Personal Pollution Monitoring: Mobile Real-Time Air-Quality in Daily Life

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ABSTRACT
Poor air quality is a growing global health concern that impacts millions of people worldwide. Although we are beginning to understand the health impacts of air pollution, it remains a challenge to provide people with the information they need to be able to make health-conscious choices. The CitiSense system gives individuals the real-time tools they need to be able to identify when and where they are exposed to poor air. We present the results of a qualitative study regarding a 4-week "in the wild" deployment of the CitiSense air-quality sensor and system. We focus on how the 16 participants responded to their new-found information about their environment, how they shared information, and what kinds of actions were enabled by having access to real-time air-quality data. Quantitative data gathered through the course of the study frames participant responses by showing what levels of pollution were experienced and what activities heightened exposure. We found that CitiSense's real-time graphical displays and everywhere monitoring provided a critical bridge between data and experience, enabling sophisticated in-the-world sensemaking and sharing with those nearby. This in turn affected behavior and attitudes, leading to shifts in how users reasoned about their world, and how they assessed their personal choices and impact.

Author Keywords
ubiquitous computing; sensors; air quality; participatory sensing; health

ACM Classification Keywords
H.5.m. J.3 [Life and Medical Sciences]: Health

General Terms
Human Factors; Design; Measurement.

INTRODUCTION
Indoor and outdoor air pollution is responsible for an estimated 3.2 million deaths worldwide each year [26] and is linked with increases in heart attacks, asthma, dementia, and cancer[3, 23, 24]. These impacts are felt most severely in developing nations where there is little regulation of emissions. However, even in the United States, where clean air regulation has been in effect for over four decades, an estimated 50,000 premature deaths each year are attributed to poor air, with additional costs of pollution-related illness estimated to be $150 billion a year [17]. Loss of quality of life due to restricted behavior, more hospital visits, 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 rather than the norm 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 to poor air quality can have life-changing health effects for sensitive groups such as the very young, or those with underlying cardiovascular disease or asthma [12, 14, 23].

The sampling currently used by governments employs stationary air monitoring stations to estimate regional air quality. This is an important starting point, but unfortunately conveys little detail about actual individual-level exposure. Regional air quality assessment is conducted by widely dispersed sensors, with many large cities being covered by only a handful of stations. Air quality can be highly variable across neighboring locales due to regional geography, industrial areas, weather, 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 major roads and freeways, and of course not in people's homes. As a result, current monitoring methods may do little to inform individuals of the elevated exposures they encounter in their daily lives while sitting in traffic, sleeping in their homes, or walking along a busy road.

This lack of awareness can make it hard for individuals to act in informed ways regarding their pollution exposure. 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.

The goal of the CitiSense project is to provide individuals with a system that makes the invisible visible: providing people, for the first time, a way to see what their pollution exposure is in real-time. To our knowledge, our 4-week deployment is the first "in the wild" study of a mobile air sensing system designed for novice users.

In this paper, we present three contributions that help inform research in the space of mobile environmental sensing:

- Results from the first month-long "in-the-wild" deployment with non-experts users for a real-time mobile air quality system.
- An in-depth look at user perspectives on, and responses to, viewing their own air quality data.
- Insight for what properties supported synthesis by users, with a particular focus on how design decisions impacted usage, adoption, and integration.

These contributions help us expand our understanding of individuals might engage with mobile sensing systems to collect, reason about, and apply sensed information in everyday life. In this paper we also look at how and when individuals chose to share their data with others, both in person and online. Finally we present design guidelines for future systems, and ideas for deployments with more diverse groups.

BACKGROUND AND MOTIVATION

Sampling air quality is an important but difficult task that researchers have explored using a variety of techniques.

Making Existing Data Accessible

Environmental data is often publicly provided by government agencies that collect it for public health purposes. However, there is often a significant gap between how agencies report data and the people who would benefit from access to that knowledge. Several systems have explored designs that bridge the gap to provide publicly collected data in an easy-to-digest format for everyday users. 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 (reported at the zip code level), and only consisted of outdoor readings, participants still reported using the system to support their decision making processes, a feature that was especially useful for individuals with respiratory problems. From these positive results we postulate that personalizing the data further to include finer-grained exposure data and including indoor air quality will empower users in their decision to an even greater degree. [8]. Systems such as iMAP and PIER have taken this approach a step further by creating pollution models from multiple data sources such as traffic patterns, weather, and regional air quality sensors [5,15]. They then provide exposure predictions based on location data collected from an individual's mobile phone.

Going Indoors

The InAir[13] and MAQS[11] systems target the significant challenge of indoor air quality sensing, an important area since, as reported by Jiang et al., on average over 90% of modern life is lived indoors [11]. InAir provided participants with a stationary indoor air quality sensor for particulate matter. Participants used the system for 2 weeks and 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. 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.

The MAQS [11] air quality system also explored improving indoor air tracking through mobile sensors that sampled CO_2 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. 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.

Taking it Outside

Wearable sensors have also been used to sample outdoor air quality. 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 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" support microclimates that can vary widely from one another [21]. The AIR project extended this research by building a mobile air quality sensor for nitrogen oxides, carbon monoxide, and ozone [4]. Participants were asked to carry the device for no longer 24-hours and then pass the sensor on to a new individual. Data was collected to create artistic visualizations intended to help communities think about their air quality.

Aoki and Willett et al.'s CommonSense [1, 25] system explored outdoor sensors in a variety of contexts including sensors mounted on street sweepers, and hand held sensors that could be used by individuals to sample interesting outdoor locations. The street sweeper deployment strove to augment a city's existing sensor infrastructure with vehicle-mounted sensors. Aoki also explored the tradeoffs in air quality management, and the requirements for collecting data to support social and political change[1]. In the CommonSense handheld deployment participants took part in a one-day workshop where they were encouraged explore their local environment with a hand-held particulate sensor. Participants were then asked to give feedback to various data visualization techniques for exploring their data[25].

We drew from these visualizations such as the "tracks" map-based visualization for our system. The CitiSense system extends the findings of the CommonSense system by exploring "in-the-moment" visualizations that support real-time analysis, in addition to providing desktop based, reflection supporting visualizations.

Opportunity for Impact

Through exploring the existing research space we found an unmet need for a wearable indoor/outdoor air quality sensor. Such a sensor could support a holistic view of personal air quality sensing, representing the indoor air readings that make up the majority of the day with the peak exposures experienced during outdoor activities. We also found opportunity for learning how such a sensor might be accepted and adopted into daily tasks through a longer term deployment. Prior work on CitiSense defined the system design, described a collection study looking at the distribution of air pollutants in an urban area and reported on how a small group of users responded to the system design and interface [2,16,18]. To our knowledge the study presented in this paper is the first month-long "in the wild" deployment of a mobile air quality system with novice users.

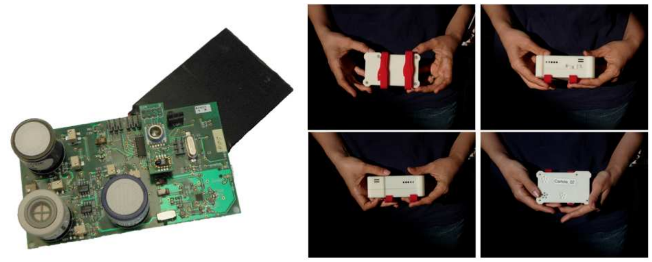
CITISENSE DESIGN

The CitiSense system is comprised of four main components: a wearable sensor board that pairs with an Android phone, a server-supported, web-based personalized daily pollution map, and a social component supported through Facebook and Twitter integration.

Sensor and Phone

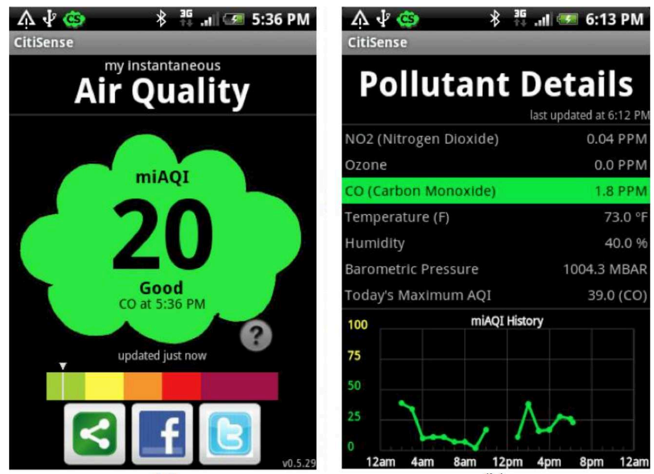
The mobile component of the CitiSense system consists of an Android mobile phone running custom application and a mobile air-quality monitoring unit that sends sensor data to the phone via Bluetooth. The air-quality monitoring unit contains the following 6 sensors attached to a custom board; Carbon Monoxide (CO ppm), Nitrogen Dioxide (NO2 ppb), Ozone (O3 ppb), Temperature (F°), Barometric Pressure (MBAR), Humidity (reported as percentage).

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 developed a modified version of the Environmental Protection Agency's (EPA) Air Quality Index (AQI) number and color mapping to help our users easily and quickly interpret sensor data. While the EPA's AQI values represent an average pollutant level at a location over time, CitiSense provides an instantaneous report of the same value. 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 My Instantaneous Air Quality Index (miAQI).



(a) (b)

Figure 1. (a) sensorboard. (b) Sensorboard in printed plastic case. Velcro straps are attached to the case so users can easily attach the sensor board to backpack straps and bike frames.



(a) (b)

Figure 2. (a) Application home screen. Cloud color and number change based on current sensor readings. The bar at the bottom indicates where on the spectrum the current reading lies. (b) Pollutant details screen. The graph displays peak readings by hour.

The miAQI number and color is displayed prominently on the mobile application home screen (Figure 2) and is also used to populate and color the balloons on each participant's personalized map page (Figure 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 webpage was designed to allow users to dig deeper into their data and see trends in their exposure. The visual nature of the time chart and map allow users to quickly locate the time and place of peak exposures. These web pages were also designed to give drivers and cyclists, who can't look at the phone display while they commute, a way to see their commute data in a safe way.

Figure 3. 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].

The webpage 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.

USER STUDY

We recruited 16 participants (8 men, 8 women) to carry the sensors for one month. The age of participants ranged from 20 to 56 years (mean age 38.5 years) and their commute distance 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 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. As this was an exploratory study we tried to select a range of commute types so that we could observe a wider variety of behaviors as shown in **Table 1**.

Table 1. Participants' commute method and total miles commuted each day (round trip). The first column encodes the age, transport method, and gender of each participant and will be used to identify users throughout the paper.

Participants self-reported commute data		
Participant ID	***Method***	***Miles/km***
43BkF	Bike	27/43.5
32CrBsF	Halfway car, halfway bus	40/64
33TnBsM	Train and bus. Sometimes train	60/96.6
45CrM	Car	65/104.6
41BsTrM	Bus and trolley	54/86.9
28BkM	Bike	20/32.2
41CrF	Car	58/93.3
20ScM	Motorized Scooter	14/22.5
48CrM	Car	50/80.5
20CrM	Car	4/6.4
56VpF	Vanpool	34/54.7
47BkM	Bike	4/6.4
48CpF	Carpool (with spouse)	50/80.5
32CrF	Car	42/67.6
44BkF	Bike	30/48.3
34CrBsF	Car to Bus	30/48.3

Our 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, attend a 30 minute training session, responding in 4 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.

To analyze our data we used an iterative approach to code the interviews and open-ended survey questions. We also conducted a focused textual analysis looking at our participants' word choices when discussing their relationship to system and to the pollution readings they encountered.

RESULTS

Our main goal was to learn how access to air quality data might affect the participant's behavior throughout the study. In this section we look at data from the surveys and interviews to learn how the sensors integrated into their daily activity and how the participants' perception of the world was shaped by access to real-time air quality readings.

Mining Sensor data for Quantitative Context

To help frame the responses from our participants we also collected location and air quality data in a central server throughout the study. This data helps give context for what the participants actually experienced during the one month deployment. In total, we computed and collected 4,824,265 miAQI readings (representing a total of 335 days worth of sensor readings). To participate in the study, participants were required to carry the sensor only while commuting or a total of about 40 hours each. However, our data reveals that the participants voluntarily carried the sensor an additional 502.5 hours on average, over 12 times the required amount. This suggests that the participants were receiving value from carrying the sensor.

In taking a closer look at the data we observe that by EPA standards, most of the air samples were well within the safe range, with 4,618,706 readings in the "good" category, 118,806 readings in the "moderate" category, and 31,227 readings in the "unhealthy for sensitive groups" category. This finding is in line with what we expected as most modern office buildings have advanced air filtration systems, and homes generally have low readings for CO, NO2, and Ozone. Emissions from gas stoves and burning incense are two exceptions in the home that were noted by our participants.

Yet, all of our participants also experienced periods of exposure to unhealthy air. Over the course of the study a total of 55,526 readings were observed in the unhealthy range (miAQI > 150). Delving deeper into the poor air readings collected, we compared stationary to mobile readings (See Table 2).

Table 2. miAQI readings separated by transportation type

	Biking	Car	Other	Stationary
Average AQI	98.58	35.55	29.26	14.9

The readings collected by our participants conform with our expectations that the air quality experienced while in transit has higher pollution levels than in homes and workplaces. The method of travel also played a significant role in the air quality experienced, with the average miAQI for bicycle commuters being over twice of that experienced by car commuters and over 6 times the average reading when stationary. This disparity between the data collected by cyclists and car drivers is addressed in the Discussion.

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. 32CrF 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." - 32CrF

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.

Reconciling readings with previous beliefs

Prior to the study, 15 of our 16 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 15 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 our participants when the readings they observed didn't 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. 47BkM'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." -47BkM

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.

"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." -33TnBM

Discovery of air pollution in unexpected places was another source of surprise for participants. 20CrM shared his surprise over learning that his lab, where he solders electrical equipment, often had unsafe pollution levels that he couldn't 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. –20CrM

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. 44BkF 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 goes 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." – 44BkF

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 our participant's understanding of when and where they experienced bad 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.

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 our 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 13 of the 16 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 <local college> - I think it's when I walk through an area where several city buses are stopped and running. I think it's very interesting!!!" —32CrF

"*Burning incense is terrible for my health"-43BkF*

"It seems like my gas stove kicks out carbon monoxide and it isn't vented." —33TnBsM

The remaining 3 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 <local monument> the pollutants were at 250ish for quite a few days...what's over there?"—56VpF

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, our participants were also able to use the sensors to help understand physical reactions they were having to their environment, as in 32CrBsF'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." —32CrBsF

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

"I really liked that the readings were real time […] so then I could be like at this specific moment the spike happened because, because if there was a delay, I wouldn't, you wouldn't, you forget what you did five minutes ago." —34CrBsF

On the extreme end of sensemakeing were reports like 38BsF'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

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 looking at our data we were careful to watch for language that suggested feelings of helplessness, and also watched for language that indicated feelings of empowerment. While we did see some language relating to feelings of limited ability to alter daily commute routes, our 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 48CpF 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." —34CrBsF

"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" —33TnBsM

Participants also related stories of how the data they collected with their sensors resulted in positive for those around them. For example, 43BkF related that *"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 43BkF 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. Similarly, by sharing his sensor readings with his fellow electrical engineering students, 20CrM encouraged them to avoid bad air 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**." —20CrM*

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

"If they know how it's impacting them, and their children, then that's when they start to take action on it." —48CpF

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. 41BsTrM 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**!" —41BsTrM*

This sentiment was echoed by other participants like 33TnBsM, 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**." —33TnBsM*

Even in cases where participants didn't 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." —44BkF

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 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.

Sharing within communities

In our study we included functionality in both the mobile app and webpage to facilitate online sharing through social networks. In addition to this online sharing, participants also frequently shared with the people around them.

Online

Online sharing was a 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 Figure 4 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 Figure 5). This introduction set the stage for his subsequent air quality posts.

While some participants received responses from friends on their online posts, 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**." —48CpF*

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.

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 16 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." —33TnBsM

For 33TnBsM, 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 correlations between spans of bad readings and the possible bad air sources near the train.

Figure 4. Example of a CitiSense post shared on Facebook. The URL links to the live map page showing the points from the time window that the participant decided to share.

Figure 5. 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.

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.

Same place, different realities

Our participants represented a range of commuting methods, which brought to light an unexpected dichotomy. Although some of our 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 48CrM 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, 32CrBsF, 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."* This discrepancy stems from the fact that even though our participants were in the same space geographically, the exposure of ones riding in modern cars were often mitigated by air filters and vehicle bodies. Being aware of only their own readings, participants generally couldn't observe this discrepancy, and expecte that the readings they were observing generalized to the general population. 44BkF 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." – 44BkF

This finding is important as we consider additional opportunities for citizen sensing. All community members do not have the same experience and exposure, even when traveling to, and living in, the same places. Without ways to allow users to compare and learn from each other's readings it is very possible for individual users to adopt a skewed view of reality. In this deployment of CitiSense, we did not provide a way for users to share their readings with each other, which resulted in our participants leaving the study with quite different views on the state of the air in their shared community. In future systems, finding ways to help participants see how their personal data fits within a greater corpus of collected data may help clear up some of these discrepancies.

Bridging Data and Real Life

Three features of the CitiSense system played a key role in our 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, 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.

The third and possibly most important 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, not a single user referred to the raw sensor readings we provided on the details screen. Instead, they would refer to the color or miAQI value, like 20CrM, 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?"

Mobile can go where public services stop

Another benefit of the CitiSense system was that 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 is 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.

As we begin to use this type of mobile sensor data, there are new concerns regarding privacy and validity that must be addressed. 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. Perhaps even more importantly, it will be important as we consider systems that share this data between individuals, to remove 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, which can be a good indicator for when an individual is indoors. GPS could be 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.

Technologies that engage the physical 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 exposing "common ground" to proximate individuals, as CitiSense does with air pollution, is key to achieving this goal.

Future Directions

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 towards empowering communities rather than creating a sense of helplessness.

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.

CONCLUSION

In this paper we introduced the CitiSense mobile air-quality system and presented results of a 4-week "in the wild" study with 16 participants. We provided in depth discussion regarding the usage and adoption of the system using quantitative and qualitative methods. The observations and lessons we learned from this study of the CitiSense system can be of benefit to researchers and practitioners building similar systems, helping to avoid pitfalls and to think about what design decisions may best serve their target populations.

ACKNOWLEDGMENTS

Omitted for Review.

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