Human Olfactory Assessment of Scented Volatile Chemical Product Emissions

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ABSTRACT

This study focuses on the development of an inert controlled environmental chamber (ICEC) that will be able to isolate chemical emissions from scented volatile chemical products (sVCPs) by housing them within a completely pollutant-resistant environment. The two overarching goals of the ICEC are to: (1.) study these chemical emissions in conjunction with human participants to evaluate their associated psychological and emotional response and (2.) isolate samples from sVCPs that are uncontaminated by outside air for high-resolution online mass spectrometry analysis. Personal care and household products are potent sources of indoor air pollution as they contain volatile organic compounds (VOCs) that interact and transform within the indoor atmospheric environment. Scented products that individuals bring into their homes, cars, and workplaces are of particular interest in this study as their value is rooted in creating smellscapes that appeal to the emotional perceptions of the consumer rather than a discernible function that is offered by skin products that moisturize skin or hair care products that add shine to hair.

This study utilizes the ICEC with widely available sVCPs to isolate them in a single-zone reactor supplied with filtered zero air at variable relative humidities to ensure that the sVCP emissions are not altered by influences like excess ozone and particulate matter. Emission concentrations are then diluted with zero air with a specialized system of mass flow controllers to deliver variable dilution to a human participant through a stainless-steel sniffing port. The sniffing port delivers diluted sVCP emissions to the participant for their sensory evaluation. The participant's heart rate (HR) and blood oxygen saturation (SpO2) are monitored using non-invasive measures to evaluate any changes in breathing and HR patterns through each dilution phase. For odor and emotional assessment, this study utilizes the Geneva Odor and Emotional Scale (GEOS). This scale is an effective tool in measuring the subjective experience triggered by commonly experienced odors and scents using a series of Likert scales in six dimensions including disgust, happiness-well-being, sensuality-desire, energy, soothing-peacefulness, and hunger-thirst. This tool aids in understanding the motivation to incorporate certain products into one's smellscapes. Starting at the highest dilution setting, the participant will inhale at the top of the sniffing port and respond to a series of questions on the GEOS regarding their perception of the odor they are asked to perceive. This will occur in 7 stages as the emission concentration increases and dilution decreases, using an online mass spectrometer to concurrently track the VOC concentrations.

Here we present our preliminary results to demonstrate the effectiveness and operational parameters of the ICEC in tandem with implementation of the designed and approved human subject protocol through results obtained via participation of twelve human subjects. This study is expected to find a relationship between the increased concentration of VOCs introduced from the sVCPs and stress-response factors reflected in the olfactory assessment and biometric data. The incorporation of the ICEC with human participants, odor and emotional assessment, and biometric data will contribute a well-rounded perspective to the literature expanding on relationships between sVCPs in the indoor environment and human olfaction perception with emotional and physiological responses.

1. INTRODUCTION

Residents of the built environment interact with fragranced household and personal care products (PCPs) in their daily routines. Products like perfumes, deodorizers, air fresheners, essential oils, dish soap, lotions, salves, laundry detergents, cleaning products, and candles are constantly being marketed with lemon, lavender, pine, and vanilla to appeal to a consumer's sense of smell. Even scent names describing an experience or attractive wordplay like "waterfall", "clean laundry", "dark temptation", and "clean breeze" are commonplace in the household and PCP industry. Indoor air pollution is characterized as a complex mixture of gas- and particle-phase pollutants and PCPs, along with other scented household products, are potent sources of air pollution. Source ingredients for these products are complex mixtures of organic and inorganic species, including volatile organic compounds (VOCs). These mixtures interact with the already present compounds in the air when released into the atmosphere adding to and creating indoor air pollution. Products containing VOCs are known as volatile chemical products (VCPs), and those intentionally fragranced as scented VCPs (sVCPs). VOCs are represented in products such as the smell of pine, lavender, tea tree oil, bergamot, and citrus, among many others. VCPs and sVCPs are potent sources of indoor air pollution as they react with present gas-phase compounds in the air including ozone (O_3), changing the chemical composition of indoor air. D-limonene is a common VOC found in sVCPs including candles, air fresheners, and cleaning products for its distinct lemon scent. Research suggests that when d-limonene interacts with certain gases widely present in the indoor environment, like O_3, ultrafine particles are formed that can lead to sensory irritation and other acute health effects (Wolkoff, 2020).

Heating, ventilation and air-conditioning (HVAC) systems facilitate the exchanging of indoor and outside air, diluting pollutants, including VOCs, building up inside indoor spaces. Inadequate building design, construction, and maintenance contribute to poor ventilation in indoor spaces (Joshi, 2008). Considering factors as socioeconomic status of building owners, local building code compliance, and regular ventilation system maintenance, it cannot be assumed that all indoor spaces are operating in accordance to the ASHRAE standards for proper ventilation. Adequate ventilation is significant when considering indoor air quality, it is crucial to identify already present sources of indoor air pollutants.

It is well accepted in the literature that North Americans spend approximately 87% of their time inside buildings (Klepeis et al., 2001). The quality of indoor air is crucial to occupant well-being, due to the amount of time humans spend indoors and the ability of buildings to directly and indirectly influence human health (Allen et al., 2016). Acute and prolonged exposure to indoor air pollution poses a variety of health risks to humans as this pollution has the great potential to infiltrate the body through the nose, eyes, mouth, and even skin. It is well established in the literature that health outcomes as a result of prolonged air pollution exposure can result in respiratory, cardiovascular, and other physically represented ailments (Wolkoff, 2020). This investigation will explore the gap addressing how air pollution characterized by VOCs from sVCPs changes indoor smellscapes and atmospheric chemistry, influences cognitive function, and incites physiological change reflected as a response to stress.

Health outcomes influenced by the built environment extends to human physiology and mental health. Physiology is the branch of biology studying the mechanisms and functions of living organisms and their bodies. Living organisms, including humans, respond to stimuli in their environment with modifying responses, or physiological changes. In biology, a stressor or stress serves as a perceived environmental challenge or threat that would trigger a response from an organism (Stress | Description, Causes, & Effects | Britannica, 2024). In a situation perceived as stressful, a physiological change may be reflected as a change in heart rate, the production of stress hormones, sweat gland activity on the skin, or increased blood pressure (Chu et al., 2023). This investigation provides an opportunity to evaluate the human within their built environment among various smellscapes created by VOC emissions from commonly used sVCPs while recording their physiological response.

For this investigation, data collection of biometric changes resulting in physiological changes needed to pose a minimal distraction to the participant, so as not to impose additional stress to the environment. Therefore, traditional heart rate (HR), heart rate variability (HRV), and blood oxygen saturation (SpO2) levels are utilized for this study. Traditional HR looks at the heart beats per minute, while HRV measures changes in time between heartbeats (Sacha, 2014). It is suggested in the literature that high HRV in a rested state is favorable, and low HRV in a rested state may be a strong indication of stress (Kim et al., 2018). HRV is utilized as a reliable method for assessing the body's physiological response to stress (Peabody et al., 2023). SpO2 is the value of oxygen concentrated in the blood's hemoglobin communicated as a percentage of the blood's oxygen-carrying capacity. SpO2 in a healthy adult body is between 96% and 98%. Lower percentages may occur as a result of shallow breathing or quick inefficient breathing that does not carry enough oxygen through the blood, this may occur in times of stress or anxiety (McDowell et al., 2021). Although current research demonstrates that stress influences blood oxygen saturation and has the potential to be used in stress monitoring analysis, it is recorded non-invasively in this investigation, but not used as the primary indication of physiological stress (Taj-Eldin et al., 2018).

Understanding odor and odor perception is necessary as it is a driving motivation of human behavior. When odor molecules enter the nose, information is communicated by sensory neurons to the mass of tissue in the brain called the olfactory bulb (Pashkovski et al., 2020). The olfactory bulb, the part of the brain credited as the smell center, sits between the amygdala and the hippocampus. The amygdala is associated with emotional processing, while the hippocampus is associated with associative learning. This careful placement contributes to the well-researched idea that the human sense of smell is the most powerful in the human body for memory retrieval, this can be reflected as an emotional, physical, or physiological response associated with a previous experience (Herz, 2016). The prefrontal cortex (PFC) in the brain is associated with regulating actions and emotions by communicating with other regions of the brain, while the orbitofrontal cortex (OFC) located inside of the PFC is credited with combining sensory inputs like smell, taste, touch, and vision (Arnsten, 2009). This leads to the understanding that the OFC is the key player in processing olfactory stimuli and associating them with perceived rewards. Perceived rewards drive human behavior and actions like eating and drinking, or more complex behaviors like purchasing a candle that reminds an individual of baked bread (Rolls, 2000). Human behavior and olfaction may be closely connected to cognitive function, which refers to mental abilities like learning, thinking, problem-solving, decision-making, and attention (de Paula et al., 2021). The PFC, OFC, and other structures in the brain's "smell center" work together to process stimuli, like scents, for associative learning, perception, and memory. These associations are just aspects of the cognitive functioning abilities produced by the brain. Ultimately, odor stimuli, along with other sensory cues from the environment, do impact cognitive functioning through the pathways of memory processing and retrieval, selective attention, emotional processing, and cognitive performance.

VOCs present as indoor air pollution within buildings can influence an individual's mental and physical well-being. Evidence demonstrates that VOCs in the built environment, which may or may not be consciously perceived by individuals, can impact their cognitive function reflected in the electrical activity in the brain (Wang et al., 2023). The cognitive aspect of this assessment is conducted as an emotional and odor assessment with the United States English version of the Geneva Emotional Odor Scales (GEOS). The objective of these scales is to gauge the subjective emotional response provoked by odors presented to the GEOS user. Participants express the intensity of their olfactory perception on the sliding scale ranging from "Not at all intense" to "Extremely intense" with an option for "Not understood". The GEOS utilizes 37 terms divided into 6 categories disgust, happiness/ well-being, sensuality/desire, energy, soothing/peacefulness, and hunger/ thirst (*Emotion and Odor Scales - Swiss Center For Affective Sciences - UNIGE*, 2016). The GEOS is a validated measure of basic emotional response, ideal to be later compared with physiological and biometric data. Olfactory assessment is achieved through the use of an inert controlled environmental chamber (ICEC) that isolates VOC emissions, and therefore smellscapes, associated with a specific sVCP. The ICEC integrates a stainless-steel sniffing port for olfaction evaluation and a proton transfer reaction time-of-flight mass spectrometer (PTR-TOF-MS) for real-time VOC measurement.

2. METHODS

The methods section presents the following: (3.1) the design and construction process of the ICEC that will be used for conducting controlled olfaction experiments for sVCPs, (3.2) ICEC operation and system description, and (3.3) integrating human participants in olfaction experiments with the ICEC. As this investigation is ongoing, we describe the experimental protocols fully, yet only the results of the preliminary experiments are reported in the results.

3.1 Design and Construction of the ICEC

The primary goals of this phase of the project were to develop, construct, and utilize an instrument to: (1.) analyze sVCP chemical emissions in conjunction with human participants to evaluate their associated psychological and emotional response and (2.) isolate samples from sVCPs that are uncontaminated by outside air for high-resolution online mass spectrometry analysis. To meet the needs of this study, our team designed a controlled environmental olfaction chamber to isolate and identify VOCs from sVCPs while diluting with clean air and preparing these emissions to be evaluated by human participants. To ensure that sVCP samples are not contaminated or transformed by outside air, the ICEC must act as an inert environment with minimal potential of absorbing product residue. In addition, the chamber needed to have an internal volume large enough to: (a.) house various sized and shaped sVCPs such as candles, wax warmers, perfumes, and air fresheners, (b.) internal environmental condition monitoring and air mixing equipment, and (c,) allow for a variable air exchange rate (AER) to dilute emission samples within a relatively short period. The final design of the environmental olfaction chamber is a 226 L (8 ft^3) cube. Aesthetics were a factor while considering the ICEC design and therefore shape, color, and sound needs were recognized. The chamber needed to be opaque so as not to reveal the contents of the chamber to participants leading to the natural bias individuals may have for the scented product inside. The experiment would also operate best if the chamber itself did not serve as a source of stress, intimidation, or distraction for the participant. In response, the chamber was constructed with simplicity in mind, taking additional measures to minimize sound and exterior hardware visibility.

The controlled environmental chamber's frame was constructed with two grade 316 stainless steel panels shaped together to form a cube. This method required minimal welding with the benefit of increased structural integrity and reduction in potential vibration and sound. As sVCPs and instruments are integrated and changed, the ICEC maintains an airtight seal with a PTFE gasket serving as a point of access for electrical cords and sampling lines. The inert environment to prevent contamination of the introduced sVCP emissions required from the ICEC was a crucial component of this investigation and exclusive materials were incorporated into the construction of the ICEC including polytetrafluoroethylene (PTFE) or Teflon, borosilicate glass, and stainless steel. To avoid rust and corrosion of the stainless steel chamber, the interior and exterior surfaces were electropolished. This process resulted in a smoother finish on the stainless-steel surface making it less likely for any product residue to adhere to the material (Lebedeva et al., 2021). Typically, the air we breathe has a certain relative humidity depending on the heating and cooling season. The olfactory port of the ICEC was designed to provide as natural as possible air through the sniffing port. This required introduction of moisture into the chamber in addition to the pollutant-free zero air (typically dry, denoted as dry air in Figure 1). This would result in successful, yet controlled, replication of a sVCP emission assessment as relative humidity (RH) is present in most indoor air settings and is often detectable with the human nose. A specialized system constructed from borosilicate glass and stainless steel uses distilled water to safely reintroduce moisture into the chamber (denoted as wet air in Figure 1).

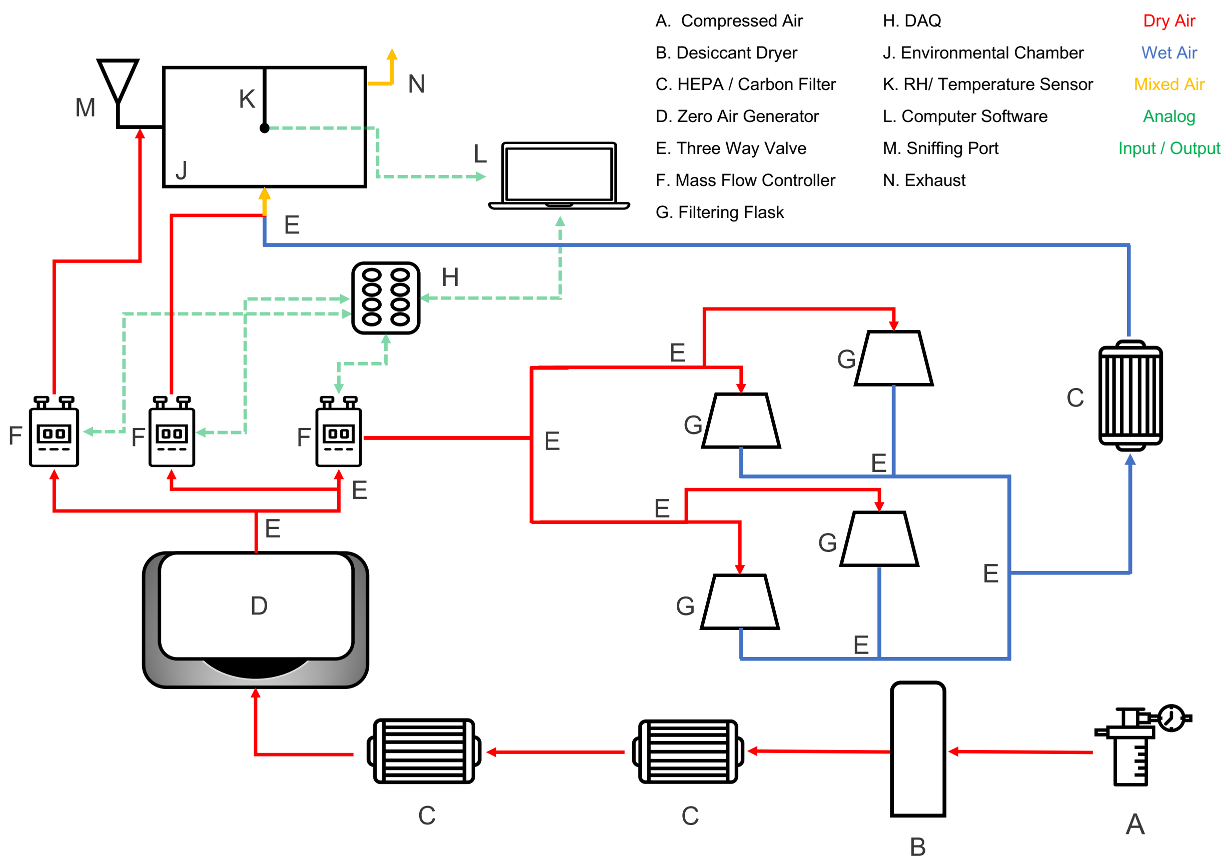

Figure 1: Complete ICEC setup for conducting the olfactory assessment experiments with sVCPs.

3.2 ICEC Chamber Operation and System Description

The ICEC's successful operation is characterized by several specialized systems controlling and monitoring the conditions inside the chamber. A zero air generator (ZAG) supplies pollutant- and impurity-free air from a compressed air line in conjunction with high-efficiency particulate air (HEPA) and carbon filters upstream and downstream of the ZAG; this can be seen in Figure 1 parts A-D. These filters are incorporated as an added defense against impurities to maintain the inert integrity of the ICEC as well as to prolong the life of the ZAG. The chamber system is controlled with LabVIEW software to facilitate data communication and functionality between a data acquisition board (DAQ) and analog input and output between the mass flow controllers, RH and temperature probes, and graphical interface on a computer; this seen in Figure 1 parts F, H, J, K, L, and N. The RH system, seen in Figure 1 parts E and C, uses vaporized distilled water to introduce moisture into the ICEC. Using LabVIEW software, the wet and dry flowrate mixing ratio can be controlled manually or through the proportional-integral-derivative (PID) function to achieve a desired RH set-point. Three mass flow controllers, demonstrated in Figure 1 parts F, control the flowrate of air throughout the system, through a line of exclusively dry air and a line of wet air leading directly to the ICEC, and a line of dry air leading directly to the olfaction port of sample dilution. Fans with stainless steel blades are placed at the top and bottom of the chamber to ensure well-mixed conditions inside the chamber. The side electrical port and sniffing port have integrated access for sampling lines to a multitude of instruments including the high-resolution PTR-TOF-MS that will capture the development of VOC profiles inside the chamber in real-time. Finally, in the bottom center of the ICEC, an sVCP can be placed and operated. For this experiment, a store-bought candle wax warmer is placed in the chamber and operated through the power switch threaded through the PTFE electrical port.

3.3 Integrating Human Participants

This investigation will operate under a quasi-experimental model recruiting 30 adult participants between the ages of 18 and 45 years old from the Greater Lafayette, Indiana area surrounding and including the Purdue University campus. A priori analysis determined a sample size of 30 participants to be appropriate considering $\alpha = 0.05$, $1 - \beta = 0.80$, medium effect size of 0.5, and 4 predictors. This priori power analysis was calculated using G*Power. As this investigation monitors biometric data, on the day of their respective site visit eligible participants must be non-smokers and abstain from ingesting caffeine, stimulants, and depressants. Due to the olfaction sensory nature of this investigation, participants must also agree to not incorporate scented products into their day-of routine to not influence their perception of the presented samples to them during the experiment. This includes deodorants, perfumes, and other PCPs. The research team acknowledges that sVCPs are integrated into the participants' daily lives and expects this guideline to be followed within reason. A potential participant is deemed ineligible if they experience heart palpitations or adverse heart conditions in response to strong smells, experience allergies or sensitivities to the ingredients or plant derivatives used in the study, experience asthmatic symptoms or difficulty breathing in response to scents that will be used in the study or have a recent history of brain injury or trauma.

In summer 2024, the human-integrated investigation will take place housing the above described ICEC chamber in a specialized IAQ chamber at Herrick Laboratories on the Purdue University campus. The IAQ chamber is a 95.16 m^3 specialized test chamber designed to simulate conditions of the indoor environment including light, temperature, AER, and RH. The walls, ceiling, and door are equipped with R-40, R-20, and or 4 inches of concrete to discourage thermal fluctuation influenced by the outside temperature. Air temperature can be controlled within ± 0.5 °F with the and supply air temperature within ± 1.0 °F. This is a crucial measure in ensuring the thermal comfort of the participant is being met and environmental conditions are consistent across all experiments. Additionally, the IAQ chamber does not have external windows, this discourages variation in the participant sensory experience between experiments. Like the ICEC, operations are controlled and monitored through LabVIEW software accessible outside of the chamber on computer integrated with a DAQ system.

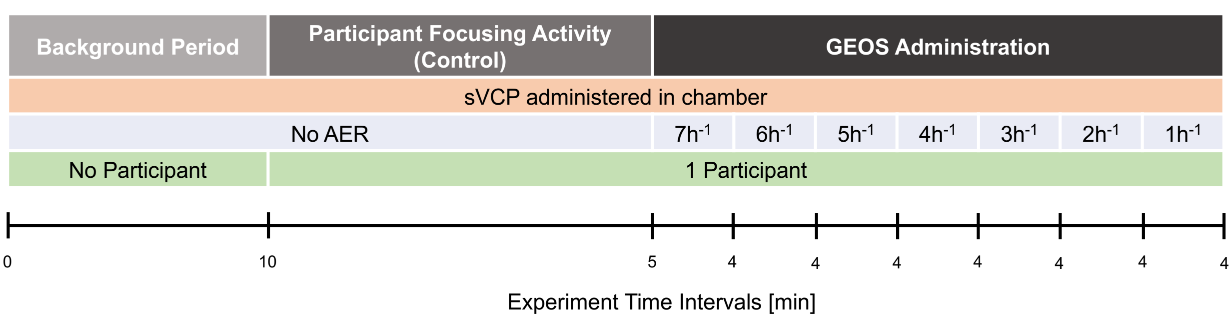

Figure 2: Olfaction experimental protocol for participating human subjects.

By placing the ICEC in the IAQ chamber, emissions generated by human participants during the experiment can be characterized while the ICEC is simultaneously characterizing emissions from sVCPs. The mechanisms involved in the olfaction aspects of the experiment are controlled inside the ICEC, while environmental conditions will be controlled and monitored by the IAQ chamber. Conditions like indoor light, temperature, RH, sound, and AER can be monitored and controlled to minimize variable experiences across participants, while at the same time, VOC profiles of the IAQ chamber will be monitored and compared with unaltered sVCP emissions inside of the environmental olfaction chamber.

On the day of each experiment, each participant will go through a day-of health questionnaire and revisit the risk and benefits and consent form with the lead researcher. Once consent is obtained, all notifying personal devices (cell phones, laptops, and smartwatches) will be silenced and put away. The smartwatch will be administered for baseline biometric data to the participant for 5 minutes while they complete a focusing activity. This time is valuable as the participants will also be acclimating to the conditions of the IAQ chamber during this time. Once this period has concluded, the researcher will instruct when the participant is to place their nose at the olfaction port, step back, and answer the questions of the GEOS administered on a laptop screen. The first phase will consist of no airflow through the olfaction port and will serve as a control assessment. The researcher will be consistently decreasing the dilution of the presented sample through each phase. Figure 2 reflects the timeline in which each phase of the experiment occurs under the respective AER conditions which is indicative of the gradually increasing scent concentration.

Each phase will allow for approximately two minutes at the olfaction port and two minutes to answer the GEOS questions. The part of the experiment is expected to last about 28 to 30 minutes. Figure 3 illustrates the interactions between the ICEC and the human participant. Once concluded, the results of the GEOS will tell us which emotions were perceived as being the most intense in response to specific sVCPs. Results will also demonstrate if HRV or SpO2 increases or decreases with (1.) perceived emotional intensity or (2.) increased sVCP emission concentration, thereby indicating if the body responds to these two variables with physiological stress.

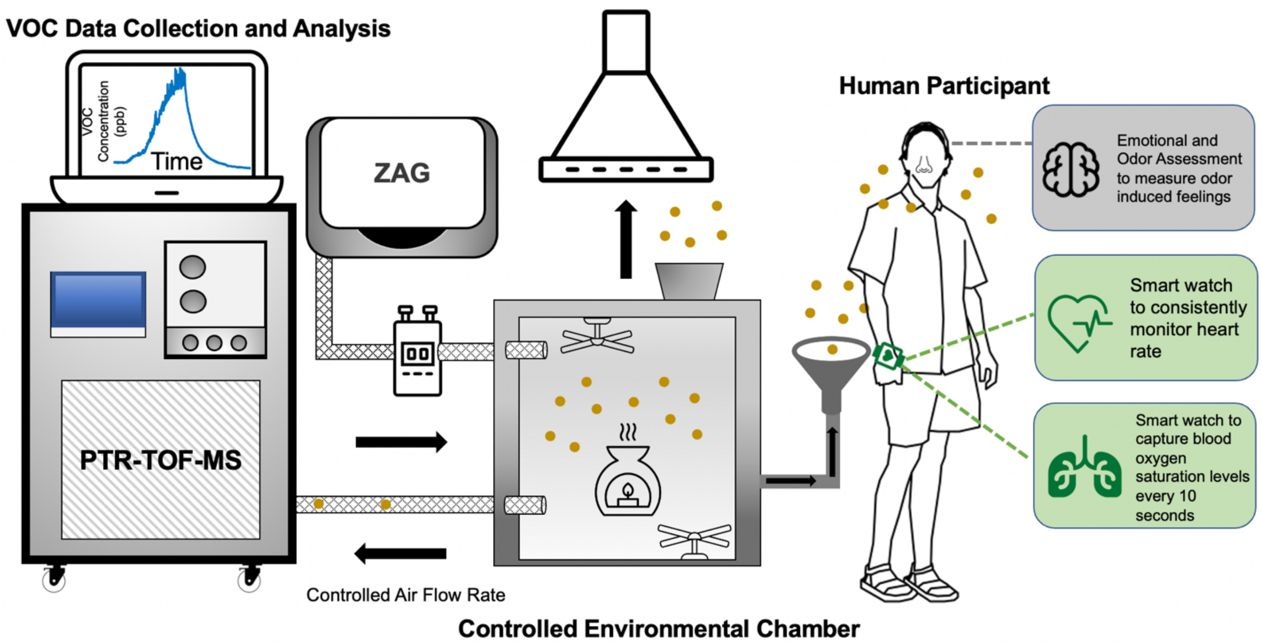

Figure 3: Experimental instrumentation set up with the ICEC, PTR-TOF-MS, and human participants.

4. PRELIMINARY RESULTS

This section shows our preliminary results to demonstrate the effectiveness and operating parameters of the ICEC in tandem with implementation of the designed and approved human subjects protocol through results obtained via participation of twelve human subjects. Initial tests to establish protocols and operating parameters for the ICEC were successful. This is represented in the ICEC's ability to maintain a stable internal temperature with desired RH set-points between 50 and 70%, reflective of general indoor built environment conditions. LabVIEW successfully controlled the airflow rates pertaining to the RH system, sniffing port, and dry pollutant-free air managing the ICEC's operational AER. Extensive testing was conducted to ensure that no excess of O_3 or particulate matter could be introduced into the system through the RH system or the ZAG by integrating additional filters into the system.

During the initial tests, twelve human subjects participated in preliminary experiments that included completion of an olfaction experiment and recoding that information using Geneva Emotional Odor Scales (GEOS) while they were exposed to an evaporated wax warmer/melt sample providing constant smellscapes (without variable dilution over time). This is similar to an activity a participant would conduct in their personalized home or office environment. 10 g of a scented wax sample was used in this investigation. Each participant was exposed to VOC emissions from the melted wax sample with identical chamber conditions for between 2 and 2.5 minutes while filling out the GEOS. As previously noted, the product was hidden from the participants, and they were asked to fill the GEOS survey and assess their sensory smellscapes provided via the olfaction port of the ICEC. The wax sample used was marketed and sold as scent smelling like "car exhaust" according to the distributor. Figure 4 shows the results from participants' responses. On a Likert scale from 1 to 5, 1 being "not at all intense" and 5 being "extremely intense", participants rated the perceived intensity of each emotional state group evoked by the odor they were being exposed to. The option of "not understood" was available. This version of the experiment used wax melts that are sold as a specialty product and produce smellscapes of a "car exhaust." After the GEOS survey concluded, participants were asked to describe the scent they experienced. "Masculine", "musky", "Like a temple or church", and "smokey" were among the four most common descriptive words used.

As indicated earlier, this study would need to use a larger sample size in the future to determine if sVCP emissions have a consistent influence over emotional perception, especially as the nature of the GEOS is subjective. The objective of this preliminary test was to evaluate the existing experimental protocols as well as the functionality of our newly developed ICEC, and without a larger sample size the results can only be assessed qualitatively revealing that participant's perceptions of sVCP emissions can vary widely and are influenced by prior experiences.

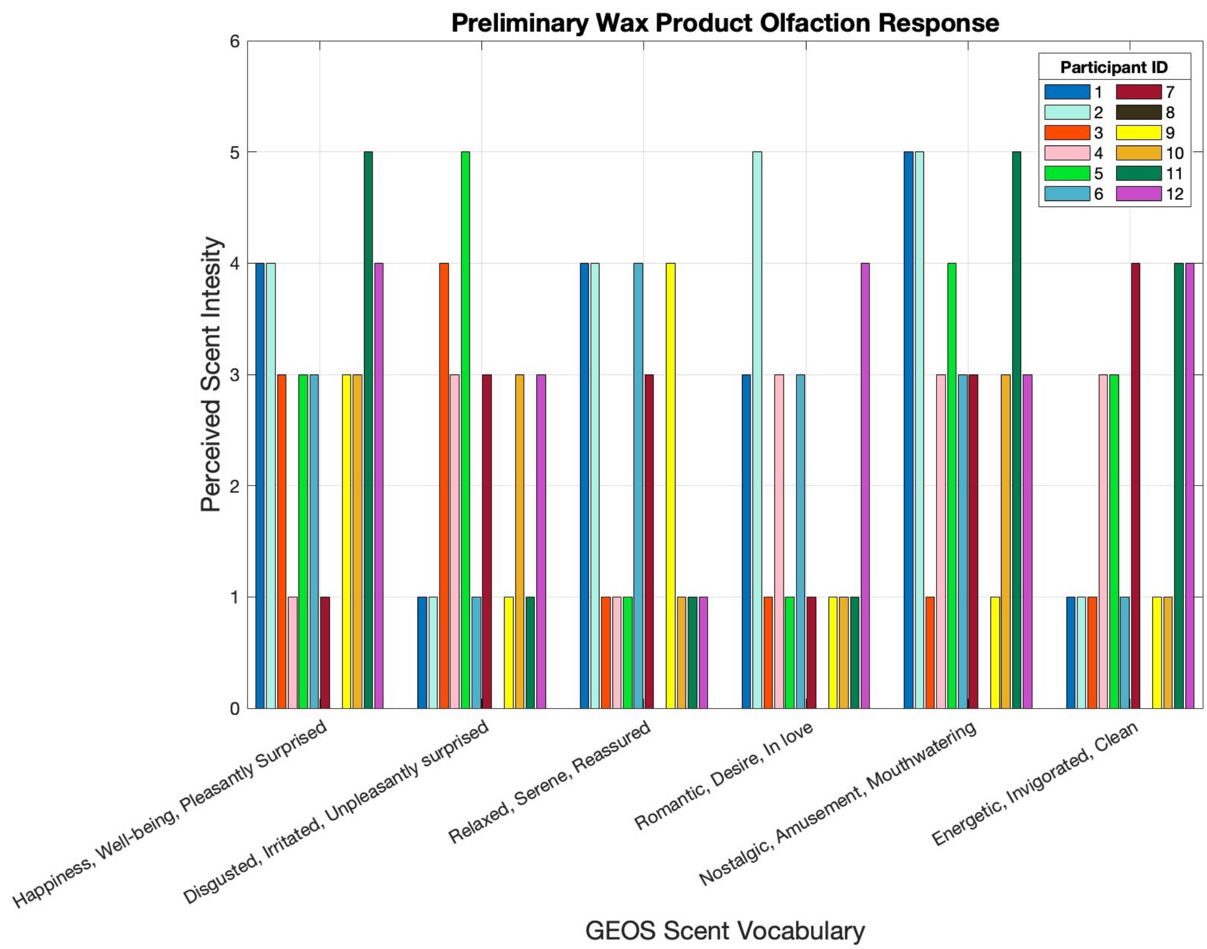

Figure 4: Preliminary GEOS survey results for olfaction assessment of VOC emissions from a sVCP in the ICEC.

5. CONCLUSIONS AND ONGOING WORK

Presently, preliminary experiments establishing parameters for stable and inert environmental conditions inside of the ICEC have been successfully concluded. The systems for integrating RH control, remote data collection, mixed internal air, chamber condition monitoring, and zero air have been established. The next step will be to organize the entire chamber system onto a single platform to be easily mobile and integrate it into the IAQ chamber at Herrick Laboratories. In the summer of 2024, the investigation will begin to recruit individual participants under IRB #2022-343. Contributions by the application of the ICEC and human participation in this study will be invaluable in examining the impact of sVCP emission exposure within the indoor atmosphere on the human body and mind.

REFERENCES

Allen, J. G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., & Spengler, J. D. (2016). Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. *Environmental Health Perspectives*, *124*(6), 805–812. https://doi.org/10.1289/ehp.1510037

Arnsten, A. F. T. (2009). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature Reviews. Neuroscience*, *10*(6), 410–422. https://doi.org/10.1038/nrn2648

Chu, B., Marwaha, K., Sanvictores, T., & Ayers, D. (2023). Physiology, Stress Reaction. In *StatPearls*. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK541120/

de Paula, G. C., Brunetta, H. S., Engel, D. F., Gaspar, J. M., Velloso, L. A., Engblom, D., de Oliveira, J., & de Bem, A. F. (2021). Hippocampal Function Is Impaired by a Short-Term High-Fat Diet in Mice: Increased Blood–Brain Barrier Permeability and Neuroinflammation as Triggering Events. *Frontiers in Neuroscience*, *15*. https://www.frontiersin.org/articles/10.3389/fnins.2021.734158

Emotion and Odor Scales—Swiss Center For Affective Sciences—UNIGE. (2016, June 29). https://www.unige.ch/cisa/eos/

Herz, R. S. (2016). The Role of Odor-Evoked Memory in Psychological and Physiological Health. *Brain Sciences*, *6*(3), Article 3. https://doi.org/10.3390/brainsci6030022

Joshi, S. M. (2008). The sick building syndrome. *Indian Journal of Occupational and Environmental Medicine*, *12*(2), 61–64. https://doi.org/10.4103/0019-5278.43262

Kim, H.-G., Cheon, E.-J., Bai, D.-S., Lee, Y. H., & Koo, B.-H. (2018). Stress and Heart Rate Variability: A Meta-Analysis and Review of the Literature. *Psychiatry Investigation*, *15*(3), 235–245. https://doi.org/10.30773/pi.2017.08.17

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. V., Hern, S. C., & Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology*, *11*(3), 231–252. https://doi.org/10.1038/sj.jea.7500165

McDowell, C. P., Newman, L., Monroe, D. C., O'Connor, J. D., Knight, S. P., Kenny, R. A., & Herring, M. P. (2021). The Association Between Generalized Anxiety Disorder and Resting-State Prefrontal Cortex Oxygenation Is Modified by Self-Reported Physical Activity: Results From The Irish Longitudinal Study on Ageing. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *76*(8), 1391–1397. https://doi.org/10.1093/gerona/glab090

Pashkovski, S. L., Iurilli, G., Brann, D., Chicharro, D., Drummey, K., Franks, K. M., Panzeri, S., & Datta, S. R. (2020). Structure and flexibility in cortical representations of odour space. *Nature*, *583*(7815), Article 7815. https://doi.org/10.1038/s41586-020-2451-1

Peabody, J. E., Ryznar, R., Ziesmann, M. T., & Gillman, L. (n.d.). A Systematic Review of Heart Rate Variability as a Measure of Stress in Medical Professionals. *Cureus*, *15*(1), e34345. https://doi.org/10.7759/cureus.34345

Rolls, E. T. (2000). The Orbitofrontal Cortex and Reward. *Cerebral Cortex*, *10*(3), 284–294. https://doi.org/10.1093/cercor/10.3.284

Sacha, J. (2014). Interaction between heart rate and heart rate variability. *Annals of Noninvasive Electrocardiology: The Official Journal of the International Society for Holter and Noninvasive Electrocardiology, Inc*, *19*(3), 207–216. https://doi.org/10.1111/anec.12148

Stress | Description, Causes, & Effects | Britannica. (n.d.). Retrieved April 10, 2024, from https://www.britannica.com/science/stress-psychology-and-biology

Taj-Eldin, M., Ryan, C., O'Flynn, B., & Galvin, P. (2018). A Review of Wearable Solutions for Physiological and Emotional Monitoring for Use by People with Autism Spectrum Disorder and Their Caregivers. *Sensors*, *18*(12), 4271. https://doi.org/10.3390/s18124271

Wang, Z., Pei, J., Song, Y., & Liu, J. (2023). Experimental investigation of VOC influence on cognitive function at low concentration in a full-fresh air environmental chamber. *E3S Web of Conferences*, *396*, 01013. https://doi.org/10.1051/e3sconf/202339601013

Wolkoff, P. (2020). Indoor air chemistry: Terpene reaction products and airway effects. *International Journal of Hygiene and Environmental Health*, *225*, 113439. https://doi.org/10.1016/j.ijheh.2019.113439

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