Personal and Ubiquitous Computing
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ORIGINAL ARTICLE

Personal pollution monitoring: mobile real-time air quality in daily life

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Abstract
Researchers have learned much about the health impacts of air pollution, but it remains a challenge to provide people information for making healthy choices. The CitiSense air quality sensor and system enable individuals to identify when and where they are exposed to poor air in real time. We present a qualitative analysis of a 4-week field study of 29 commuters using CitiSense. We focus on how they reasoned about, acted on, and shared the new information. We found that CitiSense's mobile monitoring and real-time displays provided a bridge between sensing and understanding, as well as shifting how users reasoned about their world, how they assessed their personal choices, and how they impacted and connected with their communities. In a sub-study of 13 participants with public displays at their workplace, we found evidence that the displays helped non-sensor wearers engage with the data and contributed to feelings of community.

Keywords Ubiquitous computing · Sensors · Air quality · Participatory sensing · Health

1 Introduction

Emerging sensing and mobile computing technologies are making it possible for us to see the invisible wherever we go. This is fortuitous, as air pollution—largely invisible—remains a persistent problem throughout the world, and air quality monitoring has been relatively expensive and sparse. Emerging technologies hold the promise of increasing awareness of the problems of air pollution, potentially enabling individuals to change their behavior and for groups to advocate for changes in environmental policy. Important questions include how to design these technologies to be most effective, how those technologies are used by people in their daily lives, and how it affects their awareness, attitudes, and behavior.

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1.1 Background and motivation

Indoor and outdoor air pollution is responsible for an estimated 3.2 million deaths worldwide annually [33] and is linked with increases in heart attacks, asthma, asthma attacks, dementia, and cancer [6, 32, 34]. These impacts are felt most severely in developing nations where there is little regulation of emissions. However, even in the USA, where clean air regulation has been in effect for over four decades, an estimated 50,000 premature deaths are attributed to poor air each year, with costs of treating pollution-related illnesses estimated to be $150 billion a year [20]. Loss of quality of life due to restricted behavior, more hospitalizations, and an unpleasant outdoor environment are additional costs borne by communities with poor air quality.

Surprisingly, even in regions where air pollution is the exception, there is still cause for concern. While scientists have known for some time that prolonged exposure to pollutants has negative health effects, new research suggests that even short-term exposure can have life-changing health effects for sensitive groups such as the very young and those with underlying health conditions like cardiovascular disease or asthma [12, 15, 32].

Regional air quality assessment is typically conducted by distributed monitoring stations, with many large cities being covered by only a handful of stations. As one example, San

Diego County, CA, has about ten monitoring stations for its three million residents living over a 4000-square-mile region [24]. Such stations can cost $500,000, although costs are declining with advances in technology. Real estate costs are also a significant factor in some regions. Air quality can be highly variable across small regions due to geography, weather, industrial activity, and traffic patterns. Also, for pragmatic reasons, regional air quality monitors are often placed in locations removed from where people actually spend their time, such as on top of buildings, away from homes and major roads, and of course, not inside people's homes.

As a result, current monitoring methods often do little to inform individuals of the elevated exposures that might be encountered while sitting in traffic, walking along a busy road, sitting at work, or sleeping at home. Many harmful pollutants are invisible to the human senses, and without the ability to see or smell contaminants, it is hard to devise ways to avoid them. This invisibility makes it hard for individuals to act in informed ways regarding their pollution exposure.

1.2 Early work in localized air monitoring

Several systems have explored system designs to bridge the gulf between sparse regional monitoring and personal exposure. These systems vary along three primary design dimensions that affect a number of trade-offs, including how useful the data is for assessing personal exposure: (a) stationary vs. mobile sensing, (b) who controls or possesses the sensors, and (c) the ubiquity of the sensing. To date, this has resulted in four major design approaches: enhancement and repurposing of government-collected data, monitoring of controlled indoor environments, mobile regional sensing, and ubiquitous personal sensing.

Repurposed regional sensing The Ergo SMS-based system was the first to provide individuals with access to localized data in real time. While the data reported was limited in precision (outdoor readings reported at the zip code level), participants still reported using the system to support their decision-making processes, a feature that was especially useful for individuals with respiratory problems [21]. Systems such as iMAP and PIER took this approach a step further by creating pollution models from multiple data sources such as traffic patterns, weather, and regional air quality sensors [5, 17]. Exposure predictions are then provided to users based on location data provided by the user's mobile phone.

Indoor monitoring Regional sensing generally cannot reach indoors, a significant gap since on average over 90% of modern life is lived indoors [11], and heating systems, cooking, and smoking (for example) can emit life-threatening levels of pollution. The InAir and MAQS systems targeted various questions and challenges of indoor air monitoring.

InAir was investigated in a pair of user studies, one 4 weeks [13] and the other 4 months [14]. Participants were provided with a stationary indoor air quality sensor for particulate matter. Participants were allowed to install the system in any easily observable space in their home (e.g., next to the bed, on the kitchen counter). Real-time visualizations were provided by a paired iPod touch that displayed daily graphs of the observed particulate readings at the installed location. Each home was paired with another home of the first home's choosing for 2 weeks of the study, both having the sensor, to gain insights on sharing. Similar to the Ergo study, participants reported building the checking of air quality into their daily routines, again suggesting that there is general interest in this type of environmental sensing. They also reported that engagement was generally sustained, awareness was increased, some participants quit smoking (in part due to social influence), and privacy was not an issue. On the other hand, participants generally wanted a less literal display of air quality measures and found it hard to find pollution sources or reduce pollutant levels. We will return to these results on indoor stationary sensing later, when we discuss the results of our study. The longer study added insights on how participants learned to connect mundane behaviors to increased pollution in the home and then change their behaviors to improve air quality.

The MAQS [11] air quality system also explored improving indoor air tracking through mobile sensors that sampled carbon dioxide and interpolated VOCs (volatile organic compounds) using air exchange rates. The focus was to give personalized, room-level data to individuals that used the system. Participants in the MAQS study spent 12 weeks training a location algorithm on Android phones to get accurate room-level data with weekly meetings with the sensor carriers to verify accuracy. Participants then carried the MAQS mobile air sensor for an additional 3 weeks to collect air samples of their daily exposure patterns. Sampled data was made available to sensor carriers and other collocated individuals, although the nature of the data format and interface is not reported. In a systems study, Jiang et al. found that participants frequently experienced poor indoor air quality during the course of the study in a variety of indoor locations, suggesting that further research in indoor air quality sensing could benefit users.

Mobile regional sensing To overcome the limitations of sparse stationary air quality monitoring, mobile sensors have also been used to more densely map regional air quality, closer to where people actually spend their time. The GasMobile System explored a bicycle-mounted Ozone sensor to discover urban pollution distribution. In the data collection phase, researchers rode the bicycles to collect air samples and discovered a high variance between different outdoor locations, including those with close proximity to one another. This supports the findings of Vardoulakis et al. who reported that "urban street canyons" help create microclimates that can vary widely from one another over a short distance [29]. The CommonSense system explored outdoor sensors in a variety of contexts, including sensors mounted on street sweepers [1]. The deployment strove to augment a city's existing sensor infrastructure with vehicle-mounted sensors. Through interviews, Aoki also explored trade-offs in air quality management, and the requirements for collecting data to support social and political change [1]. Recently, Google announced that its Google Streets cars, which pervasively capture street-level imagery around roadways, are being outfitted with air quality monitors from Aclima [16]. A trial in Denver, CO, collected 150 million samples with three vehicles driving a total of 750 h. Although a location is resampled infrequently, and different locations are sampled at different times, it can be correlated with data from EPA's sparse monitors to generate estimates at other days, months, and times. This work was preceded by a similar effort that used Google Streets cars to find methane gas leaks [26, 31].

Ubiquitous personal sensing The above systems are one step removed from truly personal monitoring, creating uncertainty about your personal exposure, wherever you might happen to be. It is also hard, for example, to explore how changing one's route affects exposure or use the sensor data to identify pollution sources. This motivates instantaneously-reporting body-worn sensors.

AIR, conceived as a new-media public art project, built a mobile air quality sensor for nitrogen oxides, carbon monoxide, and ozone [22]. Participants were asked to carry the device for no longer than 24 h and then pass the sensor on to a new individual. Data was collected for artistic visualizations intended to help communities think about their air quality.

The abovementioned CommonSense project explored a system design to help novices participate in citizen science efforts that collect and analyze air quality data [35]. They designed a number of visualizations, and then recruited several local citizens to gather particulate data during a several-block walk-around. Afterwards, each citizen was asked to use the designed interfaces to explore their data, combined with the data collected by others earlier. The results suggest that the interfaces were generally effective in helping the citizens understand what they saw and draw inferences about the sources of pollution, such as a nearby highway. We drew from these visualizations, in particular the "tracks" map-based visualization for our system. Unlike the indoor InAir study, this study was not focused on investigating real-time visualizations while on the street, nor use in one's daily life.

Recently, researchers assessed the potential value of personal air quality sensing in a 2-day study in Barcelona [18]. They found that a personal black carbon microaethalometer (the AethLabs AE51) provided unique data compared to modeled particulate matter exposure. In particular, the model severely underestimated exposure during commutes, but did better indoors. Microaethalometers are still quite expensive, however. The AirCloud project investigated ultra-low-cost particulate sensing and the technology required to support accurate wide-scale sensing and inference [3]. AirCloud's portable miniAQM sensor employs a pair of far-infrared dust sensors and a fan to properly regulate the sensors' exposure to dust. The power consumed by the fan limits the ability to run the device for long periods. Modeling based on machine learning manages the noise in the data and extrapolates the data sampling into a regional pollution map.

1.3 Challenge and questions: always-on ubiquitous personal sensing

The above results highlight the need for, and promise of, air pollution sensing for personal exposure—showing the high variance of air pollution over space, time, and type of space and people's interest in that data. Yet, no such system had been developed and studied for fully ubiquitous, always-on, real-time personal-exposure monitoring. The longest study, just 2 weeks, studied the use of stationary indoor sensing. The longest outdoor study, just a few hours, did not investigate real-time displays, nor use, throughout one's daily life.

This motivated the design and study of the CitiSense sensor and supporting reporting infrastructure. Such a sensor would support a holistic view of personal air pollution exposure, representing both the indoor exposure that makes up the majority of one's day with the peak exposures experienced during outdoor activities. The high mobility, long battery life, and readily accessible data of such a system also invite questions about how such a sensing system might be accepted and adopted into daily life.

Prior work on CitiSense described the design of our monitoring device [37] and our machine learning methods [30], described the system and investigated the promise of using personal sensing data for investigating questions in population health [19]. A short paper based on a poster provides a brief preliminary analysis of how the first group of users in Study 1 of this article (8 total) responded to the system and interface design interface [2]. The analysis introduces three of the seven issues discussed at length in Section 4: discovery and exploration, attitude change, and sharing.

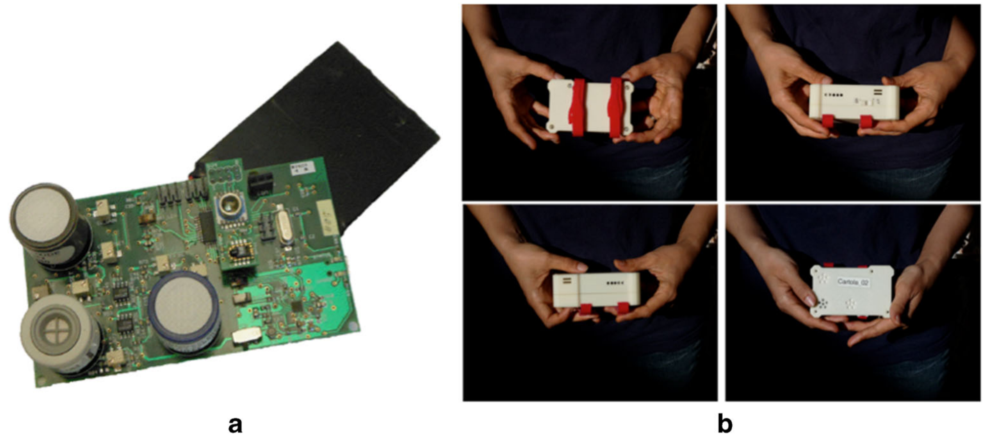

Fig. 1 **a** Sensor board. **b** Sensor board in 3D-printed plastic case. Velcro straps are attached to the case so that it can be easily attached to backpack straps and bike frames

What's missing from the literature, then, is a comprehensive understanding of how such a system is adopted into daily life: how ordinary people incorporate such a system into their daily activities; how they use and relate to it; how they draw inferences from the system; how it affects their awareness, attitudes, and behavior; and how the data is shared with others; and how it affects them. An important dependent question is how such a system can be better designed for its intended use.

(The addition of personal mobile sensing to the air quality monitoring equation raises additional questions in the area of personal informatics (PI), also known as quantified self (QS) [23, 36]. The research questions of PI are generally beyond the scope of the present article, but our results are complemented by its insights (and perhaps vice versa). For example, a key insight from personal informatics is that tracking is often abandoned after an initial period of concerted use [4]. This initial period can bring considerable insight by making the invisible visible, but the effort required to continue tracking can outweigh the benefits of the additional insights derived from continued use. However, there is potential for improved design for long-term tracking, as well [7].)

To answer these questions, this paper reports on two 1-month studies. The first study recruited 16 commuters (in two groups of 8) from the UC San Diego community. The second recruited a community of 13 users from our computer science department, where a large public map display provided a shared view of the community's exposure, in addition to the views provided natively by the CitiSense system.

At a high level, we found that CitiSense's mobile real-time glanceable design enabled in-the-world sensemaking that afforded unique insights. These insights affected the attitudes and behavior of some participants. Interestingly, we also found that mobile personal sensing of the world increased engagement with one's surroundings, counter to the disengagement that personal technology often causes.

In the following, we begin by reviewing CitiSense's design (Section 2). We then describe our user study designs and provide quantitative results that help put our qualitative results in perspective (Section 3). We then provide an analysis of the studies' survey and interview data to reflect on our main research questions (Section 4). The paper concludes with a discussion of design issues (Section 5) and a conclusion that highlights the takeaways from this research (Section 6).

2 CitiSense design

The CitiSense system is comprised of four main components: a wearable sensor board, an Android smartphone running a monitoring application, a Web server providing a personalized daily pollution map, and a social component supported through Facebook and Twitter integration.

2.1 Sensor and phone

The mobile component of the CitiSense system consists of a mobile air quality monitoring unit and an Android mobile phone running a custom application (Figs. 1, 2, and 3) that sends sensor data to the phone via Bluetooth. The air quality monitoring unit contains the following six sensors attached to a custom board: carbon monoxide (CO ppm[1]), nitrogen dioxide (NO_2 ppb), ozone (O_3 ppb), temperature (Fahrenheit), barometric pressure (millibars), humidity (reported as a percentage) [37].

As we recruited individuals with no prior air quality sampling experience, we wanted to focus on presenting the data in an easy-to-understand way. We adopted the Environmental Protection Agency's (EPA) Air Quality Index (AQI) number and color mapping (see Fig. 4) to help

[1]The acronyms ppm and ppb mean parts per million and parts per billion, respectively.

Fig. 2 The boards can be carried attached to a backpack strap, secured to a bicycle frame, or carried by hand

our users easily and quickly interpret sensor data [28]. An AQI number is calculated for each measured pollutant, and then the maximum is chosen as the final value [27]. While the EPA's AQI values represent an average pollutant level at a location over time, typically an hour, CitiSense provides an essentially instantaneous report of the same value (an average over 6 s). Since the CitiSense sensor is mobile and we expected users to be interested in locating times of peak exposure, an instantaneous report was deemed more appropriate. We call this number the My Instantaneous Air Quality Index (miAQI).

2.2 Problem formulation

The miAQI number and color are displayed prominently on the mobile application home screen (Fig. 3) and are also used to populate and color the balloons on each participant's personalized map page (Fig. 5).

2.3 Web and social

A personal map page was maintained for each participant throughout the course of the study. These pages were generated in real time, and feature a daily exposure map, and a chart displaying pollution exposure by time of day. This web page was designed to allow users to dig deeper into their data and see trends in their exposure (Fig. 5). The visual nature of the time chart and map allows users to quickly locate the time and place of peak exposures. These web pages were also designed to give drivers and cyclists, who cannot look at the phone display while they commute, a way to see their commute data in a safe way.

The web page and Android application both support sharing through the Facebook and Twitter social networks. This integration allowed users to post air quality data directly to their social networks with a single click.

2.4 Public displays

In the second study, large-scale public displays were utilized to collectively share the data collected by the participants.

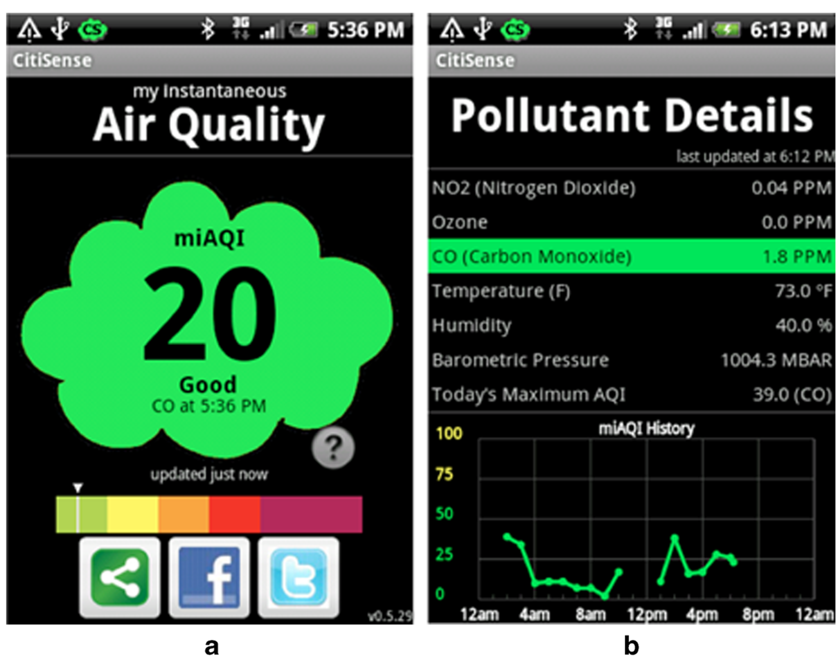

Fig. 3 **a** CitiSense application home screen. The cloud's color and number change based on the sensor readings. The color bar underneath indicates where on the scale the reading lies. Tapping the "?" button displays the official EPA color chart (Fig. 4) along with a link to details on each pollutant and its health implications. **b** Pollutant details screen. This screen displays the exact readings for each sensor and a graph indicating the maximum miAQI recorded each hour

Fig. 4 Color-coded air quality safety chart created by the Environmental Protection Agency (EPA) [28]. The per-pollutant AQI is calculated from the shown cutoffs and linear interpolation; the final single AQI number and associated color number are the maxima of all the pollutants measured [27]. The CitiSense system uses the EPA's colors and numbers to generate easy-to-reference values for the main screen

	Good	Moderate	Unhealthy for Sensitive Groups	Unhealthy	Very Unhealthy
O3 (ppm)	0-.059	.060-.075	.076-.095	.096-.115	.116-.135
CO (ppm)	0.0-4.4	4.5-9.4	9.5-12.4	12.5-15.4	15.5-30.4
NO2 (ppm)	-	-	-	-	.65-1.24

The screens were installed in a four-story building and were centrally located in common areas near the elevators and staircases. The screens ranged in size from single 52-in. diagonal displays on the first and second floors to 2×2 grids of 52-in. diagonal displays on the third and fourth floors (Figs. 6 and 7).

3 Study setup

As motivated in the Section 1, we sought to understand how a system like CitiSense is adopted into daily life: how ordinary people incorporate such a system into their daily activities; how they use and relate it; how they draw inferences from the system; how it affects their awareness, attitudes, and behavior; and how the data is shared with others; and how it affects them.

For these purposes, we designed two 1-month studies to give participants time to explore how they might use personalized air quality data, and to provide enough time for longer term phenomena to develop, such as the development of attitudes and new behaviors.

Quantitative data on air readings, time, and location, were continuously collected from the sensor and phone throughout the length of each study. Prior to each study, we administered a basic demographic survey, which gathered the data for Tables 1 and 2. Qualitative data was collected at several points during each study, as well. Weekly, we administered a short open-ended survey, where the main question was "Please share a story about how you recently used the

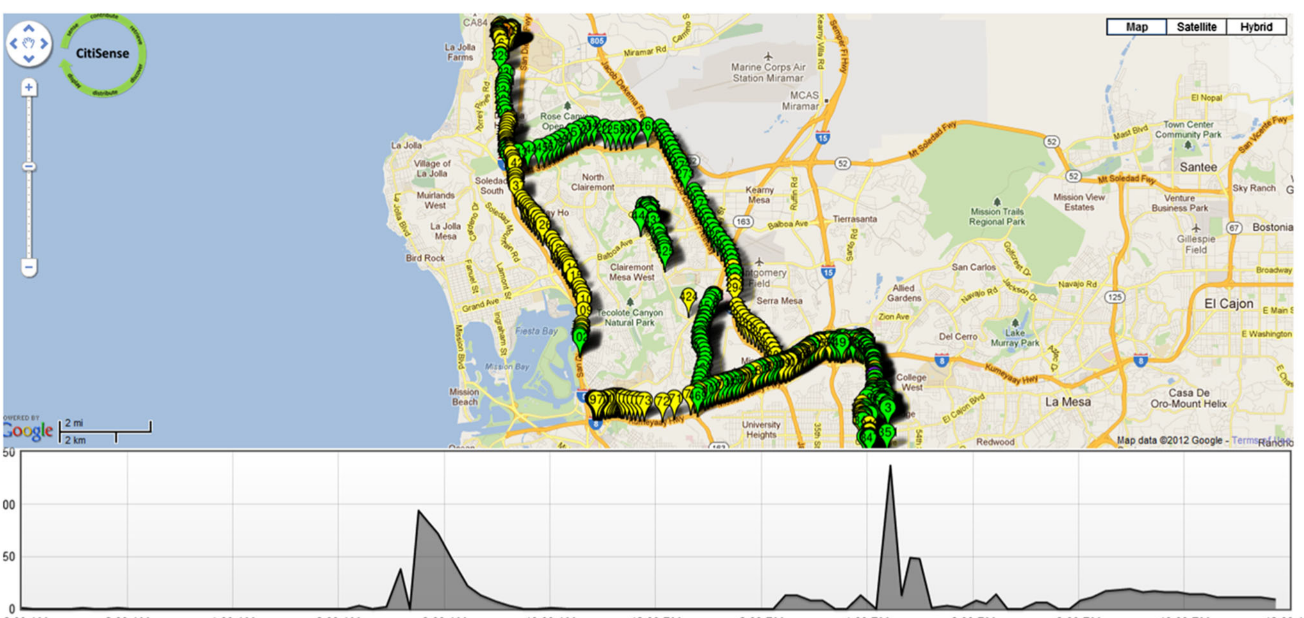

Fig. 5 Personalized map page with miAQI plotted by location. Users can click a balloon to learn more detailed information. The graph displays samples plotted by time of day. In this case, you can see the user's commute to and from work as the two peak exposure times. Our maps are implemented as an overlay on the publicly available Google Maps framework[9]

Fig. 6 Large-scale displays installed in communal areas on each floor of the building provided natural opportunities for sensor carriers and others to view and discuss the air quality data collected

CitiSense system." We also gave a longer, more detailed survey at the middle of the studies, with questions such as "Have you discovered anything about your environment while carrying the sensor?", along with follow-up questions about surprises, and negative versus positive findings. We gave a more quantitative and summative survey at the end of the study, with questions like "I forgot to carry the sensor with me (choose one): Never, Less than one day, 1 day, 2 to 3 days, 4 or more days." Finally, at the end of the study, an hour-long semi-structured interview was conducted with each participant. The interview revisited many questions from the mid-term survey, giving the participant a chance to provide a more recent example. One novel question was "In using CitiSense, did you notice any patterns in your air quality?"

The surveys and transcribed interviews were analyzed for themes using affinity diagramming [10]. In particular, we parsed the survey and interview data into phrases,

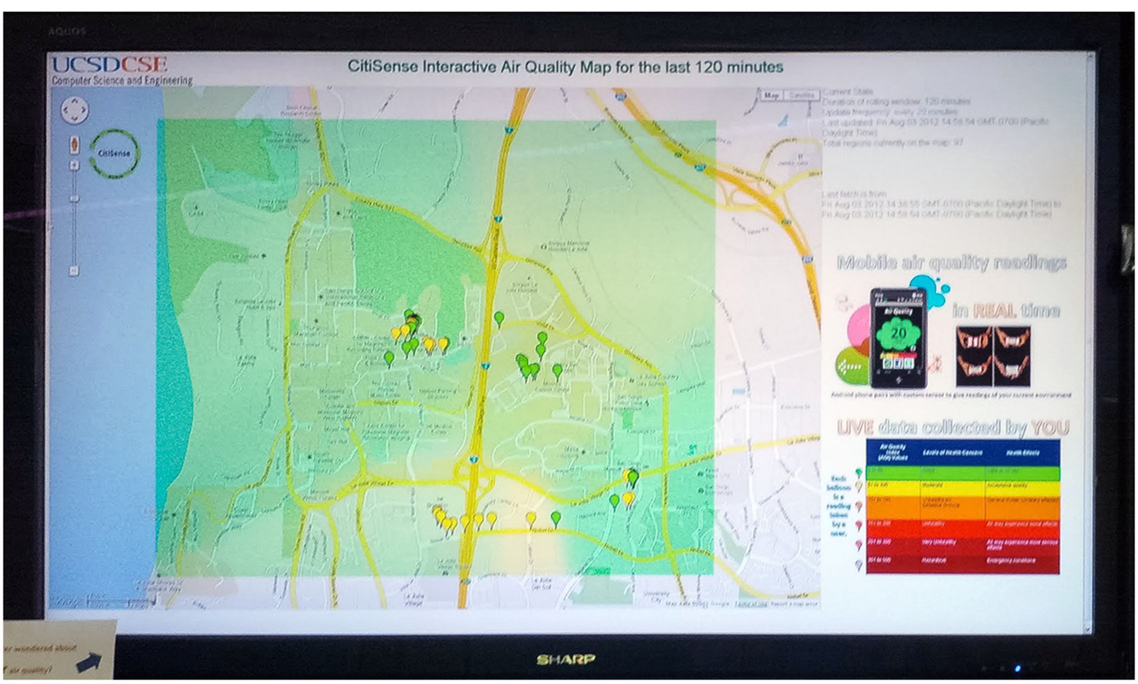

Fig. 7 The large-scale displays included both a live map showing all sensor readings in the past hour as well as a transparent interpolated color layer generated from machine learning algorithms developed by Verma [30]. In addition to the map, a short explanation of the project was included to help non-sensor wearers understand the data readings they were seeing

Table 1 Participants' self-reported commute data. ID encodes age, gender, and transport method

Partic. ID	Study	Method	Miles	(km)
43FBk	1	Bike	27	(43.5)
32FCrBs	1	Half car, half bus	40	(64)
33MTnBs	1	Train and bus	60	(96.6)
45MCr	1	Car	65	(104.6)
41MBsTr	1	Bus and trolley	54	(86.9)
28MBk	1	Bike	20	(32.2)
41FCr	1	Car	58	(93.3)
20MMc	1	Motorcycle	14	(22.5)
48MCr	1	Car	50	(80.5)
20MCr	1	Car	4	(6.4)
56FVp	1	Vanpool	34	(54.7)
47MBk	1	Bike	4	(6.4)
48FCp	1	Carpool	50	(80.5)
32FCr	1	Car	42	(67.6)
44FBk	1	Bike	30	(48.3)
34FCrBs	1	Car and bus	30	(48.3)
28MBk	2	Bike	3	(4.8)
30MWk	2	Walk	2	(3.2)
55MSc	2	Scooter	2	(3.2)
29MWk	2	Walk	3	(4.8)
25FCr	2	Car	10	(16)
49MCr	2	Car	15	(24)
68MCr	2	Car	24	(38.6)
36FCr	2	Car	28	(45)
58MCrWk	2	Car and walking	32	(51.5)
27MCr	2	Car	28	(45)
26FCp	2	Carpool	60	(96.6)
28FCp	2	Carpool	16	(25.7)
25MCr	2	Car	6	(9.7)

and then organized those statements into groupings based on their thematic cohesion. To sharpen our interpretation of the phrases and add depth to our understanding, we looked at each participant's responses in the context of the quantitative sensor data they collected and their primary transportation method. In some instances, one phrase could be placed into two groupings (e.g., Mobile and Privacy), requiring a copy of the phrase to be introduced. Also, for two related groupings, such as Public versus Private, the groupings were placed next to each other to allow phrases to be plotted on a spectrum between the two themes to capture a notion like semi-private, such as a workplace.

3.1 Study 1 design

For the first study, we recruited 16 participants (8 men, 8 women) to carry the sensors for 1 month. The age of participants ranged from 20 to 56 years (mean age 38.5 years) and their commute distances ranged from 4 miles (6.4 km) round trip to 65 miles (104.6 km) round trip (mean of 36.4 miles or 58.5 km). Our recruitment criteria were that participants commute at least five days a week

Table 2 Combined commute types represented in the deployment studies. Several participants used a combination of commute methods for their daily commute. See Table 1 for details

Mode	Count	Comment
Walking	4	
Biking	4	
Electric scooter	1	
Motorcycle	1	
Van	1	Vanpool
Bus	4	
Train/trolley	3	
Car	17	3 carpool

and that they be regular users of online social networks (defined as posting content multiple times per week). We recruited participants through an on-campus mailing list for commuters. Due to the limited number of available sensors, we ran the 16 subjects in two sequential groups of 8. All participants worked on the same large university campus, but they did not work in the same department or building. As this was an exploratory study, we tried to select a range of commute types so that we could observe a wider variety of exposure profiles, as shown in Table 1 and summarized in Table 2 along with the Study 2 participants.

The participants came from a variety of backgrounds, including a librarian, a science writer, a programmer analyst, a public information officer, a fund manager, a student advisor, a maintenance painter, a professor, a postdoc, an administrative assistant, a pulmonologist, a senior budget analyst, a graduate program advisor, a faculty assistant, and two students. Participation in the study consisted of carrying the sensor and phone during commuting activity, attending a 30-min training session, responding in four weekly diary entries, a pre- and post-study survey, and participating in an hour-long in-person, open-ended interview at the end of the study. While participants were primarily asked to carry the sensor while commuting, we invited them to take the sensor anywhere they wanted over the course of the study. Participants were compensated $75 for their time and travel costs.

3.2 Study 2 design

The second study was conducted using the same study design as the first, with the exception that all participants worked in the same building representing a single academic department on campus, the computer science department. Of the 13 participants in the second study, 9 were men and 4 were women. The age of participants ranged from 25 to 68 years (mean age 37.2 years) and their commute distances ranged from 2 miles (3.2 km) round trip to 60 miles (96.6 km) round trip (mean of 17.6 miles or 28.3 km). Occupations represented in the second study included professor, graduate student, administrative assistant, and facilities manager.

Because of the substantial overlap in the study setups and research questions between the two studies, in the following we consider their results together. The results specifically concerning the public display are discussed under the general topic of sharing, in Section 4.7.3.

3.3 Limitations

The nature of a naturalistic field study with novel technology puts some limitations on what data could be gathered, and hence what can be concluded from the study.

For one, it was not possible to ascertain whether the conditions reported by a sensor were the true conditions experienced by the participant carrying the sensor. The sensors were calibrated prior to deployment, but sensors do lose calibration over time, and are subject to cross-sensitivity (responding to a compound for which it is not advertised), as well as influence from extremes in temperature, humidity, and barometric pressure. Collecting ground truth from high-accuracy sensors would have been both intrusive and prohibitively expensive. As a consequence, we have refrained from making conclusions that depend on actual pollution exposure.

Two, for qualitative insight, this study depended heavily on questionnaires and interview data, which are retrospective. We chose not to use ecological momentary assessment (EMA) [25] for two reasons. One, we reasoned that its use over a month would be tiresome. Also, we felt that EMA could incidentally remind participants to use CitiSense, reducing the naturalness of the study. In particular, we wanted to see how the conditions around participants would lead them to use CitiSense. As a result, we employed weekly questionnaires to balance the tension between naturalness and dependence on recall.

Three, in 4-week, wide-scale naturalistic studies like this one, it was not practical to gather observational data, except in a few limited instances around the public displays in Study 2. Our quantitive data, however, was sufficient to verify that participants actually used the sensor, and in particular kept the sensor running (i.e., we collected ample data) and carried it with them (i.e., we measured regular movement). In a similar vein, we could not directly study the effects of the sensors on the participant's friends, family, and acquaintances, except in those instances where they made a post on the participant's CitiSense-driven Facebook posts. Consequently, this study does not make conclusions on detailed behavior and depends on the abovementioned questionnaire and interview data for insights on high-level behavior.

Finally, the 4-week length of the studies limits the conclusions we can draw about long-term behavior. In particular, we do not know whether the behavior changes reported would be sustained with continued sensor availability use (or without, for that matter). We also do not know how CitiSense would be used in the long term, outside the parameters of a research study. Indeed, because the sensor is a somewhat clunky research prototype, a longer-term study would benefit from a more refined implementation.

4 Results

In this section, we examine the data from the surveys and interviews to learn how the sensors were integrated into their

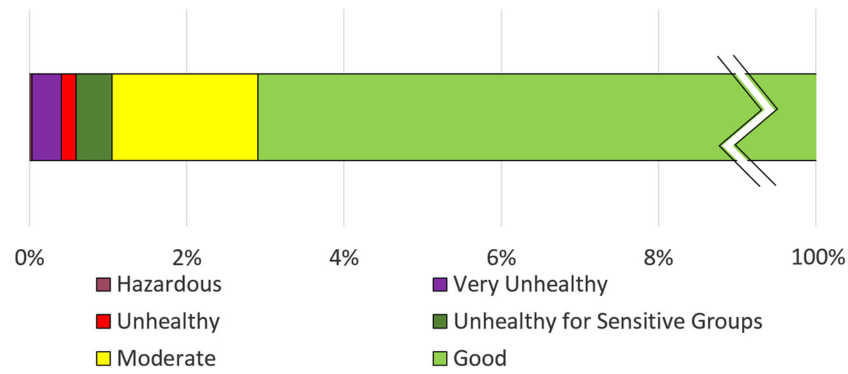

Fig. 8 Distribution of AQI values over the EPA's categories. Note that the "good" category is truncated in the graphic so that the percentages in the other categories are visible

daily activity and how the participants' perception of the world was shaped by access to real-time air quality readings. The primary focus of both studies was to explore how access to real-time air quality data might impact individual understanding and beliefs. For this reason, we report on both studies together for individual measures such as discovery, sensemaking, and awareness. Because of CitiSense's social features, as well as Study 2's deployment to an existing community with sharing of data through public displays, we present results regarding sharing in Section 4.7.

4.1 Quantitative backdrop

To help frame the responses from the participants, we collected location and air quality data in the CitiSense server throughout the study. In total, we computed and collected 7,672,926 miAQI readings (representing a total of 12,788 h of sensor readings). Although participants were required to carry the sensor only while commuting or a total of about 40 h each, the data reveals that the participants voluntarily carried the sensor an additional 441 h on average, 11 times the required amount. This suggests that the burden of charging and carrying the device was minimal compared to the value they were receiving from carrying it.

In taking a closer look at the data, we observe that by EPA standards, over 95% of the readings were well in the "good" category, as shown in Fig. 8. Over the course of the study, 1.4% of readings were above "moderate," and 0.9% of readings were observed in the unhealthy range (miAQI greater than 150). This pattern is in line with what we expected, as the participants generally live in suburban areas of a city (and region) with generally good air quality. Also, indoor air quality is typically good, and our participants generally spent most of their time indoors (e.g., working in offices, sleeping at home). Emissions in the home from gas stoves and burning incense are two exceptions that were noted by the participants. Yet, even while all of the participants had low average readings, all also recorded readings in the unhealthy range.

Delving deeper into the poor air readings collected, we compared readings captured while the participants were stationary versus mobile. Table 3 shows the miAQI readings captured at various speeds of travel. Although we do not know definitively which mode of transport was being used at any given speed, analysis still yields insight. The readings collected by the participants conform with our expectations that the air quality experienced while in transit is generally worse than in homes and workplaces, although the fact that exposure at slow speeds (presumably walking) was somewhat lower is intriguing.

Table 4 breaks out the readings for each category of commuter according to the speeds that the category typically travels. Although the sample sizes are too small to say what the larger population might have experienced, this data does convey what the participants experienced according to the type of their commute. In particular, we see that the walkers experienced especially low pollution exposure while walking, while the bikers experienced much higher exposures while biking. Our walkers were walking short distances, suggesting that they were walking on minor roadways, which would carry less vehicular traffic, and hence produce less air pollution. The higher average levels

Table 3 Average miAQI readings by speed of travel. The slow speed of travel corresponds to typical walking speeds, medium to typical biking speeds, and fast to typical powered vehicle speeds

Stat. [0–1 mph]	Slow (1–3.5]	Med. (3.5–23]	Fast (23–85]
9.7	5.9	13.3	22.9

Table 4 Average miAQI readings by commuters' transportation type, matched to type's typical speed. Readings for commuters who used both bicycle and another vehicular method were excluded from the medium-speed categories due to the inability to definitively assign a reading to a transportation method. The speed ranges are reported in Table 3

Walker's	Biker's	Mass Trans's		Car's	
Slow	Med.	Med+Fast	Fast	Med+Fast	Fast
5.7	31.7	21.2	25.0	16.0	22.1

of air pollution in the faster transportation categories are evidence of a higher number of unhealthy readings. For example, the bike commuters' readings at medium speed have an average standard deviation of 55.4.

4.2 User experiences with personalized air data

It was the first time for all of the participants to have access to their personal air quality data. We were especially curious how they would use and interpret the readings, and whether having access to this data would impact their behaviors and their understandings of their environments.

4.3 Discovery and experimentation

CitiSense provided what some users called a sixth sense, the ability to see what had previously been invisible to them and the people around them. This new ability was described by participants as "fun" and "informative." As the study progressed, participants reported settling into a more sustained pattern, shifting from checking their phone at regular intervals, to only when they were prompted by an anomalous observation, such as walking past a new construction site, or driving behind a particularly smelly truck. 32FCr summed up her experience with the system saying

> [It was] very cool that you can quantify the hunches that you may have [...] I mostly just did my everyday thing, and then checked it in particular places that I thought were interesting. –32FCr

This ability to verify pollution expectations allowed participants to develop a better sense of real pollution source, an ability that, as is described in the next section, often challenged their prior belief about air and pollution distribution.

4.4 Reconciling readings with previous beliefs

Prior to the study, 23 of the 29 participants had mental models that were inconsistent with actual air distribution, believing instead that pollution was distributed evenly, or not professing any beliefs at all. These 23 also reported that air quality was something they rarely thought about, a reasonable omission given they possessed no means to measure or view their exposure. The main information source for local air pollution was print and broadcast news, formats that generally focus on broad regional readings, and often only at times of abnormally high pollution levels. Thus, this new window into air quality generated surprise for many of the participants when the readings they observed did not match their pre-existing beliefs of where bad and good air should be. One major source of surprise was how variable air quality was over short distances. 47MBk's response was representative:

> The very localized spikes in pollutants near major roads was a bit of a surprise. I expected overall air quality to not be as variable over short distances. –47MBk

> I would have expected more of a gradient, but what surprised me was the moment I would step onto Gilman [Drive], just to cross the road, there would be a spike. –30MWk

As participants began to attribute these variations to sources such as roads and intersections, they began to shift their mental model to incorporate their findings.

> The most surprising thing was the high readings downtown. I guess it would only make sense that it would be more polluted downtown where there's more people. –25FCr

> I've become more aware of how things like freeways, power plants, etc. affect the surrounding area. I guess I always just thought of the atmosphere as being evenly mixed but it is not. –33MTnB

Discovery of air pollution in unexpected places was another source of surprise for participants. 20MCr shared his surprise over learning that his lab, where he solders electrical equipment, often had unsafe pollution levels that he could not otherwise sense:

> The places I thought would be good, like inside buildings for the most part are clean but then anywhere where you're working with electrical equipment or chemicals, like the air quality seems fine, but the readings say otherwise. –20MCr

Another misconception that was challenged through data observation was that faster roads would have worse quality air than slower roads. In reality, there are many factors that contribute to poor air. For example, a slow road that climbs a steep grade may have much worse air quality than a fast but flat freeway. 44FBk noted, for example:

> I would expect it to be bad on the freeway, but I wouldn't expect it to be bad on single lane roads that go 30 [miles per hour], but that just doesn't make any sense I guess. So I was surprised at how bad the air quality was all around. –44FBk

These reflections are evidence of the intellectual work that participants undertook to process the readings they observed. Carrying the sensor with them and having access to real-time data allowed the participants to observe, reason about, integrate, and adapt their mental model of air pollution to be consistent with the new data they were observing. These observations helped form and shift the participants' understanding of when and where they experienced poor air quality. The data challenged previously held beliefs of safe and unsafe places, and also helped solidify understanding that had been based previously on guesses.

4.5 Sensemaking: correlating data within environmental context

Another aspect of interest was whether participants would be able to correlate the readings they observed with the environment around them. This issue is important because, as Kim and Paulos discuss in their work, the ability to identify the source of a high pollution reading is key in designing systems that enable change and avoid triggering feelings of powerlessness [13]. To investigate this, we focused on how the participants spoke about their readings and the way they attributed causation for the readings they observed. We particularly looked for occasions where participants spoke about bad air and gave attribution to objects in their environment that they perceived to be the source. An example of such an attribution is "I could see that idling my car resulted in bad air quality" as compared with "I saw that I frequently experienced bad air," where the formulation of the sentence implies causation to the action of idling the car rather than just observations about the readings.

In our analysis, we found that 24 of the 29 participants used language that attributed cause to objects in their environment, saying things like:

> I always see a spike in the air quality values when I arrive at SDSU - I think it's when I walk through an area where several city buses are stopped and running. I think it's very interesting!!! –32FCr

> Burning incense is terrible for my health –43FBk

> It seems like my gas stove kicks out carbon monoxide and it isn't vented. –33MTnBs

> It was interesting, what was the air quality that I was receiving throughout the day. SO I could say my commute to work was this, or if I took this route in, it would be this. Or if I went out into east county it would be like this –58MCr

The remaining 5 subjects did notice differences in their readings, but instead of associating higher readings with particular objects or environments, referred to them as "sporadic." There were also several cases where participants noticed a consistent pattern in their data but struggled to attribute cause:

> It's fascinating... walking up to the Triton statue the pollutants were at 250ish for quite a few days... what's over there? –56FVp

These unidentifiable spikes seemed to generate feelings of curiosity rather than helplessness, likely because the locations of the readings were outside their routine, in easily avoidable places. In addition to linking sensor readings with environmental context, the participants were also able to use the sensors to help understand physical reactions they were having to their environment, as in 32FCrBs's experience of an air quality–related health event.

> I liked being able to see what the air around me was like. Especially when I was having a hard time breathing and then found out that ozone was in the purple range. –32FCrBs

Perhaps the largest factor for participants in making these linkages between the sensor readings and their environment was the real-time nature of the device.

> It's pretty cool technology to have everything integrated and be able to look in real time what the sensor is reading. –25MCr

> I really liked that the readings were real time [...] so then I could be like at this specific moment the spike happened, because if there was a delay [...] you forget. –34FCrBs

On the extreme end of sensemaking were reports like 38FBs's, who conducted her own mini-experiments with the sensor while riding in her friend's car. "I am experimenting, [...] trying windows down or up, air conditioning on or off, with or without recirculated air." The real-time nature of the system allowed her to purposefully manipulate her environment and observe how her actions impacted the readings on the screen, allowing her to make assessments of how her actions impacted her air quality.

4.6 From awareness to empowerment

Air quality provides a different challenge when compared with many other health concerns, because unlike things like calorie counting or exercise, it is difficult to change air quality or exposure at the individual level. We had been concerned that exposing individuals to pollution readings may inspire feelings of powerlessness due to inability to change their circumstances. In examining the data, we looked for language that suggested feelings of helplessness, and also looked for language that indicated feelings of empowerment. While we did see some language relating to feelings of limited ability to alter daily commute routes, the participants did not express much concern over this lack of flexibility. We do not take this as an indication that lack of control over pollution exposure is not an issue, but rather that in this study its importance was lessened due to pollution exposures being generally low, even during commutes, with occasional spikes into unhealthy ranges. Ridesharer 48FCp summed up her experience, saying “there wasn’t any data that concerned me to the point where I thought, ‘Oh, I’m not going to go over there.”’ Instead, what we observed was empowerment through a collection of smaller-scale changes. Some of these changes happened at the individual level, and some were broader, positively affecting the communities of people who lived and worked with the participant.

Small-scale changes at the individual level were some of the simplest ways that participants acted on the readings they observed through using the CitiSense system. While these modifications did not change the overall commute structure—carpoolers still carpooled, bus commuters still bussed—these small modifications allowed users to lessen their overall exposure by identifying and avoiding behaviors that they correlated with high readings:

> My husband drops me off at the bus stop, and it’s a minor thing, but he drops me off in front of the bus so that I don’t get out near the fumes. –34FCrBs

> I’m more conscious of leaving my car idling and keeping the windows closed on the freeway. I am also more careful to walk on side-streets instead of busier roads –33MTnBs

Participants also related stories of how the data they collected with their sensors resulted in positive changes for those around them. For example, 49MCr purchased carbon monoxide sensors for his house after seeing how using his stove impacted his air quality. 43FBk related a change of a slightly larger scale, saying “My boss ... saw so many red and orange and yellow data points on my sensor [...] and went out and bought the office air filters.” Because 43FBk was able to easily sample and share her real-time readings with others who worked with her, people who had the power to make positive changes did so. In a similar way, by sharing his sensor readings with his fellow electrical engineering students, 20MCr encouraged them to change practices in the lab while they were soldering.

> The only ventilation would be like going out this small door in front, but the lab is like long and narrow, so like if you’re at the end the ventilation wouldn’t go out as much [...] we try to do everything outside now that releases fumes. –20MCr

Perhaps one of the most interesting changes we saw in the study was a change in attitude and concern toward local air quality. As 48FCp noted, it is hard to care about something you cannot see:

> If they know how it’s impacting them, and their children, then that’s when they start to take action on it. –48FCp

This new awareness about local air also leads to considering how air quality might impact different groups of people.

> For local air quality, if you’re rich you are able to escape it, but it you are poor, you are probably going to be living somewhere with bad air quality. –49MCr

Over the course of the study, participants gained a better understanding of the pollution in their communities and their interest in making positive changes increased. 41MBsTr described how carrying the system increased his interest in local pollution levels.

> I am enjoying collecting data at home, work and in my public transportation commute using the CitiSense system. Despite my initial lack of interest in commonplace city airborne pollutants, I am now fostering an enthusiasm about its relevance! –41MBsTr

This sentiment was echoed by other participants like 33MTnBs, who felt that his new understanding of air pollution made him more receptive to political measures related to clean air.

> I’m more inclined to support regulations to improve air quality. It’s made me aware that polluting our air is like fish pooping in their tank. –33MTnBs

Even in cases where participants did not alter their behavior, participants related that using CitiSense had changed the way they thought about the choices they made:

> It might not have a big effect on how many times I ride on the road verses the canyon, but it affects how I think about it. –44FBk

> It highlighted low lying regions as places to be suspicious in terms of air quality. I did have the thought, if I find an apartment I should look for one at the top of a hill rather than at the bottom of a hill. –29MWk

Having access to the sensor data meant that participants were able to quantify their exposure and make more informed choices based on real data, rather than guesses. These types of responses suggest that there may be opportunities for these systems to motivate people to advocate for change both at the behavioral level and at the policy level. The CitiSense system makes the previously

Fig. 9 Example of a CitiSense post shared on Facebook. The URL at the end of the post (obscured for privacy reasons) links to a live map page showing data points from the time window that the participant decided to share

invisible problem of poor air quality both visible and quantifiable, which may help people feel informed enough to make informed personal choices and to get involved to help improve their communities.

4.7 Sharing within communities

Somewhat surprising results emerged from our participant data regarding online sharing versus sharing with the people around them.

4.7.1 Sharing online

Online sharing was one way that participants shared their air quality data with their friends and family. The response from friends was mixed, with some friends engaging and asking questions, while others were confused about their friend's sudden interest in air quality (see Fig. 9 for a typical conversation on Facebook). One participant in particular received very positive feedback from his online friends, which may be due to him officially introducing the study on Facebook through the sharing of an annotated photograph (see Fig. 10). This introduction set the stage for his subsequent air quality posts.

While some participants received responses to their online posts from friends, others did not. However, even in the cases where participants did not receive online responses, it was common for local friends to ask about the posts in face-to-face conversation:

> The Facebook posts, to me, were a jumping off point, when I would see someone in real life they would bring it up, whereas I probably wouldn't just bring it up in conversation with anybody, unless they saw on Facebook that I was doing it. [...] Starting the conversation usually happened because of a Facebook posting. –48FCp

In this way, the online posts acted as a catalyst for face-to-face conversation, where participants could share their current miAQI reading, and also explain the study.

4.7.2 Sharing in person

In addition to the local sharing inspired by the online posts, participants found other opportunities to engage with proximate others to share their readings. The hyper-local nature of the data often prompted our participants to share with others nearby, even strangers. Four of the 29 participants reported occasions where they had shared their sensor data with strangers who were sharing their commute:

> I share the readings with the people I ride the train with and anyone else I interact with and they are usually interested. They seem pleased to see that it is pretty good and like me, surprised at the difference near the freeways. –33MTnBs

For 33MTnBs, who shared his commute—and thus his air—with his fellow passengers, it was natural to share with them the data he was collecting. Together, they were able to reason about the readings they observed, drawing

Fig. 10 Unprompted introductory post created by one participant. By introducing his online community to the CitiSense project, he better prepared them for understanding and responding to his subsequent air quality posts

correlations between spans of bad readings and the possible bad air sources near the train.

4.7.3 Impact of display

In the collocated deployment, the large-scale displays offered yet another opportunity for social engagement. The displays offered the ability for groups to view the data together. 26FCp had a group of friends that she regularly went to lunch with, and they would encounter the screens when they reentered the building and then look and reason about the displays as a group.

> We looked a lot at I-5, a lot of people go up and down. There's a variety of data on that too. Sometimes it's yellow and orange and we're thinking maybe that's someone on a bike, or maybe a car you don't want to buy, or a bus. The other day there was a Sorrento Valley spike and we thought maybe we shouldn't go there because it's all orange and gross. –26FCp

This type of interaction highlights the three most valuable aspects of the public displays: they are large enough to easily view as a group, make data available to non-sensor wearers, and are ambiently available in the physical space allowing for serendipidous encounters. Beyond these utility features, participants also reported feeling that the combination of carrying the sensor and the shared large-scale displays felt like they were able to contribute to the community in a meaningful but low-effort way.

> The fact is that we're off doing our own thing[...] and anything we can do that doesn't distract us, but brings us together seems like a nice thing. –55MSc

> It was cool having other people do it instead of just doing it on my own. –36FCr

Being part of a community is often desirable, but it can be difficult to maintain when work and other obligations make demands on one's time. The CitiSense display provided a way for individuals to contribute to the community in a low-effort way. As the display updated with a rolling 1-h window, it also allowed people to visualize movement within the department as markers would appear as people commuted to work, wander the campus on their breaks, and finally left in the evening.

5 Design discussion

The deployment of the CitiSense system provided an opportunity to observe how people used and integrated our mobile sensing system into their everyday lives. In this section, we take a high-level view of both the positive outcomes and the challenges faced in this deployment, highlighting what design decisions provided significant benefit to the users and what changes might be considered for future systems of this type.

5.1 Bridging data and real life: real-time, glanceable color scheme, and mapping

Three features of the CitiSense system played complementary roles in participants being able to reason about and link the data they were collecting with their real-world experiences.

The first, real-time readings, provided insight about the sources of pollution. When participants saw a bad reading, their first instinct was to look around and try to identify the source. Conversely, when participants observed something in their environment that they expected would have an impact on their air quality, they could check immediately to see if they were correct in their assumption. This ability to quickly verify assumptions allowed users to easily test their beliefs and revise their understanding.

The second feature of CitiSense was the conversion of raw sensor readings into a cohesive color-coded and numbered reading. Although there were three pollutant sensors on the board, only the miAQI value was reported on the main screen, a value generated from an equation that takes the raw sensor readings into consideration. This simplification allowed participants to quickly distinguish good" and "bad" air without having to memorize numbers or ranges. When participants discussed their readings in interviews and surveys, only one user discussed the raw sensor readings we provided on the details screen. Instead, participants primarily referred to the color or miAQI value, like 20MCr, who stated: "For the most part I looked at it and it was in the green, so it wasn't too bad." We expect that by decreasing the burden of data interpretation, participants were freer to think about "why am I getting this reading?" rather than focusing on "what does this reading mean?"

The third feature, personal pollution maps, supported users' ability to connect data collection with their real-world experiences by providing a visual link between the data points and familiar locations. When participants reviewed their maps, they had an easy time locating places where they had been stuck in traffic, or walking past construction sites. By seeing all the data in one place, rather than seeing just one or two readings, they had an easier time reasoning about larger-scale sources of pollution.

5.2 Mobile personal monitoring is a unique modality

As hypothesized in the "Introduction," air quality monitoring that is both mobile and personal has distinct characteristics from other variants of monitoring.

In their first study of in-home stationary air quality monitoring with InAir, Kim et. al found high engagement and curiosity about air quality not only inside participants' homes, but also on the road and at work [13]. Stationary monitoring did not satisfy these participants' curiosity. Although there are ways to power stationary devices so that they can become mobile, they still lack the location-based informational displays (samples plotted on maps) that ultimately make a large number of readings sensible.

With CitiSense, participants were able to gain a full picture of their individual pollution exposure, both indoors and out. Because of the high variability of pollution over even short distances, the cost and complexity of pervasively instrumenting the environment are not, at least today, a practical alternative. Even if appropriate densities could be achieved, stitching together a holistic picture across the different administrative domains (government, work, personal spaces, every storefront business, homes of friends, etc.) would be complex and expensive. Mobile sensors that move with individuals are the easiest way to begin collecting this kind of "whole picture" data to learn what pollution levels are actually being experienced by individuals on a daily basis.

The participants from the first InAir study also reported a feeling of powerlessness, in part because they found it difficult to locate sources of indoor air pollution with the stationary sensor. However, they did feel they had enough control to alter their habits and environment to improve air quality in the home, and many did. Many of the participants used the mobility of the sensor to explore variations in air quality by moving it about.

Although we hypothesized that the participants would feel powerless because they would lack the ability to alter their environment outside the home, the participants were creative in altering their work environments and commuting habits. In the second InAir study, which ran to 4 months and included reports of outdoor air pollution provided by the local air quality management district, the participants had more time and resources to identify sources of air pollution [14]. Additional time was a factor because the participants were home only a part of the day [13, p. 1868], an issue that a personal monitor helps overcome. Their results also point out that multiple stationary monitors can provide some of the same information as mobile monitors. However, as noted in the "Introduction," outdoor stationary monitoring is still quite sparse, generally resulting in broad regional reports, averaged over an hour. Our subjects discovered, however, that levels of pollution often vary widely over locales, particularly roadways and transit stops. This information was critical to the participants changing their habits when commuting. Also, as noted above, personal monitoring of the workplace, currently beyond the reach of government monitoring, was also valuable to the participants to altering their habits and environment.

In the above, although we referred to multiple monitors emulating mobile monitoring, it can actually be the other way around. Since some amount of time passes between collecting data in one place and the next, there is always the chance that the passage of time itself has something to do with any change in values. Our participants used small time intervals and repeated visits to add confidence to their inferences. But, as discussed in Section 5.3, one participant wanted to make inferences between morning and afternoon readings on the same road, leading us to observe that personal mobile monitoring itself can be augmented by the sharing of readings among multiple mobile monitors. As is, CitiSense's map overlays of AQI inferences and personal plots of readings provide additional information to add confidence to inferences.

Sharing is supported by both InAir and CitiSense, but in different modalities. InAir supports linking to other households that have InAir. The InAir studies recruited groups of friends and family for sharing, all in the same region. With InAir, sharing was embraced, often playfully, and was even used for locating sources of pollution, again exploiting the potential of multiple stationary sensors. Our studies extend these results, revealing the hyper-local nature of air pollution data. For one, we found that sharing outside the participant's region did not create engagement (although perhaps it would if there were strong ties, such as parent–child), something not explored in the InAir studies. Yet, the same sharing engaged those local to the participant, often serving as conversation starters in later face-to-face encounters. Further, the presence and use of the device in public settings often led to conversations with strangers, showing that mobile personal sensing adds a unique dimension to the local character of air quality data.

On the issue of privacy, the InAir studies revealed no issues, but the authors suggested that more study was warranted. This is true as well in our studies. Mobile monitoring dramatically increases the amount of location data that can be shared, so we designed our social features to use active, explicit sharing. Consequently, no issues arose. However, in post-facto analysis of the location data from our studies, we observed potentially embarrassing information about where people spent time, highlighting the importance of a privacy-aware design for mobile monitoring. As with all services that collect personally identifiable data, it is critical to obfuscate data collectors to reduce the possibility of harm coming through the use of the service.

Additionally, as we consider systems that share this data between individuals, it will be important to properly handle data points that have been collected in private residences and businesses. When interpolating a model of the outdoor air, sporadic data points collected from indoor sources will falsely influence the model. One possible solution to maintain data quality for both individual and community users might be using the phone's GPS capability to segregate indoor and outdoor data. The structure of most buildings blocks GPS signals, and receiving poor GPS connection could be a good indicator for when an individual is indoors. GPS could be also used to label data as being collected in a car (whose filtration system and body reduce readings), by using the GPS readings to infer speed. Then, data points collected while driving could be treated differently in inferring pollution outdoor levels versus individual exposure.

5.3 Divergent experiences demand expanded analysis and sharing

Our participants employed a range of commuting methods, which brought to light an unexpected dichotomy. Although some of the participants traveled the same paths, their experience and exposure to pollutants could be vastly different depending on their choice of transportation. For example, car commuter 48MCr shared his surprise at how much better the air was than he expected. "I'm just surprised of generally, how clean the air is in the freeway areas... :)" Conversely, 32FCrBs, who often rode the bus, left the study realizing that she was being exposed to much higher levels of pollution than she had expected: "I really had no idea how frequently I am exposed to pollutants." (We reiterate that the participants' air quality was generally good, so it is likely 32FCrBs was speaking of brief high exposures.) This discrepancy stems from the fact that even though the participants were in the same space geographically, the exposure of participants riding in modern cars was apparently mitigated by vehicle bodies (e.g., air intakes mixing blasts of automobile exhaust into other air, reducing high readings), activated carbon cabin air filters, and modern sensor-driven HVAC systems that close a flap over the intake when outside pollution spikes [8]. Being aware of only their own readings, participants generally could not observe this discrepancy, and expected that the readings they were observing generalized to the general population. 44FBk was one of the few who observed how her choice of transport influenced her exposure, and only because she commuted in two substantially different ways:

> [What] stood out the most to me is how I drove to work, and then I rode my bike back the same way. And on the way there the air was perfect, green, the whole way, and on the way back it was terrible the whole way. So, like the car protected me from the bad air and that was shocking to me, [...] Like here I am riding my bike and I'm, it's probably worse for me. – 44FBk

Of course, 44FBk may have jumped to a conclusion, as late afternoon air pollution is often worse than morning air pollution.[2] But this is part of the point we wish to raise. If she had been provided a way to help her see how her personal data compared to the greater corpus, it could help clear up discrepancies as well as expose hidden patterns (disparities).

5.4 A technology that engages people with the surrounding world

Mobile communications and computing technologies are typically seen as distracting people from their immediate surroundings, altering interpersonal interactions and creating dangerous situations. In contrast, the hyper-local nature of CitiSense's design encouraged engagement with physically proximate people:

> It was nice, technology as a conversation starter [...] previously I would sit on the bus and I wouldn't talk to anybody, I would be on my cell phone. And so that was a use of technology that basically cuts me off from my environment and my community, whereas actually this, because I was becoming aware of my environment, and I was aware that people were sharing the environment, it then helped me to talk to people. –34CrBsF

There are likely more opportunities in this space for creating technologies that connect individuals with the people around them. We hypothesize that sensing and exposing "common ground" to proximate individuals, as CitiSense does with air pollution, are key to achieving this goal.

5.5 Future directions: disparities, asthma, and calibration

This study focused on healthy adults from middle-class backgrounds. By choosing this set of participants, we were able to learn about how a real-time mobile air quality system might be used in everyday life. In future studies, we plan to explore more diverse populations to gain a broader view of how these systems may be used in situations where poor air quality is more typical at home and work. With road workers on a highway, for example, it may be very difficult to institute changes to avoid unhealthy air. It is important that we look toward empowering communities rather than creating a sense of helplessness.

[2]The complete reasoning for this phenomenon is beyond the scope of this paper, but two contributors are the sunlight over the day that converts NO_2 to O_3 and lower nighttime temperatures that tend to precipitate the day's pollutants out of the air.

In another dimension, we plan to run studies with families of asthmatic children. We believe that a technology like CitiSense can be useful for parents who want to pinpoint areas of high exposure so that they can help their children avoid unnecessary hospitalizations.

Finally, an open challenge with personal or citizen sensing is the correct calibration of the sensors. Sensors, in part due to their ongoing exposure to the environment, change behavior over time, becoming increasingly inaccurate. Moreover, this degradation can be continuous and subtle, making detection by a human difficult. In a project called MetaSense, we are investigating the potential for a system of personal monitors to detect and even correct such problems while in deployment, using machine learning techniques related to those that infer the pollution maps in CitiSense [30].

6 Conclusions

People can benefit from being able to see the invisible through emerging mobile sensing systems. Body-worn sensors are particularly appealing due to the personal nature of the data, but there has been little study of how such systems are used in everyday life over a significant period of time. This paper contributes both a detailed description of the user side of the CitiSense mobile air quality system and the results of two 4-week "in the wild" user studies, one of 16 UCSD commuters, and the other of 13 participants drawn from a single campus workplace.

From these studies, we highlight the following takeaways:

CitiSense's design and data support sensemaking Participants were comfortable using the CitiSense application's displays to draw inferences about pollution sources, using additional clues and knowledge from the environment. The mobile phone–based AQI-style glanceable display of instantaneous readings was central to the inference activity.

Mobile personal sensing provides unique insight, and interpersonal sharing would further enhance The ability of the sensor to go wherever a participant went both provided a uniquely complete picture and created a unique self-interest in the data coming from the sensor.

The data provided by CitiSense often contradicted participants' preconceptions about the nature of air pollution. Participants learned that air pollution can be highly variable over small distances rather than uniformly distributed. Also, participants were often surprised where air pollution was high, revealing not only misconceptions but also suggesting that air pollution phenomena are complex. Especially surprising were the distinct experiences bus riders, biker commuters, and car commuters had, even in the same place.

Due to the disparate experiences of different types of commuters, we believe that directly contrasting those personal experiences would further heighten interest in one's personal data by making it possible to draw better conclusions and see disparities in exposure.

Mobile personal air pollution data supports forming attitudes and modifying behavior Contrary to expectations, several participants modified their behaviors or environment to reduce their exposure or to reduce their own contributions to air pollution. Participants generally felt empowered. This result might not generalize to less affluent contexts, however.

Air pollution data's relevance is socially hyper-local In-person sharing and discussion of readings from the CitiSense sensor were common, as people generally found the air pollution data both interesting and non-controversial. Despite built-in features for sharing on Facebook and Twitter, online sharing was infrequent and did not generate much interest. Online sharing was most successful with friends who lived locally—who had a selfish interest in the data—and in such cases often led to face-to-face conversations about the data. The public display in the second study, providing another sharing opportunity, gave participants a sense of contributing to a purpose bigger than themselves.

More generally—although air pollution data has unique properties—this study highlights the promise of always-on body-worn environmental sensing to increase people's awareness of their environment, change their attitudes (and perhaps behavior), and facilitate positive face-to-face social encounters.

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