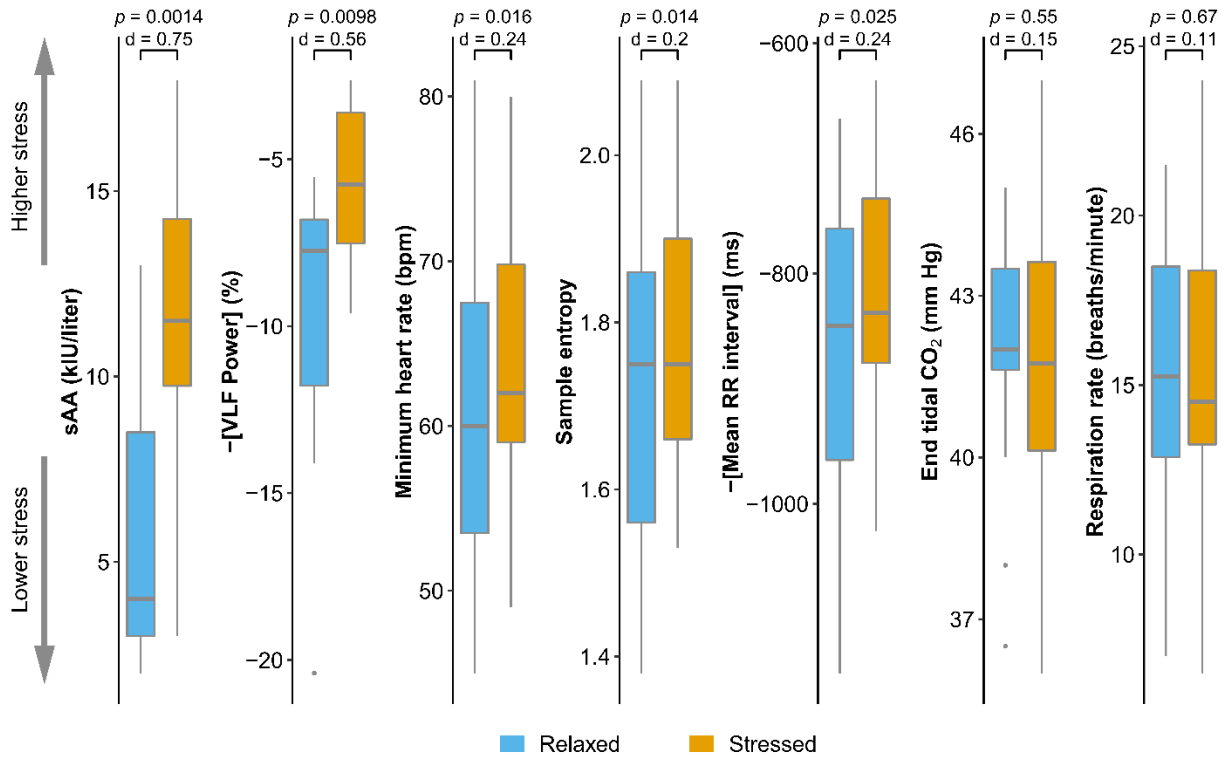
257 Data and analysis scripts/functions are publicly available and can be downloaded from
258 the Dryad repository: <https://doi.org/10.5061/dryad.gb5mkkwmk>.

259 **4. Results and Discussion**

260 *4.1 Objective and subjective indicators of occupant stress*

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

269



270
 271 **Figure 2.** End tidal CO₂, salivary alpha amylase (sAA), respiration rate and summary of key
 272 indicators of heart rate variability data: fraction of power in the very low frequency (VLF)
 273 band, minimum heart rate, sample entropy and mean of the RR interval (interval between
 274 heart beats) measured in the relaxed and stressed activity.

275 Salivary alpha amylase levels are elevated during stressed activity compared to relaxed
 276 activity (p -value = 0.0014, d = 0.75, a medium to large size effect). Salivary alpha amylase
 277 levels are known to follow a diurnal course, and prior studies recommend controlling for time
 278 of day;⁴⁶ our design had occupants entering the chamber at ~14:00 (Table S1) each day and
 279 the relaxed/stressed activities occurred over a period of ~120 min. Nevertheless, the study was
 280 counterbalanced, which will address the potential for confounding due to diurnal changes in
 281 salivary alpha amylase that may have occurred over this 120-min period, though we expect
 282 this effect to be small based on the diurnal profiles presented by Nater et al.⁴⁶. We analyzed
 283 51 parameters of heart rate variability; as noted from previous studies,⁴⁷ not all parameters are
 284 expected to yield a significant difference when stress is imposed on people. Note that one
 285 participant's data was lost on day 3; subsequent analysis used data from fifteen participants. In

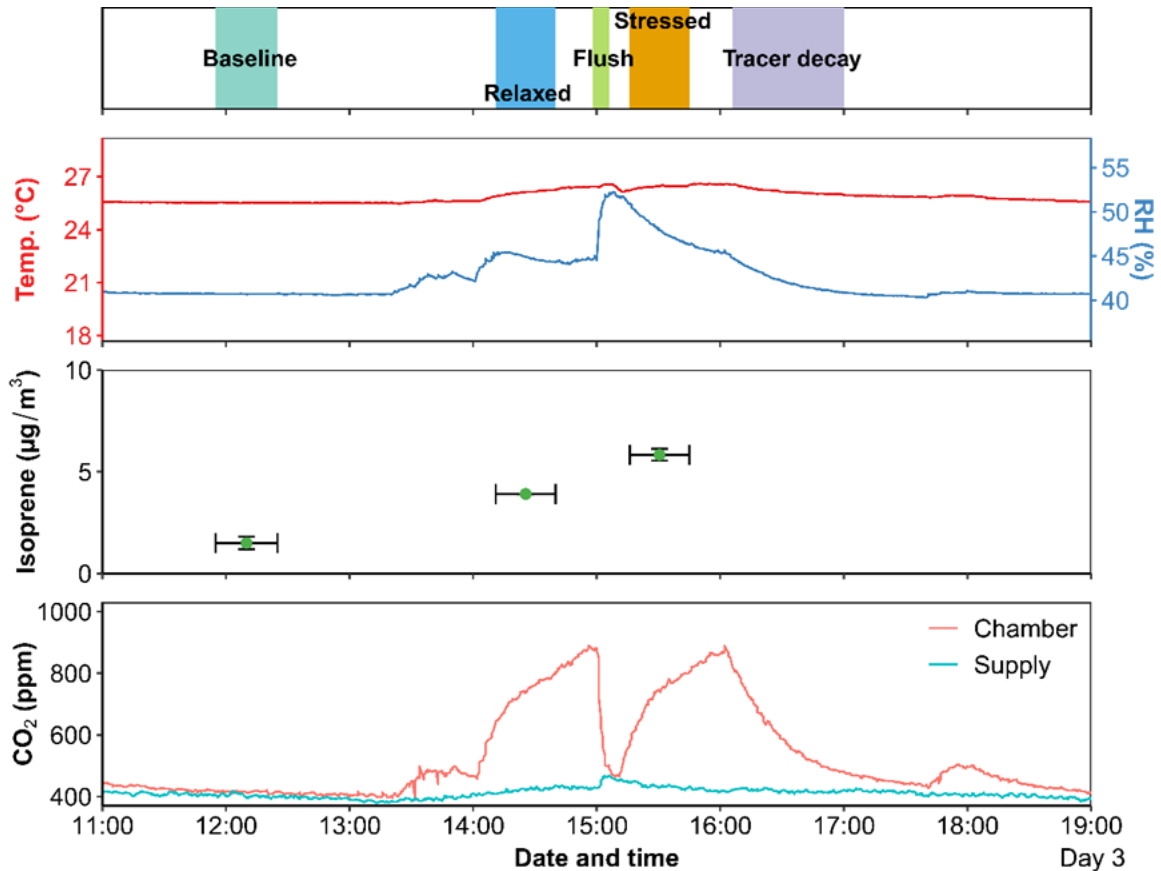
286 Figure 2 are four metrics showing differences due to external stress, evident due to
287 statistically significant differences from the relaxed to stressed activity in the nonparametric
288 statistical tests and Cohen's D. The VLF power is the percentage of power in the Very Low
289 Frequency band ($0.003 \leq f < 0.04$ Hz) of the frequency domain transformation (Fast Fourier
290 Transform) of the time domain RR (interval between heart beats) interval data ($p = 0.0098$, $d =$
291 0.56 , a medium size effect). The degree of heart rate variability (HRV) in terms of VLF power
292 is expected to reduce as activity intensity increases,⁴⁸ an effect observed in our data. The
293 minimum heart rate was lower during relaxed activity ($p = 0.016$, $d = 0.24$, a small size
294 effect). Sample entropy, which indicates randomness of the data (lack of regularity in heart
295 rate), was higher for the stressed activity ($p = 0.014$, $d = 0.2$, a small size effect). Finally, the
296 mean RR was significantly higher during the relaxed activity, indicating greater heart rate
297 variability and hence less stress ($p = 0.025$, $d = 0.2$, a small size effect). Results of subjective
298 feedback assessments (sleepiness, thermal preference) and pupil dilation data are provided in
299 the Supporting Information. Mean and median pupil size were significantly larger during
300 stressed than relaxed activity, shown in Figure S4 of the Supporting Information, another
301 objective indicator associated with stress.⁴⁹ Collectively, these objective indicators
302 demonstrate that cognitive testing vs. nature documentary was effective in causing a relative
303 increase in participants' stress.

304 The end-tidal CO₂ (etCO₂) and respiration rate data did not show significant difference
305 between relaxed and stressed activity periods ($p > 0.7$), determined using a t-test since
306 distributions were normal. This finding was somewhat unexpected given that emission rates of
307 CO₂ calculated from chamber air during occupied periods (Section 4.3) are elevated during
308 stressed compared to relaxed activity. Importantly, etCO₂ was measured post-testing, over a

309 period of ~10 minutes following completion of relaxed or stressed activity while bioeffluent
310 CO₂ emission rates are calculated with data collected during the 30-min of relaxed or stressed
311 activity. No significant changes in etCO₂ implies body CO₂ levels were similar at the end of
312 the two periods. As respiration rates are also similar, in conjunction with etCO₂ values, this
313 indicates that the body is able to effectively ventilate the additional CO₂ being generated
314 during the test period, possibly through breathing in greater volumes of air.

315 *4.2 Human emissions of CO₂ and isoprene*

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



323 **Figure 3.** Representative experimental results for chamber dry-bulb air temperature, relative
 324 humidity, isoprene levels during baseline and occupied periods and time-series measurements
 325 of carbon dioxide.
 326

327 The effect of occupancy on CO₂ levels and the flushing of the chamber in between the
 328 two occupied periods is apparent in Figure 3, the flushing due to a temporarily placed fan that
 329 evacuated air from the chamber, replacing with ambient laboratory air and reducing to near-
 330 background levels of CO₂ prior to the initiation of the second test activity. The test chamber
 331 CO₂ level was monitored and observable in real-time, and was used to ensure the second test
 332 activity of each day occurred with initial CO₂ conditions similar to that of the first test. The
 333 short duration for flushing the chamber between occupied activities is one reason for limiting
 334 analysis of chemical emissions to CO₂ and isoprene, both compounds that are predominantly
 335 present in the gas-phase. There existed no aqueous water present in the chamber and surfaces
 336 were impermeable, hard surfaces. CO₂ sorption to surfaces indoors is typically taken as

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

347 We calculated source strengths during baseline, relaxed and stressed activities for CO₂
 348 and isoprene. Results of the source strength calculation are shown in Table 1 for isoprene and
 349 CO₂, which met the three-group comparison ANOVA criteria of $\alpha < 0.05$.

350 **Table 1.** Chamber conditions and magnitudes of carbon dioxide and isoprene emissions
 351 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
								rep1	rep2		
		°C	%	ppb	ppm	ppm	$\mu\text{g}/\text{m}^3$	$\mu\text{g}/\text{m}^3$		g/h/p	$\mu\text{g}/\text{h}/\text{p}$
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

352 *CO₂ levels were measured in 1-min interval in the inlet and room, averages over the 30-min
353 test periods are reported here for brevity. See Figure S5 for full time-series analysis of CO₂
354 data.
355 # baseline CO₂ and isoprene emission rates are presented on a per-person normalized basis,
356 though no humans were present in the chamber during baseline conditions, to enable
357 comparisons to the occupied (relaxed and stressed activities). All per-person normalizations
358 were made by dividing the total emission rate into the chamber by five, four participants plus
359 the experimenter.
360 % isoprene levels were corrected for field blanks in calculations of isoprene source strength
361 (field blanks were 0.27, 0.27, 0.27, and 0.45 µg/m³ on days, 1, 2, 3 and 4, respectively)
362

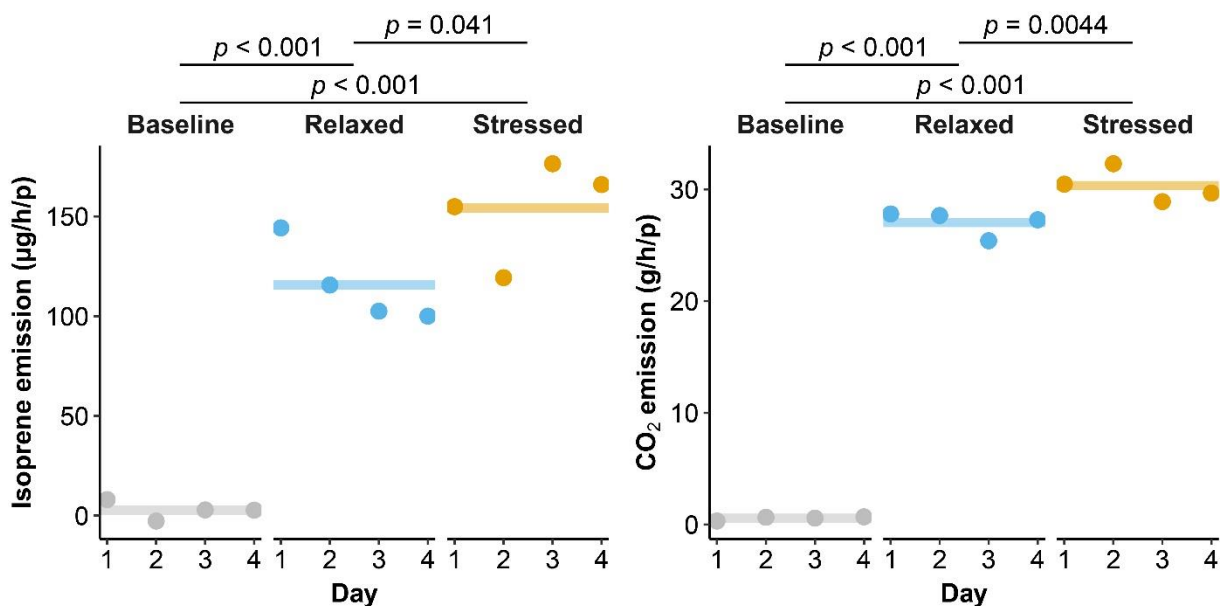
363 Emission rates calculated from mass-balance models during accumulation of CO₂ in
364 the test chamber (28.7 g/h/p averaged across all participants and conditions) are in agreement
365 with prior estimates of per-person CO₂ generation rates. Values reported here are consistent
366 with estimates for adults in residences and bedrooms, and slightly lower than values typically
367 assumed for office environments.^{1,18} Per-person CO₂ emission rates reported here are similar
368 to those reported by Stöner et al.²⁸ for adults (30 g/h/p) and Wang³⁵ for students (27 g/h/p
369 during lecture, 38 g/h/p during exam). Our results are somewhat higher than the average
370 reported by Tang et al.² in an occupied college classroom (21 g/h/p). Our per-person
371 emission rate for isoprene is 135 µg/h/p across all occupied conditions (132 µg/h/p if the
372 aforementioned baseline emission is accounted for), are in general agreement with prior
373 studies. Three independent prior studies reporting per-person isoprene emission rates for
374 adults are 105, 162, and 166 µg/h/p.^{2,27,28} Our estimate for per-person isoprene emission rate
375 is near the average of these prior studies.

376 *4.3 Impact of cognitive tasks on isoprene and CO₂ emission rate*

377

378 Full results across the four days of repeated testing are shown in Figure 4 for carbon
379 dioxide and isoprene. Per-person CO₂ emission rates were greater for stressed than relaxed
380 conditions (30.3 ± 2.1 vs. 27.0 ± 1.7 g/h/p, $p = 0.0044$, mean ± standard deviation) and

381 isoprene emission rates were also elevated under stressed vs. relaxed conditions (154 ± 25
 382 $\mu\text{g/h/p}$ vs. $116 \pm 20 \mu\text{g/h/p}$, $p = 0.041$)



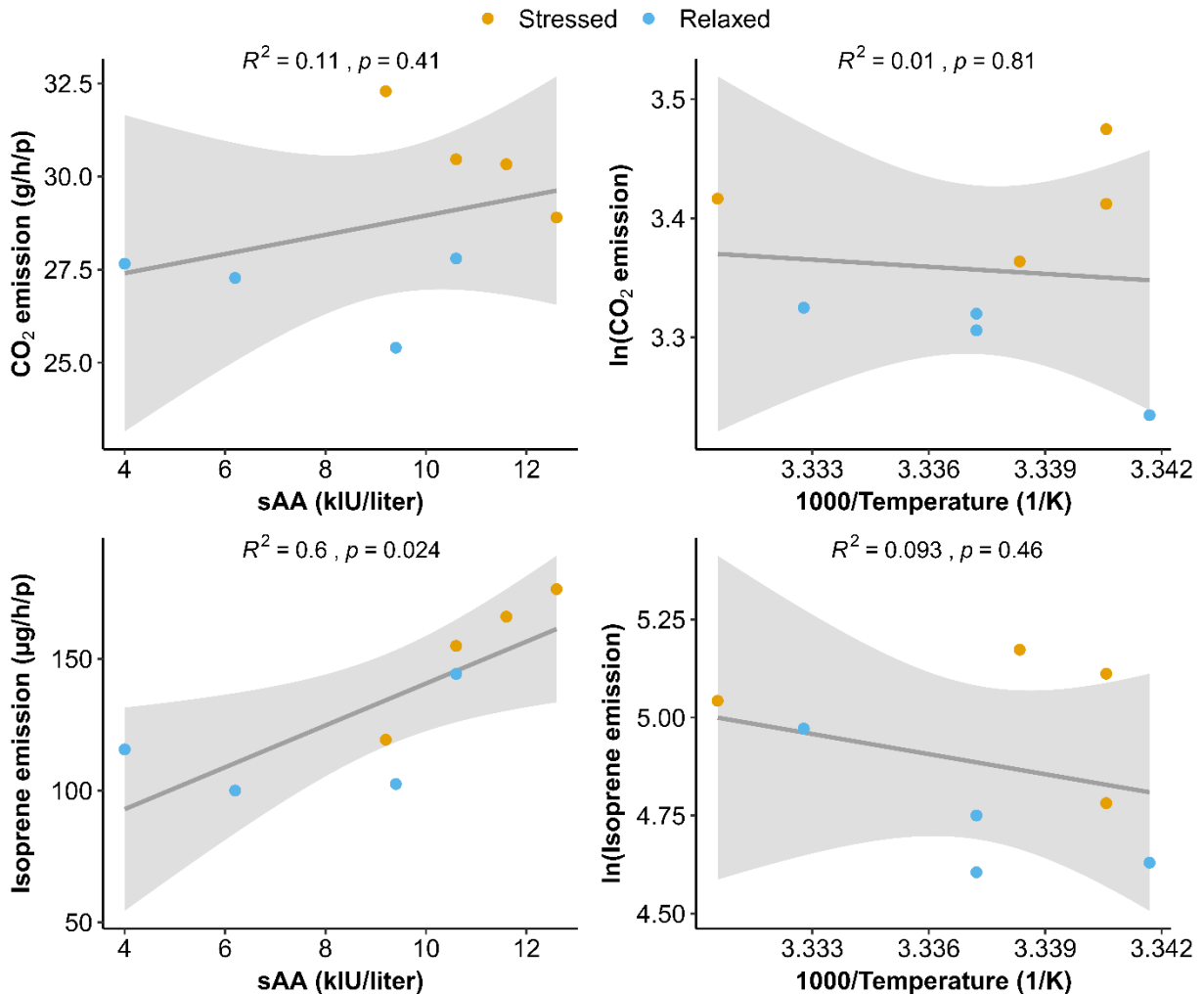
383
 384
 385 **Figure 4.** Per-person emission rates of carbon dioxide and isoprene. The horizontal bar is the
 386 average across all days of testing, each dot shows the measurement for a particular day.
 387 Values of emission rates shown for occupied condition emissions (i.e., relaxed and stressed
 388 activities) do not subtract unoccupied (baseline) estimates of emissions.

389 Shown in Figure 4 is that carbon dioxide emission rates are consistently higher (12%)
 390 during stressed activity than relaxed activity for all repeated trials of the study; regressions
 391 used to estimate emission rates from dynamic CO₂ data each day of testing are shown in
 392 Figure S5 of the Supporting Information. Because the study was counterbalanced, consistently
 393 elevated CO₂ emissions imply that it is the stressed activity that caused the elevated CO₂
 394 emission, rather than the order of tests conducted. Inspection of isoprene emission rates also
 395 reveals elevated emission rate under stressed activity; isoprene emissions were 33% higher
 396 than the relaxed activity. The finding of greater relative increases in isoprene vs. CO₂
 397 emission rate is interesting given that demand-controlled ventilation systems are typically
 398 based on CO₂ levels; results here indicate isoprene may be a useful additional parameter for
 399 designing building ventilation systems with sensitivity to cognitive tasks.

400 As presented in Section 4.1, we measured objective indicators of occupant stress,
401 including biomarkers of salivary alpha amylase and metrics associated with participant's heart
402 rate variability and pupil dilation. We also measured chamber temperature and relative
403 humidity conditions. To explore the utility of these objective biomarkers and environmental
404 conditions as possible predictors of the observed elevation in bioeffluent emission rates, we
405 performed regression to observe relationships to variance and change in CO₂ and isoprene
406 emission rates. Full results of this analysis are shown in Figure S6 of Supporting Information
407 for biomarkers observed to be statistically significantly different between stressed and relaxed
408 activity and temperature and RH. Note that since bioeffluent emission rates are the average
409 per-person emission for individuals present in the chamber, we regress these emission rates
410 against biomarkers averaged for those same individuals. The sAA data here includes that of
411 the experimenter who was inside the chamber, was not subject to the same research protocol,
412 but nevertheless contributed to CO₂ and isoprene emissions. However, since the experimenter
413 did not wear an HRV monitor, the HRV related markers do not have his information.

414 We found that of biomarkers measured, only subject salivary alpha amylase (Figure 5)
415 is significantly related to isoprene emission rates (p -value = 0.02), and that a substantial
416 portion of the variance in observed isoprene emission rates is explained ($R^2 = 0.60$). This
417 result is interesting considering a prior study identifies isoprene as a marker associated with
418 emotional stress arising from moviegoers' interaction with audiovisual stimuli during films.³⁶
419 Stöner et al.³⁷ suggest that isoprene emission and variability in isoprene level could be useful
420 as an objective indicator for recommending age-appropriateness of different films. Isoprene is
421 thought to be generated during cholesterolgenesis⁵² and some studies suggest measurement of
422 breath isoprene levels may be useful as a non-invasive method for assessing blood cholesterol

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



433 **Figure 5.** Regression of isoprene and CO₂ emission rates vs. salivary alpha amylase and
 434 chamber air temperature. Shown above each plot are the r-squared and p-value associated with
 435 the linear regression slope. Curves around each linear regression are the 95% confidence
 436 interval. Note that the target chamber temperature was constant at 26 °C; the above plot
 437 investigates whether incidental variation in temperature is related to observed changes in
 438 emission rates of isoprene and CO₂.
 439

440 Changes in salivary alpha amylase were not significantly associated with changes in
 441 per-person CO₂ production rates. It is possible that CO₂ production was elevated due to
 442 temporary increase in metabolism during the stressed activity, but was not correlated with
 443 endogenous production of salivary alpha amylase. Other biomarkers measured associated with
 444 heart rate did not appear to have statistically significant correlation with changes in isoprene
 445 or CO₂ emission rate or explain variance in observed CO₂ or isoprene emission rates. From

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

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

459 A recent study explored the relationship between temperature and human chemical
460 emissions, finding increases in ammonia emissions from humans with increasing
461 temperature.³⁴ Our study design aimed to hold temperature constant; temperature averaged
462 26.2 ± 0.49 °C (mean \pm standard deviation). Given the known association between air
463 temperature and human CO₂ emissions¹⁸ and recent observation of temperature dependence
464 on ammonia emissions, Figure 5 includes a regression of CO₂ and isoprene emission rates as a
465 function of chamber air temperature, plotted as the natural log of emission rate vs. the inverse
466 of temperature. While slopes are in the expected direction (i.e., a negative slope, implying
467 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 CO₂ 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

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

493 **Supporting Information**

494 The Supporting Information contains additional information concerning the test bed facility,
495 experimental conditions, details of cognitive tests used for the “stressed” activity,
496 characteristics of participants, and additional details of indicators of participant stress and
497 feedback. Further information is provided concerning the measurement of isoprene and
498 resulting calculation of isoprene emission rates. Additional data is reported from the
499 subjective feedback and pupillometry, analysis of CO₂ regressions to determine CO₂ emission
500 rates, and full results of regression of CO₂ and isoprene emission rates with stress indicators
501 and chamber temperature and RH conditions.

502 **Author Contributions**

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

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512

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