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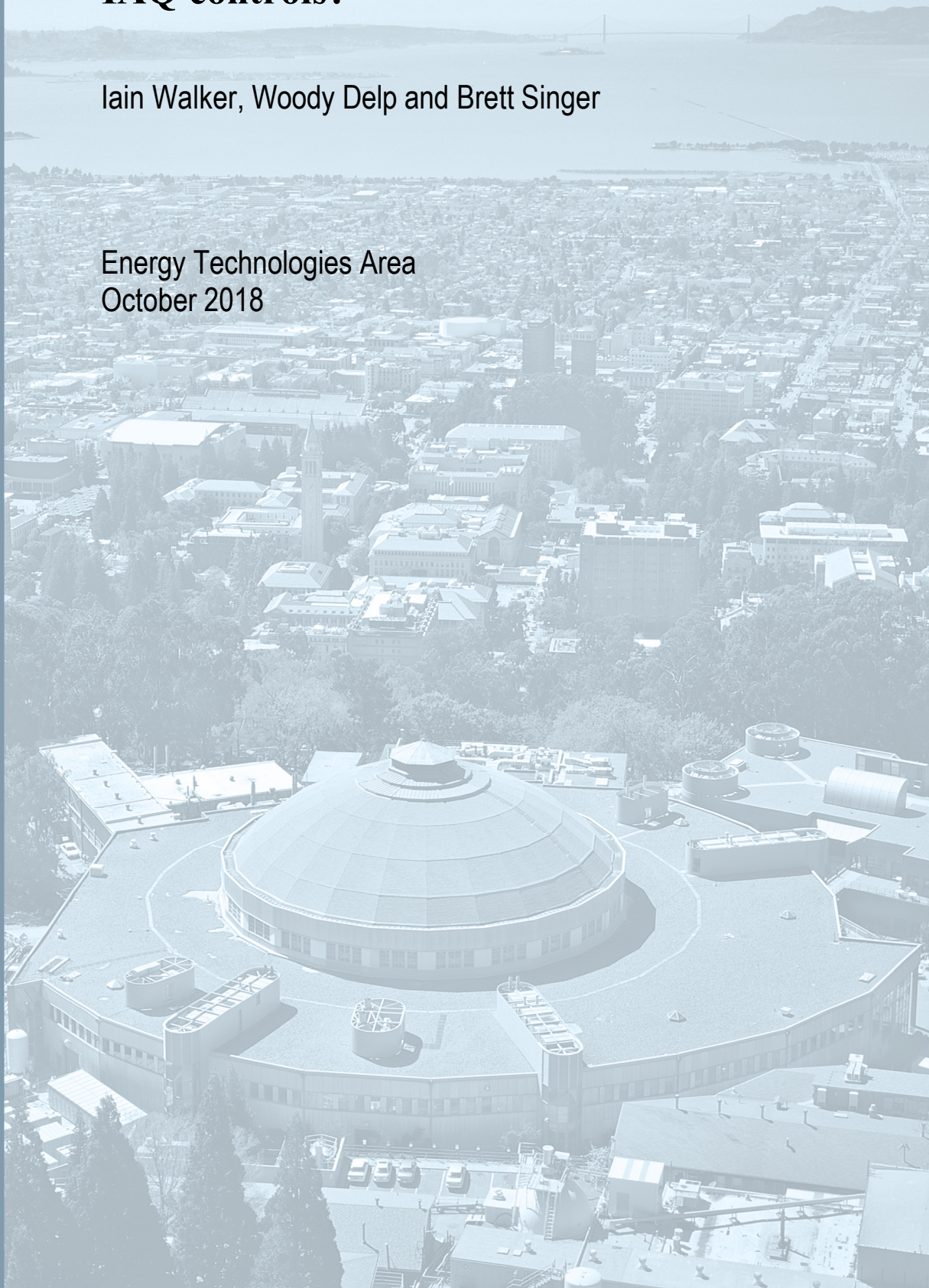
Are low-cost sensors good enough for IAQ controls?

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Disclaimer:

Abstract

Over the past few years there have been advances in sensing of some pollutants, primarily particles, that might lead to ventilation controls based on direct sensing of pollutants – particularly those relating to health. In this study we evaluated low-cost (about $200 US) IAQ monitors that measured PM2.5 - the most important health-related pollutant in indoor air. Controlled laboratory tests were carried out with known sources of particles (cooking, cleaning, candles, cigarettes) and by comparing the IAQ monitors response to research-grade and reference measurement methods. The results show a wide range of performance with the better IAQ monitors able to detect most particle sources/events and the worst ones detecting almost none. The best devices perform well enough to reliably operate a ventilation or filtration system but do not always report the correct magnitude of PM2.5 so there are restrictions on their use for calculating health effects.

Keywords

Sensors, Controls, PM2.5, IAQ, laboratory testing

Introduction

Current Indoor Air Quality (IAQ) standards and approaches to minimizing pollutants depend almost exclusively on using dilution with outdoor air for some generic, continuously generated contaminant (e.g., ASHRAE Standard 62.2-2016). Some standards include measurement of CO_2 (e.g., EN 13779 standard (CEN, 2007) and NEN 8088 (NEN, 2011)) – however this is not because CO_2 itself is a pollutant of concern, but rather because it can be used as an occupancy indicator or as something that correlates with bioeffluents. Ideally, we would like to measure contaminant concentrations directly and ventilate to control their concentration within acceptable limits. This would ensure that concentrations do not got too high (as they can if emission rates exceed our assumptions) and also allow for ventilation reductions, and resulting energy savings, if concentrations are low. Until recently, it was impractical to consider direct contaminant control in residential (and many commercial) spaces due to the high cost and maintenance requirements for monitoring equipment. In the past couple of years low-cost sensors have been developed for some contaminants of concern – the greatest example of which is for particles. These sensors have been incorporated into low-cost (<$250 US) IAQ monitors. This has opened up the possibility of direct control of ventilation (and filtration systems) by sensing particles. However, it is important to evaluate these monitors to determine if their results are sufficiently good to control a ventilation system.

In this study we performed laboratory experiments to compare the output of seven low-cost monitors to laboratory grade and reference particle measurement methods. The laboratory tests used a range of particle sources to determine if the monitors can reliably detect common household particle emission events. It should be noted that an important aspect of this work is consider particle size. The current state of the art is that particles less than 2.5 microns in diameter (PM2.5) are of the most concern for health. There are some

concerns that smaller submicron particles (less than 0.1 microns in diameter) may also be a health hazard, although the evidence for these smaller particles being a significant health hazard is not as strong. Most of the monitors evaluated for this study do not directly have a way of disaggregating results by particle size. For those that do we used the total and did not size disaggregate the results. Instead they employ calibrations or signal conditioning to take the raw output of a particle sensor and translate it into a reported particle concentration. Therefore, our results include both the response of the particle sensor and whatever calibration has been used by the manufacturers of the IAQ monitors. Not all particle emission events emit particles in these ranges (as will be shown in our results). The results can be used to assess the ability of these devices to provide a reasonable control signal for a ventilation system. The results of this study are discussed in more detail in Singer and Delp (2018) together with more information regarding individual sensor performance and discussion of potential indoor particle sources.

Laboratory testing

The experiments were conducted in a 120 m^3 laboratory with a 5.8 m by 7.1 m floor plan, as illustrated in (Figure 1). The room was continuously mixed with fixed direction and oscillating fans. Consumer and research particle monitors were placed on a wire shelving unit co-located with reference instruments in the central area, sufficiently far from source activities that measurements should reflect average room conditions rather than concentrated plumes. In a subset of experiments, filter samples were collected for time-integrated, gravimetric mass determination. During source activities, outdoor air exchange was provided solely by natural infiltration with no mechanical ventilation systems operating. After the source activity ended, particles were allowed to naturally decay over a period of variable duration. In most experiments, after about 1 hour of decay exterior doors at opposite ends of the laboratory were opened to rapidly ventilate the room and remove residual particles and co-pollutants. During the experiments, the outdoor air exchange rate was measured by a tracer decay method and varied from 0.5 to 1.1 h^{-1} with a median of 0.7 h^{-1}. Several mixing fans were placed in the test chamber to create uniform particle concentrations. Baseline measurements were taken prior to each source activity. The baseline values were subtracted from the measurements taken during the source activity and integrated over time to calculate mass integration measurements for the source.
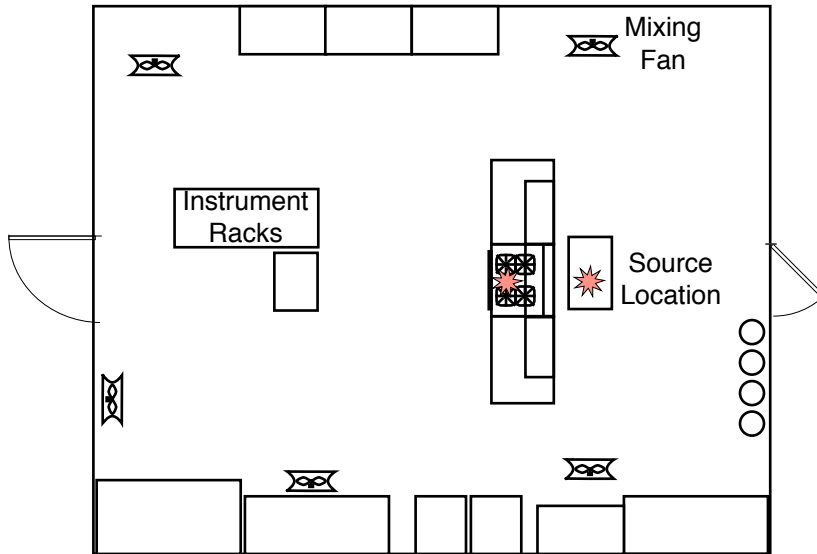
Figure 1. Plan view of test laboratory .

Particle Sources

The purpose of this study was to compare consumer and research monitor response to reference instrumentation for typical indoor-generated aerosols, therefore, we did not try to precisely control the source emissions. Instead, we used sources that might commonly occur in a home. There were 16 distinct sources: recreational combustion included candles, cigarettes, and incense; mineral sources included an ultrasonic humidifier without a filter, Arizona test dust, and shaking of a workshop dust mop; cooking sources included heating oil in a steel wok on gas or electric burners, frying bacon and toasting four slices of bread in a toaster oven, and stir-frying green beans in oil on a gas burner. Cooking sources that produced large numbers of particles with low to moderate mass concentrations and almost all below 0.3 m included heating water in a covered pot on a gas stove, heating a gas oven, cooking a pizza in the gas oven, cooking pancakes on a lightly oiled pan over medium heat, and toasting bread in a well-used electric toaster oven. Each source was active for about 10-15 minutes.

The highest 5-min baseline-subtracted mass concentrations (adjusted Mini-WRAS data) varied from 21 g m^{-3} for the pancakes to 721 g m^{-3} for one of the green-bean stir-fry experiments. The highest number concentrations varied from the AZ test dust and dust mop experiments (at 2–5 x10^3 cm^{-3}) to the Bacon + Toast experiment at 2 x10^5 cm^{-3}. The five experiments with the lowest peak mass concentration (Pancakes, Pots on gas burners, Oven, Pizza, Burnt Toast) were in the middle of the distribution of peak number concentrations (6th to 18th).

Table 1. Particle sources

Source	Description
Humidifier	Ultrasonic humidifier, cleaning cartridge removed
Incense	Incense stick (Shanthimalai Red Ng Champa)
AZ Dust	AZ test dust (0-3micron) manually puffed from bag
Beans	150g frozen green beans, 15g canola oil stir fried in steel wok on gas stove
Toast	Single piece of bread, medium-toasted in used electric coil toaster oven
Bacon+Toast	280g bacon fried on gas stove; 4 slices bread med-toasted in toaster oven
GB Oil	15g of canola oil brought to bubble in steel wok on gas stove
Burnt toast	Slice of bread, dark-toasted in used electric coil toaster oven
Dust mop	Aggressive shaking of a 90cm wide workshop dust mop
Candles	5 unscented dinner candles, lit with butane lighter
Gas+Pots	Two covered 5L pots, half-filled w/H_2O, heated on gas stove
Oven	Gas oven heated to 400F over 12 min after ~4 y of no use
Pancakes	Two batches pancakes cooked on a lightly oiled fry pan on gas burner
Pizza	Gas oven heated to 400F 14 min; frozen pizza cooked
Cigarettes	3 cigarettes lit with butane lighter, smoldered until self-extinguished
Electric Oil	15g canola oil brought to bubble in fry pan on an electric coil burner

Particle Monitoring Devices

A Grimm Mini Wide Range Aerosol Spectrometer Model 1.371 (Mini-WRAS) was used as a reference for 1-minute resolved data and also to provide distributions of particle number and mass concentrations. The Mini-WRAS combines an electrical mobility analyzer that counts particles in 10 size bins from 10 to 200 nm with a laser-based optical particle counter that provides particle counts in 15 size bins from 0.2 m (200 nm) to 2.5 m plus 16 bins between 2.5 and 35 m. The Grimm estimates volume concentration from the size-resolved number concentrations by assuming the particles are spheres, then calculates mass assuming a density of 1.68 g cm^{-3}. The density is a user-definable parameter that enables the Mini-WRAS to measure aerosols with varying composition.

Seven consumer grade monitors were selected for testing. All devices were available for retail purchase in the US in early 2017 and had either been tested previously by the US EPA or AQ-SPEC for outdoor use, or the research team had learned of their use in one or more citizen science projects. We also used two research-grade monitors that are often used in field and laboratory studies. Summary information for the monitors is listed in Table 2. All of the monitors have a data reporting interval that is reasonable for use as a ventilation controller where we are unlikely to want to make changes on a time scale of less than 5 or 10 minutes.

Table 2. Consumer and research grade monitors evaluated in this study.

Device [Code]	Cost ($US)	Data interval	Particle sensor	Notes
AirBeam [AB]	$249	1 sec	Shinyei PPD60PV	Full schematics and program available on github https://github.com/HabitatMap/AirCastingAndroidClient/tree/master/arduino/aircasting Web site mentions $PM_{2.5}$ several times, but does not list the specs
Air Quality Egg [AQE]	$280	1 min	Shinyei PPD42	Talks about PM2.5, but lists the operating range 0.5-10μm
AirVisual [AVN]	$200	10 sec	AVPM25b	Sensor developed by AirVisual. Nominally reports $PM_{2.5}$ for particles 0.3-2.5μm.
Awair [AWA]	$199	10 sec	Sharp GP2Y-1010AU0F	Product lit describes measurement as "PM". Range of 0-500 μg/m^3. (This corresponds to linear range for voltage output as specified on Sharp sensor sheet.)
Foobot [FOB]	$199	5 min	Sharp GP2Y-1010AU0F	Proprietary 'learning' algorithm applied to the signal. Product literature describes as $PM_{2.5}$ covering range of 0.3-2.5μm 0-1,300μg/m^3 ±4μg or ±20%
PurpleAir PA-II [PA]	$229	80 sec[1]	Plantower PMS1003	Reports # in 6 size bins; PM_1, $PM_{2.5}$, PM_{10}. Calibrated to ambient PM in Beijing. Counting efficiency: 50% @0.3μm 98% >=0.5μm Consistency error: ±10μg/m^3 @0-100μg/m^3, ±10% 100-500μg/m^3
Speck [SPK]	$200	1 min	Syhitech DSM501A	Calibrated with AZ dust. Machine learning algorithms applied to sensor signal. Product literature notes range of 0.5-3μm.
Thermo pDR-1500 [PDR]	~$6000	20 sec	Proprietary	Calibrated with SAE Fine AZ dust. Precision: ±0.5% of reading or ±0.0015 mg/m^3, whichever is larger, for 10 sec averaging time. Accuracy: ±5% of reading ±precision
MetOne BT-645 [BT]	~$3000	1 min	Proprietary	Calibrated with 0.54 m diameter polystyrene latex spheres Accuracy: 5%

RESULTS

Example data

Figure 2 presents some example results illustrating the different time and magnitude responses of the monitors. The plot shows two very large sources – candles and oil heated on a gas burner – that produced clear and substantial, though not fully quantitative responses by all analyzers. The Egg, Awair and Speck all reported only a small fraction of the actual mass concentration. Emissions from the dust mop, which were concentrated in the largest particles, produced responses of some but not all devices; though for this source the Speck response was substantially higher than the estimate of actual mass concentration. Using the gas cooktop burners to heat water in covered pots and heating the empty oven produced large numbers of particles below 100 nm and modest mass concentrations as indicated by the Mini-WRAS signal (GRM), but no perceptible response of the other monitors. It is also interesting to note that the Speck baseline appears to have shifted following the candle source event.
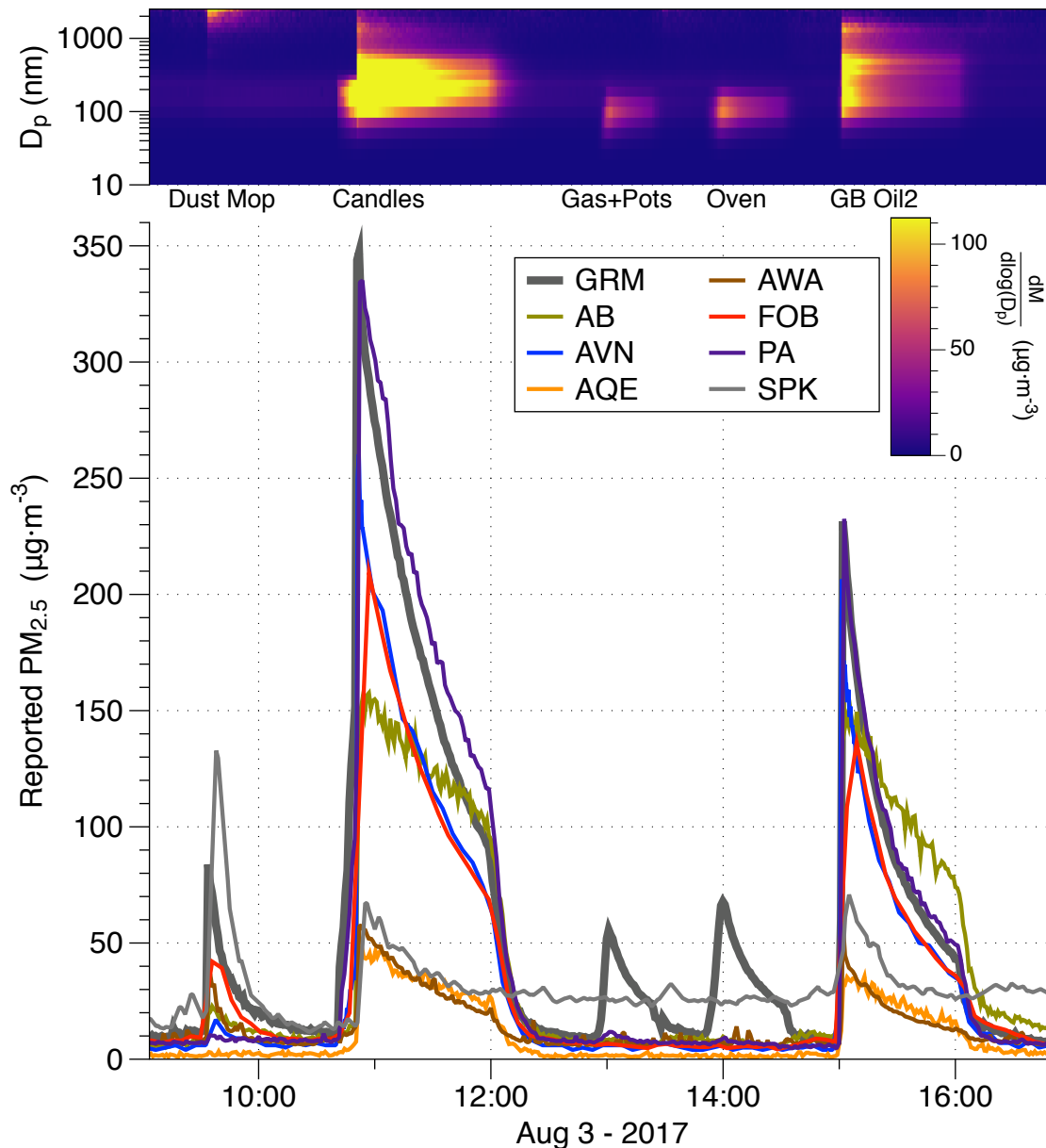
Figure 2. Example results from five source experiments. For devices that sampled more frequently than each minute, data have been averaged for 1-min resolution. The top portion of plot shows the distribution of mass by particle size.

Figures 3 through 7 summarize the test results for the monitors, broken down by the type of particle source. The inset plot in each figure shows the particle size distribution. This is important because these results show that the monitors are sensitive to particle size – in particular for the <0.3 micron particles from combustion & cooking (in Figure 7).
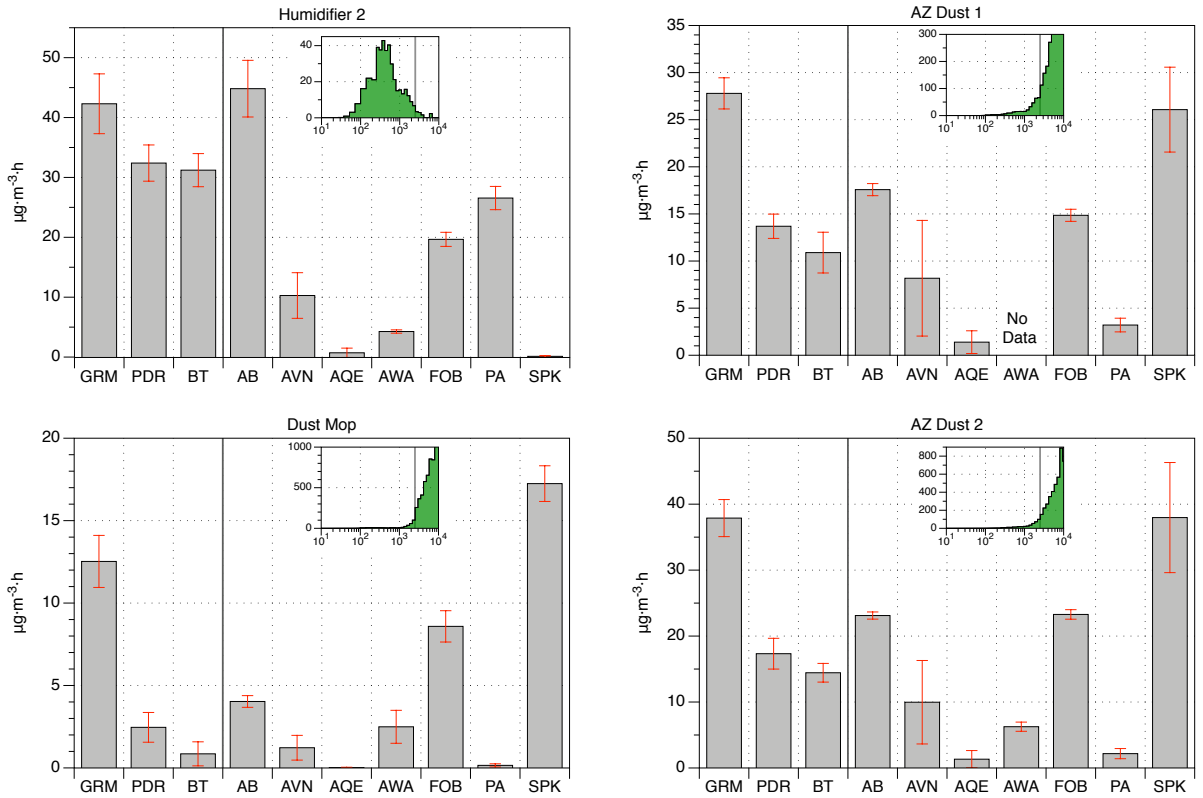
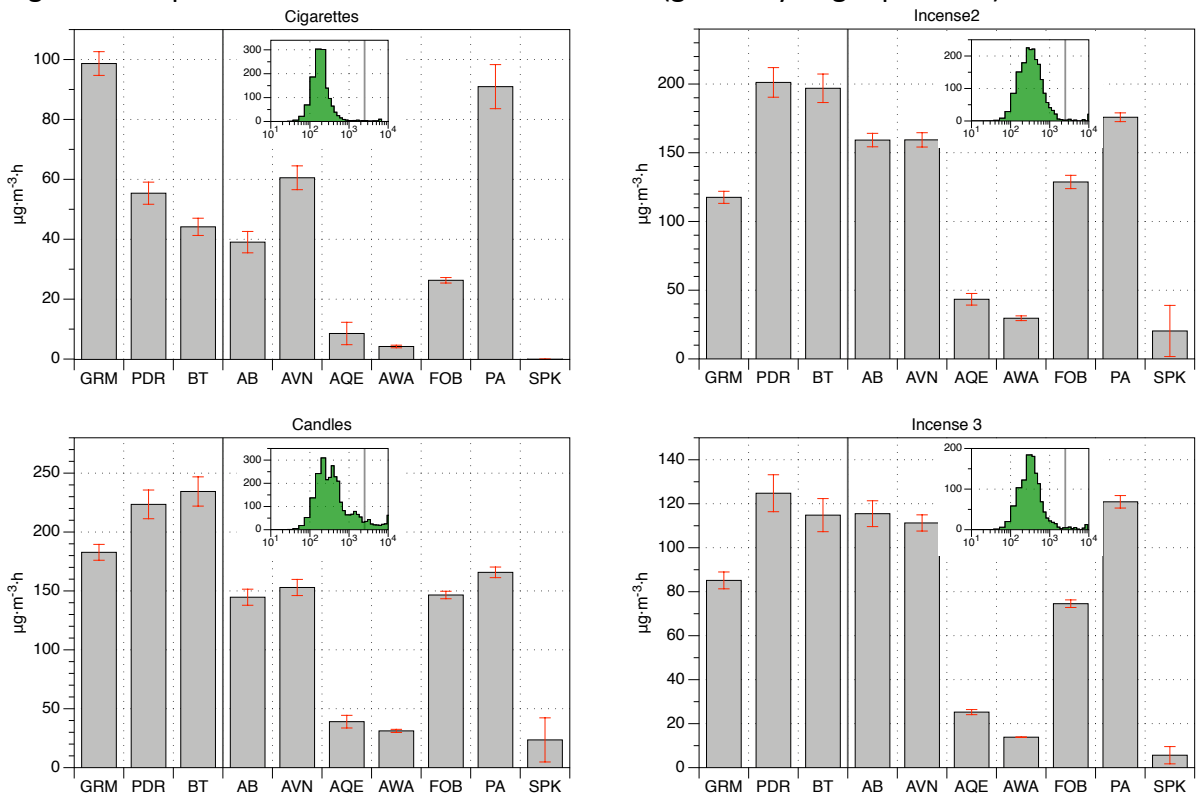Figure 3. Response to dust and humidifier sources (generally larger particles)

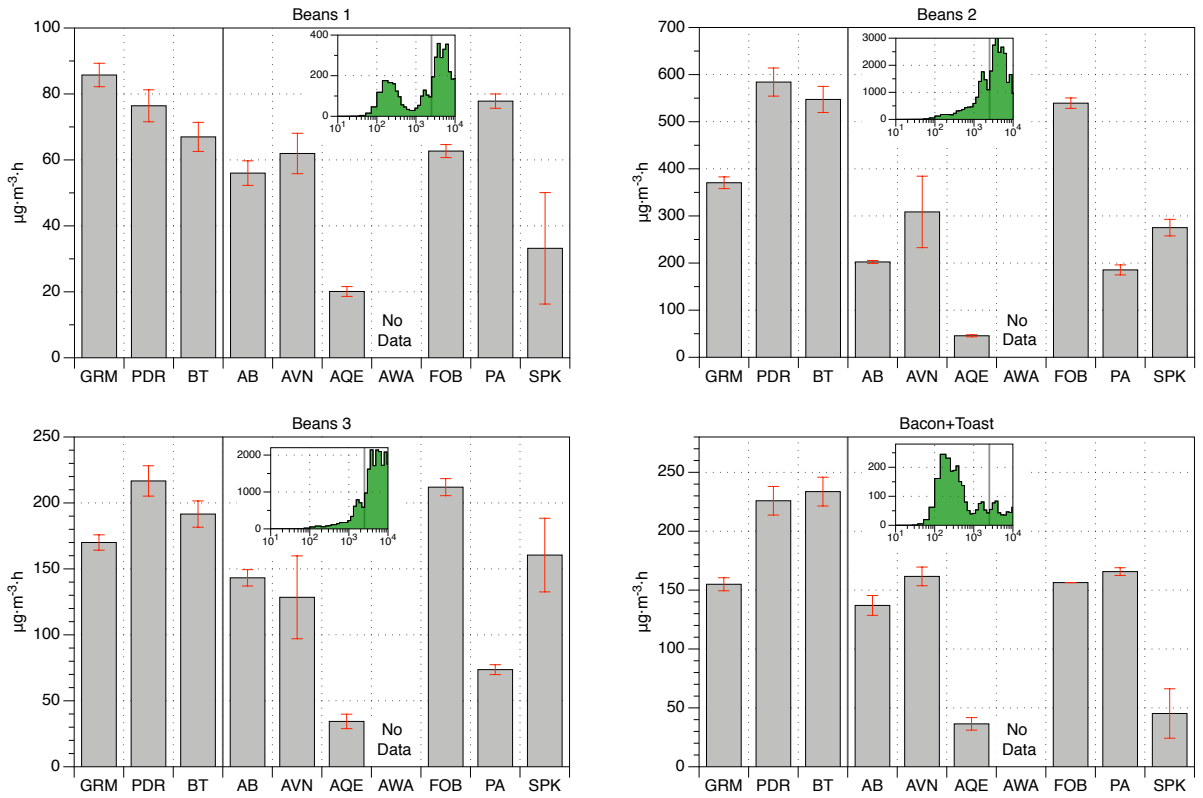Figure 4. Response to recreational combustion sources

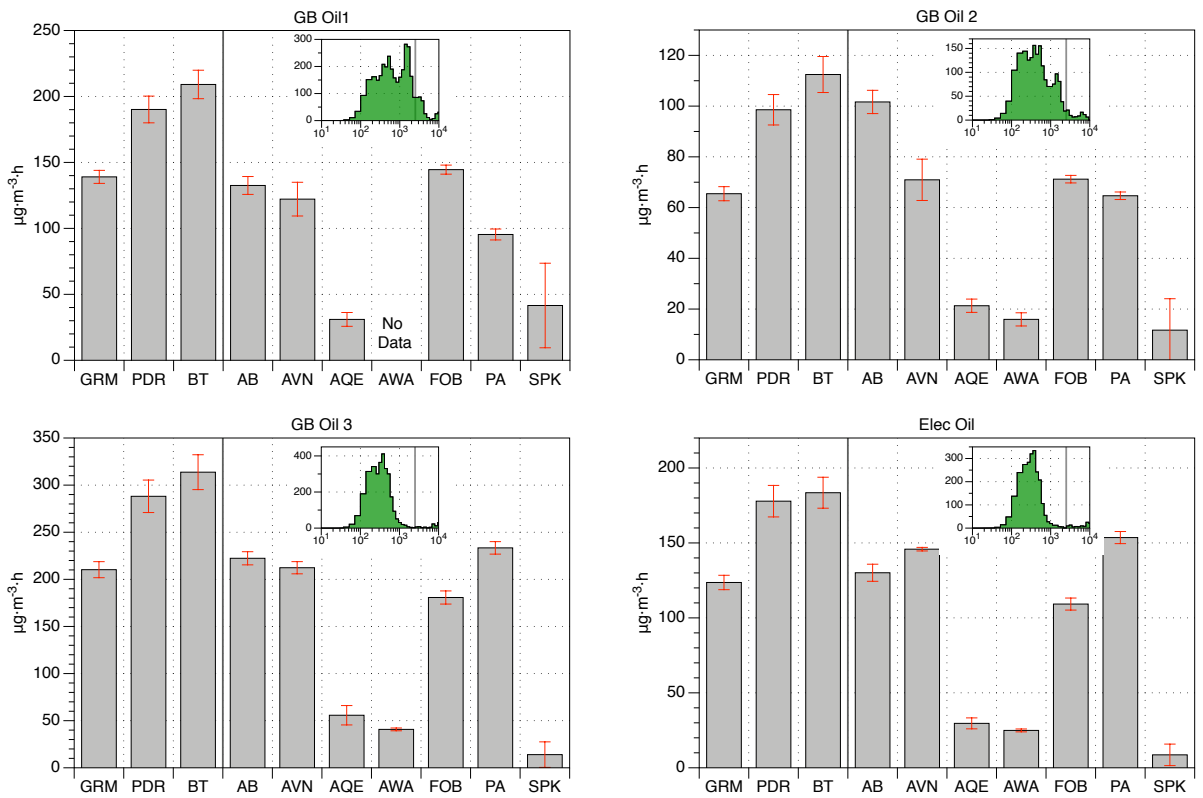Figure 5. Response to frying and toasting

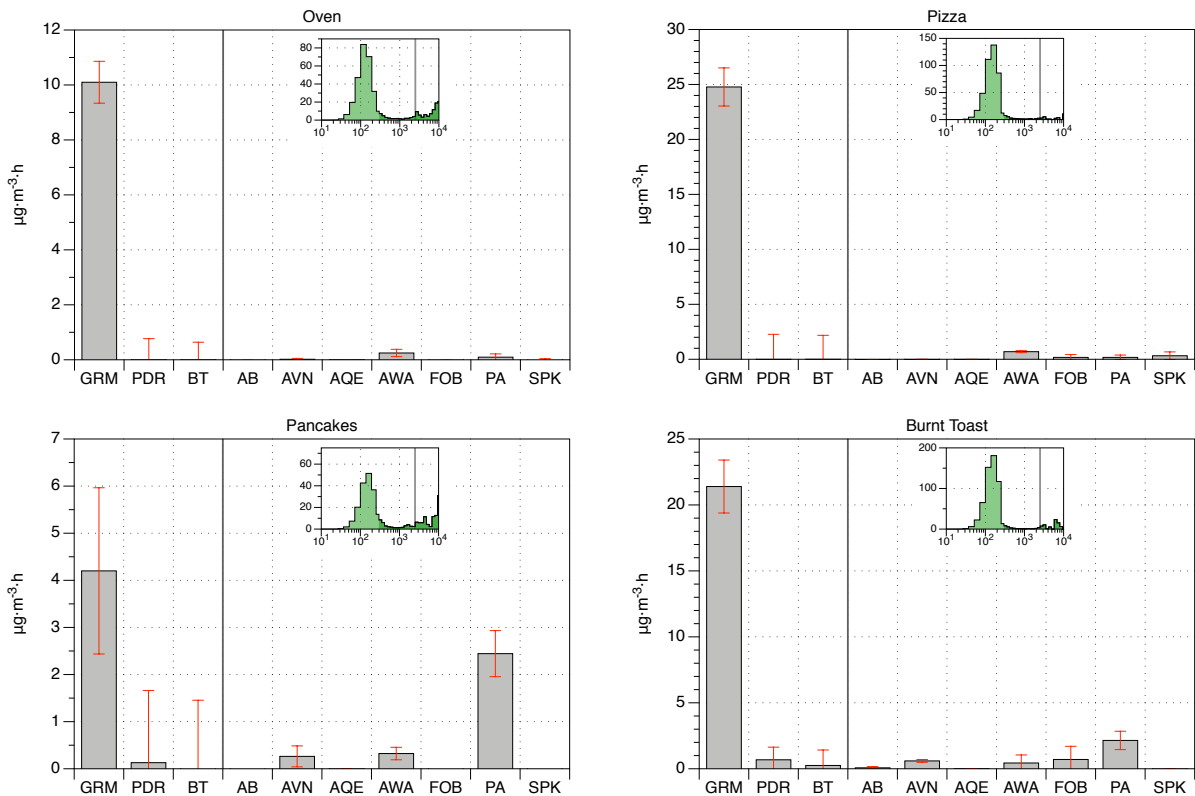Figure 6. Response to heating oils on gas and electric cooktops

Figure 7. Response to cooking events that mostly emit small particles

Discussion

The results show that the research-grade devices worked well, with the exception of events dominated by small submicron particles. This is expected due to the inability of the light-scattering sensors in these devices to detect such small particles.

Among the consumer grade monitors, the Egg and Speck showed the most problems. The Egg had very low responses across a wide range of events. The Speck had inconsistent correlation. The Awair had decent correlation but also had responses that were consistently low in magnitude. The AirBeam, AirVisual, Foobot, and Purple Air were better at detecting a wide range of sources, with the Foobot and Purple Air generally showing the most accurate responses. The exception for the Purple air was low responses to events dominated by large particles, such as the Arizona dust and the duct mop. For both the Speck and Awair the manufacturer claims to have upgraded the sensor since these experiments were performed.

As a group, the monitors generally missed sources that had the vast majority of their mass below 0.3 microns, including use of gas oven or cooktop cooking that did not include frying with oil. The exception was the Purple Air, which had low responses but high correlations, suggesting that it saw the events but not quantitatively. Note that PurpleAir is particle counter, which is more sensitive to low-levels.

Conclusions

Overall, these results suggest that the low-cost monitors will miss important sources of ultrafine particles and sources that may contribute to PM2.5 mass exposures in homes, and therefore we cannot generally say that these devices are suitable for controlling ventilation systems. However four monitors were acceptable for identifying sources that emitted a lot

of PM2.5: AirBeam, AirVisual, Foobot, Purple Air, and may have some value not as a primary control for a ventilation system, but perhaps to control and auxiliary boost function to increase ventilation during high particle events. They could also be used to operate stand alone filter units.

Acknowledgements

References

CEN, 2007. NF EN 13779. *Ventilation des bâtiments non résidentiels – exigences de performances pour les systèmes de ventilation et de conditionnement d'air*.

NEN, 2011. NEN 8088-1:2011 nl *Ventilatie en luchtdoorlatendheid van Gebouwen - Bepalingsmethode voor de toevoerluchttemperatuur gecorrigeerde ventilatie- en infiltratieluchtvolumestromen voor energieprestatieberekeningen - Deel 1: Rekenmethode* (Ventilation and infiltration for buildings - Calculation method for the supply air temperature corrected Ventilation and infiltration air volume rates for calculating energy performance - Part 1: Calculation method).

Singer, B. C., & Delp, W. W. (2018). Response of consumer and research grade indoor air quality monitors to residential sources of fine particles. *Indoor Air*, *44*, 1539–16. http://doi.org/10.1111/ina.12463