Ceci N'est Pas Une Pipe Bombe: Authoring Urban Landscapes with Air Quality Sensors

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ABSTRACT

Our work explores the convergence between participatory sensing, political activism and public expressions. Unlike prior research, which focuses on personal sensing, we present low-cost, networked air quality sensors, designed to be repositioned across public landscapes by communities of citizen stakeholders. Our GPS-enabled sensors report dust, exhaust, or VOC's (volatile organic compounds), along with temperature, humidity and light levels to a website that visualizes this data in real time. The sensors can be attached to a variety of surfaces serving as research probes to demarcate ('tag') public spaces with environmental concerns. We deploy our fully functional system with four urban communities- parents, bicyclists, homeless and activists, positioning our system as a tool for studying and supporting community togetherness and public activism. Our findings highlight community sharing of the physical sensors and dialogues surrounding the collected data.

Author Keywords

Political computing, urban computing, participatory sensing

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

"Objects become things, that is, when matters of fact give way to their complicated entanglements and become matters of concern."
–Bruno Latour

A range of technologies and methods enable non-experts to collect and share environmental data through participatory sensing [3, 29, 35]. We ask how low-cost and widely available sensors can be leveraged as instruments of environmental and political change. How can citizen-collected data become a point of reflection, a tool for taking action, and a matter of public *concern*?

Participatory sensing is inspired by a history of bottom-up initiatives- from neighborhood watch campaigns to political revolutions- these movements empower stakeholders to act as agents of change. Recently, DIY (do it yourself) methods and low-cost technologies resulted in new tools for data collection, including sensor-enabled mobile phones and hand-held monitors [*e.g.,* 7] or sensors deployed on moving vehicles [2]. Despite the success of existing strategies for personal participatory sensing, there has been little exploration of important related concepts of sensor ownership, public authorship, expressions and community sensing strategies. This paper directly confronts, questions, and explores these concepts by introducing a new sensing paradigm: rather than belonging to a particular person or space, our low-cost modular sensors can be moved, left and placed throughout public spaces by various stakeholders.

Sensing as a mode of expression

We challenge the conventional notion of sensors as passive instruments of data collection. The act of placing a sensor, particularly one with politically or environmentally loaded content such as air quality, can be an overt and public act. The mere presence of such a sensor can project a statement or concern about a place, and the resulting sensor data can be broadcast within and across communities to provoke and transform perceptions, usage, and labeling of space. We explore these ideas by developing a system of networked movable sensors as tools for bottom-up community data collection and expression in the public sphere (Figure 1).

PRIOR WORK

Prior participatory sensing projects have enabled non-experts to monitor air quality with handheld monitors [7] cellphones [16] and sensors installed in private homes [22].

Figure 1. Exhaust sensor attached to fire hydrant near busy street (top left); map of exhaust data gathered by parents (top right); dust, exhaust and VOC sensors attached to bridge (bottom left); VOC sensor on park railing (bottom right).

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Air quality sensors have also been deployed on moving surfaces such as street sweepers [2], bicycles [14], robots [21] and pigeons [6], or in bounded spaces [5, 19]. Drawing from HCI work that explores the intersection between technology, art and politics [7, 9 12, 15, 17, 18,], we position our system of movable sensors as an approach for supporting community expressions and activism.

Expressions across public surfaces

Numerous technologies facilitate public engagement and authorship: Pushpin Computing [27] is a platform for computation and visualization, DataTiles [31] and Siftables [28] are programmable tile displays; 'Light Bodies' [32] are distributed interactive light nodes. We apply the flexible and modular design paradigms of past systems to the design of our public place-based sensors. Similar to LED Throwies [16], our sensors can be attached to a range of public surfaces to express and monitor environmental concerns. Unlike prior public visualizations of air quality, including wearables WearAir [23] and CO2RSET[1], the spatially-fixed pollution e-sign [20], or the municipally-installed and Air de Paris Balloon[2], our movable sensors serve as a community resource for grassroots air quality monitoring.

Community engagement and the creation of 'publics'

We explore participatory sensing as an approach for sustaining and supporting cohesive *publics* [8] –groups of people that are affected by an issue, working towards alleviating a common problem. Latour and Weibel's *Making Things Public* addresses the mechanisms by which ideas are broadcast into the public sphere, exposing the complex interplay between technology, art, space and people that fosters the creation of 'assemblies' [24]. Recent HCI literature explores design principles for supporting and creating publics [10] as well as opportunities to engage with and empower specific communities [11, 12, 25]. We present a public sensing system as a tool for monitoring and expressing community concerns. We previously explored this space through the use of sensor probes- non-working sensors that simulate the measurement of exhaust, smog, pathogens, chemicals, dust and noise, distributed to stakeholders from communities of parents, students, bicyclists, and homeless [withheld]. Participants were asked to place, leave, and move the probes throughout public spaces as if they were real sensors, and our findings suggest environmental sensing as a tool of community togetherness, engagement and activism. In this paper we re-affirm, challenge and augment these findings through the deployment of a working system with four communities of urban stakeholders.

PUBLIC PLACE-BASED SENSING

Our sensors, measuring exhaust, VOC's (volatile organic compounds), or dust, report air quality along with humidity, temperature and light levels to our central website in real time (Figure 1). Integrating commercially available sensors with off-the-shelf components, the exhaust sensors respond to gases emitted by vehicular traffic and diesel engines, VOC sensors detect compounds originating from paints, solvents or pesticides and dust sensors measure particulate matter (pollen, smoke, *etc.*). These factors are of serious public health concern within the geographic region of our study: our city was rated as one of the worst in the United States in terms of air quality and exposure to exhaust, dust or VOC's can lead to chronic respiratory illnesses, including asthma, bronchitis, inflammation or cancer [1, 4]. The sensor case is outfitted with a mounting magnet, hang strap, and carabineer, affording easy attachment to public surfaces. Measurements are displayed on a community website (not the unit itself) to facilitate *community* rather than *individual* use of the sensors.

Research objectives

To gain insights into community appropriations of public place-based sensing, we deployed our system with four groups of urban stakeholders: bicyclists, parents and their children, homeless people, and activists. Each group, consisting of four to seven participants, was asked to share three air quality sensors (VOC, exhaust, and dust), placing and leaving them throughout the city over the course of one week. A website displayed community-collected data on a comment-enabled map and interactive graphs. Our findings address questions such as, 1) how do different stakeholders interact with shared technical resources; 2) how do issues of authorship, anonymity and security affect sensing in public spaces; 3) which spaces afford curiosity about specific environmental factors across different communities; and 4) what design principles leverage participatory sensing as a platform for city-wide grassroots activism?

SYSTEM

We designed and built a system of networked air quality sensors entirely from off-the-shelf parts. We intentionally chose low-cost and low-precision sensors to develop DIY (do it yourself) technology that can be re-created by non-experts without high-end calibration procedures. Our sensors provide relative rather than absolute (PPM, *etc.*) values, and the visualization enables comparison of VOC, and exhaust levels across different times and locations. Rather than focusing on scientifically precise values, our initial goal is to highlight variability across time and space.

Sensors

Our sensor circuit is supported by a custom PCB board that can be populated with exhaust, VOC, and/or dust sensors from Figaro[3]. In order to highlight specific air quality concerns and spatial affordance, every deployed unit was outfitted with a single sensor (exhaust, dust or VOC) and our participant groups received one of each. In addition, all units include a dual function temperature/humidity sensor and a light sensor. Input is processed by an Arduino[4] mini microcontroller, which interfaces with a Telit GSM/GPRS

[1] http://itp.nyu.edu/shows/spring2008/co2rset/
[2] http://aerophile.com/
[3] Figaro sensors. http://www.figarosensor.com/
[4] Arduino microcontroller. http://www.arduino.cc

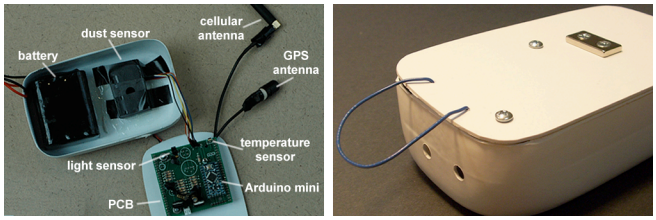

Figure 2. Exhaust sensor in case, with parts labeled (left), and back of sensor case with magnet and strap (right).

module[5] to send time-referenced sensor data along with the unit's GPS coordinates as an SMS message. Units are powered by rechargeable 6600mAh lithium batteries and enclosed in custom vacuu-formed polystyrene cases (4.0cm x 6.5cm x 13cm, Figure 2). Units are branded with our university name and logo on the front, and contact information and sensor description on the back. Small holes in the case allow for air circulation and light inside the units, and although several deployments encountered significant rain, sensor functionality was not affected.

Maximizing battery life

Our units function continuously for up to ten days by supporting three power modes: full power (300 mA) with sensors powered on and GPS/SMS transmitting, standard mode (40-100 mA) with sensors powered on and the GPS transmitter off, and low power mode (1 mA) with the system in sleep mode. During sleep mode, continuous sampling from a tilt sensor is processed to determine whether a unit is being physically moved (picked up, walked, biked or driven with). When movement is detected, units power up to full mode, transmitting GPS coordinates and sensor data every five minutes. However, if left static, units remain in sleep mode, changing to standard mode once every 30 minutes to sample sensor data and store it locally. The units then send the data in bulk every 5 hours.

Backend

Data from the units is sent as a comma-delimited SMS message to an e-mail address that is polled by cron-job. Since we did not calibrate the air quality sensors, all dust, exhaust and VOC values are scaled to a range between 1 (lowest) and 100 (highest) for consistency. Data is inserted into an SQL database, with separate tables for each of the studied communities. Consequently, participants can access sensor placements and data collected by their community.

Interface

Our front end, developed in php and javascript, leverages the Google Maps API[6] and with Google Chart Tools[7] to render data geographically (on a map) and temporally (through a series of interactive graphs).

Map

The map shows sensor placements as varied-size dots (sized according to air quality levels), connected chronologically with a line to illustrate the unit's path. Different sensors

[5] Telit. http://www.telit.com
[6] http://code.google.com/apis/maps/index.html
[7] http://code.google.com/apis/charttools/index.html

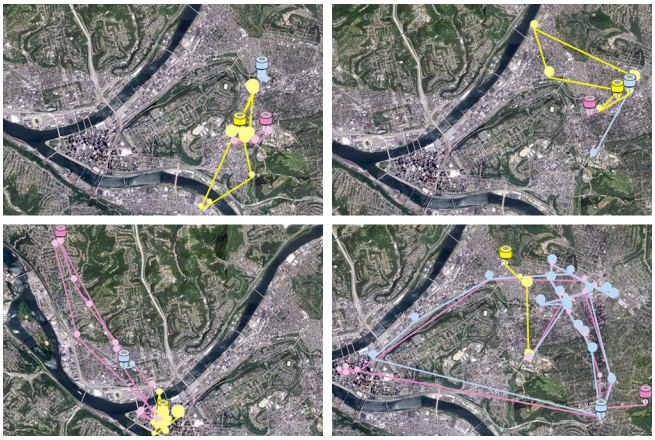

Figure 3. Sensor placements by bicyclists (top left), parents (top right), homeless (bottom left, and activists (bottom right)

(dust, exhaust and VOC) are represented with different colors and can be toggled on and off, allowing users to track the units individually. Clicking or mousing over each location activates a tabbed info window (Figure 3, bottom). The default 'Overview' tab shows the latest data from the corresponding location: exhaust, dust or VOC value on a color-coded gauge along with temperature and humidity. Other tabs include temperature, humidity, air quality, and light data from the location as static line graphs. In addition, the map supports geo-referenced comments.

Graphs

The right side of the website contains interactive graphs showing data from all three sensors in the default 'Overview' tab, and from individual sensors along with temperature and humidity data under the 'VOC', 'exhaust', and 'dust' tabs. A draggable scale bar along the bottom allows zooming into parts of the graphs, and clicking on a point activates an info window over the corresponding location on the map. The 'Comments' tab contains a feed of all community comments, and clicking on a comment activates also the corresponding location.

DEPLOYMENT

Sensor units (12 in total) were deployed with four urban communities (22 participants). We selected the following communities to gain insight into how a range of urban stakeholders approach public sensing:

- *Bicyclists/students* are a young demographic with similar educational backgrounds, traversing a range of spaces with vested interests in roads, parks and traffic
- *Parents* form an older group occupying spaces that revolve around children (schools, playgrounds, etc) as well as work (office, etc.) and friends (theatres, malls, etc)
- The *homeless* are a low-income, nomadic community, with socio-political perspectives that lead to unique appropriations of technology, often overlooked by mainstream HCI literature [26]

- *Activists* are a tighter-nit community who view themselves as agents of change and may have insights into spaces that facilitate or hinder their desired outcomes

In selecting these four communities, we hope to capture feedback from participants spanning diverse age groups, interests, urban spaces, social and economic backgrounds.

Methods

Each group completed a preliminary interview exploring community concerns as well as activism, roles and attitudes in public spaces. Participants were also asked to draw a community map showing locations they considered 'healthy', 'unhealthy', etc., on transparencies overlaying a map of [city omitted], along with spaces where they would like to monitor and publically broadcast air quality. Communities were then presented with three air quality sensors (labeled *dust*, *VOC*, and *exhaust*) and introduced to the website with a walkthrough of basic features. All participants had access to a computer during the study, including the homeless who used a shared desktop that we donated to the shelter. Groups were instructed to move, place and leave the sensors throughout the city as they preferred, over the course of one week, photographing each location (with personal cameras or a provided disposable). We encouraged participants to leave the sensors for longer periods of time, emphasizing that they were not expected to return them. We did not suggest a minimum number of placements or uses of the website, recommending that participants do 'what feels natural' for their group. After one week, participants returned for an informal wrap-up (group) interview discussing their experiences with our system. In addition, we observed participants' use of our website for 5-10 minutes to evaluate our interface. Each participant was compensated $10 for the initial interview and another $25 for completing the entire week-long study.

RESULTS

All sensors (except for 2, see 'parents') functioned as intended over the course of the study. Overall, participants enjoyed the project ("*It was fun*", parent), were impressed with our system ("*this is awesome*", homeless) and wished the study was longer ("*I wish we had more time [to place sensors]*", bicyclist). Most participants did not use the comment feature ("*I didn't really notice it, plus I wouldn't know what to say*", bicyclist). We now detail our findings, referencing data from participants in particular groups as: B, bicyclists; P, parents; H homeless; and A, activists.

Bicyclists/Students

We recruited four commuter bicyclists (1 female, age early 20's) through local bike forums. Participants are students who have been friends for several years, and three are neighbors (with two living together), such that they see each other at least a few times a week. Participants voiced individual concerns ranging from bike hazards ("*the roads are so messed up, it's dangerous to ride"*, B1), to personal safety as affected by "*drug dealers, violence and vandalism behind my house*" (B3), and the homeless:

> "*There was a hobo sleeping our my porch once and… we also found recently… there's a building [across the street]- I think a hobo made it his home and it's just like a huge room with an old furnace and there's all this stuff of the hobo's. Yea, that's probably the biggest concern I have right now."* (B2)

When asked to converge on a mutual concern, participants identified urban development, because "*we all use the city pretty heavily*" (B3), including the quality of streets, parks, and green-spaces, as well as economic and environmental disparities across the city. Participants agreed that street art was an effective approach for improving urban space ("*I think street art is like a way of art, and I see it personally as a way of doing that*", B2) and they have previously contributed to grassroots expressions including graffiti ("*by a shitty wall that could kinda use something to beautify the area*", B1), guerrilla gardening, and murals. They also discussed future plans to 'add' bike lanes to the city:

> B1: *We haven't done it yet, but we're strongly considering doing this. Just like finding areas that need a bike lane real bad*
>
> B4: *And just spray-painting it on.*
>
> B1: *Yea, just going in at night a making a big stencil of the bike think that's like kinda stretched out a little bit and just putting on some orange jackets and like just doing it.*

Sensor use and placement

Bicyclist/student participants split up the sensors for the week such that everyone had access to a sensor, without particular preference for the type of sensor they used:

> *"[B4] lives all the way in south Oakland, and we live very close to each other so, we figured [B4] should definitely get one and then I took one, and these two live together, so they took one."* (B3)

B3 and B4 (roommates) shared the dust sensor, keeping it in their backyard for most of the week. B4 also left the dust sensor overnight on a bridge near a public library:

> "*You know the factory that's like right behind the library… yea so I wanted to know what that is, so I guess I was just curious if that would somehow affect the dust sensor in any way, so I kinda like pointed it towards that. And it's also right next to the park*" (B4)

B2 carried the exhaust sensor ("*I kinda just took it with me as I went on journeys, just to spread it around*") placing it on a busy street near a thrift store ("*I thought it would be interesting to leave it for two days, just to get a dependence of time, if it goes up and down*", B2), post office, and park. B1 did not attend the final interview but kept the VOC unit at what others identified as his friend's house on the map.

Data exploration

Participants used the website a few times during the week (B3 and B4 viewing it together), as tool for tracking where they had been rather than exploring air quality:

> "*I was more interested in what you guys were doing, like your movements, not exactly the data, I didn't look into it. I just wanted to see where you guys had been."* (B2)

Tracing their movements, participants noted that the data made them to want to move around more, "*making a web around the city*" (B4). They initially felt that the air quality graphs looked "*very busy*", but became more interested in the data after a brief tutorial of the zoom feature ("*I do like the graphs now that I know how to use this [zoom]*", B4). Participants focused on re-occurring peaks in exhaust and VOC data ("*I didn't think that there'd be such a distinct hump [in exhaust data] at rush hour, that's cool*", B4; "*oh wow, that's [VOC peak] really early in the morning*", B2).

Expressions and activism

To avoid loosing sensors early in the study, participants first concealed their placements (*"I kinda wanted to get it back, so I kind of like hid it on the other side"*, B4). However, later in the week, B2 placed the exhaust sensor more overtly to explore "*the social aspects of the study*":

> "*The last time I placed it, I definitely wanted it to be found. I didn't wanna loose it early, 'cause then I thought I wanted to kinda take it around a few places but at the end I just wanted to see what would happen*" (B2)

Others were also curious about the whereabouts of the exhaust sensor ("*I wonder what they're doing with it or why they decided to take it*", B3). Participants indicated that they would place the sensors in more visible locations if they displayed the data, especially as a graph over time or in comparison to other locations such as parks:

> B4: *If it had that on it, then I would put it in really visible places as opposed to kinda tucking it behind a corner*
>
> B2: *Then you're making a statement*
>
> B4: *Cause then you're trying to say something*

Participants indicated that they would want to show their data to students- particularly environmentalists who could interpret and present it more concisely to the general public.

Parents

Three parents (1 female, ages 30's-50's) and their four children (1 female, elementary school ages) participated in the study. Participants have been friends for several years, meeting at neighborhood functions, children's play-dates and activities. Participants bike (P1), walk (P2) and drive or take buses (P3), and a shared concern involves roads and transportation. Specific issues range from streets that are not bike-friendly to a "*lack of an attractive mass transit and the shrinking amounts of mass transit*". When asked how their community could work towards resolving these issues, participants deferred to other groups:

> P1: *There is a bike advocacy group- and they work intimately with city planning department. It's the mayor's office frankly, that stalls things… somehow things don't get done in quick fashion*
>
> P3: *I get the feeling that that's something that a public works would do… I don't think those people are not on board-*
>
> P1: *They don't care*

Parents also noted a lack of a pressing need: " *[changes] cost a little bit of money and there's not like pressing need because we don't see the negative results*" (P3).

Sensor use and placement

Parents took turns using the sensors: each having all units for 2-3 days, and handing them off to the next person ("*we divided 7 [days] by 3 [families]*", P1). While parents tended to decide on locations, their children physically placed most sensors (on trees, street poles, *etc.*) and photographed the placements. P2 had the sensors first, using all three together to "*get readings from all 3 and then you can compare*":

> "*First I put it in our yard, and then I thought, OK let's put it in a more public space, so I chose to put it in front of the Rite Aide [pharmacy near her house]."* (P2)

An employee noticed the sensors and contacted the police, who in turn summoned the city bomb squad. Even though sensors were labeled with text detailing them as a locally approved research project, they were confiscated. Although the police were not initially sympathetic, we negotiated resuming the study and returned sensors to participants the same day, after several discussions with local authorities. During the interruption, batteries dislodged from the main board of two units (VOC, dust). However, participants continued to use the sensors, initially not realizing that two were broken. P3 and his children attached them to telephone poles using a ladder and nails:

> "*I wanted to basically be close to the river. We went further down and there were the factories and the robotics center, and the 43rd concrete center [factory]. There's also some foot traffic 'cause you can get to the river trail from there so there's a lot of dog walker.*" (P3)

P1 was interested in collecting more data ("*I was really going for the data, so I hung it in different places based on my interpretation of the study*", P1), placing the exhaust sensor at a street intersection and a bus stop; the dust sensor by his house and in a public park in a "*meadow rife with pollen and plants"*; and the VOC sensor in an alley, by a dumpster at a paint factory ("*we went inside [the paint factory] and we explained what it is we were gonna do.*")

Data exploration

Parents tended to check the website daily at the beginning of the study, but were later disappointed by the non-working sensors: "*I stopped checking once I found out things were not functioning properly*" (P1). Parents were especially interested in placements chosen by others in their group, and less concerned with the data, "*particularly because I never saw a high reading anywhere, so it didn't seem like the reading itself would be interesting*" (P3). Participants did notice higher exhaust values in some neighborhoods ("*where you [P3] put it, was higher*", P1). P3 was also interested in temperature data but could not find out "*when the hottest time of the day is*".

Expressions and activism

P2 was most disappointed by the police interruption, as she wanted others in her group to use the sensors ("*I hope I can pass it on*"). P3 felt 'amused' and 'sad':

> *"It seemed so funny that it happened so quickly… [it] makes me a little bit sad because I guess that's how people view*

Figure 4. Photographs of participant sensor placements: dust sensor attached to bridge by bicyclist (left), participant's daughter attaching VOC sensor to street pole (middle), and exhaust sensor outside a children's hospital placed by activist (right).

themselves as being good citizens now, and reporting terroristic threats, when if they had half a brain, they would think the Rite Aide in [city omitted] is not a big target." (P3)

Parents discussed the need for permission in various spaces:

P1: *I wonder if they [Rite Aide] owned it [the space] or not.*

P2: *Well, I didn't think of it in that way, because we can go park in their space so I thought we could do this… I thought, 'it's my neighborhood'. If I put it on the street that would've been municipal property maybe…*

Conversely, P1 explicitly asked for permission to place the VOC sensor at a paint factory (*"there was a moment when he was concerned… maybe he didn't want us to find some dirt on him or something"*). Participants were concerned with visibility, wanting people to "*see it [sensors] or be interested in it*" (P2), while at the same time avoiding sensor loss ("*I didn't want them to be taken, but I wanted them to be in a place that's open*", P3; "*I purposely hung it higher up, but it was completely visible*", P1). They suggested cameras to record public reactions to the sensors, to "*see what people actually do"*:

P1: *…how many people actually mused over these things…*

P3: *Yea, I think that's what P2 was referring to. It would be interesting to actually see some camera action on that.*

Parents were hesitant to share their data: they did not know "*what it means before showing it… at what levels does health become impaired*" (P1), and wanted to gather "*more data, collected in a more… scientific experiment*" (P3).

Homeless

We recruited five male participants (ages mid 40's-60's) from a local shelter. The shelter offers a shared dormitory, a common 'TV' area and shower facilities for a maximum of 60 days per person per year. Occupants range from people who temporarily lost housing, to individuals traveling through the state, or living in different shelters across [city name omitted] over the past decade. Consequently, some of our participants are new to the shelter while others have known each other for years, and their routines vary greatly:

"*When we leave here, everybody has some type of business to go to, to get up outta here, you know what I mean? To better their lives, and once all that is accomplished, then the park is... our meeting place, everyone comes through the park to get here.*" (H1)

The park serves as a group meeting place and lunch spot, but participants tend to visit a range of public spaces alone:

"*I'm all over the city of [omitted], outside and in smaller boroughs. I stop at the parks, talk to people, and then by 5-6 o'clock I'm back here [at the shelter].*" (H5)

Participants were in agreement about the common issues affecting their group, including inability to find jobs (*"If you work a union job, it's not what you know, it's who you know"*, H1), lack of affordable housing, and a poor (low-paying) recycling program (*"In San Diego [different city], they pay $1.80 per pound of aluminum cans"*, H3). When asked if they would consider pursing actions to resolve these concerns, participants felt resigned and powerless:

H1: *The five of us couldn't change our legislation if we wanted to.*

H2: *Couldn't change anything.*

H1: *If we would rally and sit outside, they would find some way to either lock us up, have somebody come along and discourage us, or call us in.*

Sensor use and placement

Although participants discussed specific locations (parks, street intersections, waterfront, *etc.*) to place the sensors, they did not coordinate a strategy for the study. Instead, individuals took whatever sensor was available as they left the shelter ("*whoever was up first got one, and I ended up with this one, I was the last one out the door*", H4). H4 '*ended up'* with the VOC sensor, placing it in a tree in the park frequently visited by the homeless for the entire week:

"I didn't know if they ever spray for pesticides or if they have- any chemical agents on the grass- the fertilizers." (H4)

H3 and H5 shared the exhaust sensor, placing it at street intersections and bus stops throughout the downtown area.

"I put it on the main drag, like where all the bus traffic is… I thought it'd be a good spot 'cause usually when I'm standing, waiting for the bus, I could smell the exhaust fumes." (H5)

The dust sensor was taken by H1 along with the group's disposable camera. Our website shows this sensor moving extensively throughout the north side of the city, but its particular whereabouts remain unknown as H1 disappeared from the shelter and did not attend the final interview.

Data exploration

Participants accessed the website several times. Since the shelter controlled computer access to prevent illicit, participants explored the data together. They appeared to fluidly navigate the website, clicking on peak graph values to locate corresponding points on the map. However, sharing a computer made data individual exploration difficult ("*I have to sit there to figure out what I'm looking at but he'd just keep moving it [the website] around"*, H2) and participants were mostly interested in their own sensor ("*I just looked at mine*", H5). Overall, participants were surprised to see low/moderate readings from the sensors:

> "*I was expecting it to be higher, cause the exhaust you know... it's not one bus, it's several buses are passing or stopping there. So I was expecting it to be like off the chart*." (H3)

Participants did not comment on the dust sensor (which disappeared), and generally did not discuss the data with each other (*"I tried to discuss it with them but I get nowhere with them"*, H5).

Expressions and activism

H4 wanted to avoid drawing attention to himself and the VOC sensor he placed in the park: "*somebody may have asked me, like you know, this isn't your property this is private property."* H3 and H5 placed the exhaust senor in visible spots near bus stops: "*right in [front of] everybody, where the buses pull up, right near the post, boom it's there*" (H3). While H2 did not use the sensors, he also indicated wanting to draw attention to them:

> "*I woulda put it up somewhere where it would be visible to everyone so if they read on the back of it, they woulda know the website and stuff like that, and got more data off that if they went to the computer and seen that. And they would've probably moved [the sensors] themselves... and so that could be moved around like- just having more people into it."* (H2)

Participants did not feel compelled to act on the data (*"there's really not much you can do about"*, H5), and H3 also pointed out that sensor values were not high enough to "*pursue anything*". If given the opportunity to broadcast the information, they collected the homeless suggested showing it downtown ("*because that's where everybody has a tendency to cluster*", H4), as well as to college campuses:

> *"College students are the future of this country. They're the future bosses, the fortune 500 companies, congressmen, senators, congress women, mayors, whatever… they need to know a lot of this stuff, better to get knowledge of it now than when a student becomes a senator, or whatever."* (H3)

Activists

We recruited a community of six activists (2 female, ages 20's-30's) who recently moved to [city], but have known each other through an anarchist network, coordinating and meeting at various activist events over the past 3-4 years. Participants share a strong dislike for the police, as well as public spaces that do not afford gatherings (lack of open, accessible space). Broader issues fall under the umbrella of capitalism, oppression, and hierarchy ("*we actually do have a list that we've all agreed on*", P3).

> *"There's not so much action that you take against those really broad overview things. It's more like tackling really specific, often local issues that relate to those… focusing on realistic actual things that are affecting people's lives."* (P5)

The group has previously worked to combat eviction, police brutality, gentrification, poverty and military recruitment. Participants were hesitant to disclose specific tactics, but examples range from door-to-door work, "*cooking food and serving it to people for free*", to rallies and lockdowns (physically preventing people from accessing buildings).

Sensor use and placement

Participants decided on a set of placements for each sensor and took turns moving them to these locations within the group, based on individual routines and schedules. For instance, P1 placed the exhaust sensor in a tree in a park, and P3 and P5 retrieved it the following day, placing it on a street pole near a children's hospital. The VOC and dust sensors were initially at P2's house. The VOC sensor was then moved "*by a door in an alley, near the iron workers apprenticeship*" for a few days and then brought to an urban community farm collective ("*to see how much fertilizer and stuff is in the space where they grow food*", P6). The dust sensor was moved between a busy downtown square and a public park. Participants tended to check on their sensors ("*I'd pass by it several times a day to see if it's still there*", P4), and most locations were motivated by finding contrast:

> "*I think a lot of it was going for the contrasts.., to compare what we perceived would be really high with something that would be pretty low.*" (P2)

Unlike other groups, activist planned to keep using sensors after the study, for instance to test air quality on the river ("*we should rent some kayaks and just take them [sensors] out for a day and paddle around*", P1).

Data exploration

Most participants looked at the website once or twice during the study, and tended to remember some specifics ("*It was about 40 [VOC] at my house*", P2; "*[exhaust] was higher at the children's hospital*", P5; "*I thought there'd be more dust on the street", P1)*. Participants commented on micro-level data for different areas:

> *"Whenever they put out air quality alerts, it's like a blanket thing… But if you're like way outside of [the city] up on a hill, it's probably not as bad as at the bottom of the valley, downtown. Being able to see the actual nuances of that difference is really important."* (P3)

Participants also liked being able to compare data from different locations simultaneously ("*I do like how you can hold one [info window] open and then sort of compare",* P3*)*. The graphs were considered less useful, as participants skimmed different tabs ("*I looked at each one to see what the pattern was*", P6). Participants wanted to know the scale for the data ("*does 100 mean that you're literally breathing in nothing?",* P1), and see data from all sensors along the

same graph ("*three lines on one graph*", P6). Longer-term data was also of interest: "*I'm curious if the level of pollution goes down in the winter*" (P1), *etc.*

Expressions and activism

Participants chose visible sensor placements and were not intimidated by '*suspicious*' looks unless police was involved ("*I'm sort of used to doing ridiculous things in public, but I'd wait for a cop car to go around the block*", P1). They discussed the study with the farm collective:

> "*It was pretty cool just to explain to people what was going on with it. Like we went down to [the farm collective] and we were like 'Look, you've been trying to get an idea of what's in your air for like years now and now we have a way for you to check it and it's free. Do you want to check your air quality?' And they were like sure, that sounds good."* (P3)

Individuals from the urban farm collective reportedly wanted to use all three sensors for longer periods of time ("*they wanted all three [sensors] there for like an extended period of time to get some long-term data, P4).* Participants also discussed the study with each other and their friends:

> *"A lot of the people that I talked to were really into it… I think if there were a lot of sensors around the city and this website up… a lot of people would want to check it."* (P2)

The group wanted to share their data with people from the neighborhoods where they placed the sensors ("*the people who live and work around those areas- people who spend a lot of time there*", P3), as well as other activist groups *("if there is a group of people that could do something about the air quality"*), and those most affected (e.g., "*I want iron workers to know what they're inhaling*" P1). Participants also wanted to broadcast the information at the children's hospital:

> *"By the children's hospital, I really wanted that like a display board, like look- 'it's a children's hospital, how much toxic stuff is in front of and on the side of this space.' People who bring their children to the hospital should know that"* (P6)

While participants initially did not want to pursue action based on the data ("*there's not much I can do about it*", P2) in general, they wanted to identify specific causes:

> *"It would be interesting to see who bears the most responsibility for that and then if you can sort of specifically get a group of whoever's contributing disproportionately or the most to the problem, then you can start doing something about it. Like a campaign or something like that".* (P3)

DISCUSION AND LIMITATIONS

We intentionally chose low-end sensors and did not pursue precise calibration procedures, positioning our system as a tool that can be implemented by non-experts. Consequently, our website visualizes relative measurements across time and space (values ranging between 1-100), and all four groups commented on the scale, wanting to know "*what it means*", how harmful the levels are for their health, *etc.* However, lack of absolute values did not deter participants from exploring, reflecting on, and reacting to the data. The homeless focused on individually-collected data ("*I just looked at mine*"), expecting it to be "*off the chart*". Other groups were interested in comparisons: bicyclists looked for a "*dependence of time*", tracking "*humps*" that correlated to rush hour; parents and activists compared locations ("*[exhaust] was higher at the children's hospital*", *"where [P3] put it, was higher"*, *etc.*) Moreover, participants, especially activists, wanted a longer-term deployment. Battery life is an inevitable constraint for physical systems, and future work can explore different power sources (solar panels, casing that allows battery recharging, *etc.*), as well as related research questions: what happens during prolonged deployment? Do sensors become convivial tools?

Community concerns, activism and sensor use

Bicyclists and parents split the sensors (per person or by days of the week) using them independently and tracking each others' placements on the website. These uses reflect approaches for addressing group concerns: bicyclists prefer independent acts (graffiti or murals) to "*beautify the area*", while parents defer to "*advocacy groups*" for changes in urban development, roads, *etc*. The homeless are a community by circumstance rather than choice, with each person having "*some type of business to go to, to get up outta here"*. Participants' sentiments of powerlessness and resignation ("*the five of us couldn't change our legislation if we wanted to"*) in response to mutual concerns (housing, jobs, *etc.*) echo their lack of coordinated 'strategy' for sharing the sensors: each person took and checked data from whatever sensor was available. Conversely, the activist community revolves around group action- free food distributions, rallies, lockdowns, *etc.,* to resolve issues from a "*list that we've all agreed on"* (capitalism, oppression, *etc*.). Consequently, they adopted the study as a *conjoint practice,* moving communally-shared sensors and discussing data as a group. Our findings highlight a range of group appropriations and interpretations of our system, and we emphasize adoptions of sensing systems as reflections of community structures, values and concerns.

DESIGN IMPLICATIONS

It's not a bomb!

To varying extents, our study exposed all four groups to issues of security, privacy and authority. Participants navigated tensions between authorship and theft, placing sensors "*higher up but completely visible*" or entirely concealing them in trees or "*behind a corner*". From asking for permission and explaining the study, to placing sensors covertly ("*somebody may have asked me"*), to assuming ownership of space ("*it's my neighborhood"*), to ignoring '*suspicious*' looks or defying authorities altogether ("*until a cop car goes around the block"*), communities reflected on notions of private, public, and authorized space. For parents, these tensions were explicitly foregrounded by a police intervention, ("*people view themselves as being good citizens… [by] reporting terroristic threats").*

Although our sensors were clearly branded, in a post 9-11 world, homemade DIY objects that would have previously been considered interesting, provocative, or eccentric are

almost immediately perceived as threatening. Increased surveillance as encouraged by the Department of Homeland Security warning to "*be vigilant, take notice of your surroundings, and report suspicious items or activities to local authorities immediately*"[8] has shaped and constrained artistic, academic and whimsical endeavors over the past decade (for instance, the Boston Bomb Scare [33]).

Our experience with the police reveals interesting considerations for public sensing: while theft and vandalism were major concerns across all four groups, the only sensors damaged during the study were due to police intervention; and despite suspicious glances and police presence, participants continued to pursue overt and public sensor placements- near hospitals, factories, bus stops, *etc.* We cite these findings not as reflections on law enforcement, but as points of engagement with issues of perceived safety, privacy and expressions. Participatory sensing places new tools in the hands of ordinary citizens, inevitably exposing the general public to unfamiliar technologies and contexts. The boundary between 'evocative' and 'threatening' remains unexplored, and the police (an under-studied community in HCI) may offer valuable insights for this domain. While we readily carry personal electronics and talk of a ubiquitous computing future, publically-placed technologies and sensing is fraught with a myriad of challenges – namely those embedded within a culture of fear. Future research can focus on design factors such as enclosure shape, color, texture, and sensor legibility to lessen such public concerns.

Broadcasting and sharing sensor data

Our earlier work [withheld] with probes suggested sensor data as a 'social currency'- a potential for communicating concerns within and across communities of stakeholders- and findings from the deployment of our fully functional system suggest a range of opportunities for visualizing this information. On one level, our participants were interested in data within their own groups: from tracking where their friends put sensors to comparing measurements between neighborhoods, or exploring trends over time, stakeholders expressed a need for community-specific interfaces. For groups such as bicyclists, personal devices can present geo-referenced community data, while more independent stakeholders (*e.g.*, homeless) might prefer information from their individually-placed sensors, and tighter-knit groups (activists) could adopt visualizations that engage them as a group, facilitating data exploration as a *conjoint practice*.

Moreover, participants' desire to broadcast sensor data to other communities reveals a space for engagement between and among different social groups. For instance, while the presence of '*hobos*', raised safety concerns for bicyclists/students, the homeless considered students to be the "*future of this country"* and a receptive audience for sensor data. How would students' perceptions of '*hobos*' change if data collected by the homeless was projected to a university campus, and vice versa? Instances of group sharing might be welcomed (the farming collective wanted all three sensors) or rejected (a paint salesman "*didn't want us to find some dirt on him"*). Digital spaces can make intentions and consequences more transparent, empowering groups to collaborate towards desired outcomes. Such technologies can serve as instruments of persuasion for community concerns, linking people through their actions [13] as opposed to comparisons of individual behaviors.

Sensors as instruments of change

Our system enabled communities to engage with space and express their concerns through the placement of sensors: some spaces afforded similar questions across participants (exhaust levels at street interactions and bus stops, pollen measurements in parks, dust near factories, overall air quality at participants' homes, *etc*.), while others inspired unique interpretations (VOC's by an iron apprenticeship, pesticides in a park, exhaust by a thrift store, *etc.*). Whether to explore the '*social aspects',* inspire interest of "*people musing over these things*", or to broadcast air quality in front of a children's hospital with "*a display board"*, and bring "*more people into it"*, participants wanted to use sensors to reach the general public and transform space.

We emphasize sensing *beyond* hardware, and the inclusion of stakeholders in sensor appearance and interaction design. Groups such as homeless, for instance, may prefer inconspicuous casing to avoid attention during the act of placement, with the ability to remotely trigger a display that broadcasts data to the general public; other communities may build visualizations to target specific stakeholders (neighbors, iron workers, *etc.*) or track social aspects. More broadly, there appears to be a large opportunity for open source platforms to empower communities to create visual and material form factors, altering output modalities based on context. In doing so, groups could further leverage sensors as tools of engagement with and transformation of space. We note, however, that as any instrument, sensors can have unforeseen and unwanted outcomes: for instance, devaluing neighborhoods or small businesses through tampering with sensors to artificially manipulate readings (*e.g.,* intentionally pumping exhaust into a sensor in a strategic location). Future systems must take these potential unintended consequences into account, for example by making visualizations and functionality transparent to direct stakeholders, policy makers and the general public.

CONCLUSION

We introduced a novel system of air quality sensors, designed to be left and moved throughout public spaces. Our fully-functional sensors report air quality along with weather and light data to a server that displays it on a public website in real time. Our deployment with four groups of stakeholders- parents, bicyclists, homeless and activists, supports our system as a tool for community expressions and activism. Our findings reveal design opportunities for

[8] http://www.dhs.gov/files/reportincidents/counterterrorism.shtm

environmental data as a social currency and physical sensing systems as instruments of change.

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