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Performance Assessment Of TVOC Sensors Used in Consumer-Grade Air Quality Monitors

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Performance Assessment Of TVOC Sensors Used in Consumer-Grade Air Quality Monitors

by

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Good Thoughts, Good Words, Good Deeds.

Abstract

Performance Assessment Of TVOC Sensors Used in Consumer-Grade Air Quality Monitors

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Indoor Air Quality (IAQ) has a direct impact on overall occupant health, especially respiratory and neural health. To ensure adequate indoor air quality, we must monitor the air by regularly sampling for pollutants of concern. One important category of air pollutants is VOCs: Volatile Organic Compounds. Some VOCs may be toxic at low concentrations while others require prolonged exposure at high concentrations to become a concern. Traditionally, measuring VOCs accurately has been prohibitively expensive and/or complicated. Recently, consumer-grade air quality monitors have been advertised as affordable counter parts to the expensive and complicated research-grade monitors and sensors. We studied the performance of a unique category of Total Volatile Organic Compounds sensor called a CMOS sensor. We assessed the performance of two brands of TVOC sensors used in three consumer-grade air quality monitors. We conducted a total of 5 experiments, 3 in a real home environment and 2 in a laboratory setting using a state-of-the-art air quality sampling device called the Vocus PTR-Tof. The con-

sumer grade devices tend to exhibit some degree of uniformity in their patterns in response to pollution events, however, they can often deviate from one another in measuring actual concentration levels. The CMOS sensors studied suffer from a range of persistent challenges inherent to the CMOS technology, such as sensitivity and selectivity limitations. While improvements continue, more research is required to determine the extent to which these sensors may be useful and whether they can reliably and reasonably be used to assess indoor air quality.

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Chapter 1: Introduction

This thesis is organized as follows: Chapter 2 reviews works related to Indoor Air Quality (IAQ), delving into Total Volatile Organic Compounds (TVOCs) and their health effects in Section 2.2. Next, Chapter 3 delves into the tools and techniques used throughout the different phases of the experiments, such as the consumer-grade devices and state-of-the-art research-grade device in Section 3.1. Section 3.2 delves into the experiment setups such as the real, lived environment in an apartment, as well as the laboratory test facilities. Data processing and management is also discussed in Section 3.3. Next, Chapter 4 provides the visualized results of the data collected from the experiments, breaking down the results into details. Lastly, the Chapter 5 discusses the insights, challenges, and conclusions regarding the low-cost consumer-grade sensor technology researched in this work.

Chapter 2: Indoor Air Quality

2.1 Air Quality and Health

Proper indoor air quality (IAQ) is essential to the physical, mental, and emotional well-being of occupants, who can spend upwards of 90% of their time indoors (Robinson and Nelson, 1995). Exposure to poor IAQ poses a significant threat to public health (González-Martín et al., 2021). Indoor air contains a mixture of pollutants including those generated indoors as well as those that penetrate from the outdoor environment via infiltration, natural ventilation, and/or mechanical ventilation (Dey, 2018). In general, poor IAQ can induce or exacerbate illnesses related to the respiratory (Franklin, 2007, Lévesque et al., 2018) and cardiovascular systems (Lin et al., 2013, Chuang et al., 2017) in addition to negatively affecting occupant mood (Hummelgaard et al., 2007, Fiedler et al., 2008), productivity (Mujan et al., 2019), and performance (Mendell and Heath, 2005, Seppänen and Fisk, 2006).

2.2 Volatile Organic Compounds

Volatile Organic Compounds (VOCs) are one class of air pollutants that encompass a large and diverse range of compounds, some of which can cause adverse health effects at low exposure levels, while others require chronic exposures at high concentrations to pose a health risk (Organization et al., 2010, Feron et al., 1992). Several common VOCs include aromatics such as benzene and xylene in addition to aldehydes such as formaldehyde and acetaldehyde (Spinelle et al., 2017).

Recent studies have shown strong associations between exposure to formaldehyde and the development of adverse reproductive and developmental effects (Duong et al., 2011), asthma in children (Rumchev et al., 2004, McGwin Jr et al., 2010), and certain types of cancers (Salthammer et al., 2010, Nielsen et al., 2017). Additionally, many VOCs can be respiratory (Klopsteg, 1943, European, 2011) and sensory irritants (Cometto-Muñiz et al., 1999; 2002), carcinogens (Boeglin et al., 2006, Sax et al., 2006, Costa et al., 2019), developmental toxins (David et al., 2001, Wogan et al., 2004), neurotoxins (David et al., 2001, Covington and JR., 2012), hepatotoxins (Reinhartz, 2006), and immunosuppressants (Wolkoff et al., 2006), in addition to causing symptoms that manifest as sick building syndrome (Organiza et al., WHO, 1989).

Common activities that emit VOCs include cooking, painting, using personal care products, smoking, and cleaning (Nirlo et al., 2015, Szulczyński and Gębicki). Other sources of VOCs indoors include building materials and occupants themselves (e.g. breathing) (Liu et al., 2019). Many cleaning and personal care products contain VOCs as stabilizers, additives to create pleasant aromas, or inactive ingredients (Kwon et al., 2008). Children represent one of the most at-risk populations since exposure to VOCs can cause significant health complications during early development and beyond (Sherriff et al., 2005, Franck et al., 2014, Trevillian et al., 2005, Lehmann et al., 2002, Kwon et al., 2015).

2.3 Air Quality Monitoring

An important first step for improving IAQ in households may be to accurately monitor the home environment in real-time to detect and ultimately respond to pollution events promptly. There are a range of tools for the measurement of VOCs in the indoor environment in real-time (Hori et al., 2015, Piedrahita et al., 2014, Rüffer et al., 2018). Many of these techniques carry either significant costs (Nirlo et al., 2015, Leidinger et al., 2014, Spinelle et al., 2015), or extensive setup, calibration steps and personnel to operate (Nirlo et al., 2015). Other possible measurement technologies include Sorbent Tubes (SOR), Photo-Ionization Detectors (PIDs), Dinitrophenylhydrazine (DNPH) tubes, and colorimetric formaldehyde multi-mode monitors (FMMs) (Nirlo et al., 2015), many of which require sampling system setup, pre- and post-sampling calibration, and off-site analysis among other challenges. It is worth noting that the accuracy and precision of commercial devices (even those at low price-points) continue to improve as they become more robust (Buehler et al., 2021).

Advertised as affordable alternatives to their historically expensive and complicated (Lewis et al., 2016) research-grade counterparts, new consumer-grade IAQ monitors are seeing greater demand. However, these devices continue to face major challenges such as limited sensitivity, selectivity (range of compounds detected), and the inability to accurately detect low concentrations (Schütze et al., 2017, Liu et al., 2012). Nearly all commercially-available VOC sensors are based on one of six principles: PID, amperometric or potentiometric electrochemical signatures, optics, gas chromatography, electronic sensor arrays, or conductivity (Spinelle et al., 2017). There is currently no agreed-upon definition for what VOCs make up the value for TVOCs in these sensors (Mølhave et al., 1997), which can potentially result in two different TVOC sensors responding differently to the same VOCs (Demanega et al., 2021).

2.4 Study Hypothesis

The purpose of this study is to compare the TVOC sensors in three consumer-grade air quality monitors to assess how accurately each device measures TVOC concentrations. The hypothesis is that each of the three consumer-grade devices measures and displays the same or very similar concentrations and temporal pattern of TVOCs within the same environments. To assess the three TVOC devices' performance, a series of controlled laboratory and real-world home experiments were conducted. The contribution of this paper is a data-driven assessment of consumer-grade TVOC sensors, their performance, and a discussion on the research questions that arise in pursuit of clean indoor air using consumer-grade sensor technologies.

Chapter 3: Methodology

3.1 Devices

This study focuses on TVOC sensors that operate on the principle of conductivity, which is arguably the most affordable category of sensor technologies currently available. More specifically, the devices used in all experiments contain Complementary Metal-Oxide Semiconductor (CMOS) gas sensors. To assess the performance of consumer-grade air quality monitors that use CMOS sensors, focus was placed on sensors designed to measure TVOCs in the air and provide real-time feedback to consumers. Table 3.1 summarizes the characteristics of the three TVOC devices selected for this study. The selection criteria was designed to most closely resemble that of consumers. Selected devices have an average consumer rating of 4/5 stars or greater, a price of less than $300, and provide real-time feedback about air quality.

As a reference, we used a state-of-the-art sampling tool called the Vocus 2R Proton Transfer Reaction Time-of-Flight mass spectrometer (**Vocus PTR-ToF**), capable of detecting and measuring VOCs at the parts per trillion concentration level. The Vocus PTR-ToF has the advantage of detecting over a thousand different compounds in real-time, in contrast to consumer-grade devices that provide a single total value for the total VOC profile in an indoor space. Knowing the concentrations of specific compounds has many advantages. For example, toxicity levels of VOCs span over many orders of magnitude (Ber), so a relatively abundant compound that is benign – such as acetone or ethanol – will contribute more to the consumer-grade devices' TVOC measurement, resulting in false outputs. Therefore, the Vo-

Table 3.1: Device Selection Criteria and Performance Parameters

Consumer Devices	Device 1	Device 2	Device 3
Measured	T, RH, TVOC	T, RH, TVOC PM	T, RH, TVOC, Radon, CO_2
TVOC Sensor	SGPC3	SGPC3	BME680
Sensor Type	Coated CMOS	Coated CMOS	Coated CMOS
Calibration Gas	Ethanol	Ethanol	Ethanol + bVOC*
Price ($100 - $300)	$99	$179	$230
Avg Rating (1-5)	4	4.5	4
Data Access	✓	✓	✓
Feedback	1-5 Star Display	Mobile App**	3-Color LED Ring
Sampling Rate (once per)	10 min.	1 min.	5 min.

* bVOC mixture with Nitrogen as carrier gas consisting of Ethane (5 ppm), Isopreme/2methyl-1,3 Butadiene (10 ppm), Ethanol (10 ppm), Acetone (50 ppm), Carbon Monoxide (15 ppm).
** Mobile application provides notifications and alarms.

cus PTR-ToF enabled us to assess the performance of the consumer-grade devices when exposed to low concentrations of more concerning compounds.

3.2 Experiments

This study consisted of two sets of experiments: home experiments and laboratory experiments. We designed the home experiments to measure the TVOC concentration in a real residential environment, consisting of event-based and continuous daily measurements; Table 3.2 provides an overview of the home experiments. These experiments were conducted in an occupied apartment unit located on the first floor. During all experiments, the three consumer-grade devices were placed within 120 cm of each other to ensure equal exposure to the same environment. Following the manufacturer's instructions, the devices were set up to monitor TVOC concentrations indoors in the apartment occupied full time by two occupants during the COVID-19 pandemic to observe the quantitative and qualitative output of each device in response to common household activities.

3.2.1 Home Experiments

Table 3.2: Home Experiments Summary

Home	Phase 1	Phase 2	Phase 3
Duration	4 Weeks	2 hours	2 days
Environment	Livingroom	Kitchen	Livingroom
Objectives	Reg. Activities	Cook + Clean	Effects of Occupancy
No. of Occupants	2	2	0
Test Area	18 m^2	9 m^2	18 m^2
Total Area	90 m^2	90 m^2	90 m^2

In addition to TVOC emissions from building materials, occupant activities are major contributors of TVOCs in the lived environment with cooking and cleaning producing the greatest concentrations for short periods of time (Liu et al., 2019, Kristensen et al., 2019). Phase 1 of the home experiments consisted of an observation period of four weeks to investigate the daily TVOC patterns as reported by the consumer-grade devices and compare them to one another. During this period regular cleaning was also undertaken due to COVID-19 to eliminate potential fomites (cdc, a;b).

Phase 2 of home experiments aimed to study the effects of human sources of VOCs on the consumer-grade devices' TVOC sensor readings. High levels of TVOCs due to human activities can obscure TVOCs emitted from building materials or other environmental sources. Therefore, average TVOC levels during occupied periods were compared to an unoccupied period to assess the influence of human activities on TVOC sensor readings.

Phase 3 of Home Experiments followed next and consisted of two activities: A grocery cleaning followed by a regular cooking and cleaning event. First, grocery items were placed on a kitchen counter approximately 150 cm away from the consumer-grade devices. A solution of 80% ethanol was used to clean the grocery packages and counter-top surfaces. The window in the kitchen was kept closed per regular practice and the HVAC system was turned off for the duration of the experiment. The devices remained in the test area overnight to continue to sample the air. The second activity involved cooking and shortly thereafter cleaning all surfaces. Next, the responses of the consumer-grade TVOC devices are compared to the PTR-ToFF analysis of the same air samples collected using two airtight canisters.

Seven common VOCs of interest are studied along with a total concentration of VOCs as detected by the Vocus PTR-ToF. These VOCs - Acetaldehyde, ethanol, acetic acid, acetone, methacrolein, monoterpene, and benzene - are all relevant to indoor spaces due to abundance, toxicity, or use. Acetone, methacrolein, and ethanol are abundant in human breath. Acetaldehyde is emitted from plants and ripe fruits and is used in dyes and as a flavoring agent. Quantifying the concentrations of these seven VOCs during different events provides insight into what the consumer-grade devices appear to detect. The canisters are first flushed with zero air and then pumped down to a vacuum 25 psi lower than atmospheric pressure prior to sampling to ensure that all VOCs in the canister can be attributed to the sampling event. The canisters show a snapshot in time of the complete event. The canisters were sealed and measured by the Vocus PTR-ToF within two hours of being sampled to minimize reactions of VOCs within the canister. Canisters were sampled at four points: outside the home, inside the home before any events to determine the VOC background, inside the home during a cooking event, and inside the home during an ethanol-based cleaning event shortly after cooking.

3.2.2 Laboratory Experiments

Table 3.3: Laboratory Experiments Summary

Laboratory	Phase 1	Phase 2
Location Setting	Large Test Chamber	Small Flow Chamber
Test Volume	81 m^3	0.008 m^3
Objectives	Bleach and H_2O_2 Disinfectant Response	Controlled Step Response
Compounds Studied	Organic Disinfection Byproducts	Known Gas Standard*

* See Table 3.4

Table 3.4: VOCs present in Gas Standard

Gas Standard Name	Formula	Concentration (ppb)*
Methanol	CH_4O	556
Ethanol	C_2H_6O	517
Acetonitrile	C_2H_3N	527
Acetone	C_3H_6O	533
Isoprene	C_5H_8	517
Dimethyl Sulfide (DMS)	C_2H_6S	557

* Manufacturer reports uncertainty of $\pm 5\%$.

For the laboratory experiments, consumer-grade devices were placed inside a 6 m x 4.5 m x 3 m (81 m^3) stainless steel environmental chamber with the Vocus PTR-ToF to compare their TVOC measurements with concentrations of specific VOCs detected by the Vocus PTR-ToF. To identify compounds and concentrations, the Vocus PTR-ToF mixes H_3O+ ions from a water reservoir into the inlet. The

H_3O+ ion reacts with the VOC of interest if the proton affinity of the compound is higher than that of water. The majority of common indoor VOCs relevant to indoor air quality have proton affinities less than water and can be detected by the Vocus PTR-ToF, with the notable exception of alkanes – such as methane, propane and butane – and formaldehyde. By passing the protonated compound across a voltage onto a detector and measuring the time, the mass of the compound can be calculated at over 10,000 $M/\Delta M$ resolution.

During phase 1, cleaning events using hydrogen peroxide (H_2O_2) and chlorine bleach – active ingredient sodium hypochlorite (NaOCl) – were simulated within the chamber. Two methods were used for cleaning:

1. Spraying cleaning solution onto tables placed in the chamber,
2. Vaporizing the solution into the ambient air of the chamber.

Using two different methods allowed us to assess the quick response as well as the prolonged exposure performance of the TVOC sensors. In the spraying method, 300 mL of each cleaner was sprayed onto 6 tables evenly spaced in the middle of the environmental chamber. Total table surface area was 6 m^2. Consumer-grade devices were placed on the floor close to the corner of the room. The Vocus PTR-ToF measured via 1/8" tubing (Teflon) directly from the chamber outflow, which was controlled at an air exchange rate of 2.8 h^{-1}. The disinfectant solution sprayed on the tables evaporated quickly, producing increased concentrations in the majority of VOC concentrations within 3 minutes after application. The high air exchange rate of 2.8 h^{-1} caused concentrations of the majority of compounds to decrease back to normal levels within an hour.

For phase 2 of the laboratory experiments, we compared the consumer-grade devices' TVOC readings with known VOC concentrations. The devices were placed in an 8 L (0.008 m^3) stainless steel flow-through canister. Ultra-pure zero air and a known gas standard were flowed through at total flow rates ranging from 1.4 L/min to 4.5 L/min at varying dilution rates. To prevent any influence from VOCs other than the gas standard, first zero air was drawn into the canister for 10 hours. Next, the gas standard was introduced gradually every 15 minutes, increasing the dilution of the air being sampled.

3.3 Data Processing

Data export functionality was a requirement for our selection and is therefore available on all three consumer-grade devices. While device 1 provides a useful mobile application for providing feedback and granting data access, the app is proprietary and only available on the Apple iPhone or iPad. Device 2 provides access to the data through their mobile application available on Android and iOS. Device 3 provides a comprehensive web-based dashboard with data selection and export functionality as well, in addition to a mobile application designed to provide feedback and information about IAQ. After cleanup and re-sampling, the data were then merged into a single data set for analysis and visualization.

The devices exhibit different battery lives where devices 1 and 3 have significantly longer battery lives than device 2. Therefore, device 2 requires frequent maintenance or to be plugged in to avoid data loss during experiments. The devices were plugged in during the experiments to ensure data loss prevention. Initially, the data were cleaned to remove any unused parameter information such as CO_2 or PM from each data set, leaving only the TVOC readings and the time stamps. The data were then re-sampled to 15-minute averages (instead of 10 minutes) to better account for possible outliers and reduce imputations to a minimum while maintaining a relatively high resolution. This process resulted in the loss of $<<$1% of data points, which were resolved through linear interpolation for the single data point losses. No continuous blocks of data were lost in this process.

The Vocus data was collected using TofWerk software and processed using PTRwid to achieve a unified mass list and signal count time series data. The Vocus was calibrated using a diverse gas standard mix containing 16 compounds ranging from 33 to 429 Da. While the 16 compounds could be explicitly calibrated for by ramping the dilution factor of the gas standard with zero-air gas, the Vocus can measure more than a thousand compounds. As done previously, we produced a best fit line of the explicitly-known sensitivities versus each compound's respective H_3O+ reaction rate constant (Krechmer et al., 2018). For compounds with an unknown reaction rate constant, we assumed a default value of $2.5 \cdot 10^{-9}$ cm^3 s^{-1}.

Chapter 4: Results

4.1 Home Experiments

4.1.1 Home Experiments - Phase 1

The normalized heat-map of the consumer-grade devices for the span of the four-week study are provided in Fig. 4.1. Equation 1 was used to normalize the TVOC values to highlight the patterns. We also provide a higher resolution view of each sensor's performance during the seven-day study in this same figure. Areas A through D in Fig. 4.1 showcase similarities and differences between the patterns of TVOCs. Fig. 4.2 provides a higher resolution, seven-day subset of the initial four-week study. While devices 1 and 2 follow similar patterns, device 3 exhibits some deviations. We also observe different concentrations of VOCs being reported.

$$X_{Normalized} = \frac{X - X_{min}}{X_{max} - X_{min}} \qquad (1)$$

The consumer-grade devices also have different ranges as set by their manufacturers. This is best shown in Fig. 4.3 where the various TVOC levels, as defined by the manufacturers, are provided. For example, based on TVOC sensors alone, at levels between 200 and 350 ppb, device 1 indicates a different quality of air, than devices 2 and 3. And at values between 800 to 1000 ppb device 1 indicates hazardous levels of TVOCs, while devices 2 and 3 indicate a medium level of TVOCs. It is important to note that these ranges are set by the companies for TVOC readings alone, and the feedback provided by the devices may include other

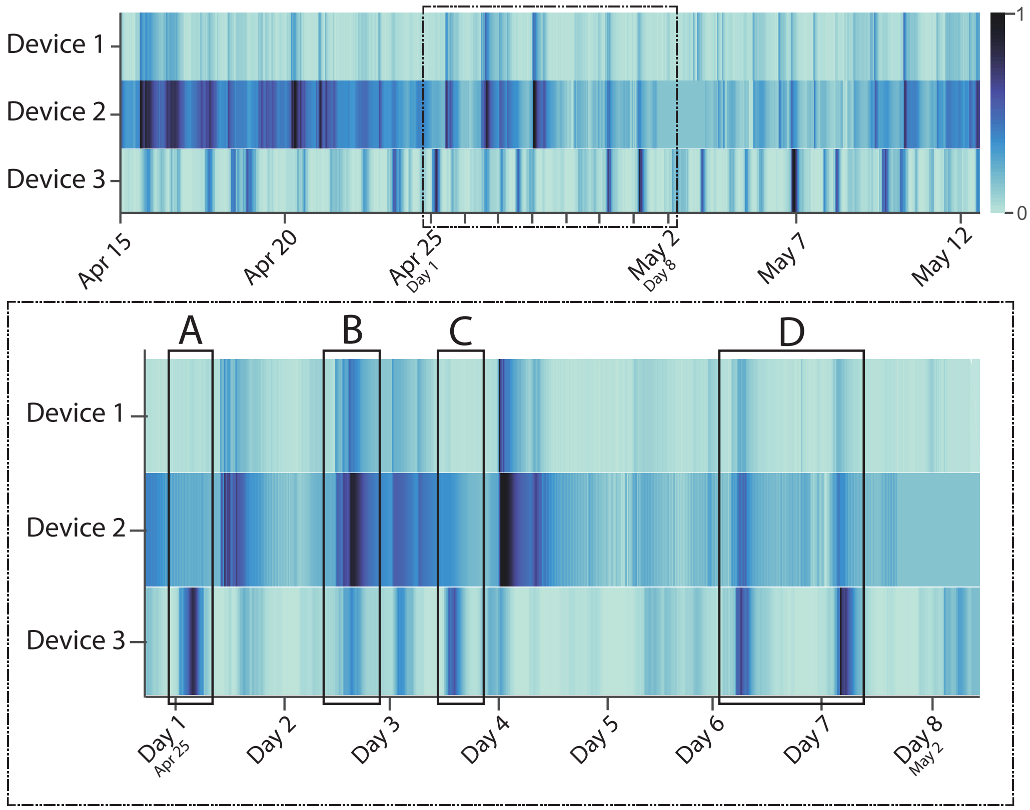

Figure 4.1: The normalized, 15-minute average levels of TVOCs (ppb) from consumer-grade devices highlighting pattern detection with 0 indicating the minimum and 1 indicating the highest normalized TVOC level for each device

parameters such as CO_2 and PM readings. Therefore, the colors do not necessarily represent the feedback provided by the device - though device 1 only has a TVOC sensor for air quality -, but rather the feedback based on the TVOC levels alone.

An overview of the distributions of each consumer-grade device's measurements is provided in Fig. 4.4, which provides insight into the devices' performances compared to one another. We first observe an offset between consumer-grade devices 1 and 2 with similar spans, while device 3 shows a significantly higher span. We also observe a bi-modal distribution from device 2, which may indicate the detection of two particular VOCs by that sensor.

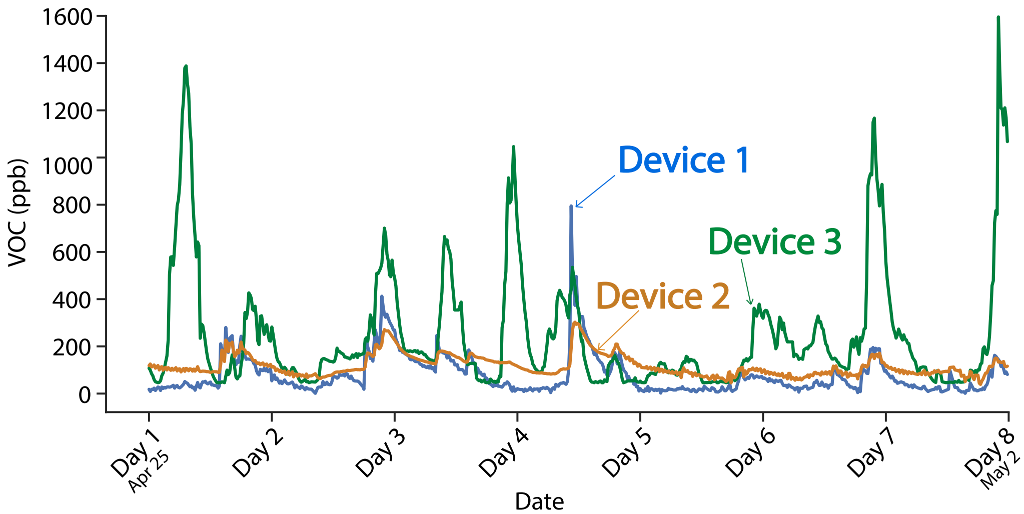

Figure 4.2: An overview of 15-minute averaged TVOC concentrations (ppb) measured by three co-located consumer-grade TVOC sensors in continuously occupied two-person apartment unit. Devices 1 and 2 more closely follow each other's patterns, while device 3 shows some deviations in its pattern.

Fig. 4.5 shows the concentrations of seven key VOCs and 202 other VOCs measured by the Vocus PTR-ToF and the responses of the three consumer devices under various conditions. As observed earlier, this experiment's patterns were observed clearly by all three devices along with same time marks. The VOCUS PTR-ToF device shows a small rise in TVOCs during cooking, while showing a significant increase during cleaning. As such, we observe a small positive trend during cooking and a significant change during cleaning. Devices 1 and 2 follow the same patterns of increasing during cooking and decreasing during cleaning. Device 3 however exhibits a consistently downward trend through the experiments. From the breakdown table provided, the particular compounds to which the sensors are sensitive are unknown.

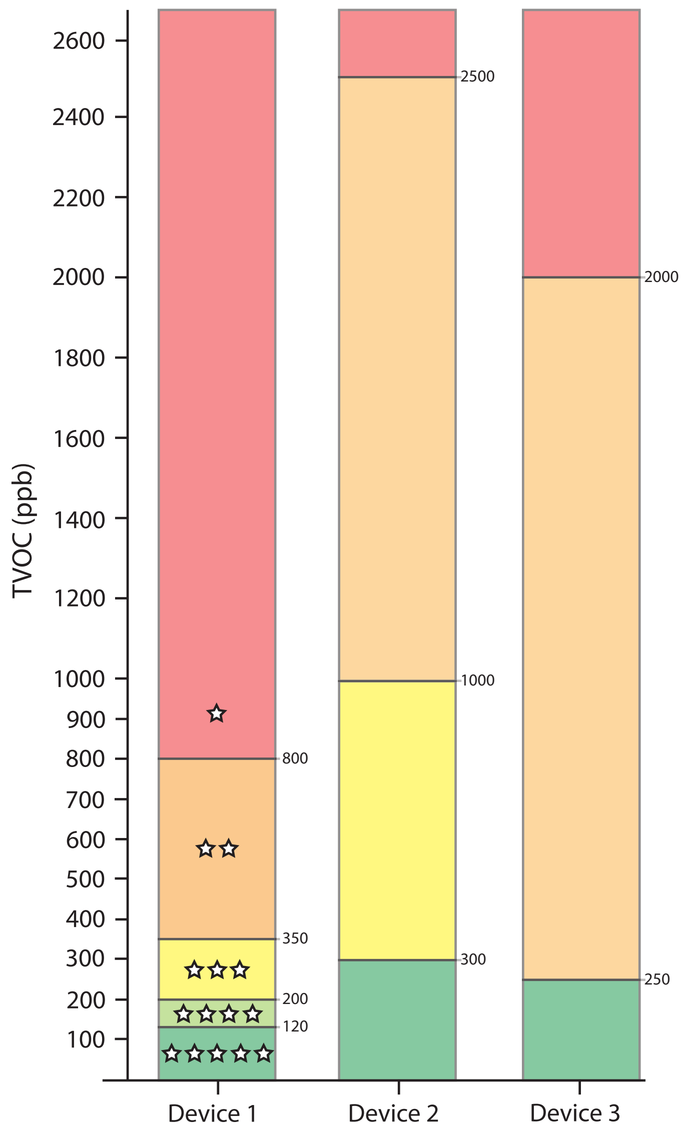

Figure 4.3: Consumer-grade devices 1, 2, and 3 feedback scales. Device 1 provides a star rating feedback, which has been translated to the same color scheme as other devices. Colors are harmonized among all consumer-grade devices. The colors do not represent the feedback of the devices as devices 2 and 3 include other sensors besides TVOC. The range of colors from green to red is used to better highlight the TVOC sensor's feedback and the discrepancies between TVOC sensor readings among the different consumer-grade devices.

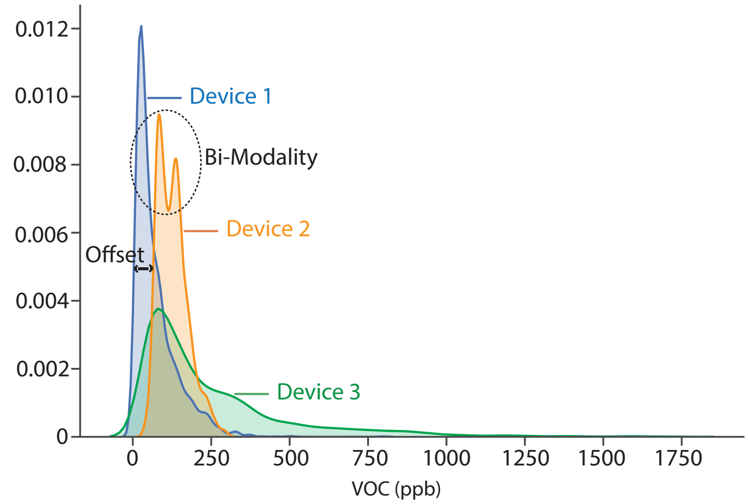

Figure 4.4: Consumer-grade device measurement distributions showing a double peak for device 2 and an offset between devices 1 and 2, which use the same TVOC sensor. The bi-modality in device 2 could indicate sensitivity to two predominant VOCs as detected by device 2. Device 3 exhibits a high span compared to devices 1 and 2. Note: Negative values are estimations by the algorithm for visualization purposes and not indicative of negative TVOC levels.

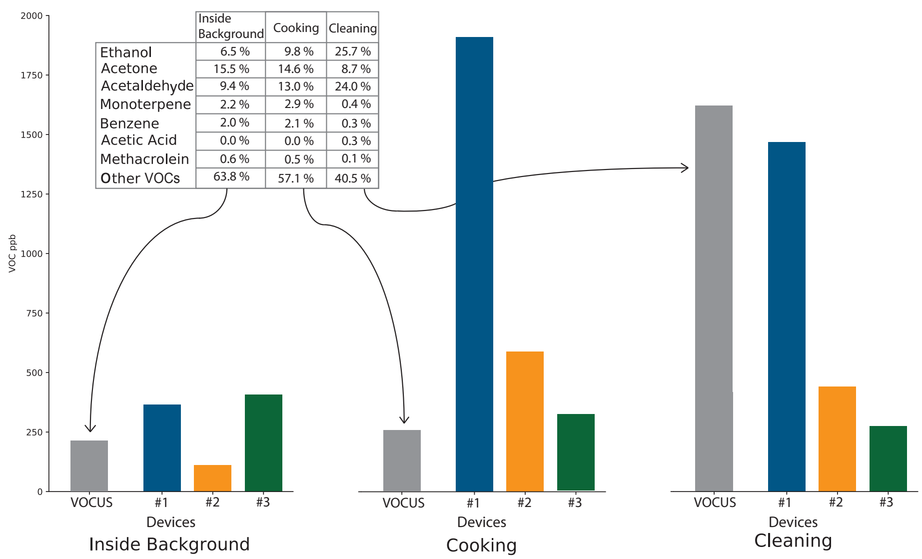

Figure 4.5: Comparison of concentrations of specific VOCs measured by the Vocus PTR-ToF (VOCUS) to the measurements from the three consumer devices under different scenarios within a home. A change in composition is observed across the different activities as reported by the Vocus.

4.1.2 Home Experiments - Phase 2

In Fig. 4.6, we observe the patterns from consumer-grade devices during both occupied and unoccupied periods. Devices 1 and 2 appear to have similar patterns while device 3 differs. However, all devices show no activity during the unoccu-

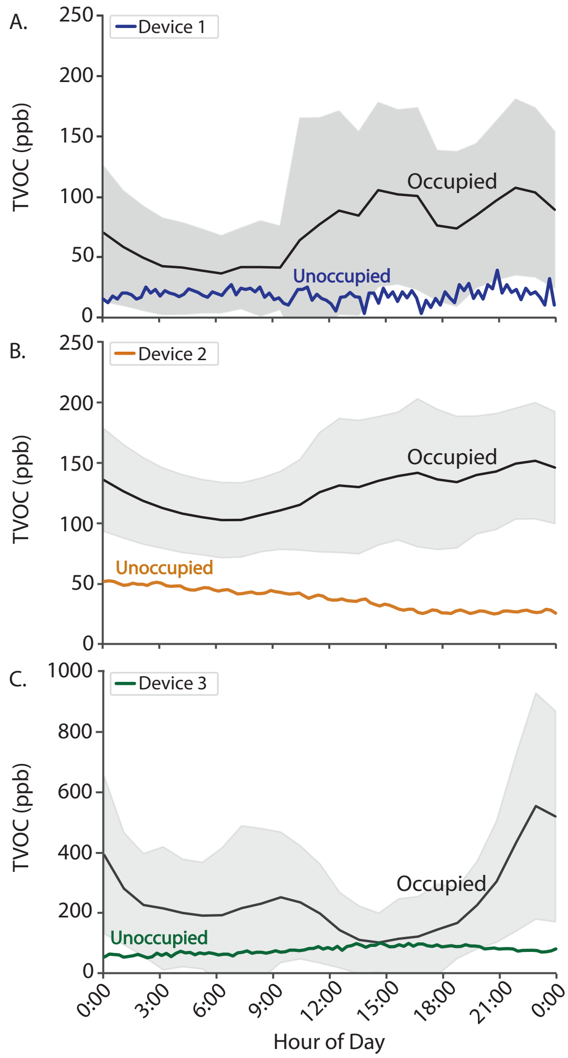

Figure 4.6: Occupancy figures with +/- 1 standard deviation range in grey. Axis limits are set programmatically to best fit the figure and to prevent information loss due to scaling. Therefore device 3 has a different range along its y-axis. Occupant impact on TVOC levels in the indoor air is observed.

pied period. These findings suggest a high degree of sensitivity by the TVOC sensors to occupants and human sources of VOCs such as those exhaled. Human presence appears to be a factor in TVOC readings by consumer-grade devices 1 and 2 as the hourly averages appear to follow standard occupancy patterns. Consumer device 3 exhibits a different trend, despite it having been calibrated against breath-VOC as discussed earlier in Table 3.1.

Another important observation from Fig. 4.6 is the average TVOC concentrations during the unoccupied periods. If much smaller concentrations of hazardous VOCs were continuously present in ambient air, the inability of the sensors to detect them could result in a false sense of security from the devices. This further highlights important limitations of consumer-grade TVOC sensors.

4.1.3 Home Experiments - Phase 3

Phase 3 of the home experiments began with the grocery cleaning event. Fig. 4.7 shows the TVOC levels and feedback, indicated by background colors, while using 80% ethanol cleaning solution. Initially, we observe that while devices 1 and 2 can detect the grocery cleaning event uniformly, this event is not discernible from device 3's output. Devices 1 and 3 appear to indicate medium quality air from the late morning (10:00 - 11:00) until the cleaning event. The most notable observation is the downward trend from device 3 from the beginning of the cleaning exercise until the late evening when devices 1 and 2 indicate lower TVOC levels than device 3. Lastly, the scales of Fig. 4.7 and Fig. 4.8 were set to automatically fit the data for better visualization. The differences are notable in the levels of TVOCs reported by the consumer-grade devices.

Phase 3 of the Home Experiments continued with the cooking experiment fol-

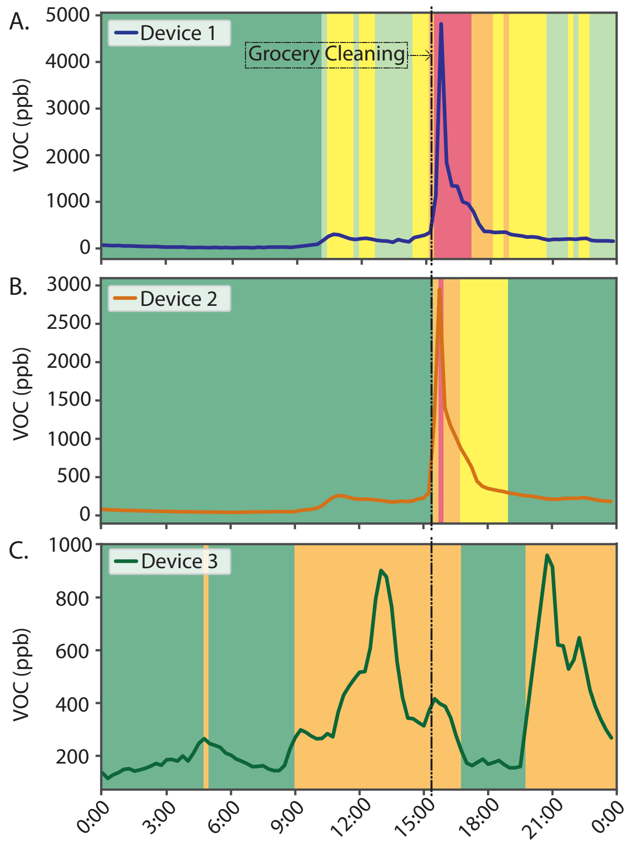

Figure 4.7: Phase 2 - Home Experiments where groceries are cleaned using ethanol solution at 15:20 hours. Devices 1 and 2 closely follow the event while Device 3 does not exhibit any reaction to the cleaning activity in this case.

lowed by cleaning of the kitchen area using 80% ethanol. In Fig. 4.8, uniform event detection is noted at the beginning of the experiment where the rise due to cooking is clear. However, we cannot clearly distinguish between the cooking and cleaning activities, or the end of cleaning based on the figures and the TVOC data. This is attributed to the closeness of the activities and how CMOS sensors inherently function.

While the consumer-grade devices show different concentrations, they exhibit similar patterns in response to TVOCs present due to cooking and cleaning. De-

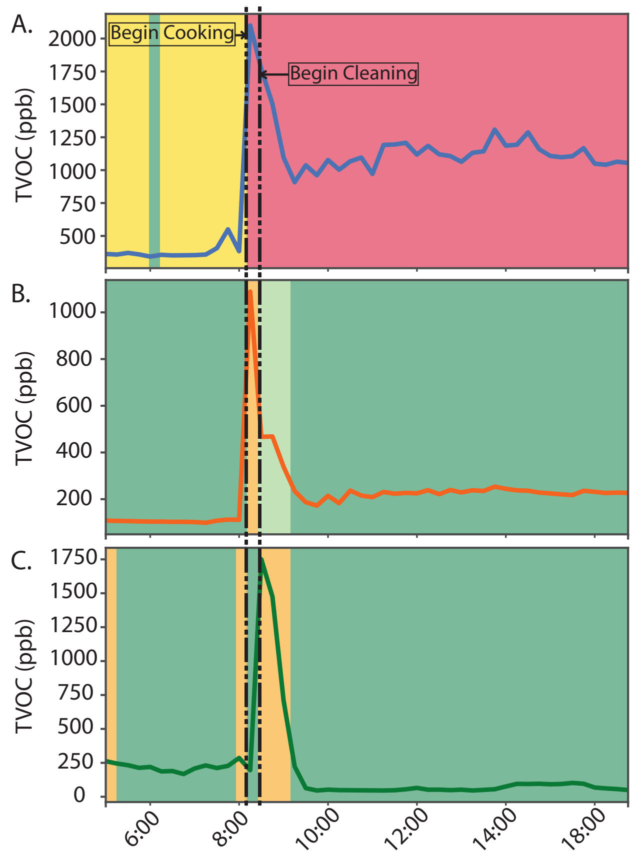

Figure 4.8: Phase 2 - Home Experiments cooking followed by cleaning activity beginning at 8:00. The cleaning activity took approximately 5 minutes. While all three devices track the beginning of the event, Device 1 provides a drastically different feedback most likely due to sensor saturation or other unknown causes.

vice 1 indicates higher concentrations of TVOCs in the air than the other two consumer-grade devices. This is most likely due to potential saturation of the sensor, which highlights yet another challenge with using CMOS sensors. Using the color-scheme described earlier to indicate air quality based on TVOCs, consumer-grade device 1 indicates poor quality air while devices 2 and 3 indicate relatively clean air by their manufacturer thresholds.

4.2 Laboratory Experiments

4.2.1 Laboratory Experiments - Phase 1

Despite the advent of sustainable and safe cleaning solutions, chlorine-based bleach and hydrogen peroxide remain two of the most common cleaning agents used in households. In this experiment, chlorine bleach and hydrogen peroxide were used to study the response of the devices to the chemical reaction byproducts of both cleaning agents. The spraying method produced a response in many different VOC concentrations – along with chlorine-containing volatile chemical byproducts – while the evaporation method resulted in elevated pseudo-steady-state concentrations that could easily be compared to the signals of the consumer-grade sensors. Both methods showed sharp increases in the majority VOCs measured with the Vocus PTR-ToF. Devices 1 and 2 collected data from both the spraying and the vaporizing experiments while device 3 was only operating during the vaporizing experiment.

In Fig. 4.9, neither device 1 nor device 2 shows a response to the cleaning event with the chlorine-based bleach with monochloramine (inorganic) as its primary byproduct. From Fig. 4.9, devices 1 and 2 respond to the acetanilide in hydrogen peroxide cleaner. While acetanilide is toxic at high concentrations, it does not pose the same dangers as the byproducts of chlorine bleach. The elevated concentrations of so many compounds during a cleaning event pose health concerns, and the inability to detect a health-threatening indoor air pollutants appears to be a considerable limitation of the consumer-grade CMOS TVOC sensors.

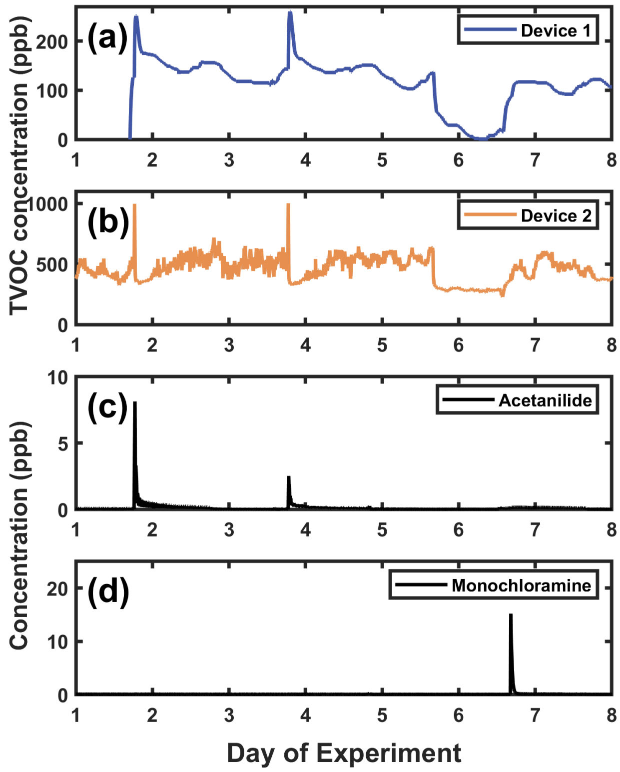

Figure 4.9: Device 1 (a) and Device 2 (b) concentration response (top two panes) compared to acetanilide (d) and monochloramine (d) concentration data measured by the Vocus PTR-ToF. The spikes in acetanilide (occuring on days 1 and 3) and monochloramine (day 6) serve as proxies for for hydrogen peroxide and bleach disinfection events, respectively.

4.2.2 Laboratory Experiments - Phase 2

Due to the flow rate relative to the volume of the canister, the concentration of VOCs introduced in the canister should stabilize and be well-mixed within 4 minutes of each step change, leaving over 10 minutes of steady-state concentrations for the devices to measure. The gas standard contains 15 VOCs, each with a concentration of approximately 500 ppb. All of the compounds should be detected by the consumer-grade VOC sensors, so the sum of all 15 compounds' concentration (gas standard TVOC) is the expected response of the devices. Fig. 4.10 shows the response to the step routine.

From 6:00 until 10:00, all three devices had stable background readings, although all devices measured non-zero concentrations of VOCs that were actually non-existent due to the constant flow of zero air. Devices 1, 2, and 3 averaged 305 ppb, 147 ppb, and 588 ppb, respectively, during the background period. The true TVOC concentration was actually 1-2 magnitudes lower than the hundreds of ppb recorded. At 10:15, a diluted flow of the gas standard was introduced in the canister. The dilution of the gas standard was decreased – leading to higher TVOC concentrations – in 15-minute increments until 12:00, when the flow of the gas standard was turned off, resulting in ultra-pure air within the canister. The maximum gas standard TVOC concentration was just over 3000 ppb. With the compounds present in the standard at these concentrations, a human present in a room would experience a very strong odor and have increased health risks from pro0longed exposure.

Consumer-grade device 1 was very sensitive to the small changes in dilution of the gas standard. Its signal immediately responded to the introduction of the gas standard VOCs, but the signal also saturated quickly compared to devices 2 and 3. Meanwhile, devices 2 and 3 showed responses up to the highest TVOC step level. While all three devices showed responses to increasing levels of VOCs within the canister, none of their readings stabilized during each step. With flow rates of 1.4-4.75 L/min being drawn into the 8 L canister, concentrations would have reached equilibrium well before the 15 minute step length. Devices 2 and 3 only collect data every 5 and 10 minutes, respectively, so with the 15 minute step length there was not enough data point to see an equilibrium state. Device 1

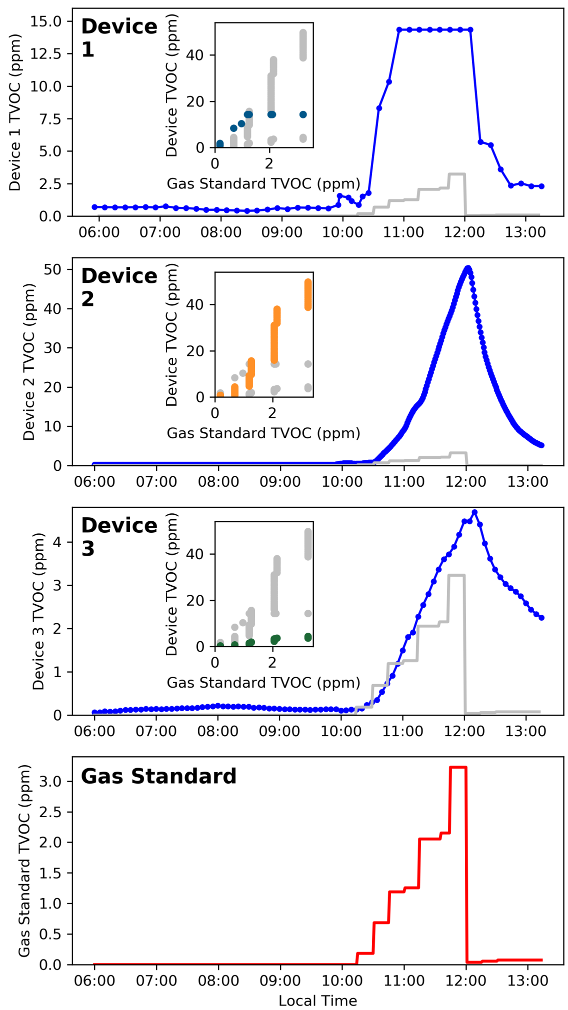

Figure 4.10: Ramp of known gas standard concentration. The top three panes show each devices' response to the gas standard ramp, with the gas standard included in each pane as a reference (light grey). The inset scatter plots show the correlation between the gas standard TVOC signal with each devices' reading. All data points with the gas standard TVOC concentration <0.1 ppm are removed in the scatter plot.

collects data every minute, which should have been sufficient to see equilibrium. The step from the highest concentration to solely ultra-pure air – occurring at noon – shows the response time of the devices to return to a low signal. All of the devices continue to show high concentrations an hour after clean air was drawn into the chamber.

Chapter 5: Discussion & Conclusion

Consumer-grade CMOS TVOC sensors studied here reported different concentrations of TVOCs in the same environment, making the numerical values difficult to use or interpret. These TVOC sensors may be capable of detecting patterns, but those patterns can differ at times across different devices, depending on the sources of VOCs present. A few challenges highlighted in this section include the differences in patterns and concentrations, slow response of the consumer-grade devices to step inputs of VOCs, the tailing off of the consumer-grade devices' outputs due to CMOS design and functionality, misleading outputs resulting in false positives or negatives, and research questions that have risen from this study.

All consumer grade devices exhibited both minor and major differences in various experiments. We observed variations during the general observation periods, while uniform patterns were observed during high-VOC-emitting activities and events. These differences are attributable to a range of causes, most important of which may be the calibration process for these sensors. Also, depending on whether the sources of VOCs are human or not, the devices can provide different outputs.

Consumer-grade CMOS gas sensors appear to be incapable of exhibiting distinct changes in the air within their sampling steps. As explained in appendix A, CMOS gas sensors operate on the basis of converting chemical reactions into electrical signals. This inevitably means that the sensor's signal is a direct function of the redox chemical reaction of the sensor, making the output signals change at the same rate as the chemical reaction. This true for both the beginning and the ending of the TVOC signals we observe.

CMOS gas sensors uniformly exhibit smooth and gradual changes in their signal outputs. As described earlier, this is most likely due to the output signal being a direct function of the redox chemical reaction, rather than changes in the air quality. We observed a gradual increase in the TVOC concentrations during our gas standard experiment, but we also observed a gradual tailing off of the TVOC signals. This is due to the continuation of the chemical reaction that is the very basis of CMOS gas sensors.

Another challenge resulting from the limitations of consumer-grade TVOC sensors are false negative and false positive outputs, which may pose problems for consumers who depend on these devices for information on the safety of their indoor air quality. This is especially true when a consumer-grade air quality monitor only uses a CMOS TVOC sensor for its air quality assessment as in device 1, effectively rendering its values a general guess for air quality. False negatives occur when the devices falsely indicate good quality air due to concentrations of TVOCs falling below the lowest levels detectable by devices. This means the devices may often indicate clean air even if there are low but concerning levels of carcinogenic compounds, resulting in a false negative. In this study, we presented the example of chlorine-bleach and its concerning VOC byproducts, which were undetected by the consumer devices. False positives occur when the devices detect higher concentrations of less harmful compounds such as ethanol, but report hazardous air quality. Implications of these readings may include occupants using more energy and taking unnecessary measures to improve what may only appear to be poor air quality.

While research continues on improving environmental sensing technology, certain important pollutants remain outside the reach of CMOS sensors. One study has found that most metal oxide and conductive sensors cannot reach levels below 100 ppb of benzene with detection thresholds two to three orders of magnitude higher for benzene in ambient air than the desired 1 ppb (Spinelle et al., 2015). Therefore, it may be best to use CMOS TVOC sensors within a suite of environmental sensors as supplementary information regarding the overall quality of the indoor air.

This study has also given rise to a range of research questions requiring further studies. First, the best configuration of environmental sensors – including TVOC sensors – is a research question of interest. Additionally, the question is raised as to what extent machine learning algorithms can be used to optimize the performance of sensor clusters.

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