Participatory Sensing in Public Spaces: Activating Urban Surfaces with Sensor Probes

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ABSTRACT
Recent convergence between low-cost technology, artform and political discourse presents a new design space for enabling public participation and expression. We explore non-experts' use of place-based, modular sensors to activate, author and provoke urban landscapes. Our work with communities of bicyclists, students, parents, and homeless people suggests design opportunities for merging grassroots data collection with public expressions and activism. Members of each community were given probes that represent the measurement of exhaust, smog, pathogens, chemicals, noise or dust, and asked to engage with them as fully functional sensors over the course of one week. Our findings offer insights into participation, environmental sensing, and data sharing within and across four different communities, revealing design implications for future sensing systems as instruments of social currency and political change.

Keywords
Participatory sensing, public spaces, urban probes

INTRODUCTION
As sensors become less expensive and more widely available, non-experts are empowered to act as scientists and environmental researchers. *Participatory sensing* refers to any mechanism by which individuals in the general public collect, share and analyze local data [9]. This practice draws from a rich history of citizen science projects, dating back at least as far as the Christmas Bird Count- a volunteer-driven bird census that has been active since 1900 [3]. More recently, participatory sensing has leveraged personal devices such as cellphones to gather data in the domains of public health, personal experience sharing, artistic expression, and environmental monitoring among others.

Prior explorations of citizen-driven environmental sensing have focused on personal sensors used by individuals to gather data in their immediate surroundings [*e.g.,* 10, 12, 30] Alternatively, public sensors have been deployed on fixed surfaces [2] or in predetermined bounded spaces [23].

DIS 2010, August 16-20, 2010, Aarhus Denmark
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We explore a research space that merges these concepts: participatory sensing as a system of low-cost modular nodes that can be moved and accessed by different individuals across a variety of urban landscapes.

Authoring Public Spaces with Environmental Sensors
We envision low-cost sensors not only as instruments of data collection, visualization and sharing, but also as an approach for authoring, engaging and provoking a wide range of public spaces by the individuals who occupy them. We draw inspiration from existing tools such as SoundMites [7] and LED Throwies [21] that enable users to leave interactive audio and video nodes on public surfaces. Our research extends these ideas to participatory (citizen-driven) sensors that can be placed and moved across a range of surfaces for environmental monitoring as well as public expressions.

We propose a system of modular, low-cost, networked sensors that measure environmental factors such as air pollution, radiation, water quality, noise, etc. Rather than belonging to a particular person or space, these sensors are designed to invite stakeholders- people occupying or passing through a space- to move and leave them in points of interest, thereby exploring and engaging with their environment. We explore this approach by deploying sensor probes amongst four communities for parents, students, bicyclists and homeless. Drawing from past probe literature [*e.g.,* 26, 31, 33], our methods rely on users'

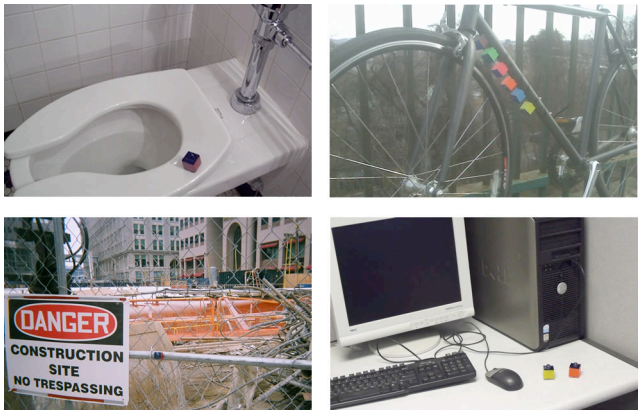

Figure 1. Pathogen sensor on toilet placed by parent (top right), all 6 sensors attached to bike while passing a bridge (top left), dust sensor on construction site fence placed by homeless (bottom right), and dust and noise sensors placed in computer lab by student (bottom left).

engagement with hypothetical prototypes to investigate questions such as 1) how do different communities of stakeholders perceive issues of authorship, anonymity and engagement in public spaces; 2) which spaces afford curiosity about specific environmental factors across different communities; or 3) what design principles leverage participatory sensing as a platform for city-wide grassroots activism. The use of probes (vs. specific working sensors) enables us to adopt Boehner, *et al*.'s open dialogical approach: we *respond* to rather than *ascertain* facts about our participants' experiences [6]. Instead of moving towards a single and correct understanding of an ultimate sensing system, our findings open broader interpretations and design trajectories in this area.

Research Objectives

We begin by discussing related work, including the political, social and artistic implications of public participatory sensing. We then present our field study, which explores the placement, appropriation and use of environmental sensors in public spaces across four urban communities of students, parents, bicyclists, and homeless people. For each group, we detail participants' 1) sensor placement, 2) authorship and expressions, and 3) awareness and action, as inspired by our sensor probes. We conclude with a general discussion of spatial affordances for environmental sensing and community expressions, suggesting design opportunities for sensing as a medium of expression by non-experts.

PRIOR WORK

Prior work employed sensor and GPS-enabled mobile phones to monitor traffic [9] or noise pollution [30], annotate spatial data with images and sound [27], share nutritional choices [35], and document plants [32] or damaged sidewalks [12]. Personal data loggers have also been used to monitor environmental factors such as air quality [15, 18], or enable users to reflect on geo-tagged photographs and annotations [34]. Alternatively, sensors have been deployed on fixed surfaces or in bounded spaces in order to gather environmental data such as air and water quality levels [2, 15, 19, 23]. Recent HCI and DIS literature has commented on the convergence of art, technology and politics [*e.g., 5*, 8, 17, 20], revealing an emergent trend towards public expression through technology. Drawing inspiration from a collection of existing projects that serve to activate public spaces, we propose participatory sensing as a novel approach for empowering community-wide authorship in urban contexts.

Activating Public Spaces

A range of interventions have addressed engagement and creativity in public spaces through small modular devices [*e.g.*, 7, 21, 36, 37] as well as large-scale interactive projections and displays [4, 14, 22, *etc.*]. In particular, we are inspired by prior systems that explore public expressions of citizen-driven content: TextTales- a medium for democratizing personal storytelling through SMS image captions [1]; PhotoSwapper- a participant-driven image repository that balances information exchange, social support, and regulation in public spaces [20], and "In Hear, Out There"- a system for collecting audio-visual urban expressions [34]. Drawing inspiration from the works of Wodiczko *et al.,* which often express political themes through artistic installations in public spaces [37], we hope to contribute to prior research by exploring political discourse as facilitated by modular public sensors.

Participatory Sensing and Socio-Political Discourse

City-wide awareness and action stem from a range of complex social, financial and political factors, often hindered by "rational ignorance"- whereby people succumb to political apathy if the efforts to educate oneself about an issue outweigh any possible changes that can be achieved by the individual [11, 25]. The role that technology plays in fostering social discourse and political activism has been widely discussed throughout design literature [1, 13, 17]. In 1927, Dewey argued that "the movie, radio, cheap reading matter and motor car" inadvertently distract people from political issues by providing an "easy and cheap" entertainment [16]. Citizens thus tend to be chaotic and disorganized until they are made aware of a significant issue, which draws them together into a cohesive 'public'. In his recent work, Carl DiSalvo suggests design principles to empower the formation of active 'publics', namely through projection- presenting "future consequences associated with an issue" and tracing- exposing the "networks of materials, actions, concepts and values that shape and frame an issue over time" [17].

Our research addresses ways in which participatory sensing fosters community-wide expressions and ultimately leads to grassroots activism through which citizens shape their environment. We rely on Cuff, *et al*.'s notion of a data commons- a repository of citizen-collected data- as a democratizing force to "provide answers, pose new questions, and open new opportunities for public discourse [15]. We investigate how stakeholders approach the collection, sharing and visualization of environmental data in public spaces. In doing so, we explore environmental sensors as convivial [24], evolvable and collaborative tools for urban communities.

STUDY DESIGN

Stakeholders

We define our stakeholders as any people who occupy or pass through public urban spaces, including policemen, cab drivers, pedestrians, construction workers, businessmen, etc. To gain insight into how stakeholders spanning diverse age groups, interests, urban spaces, social and economic backgrounds approach sensing and public authorship, we scoped our study around four communities, making the following assumptions about each:

- *Students* are a young demographic occupying spaces in and around universities, with interests that reflect similar educational backgrounds and lifestyles
- *Parents* form an older group, expressing personal and family interests in spaces that revolve around children

(schools, playgrounds, etc) as well as work (office, etc.) and friends (theatres, malls, etc)

- *Bicyclists* traverse a wide range of urban spaces with vested interests in roads, parks and traffic, among others
- 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 [29]

We hypothesize that each group embodies unique values and attachments to public spaces, and sensor placements will reveal community and individual needs. Moreover, we predict that willingness to share and act on sensor data will in part reflect participants' involvement in their particular community, as well as their perceived role in public spaces.

Environmental Sensor Probes

We chose to abstract from specific chemicals such as NO or CO2 to make the study more intuitive, especially for participants who are unfamiliar with compound names. Moreover, abstraction affords insight into the *source* of environmental concerns expressed by each community, for instance: "exhaust" suggests air pollution generated by cars or buses while "smog" hints at industrial byproducts, whereas as "CO" can imply both or neither. While there is a wide range of environmental issues that could interest our communities (UV, temperature, pollen, etc.), we ultimately scoped our study around six factors, which most participants found comprehensive: exhaust (vehicle-related pollution), smog (industrial pollution), pathogens (bacteria, germs, etc), noise, chemicals (cleaning products, pesticides, VOC's, etc.) and dust. We developed probe kits, each consisting of six mock environmental sensors (1" acrylic cubes) with an acrylic half-sphere on top to simulate sensor input (Figure 2). Magnets along the bottom of each probe enable easy attachment to metal (non-horizontal) surfaces.

Methods

Participants first completed an informal pre-study interview about their perceptions of the city, prior expressions and contributions to public spaces, and environmental concerns. We then provided each participant with a probe kit, explaining the types of measurements that were simulated by each probe (eg, "This is a mock pathogen sensor, it represents the measurement of bacteria or germ levels"). Participants were asked to use the probes as if they were real sensors over the course of one week, taking measurements, placing or leaving them throughout public locations during their daily routines. Participants photographed sensor placements with cellphones, personal cameras, or disposable cameras that we provided. Participants then returned for an informal wrap-up interview discussing their experiences over the week. Compensation included $10 for the initial interview and another $25 for completing the entire week-long study. We encouraged participants to leave the probes for longer periods of time, emphasizing that we do not need to collect them. We did not suggest a minimum number of placements or photographs, recommending that participants do 'what feels natural' as if these sensors were real.

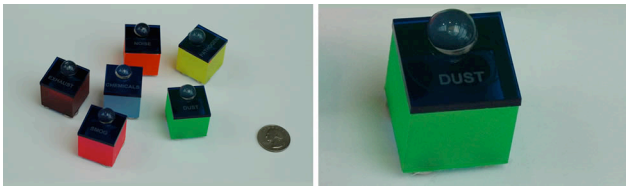

Figure 2. All six sensor probes (left) an dust probe (right).

RESULTS

Participants tended to carry all probes throughout the study ("it was easier to throw the whole box in my bag"). Everyone commented on the attention attracted by placing and photographing sensors ("funny looks putting them [sensors] in places", P5), suggesting different comfort levels for doing so (discussed for each group below). Despite wanting to monitor spaces for long periods of time, no one actually left the probes unattended, primarily because participants did not want to return for the probes in order to place them somewhere else, as well as to avoid theft or loss ("someone would steal it, we'd go back and it wouldn't be there", P9). In fact, concerns of theft dictated placement across all 4 communities: at an intersection, P2 searched for "a place where no one would go there but it's still close and no one would interfere"; P5 wanted to put exhaust sensors "a little higher", etc. We now discuss our findings for each group, including common sensor placements, means by which participants wanted to express the data, and their willingness to act on this information.

Students

We recruited 4 students who tend to use mailing lists to communicate with the student body. They routinely attend public places in or around university campus- library, student lounge, gym, as well as nearby coffee shops, bus stops, supermarkets, and parks. Students linked an ideal public place to nature, suggesting parks, clean streets or "any place that has a lot of green, something without a lot of people" (P3). Bad spaces were characterized by garbage, a general lack of cleanliness, and personal safety concerns. Prior to the study, participants have been curious about air quality, (*e.g.,* "I'm not originally from the city. I can tell the difference leaving the city- the air outside of it", P2). In addition several students wanted to monitor garbage, damaged sidewalks, and sunlight in indoor spaces.

Sensor Usage and Placement

Three students (P1, P2, P4) simulated leaving sensors in a variety of spaces around campus, suggesting that locations were primarily motivated by other students: dust and pathogens in a library ("people sit in the library for hours and hours- they get exposed to dust and pathogens", P2); dust in outdoor seating areas ("this is where students usually sit… there's lots of traffic and dust flows towards the seats", P4); dust and noise in shared computer labs; pathogens in bathrooms, trashcans and waiting room of a health center ("because more patients go there and wait

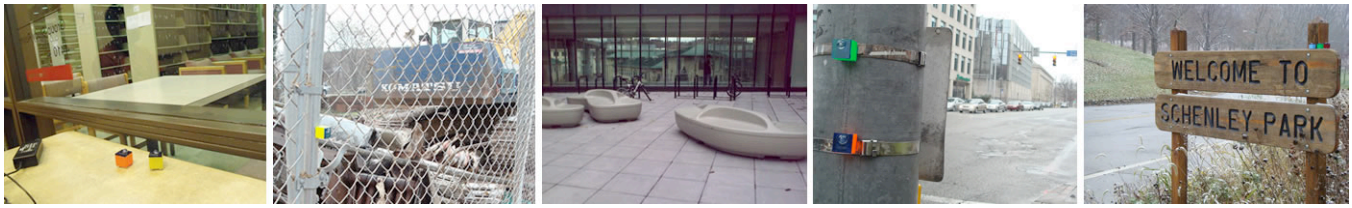

Figure 2. Student sensor placements (left to right): dust and noise in library; dust at construction site by campus; dust near student seating area; noise and exhaust at bus stop; exhaust, chemicals and smog on park entrance sign.

there", P1); dust near a pool table ("almost every hour of the day, there'd be 2 or 3 people playing", P4); exhaust, noise, and/or dust sensors near bus stops or intersections, since "there are a lot of people passing by" (P1), or to "to see if it's dangerous to me when I'm passing by" (P4);. While P3 was also curious about many of these locations, he simulated taking single measurements rather than leaving the sensors: "I just wanted to take a measurement- I don't visit that place often or I don't stay there for a long time" or "I would just take a measurement while I'm down there because I have no interest what happens when I'm not around there".

In addition, P1 wanted to monitor chemicals and pathogens in sewers across neighborhoods ("low income vs. high income to see what's the difference") and measure dust and smog at various distances from construction sites- "having sensors at different locations, one right on the site and one 20 feet away". P2 was also curious about exhaust and smog in parks vs. street intersections ("difference between a place that is green and the city center") and pathogens at a nearby school: "in the place where kids usually play there was a lot of trash. So I said wouldn't the parents like to know if the environment is safe or not".

Expression and *Authorship*

Of our four communities, students most strongly expressed feeling awkward during sensor placement, but became comfortable in time: "it's kind of awkward because when I'm trying to put it there, everyone was watching, 'she's crazy or something' it was kind of awkward but then you get used to that" (P1). Though participants liked the probes' small size, those students who wanted to leave sensors around campus asked for more visibility: P1 thought "it's good to be noticeable. It's nice to have different colors. It's a way to increase awareness of this topic" and P1 suggested that each sensor "Should be bigger or it has have a sign saying 'we're measuring …' and what these levels are". Participants wanted to represent data in terms of a benchmark ("compared with the year before or something about the normal/standard levels", P1) or abstractly ("green, red or some kind of indicator that says it's an acceptable level", P3). Several students also proposed "some application to the phone. Pittsburgh roads [in] red when it's too much traffic" (P4).

Awareness and Action

Participants who placed sensors most actively (P1 and P2) were also most driven to share data with local officials and the general public: P1 wanted to "give this information to the city center or council for them to take some action"; P2 proposed showing it to house buyers or students applying to colleges: "new house buyers should know what kind of environment they're getting". P2 was also concerned with political implications: "its great to collect data but how would it be put to use? Would the city officials be seeing this? Could it be affecting their decisions? Would someone be in charge of this or would they have a panel go into city council to discuss how this can be changed?"

Conversely, P3, who chose not to leave sensors anywhere, was less motivated to act on the data: "if I was the leader of some student organization, I would probably make much better use of it. It would be more useful to share". P3 did note that he would discuss the data with a smaller group of people: "it's useful if I find out that the dust level is too high in my place- I would share it with my neighbors. Tell them how it goes on, find out the reasons for it- whether its something they're doing or I'm doing or its just central".

Bicyclists

We recruited 3 bicyclists through local bike mailing lists and Craigslist: P5 (most active) routinely participates in community bike events, P6 spends time with other bike commuters but is not involved with any official groups; and P7 reads bike mailing lists, but tends to ride alone. P5 and P7 communicate with bicyclists through mailing lists, and P5 also meets people at 'the wall' (common event meeting place for bike events) and local bike shops/bike workspaces, while P6 tends to reach other commuters through cell phone or in person. Participants' routines include city streets, parks, public library, and a public cemetery, with an 'ideal' public space commonly characterized as being outside with little or no traffic, for example a park with "good trails" (P5). Conversely, bad public spaces have vehicular traffic, commerce, poor pavement conditions, or an appearance of "not being cared for" (P7). Participants have thought about air quality prior to the study: P6 was "curious about busy intersection where usually I have to stop [while] biking, and also out of curiosity so I can compare it to something like a park or even down by the river", and P5 commented on the "black smoke" often visible form city buses: "If you're cycling on public roads and you get behind one of these things and you inhale it all the time".

Sensor Usage and Placement

Participants wanted to use sensors while biking, to measure

either all 6 factors (P6, P7) or specifically noise and exhaust (P5). P6 placed sensors on his bike (Fig. 3) explaining: "I was more curious about how these different pollutants work together… I would take a few off and look for correlations between them to kinda figure out what some of the causes are… like on Butler street there's a lot of 18wheelers that go around so if there was a way to redirect them and there'd be less noise and exhaust but would there also be less pathogens and less chemicals?" Similarly, P7 pointed out: "I probably would just keep that on all the time. If I were able to say if there's something unhealthy in the air I'd like to know that at any given time." P5 also noted that permanently-placed sensors were not useful while biking: "I don't always hang out and stop because I'm just passing through", and was especially interested in exhaust: "It would be interesting to see if a bus gets in front of you, what kind of exhaust is there".

However, P5 also simulated placing sensors throughout the city, mostly out of concern for other riders: noise and exhaust sensors parks, bike trail near a highway ("because people use this to commute in and out of the city so it gets a lot more traffic and exhaust from that and the noise as well"), library, food co-op ("lots of people hang out there") and by 'the wall'- a meeting place for bike events. P7 wanted to place dust, smog and exhaust sensors at a park entrance to "look at it before I went riding to determine if it was worth going that day or not." P6 was curious to place sensors in harder-to-reach locations: "It would be neat to have them in some higher places like 10 feet up or the top of the cathedral or the water tower".

Expression and Authorship

Similar to student participants, bicyclists initially felt awkward about placing sensors: "At first I was self conscious but soon after it's kinda like whatever" (P6). Moreover, P7 noted that he would prefer to place sensors where others knew him: "I can just be like oh yea, this is whatever and then they'd probably tell other people too and then it probably wouldn't be weird anymore. But if I was like at the bus stop there where there's a ton of people that I don't know at all, then that's sorta different". Participants preferred less visibility for the sensors: "I'd be more comfortable leaving them places [if] I'd have something that kinda seems like it blended in" (P6); "I don't want people thinking that these are some sort of weird dangerous things. If they were very unobtrusive then I'd be more likely to [put them up]… or if I could make it look like it belonged there" (P7). Since "looking at data while trying to go somewhere" is difficult (P6), participants preferred to view data through a website or cellphone along with "what the health standards are".

Awareness and Action

P5 was most enthusiastic about sharing data with his community "If you're doing it from the cyclist perspective- people would welcome it. I'd feel like I'd be helping improve these spaces for my community." P5 suggested leveraging community activism in other domains as well,

Figure 3. Sensor placements by bicyclists: Exhaust and noise in Riverfront park (top left), exhaust, noise and smog near food co-op (top middle); exhaust and noise on bike lane (top right); all sensors on bike near library (bottom left); all sensors at intersection (bottom right).

for instance by tracking litter from a nearby grocery: "I think people would be able to get behind it and target that as the problem- because they [the store] can be like well how do you know it's us? Cause it's pretty obvious there's no other food sellers around at all, there's no other bars around you know, it's just that one place."

P6 and P7 were less optimistic. P6 indicated he would discuss the data with some of his friends: "I think people would be curious but I don't think they would be surprised if things were not great with the air quality". P7 would show the data to a mountain biking organization: "one of the mountain biking organizations would want that data… if it turned out to be a real problem they'd want to collect it and present a point to the city or something." However, he commented that sharing data with the general public might 'freak people out', or lead to inappropriate government response: "If the park turned out to be really bad full of smog and they would shut down mountain biking there- that would sort of suck right. So having the data and distributing it publically may not be the best idea".

Parents

We recruited 3 parents through Craigslist as well as local children's stores, P9 and P10 being most involved with parenting communities ("my friends are all parents", P10). Cellphones (calls, not SMS), face-to-face communication, especially during school events, and sometimes email were noted as primary means for communicating with other parents. Participants routinely spend time in grocery stores, restaurants, shopping malls, parks, and children's schools. Perceptions of an ideal public place range from parks for P8 and P9 ("the freedom of being outside rather than inside", P9), to more developed spaces for P10 "a place where everything is centrally located", i.e. "children's activity center", grocery, clothing, etc. 'Bad' spaces are characterized by a lack of personal safety feeling and poor

Figure 4. Parent sensor placements (left to right): pathogens at water fountain; pathogens, dust and chemicals in cafeteria of public recreation center; pathogens on shopping cart; pathogens, dust, chemicals on bathroom sink; pathogens on theatre seat.

sanitation (P9 especially disliked "public bathrooms… I kinda cringe. I think they're dirty, having a girl too, my daughter is 10"). Participants have not extensively considered sensing environmental data before, although P10 wanted to test water "in my own house, what's going on with my water, it's not clean".

Sensor Usage and Placement

Parent participants indicated (without prompt) that they enjoyed placing sensors, especially with their kids (eg, "It was fun to actually find the places… my kids were totally involved", P9; "they [kids] enjoyed getting to all the places, sliding through the snow", P10). Participants wanted to leave sensors for continuous monitoring, most often using the pathogen sensor in bathrooms- stall doors, sinks, toilet seats, towel dispenser, and baby changing area, Pathogens probe was also placed on theatre seats, to detect both 'germs' and lice ("people are sitting in the seats and if they have longer hair they can spread the lice all over", P9), school gym ("because people rent the gym and they're not from your area", P10), clothing store, stair railings ("I think of the bacteria on people's hands, and I would think that is not cleaned that often", P9), trashcan, and shopping cart. In addition, the pathogen probe was coupled with the dust probe in public recreation center, subway, doctor's office, and library ("I doubt that anyone's really cleaning it regularly", P10) and the chemicals probe at Wendy's restaurant, grocery store counter (to monitor "cleaning products"), and on the street near a hospital.

The exhaust probe was also common: near playground ("constant pollution is coming out, black smoke from the buses… if kids are in this playground during the summer, then they're breathing in all of that", P10), at a school bus stop ("they're [kids] all sitting there in the morning and waiting for the bus", P9), by a subway ("I would've left it on the back or even on top [of the train]", P9), near a smoking section, and at a gas station along with smog, pathogens and dust. P8 was also curious about chemicals near a sewer: "the water drains into the river and people use that, so there obviously is a concern about chemicals and pollutants that enter peoples' drinking water".

Expression and Authorship

Parent participants were less self-conscious about sensor placement ("I didn't care I thought it was pretty interesting", P9). Feedback about sensor appearance revealed a tension between visibility and secure placement. Participants wanted sensors to attract attention ("I would like them a little bit brighter so they're more noticeable", P10), from parents (*e.g.*, "I woulda left it just like that so that people can see when they go to the bathroom, just like that, boom!", P10), as well as authorities (*e.g.*, "I would've left it there, it brings attention to the city or to the company", P9). At the same time, participants were worried that visibility may cause children to "take it off", and a larger size would become unwieldy: "if it was on a shopping cart and it was sticking out, it might break off" (P9). As for visualizing the data, parents also emphasized seeing a scale or a benchmark ("you'd want some baseline… allow the raw data to make sense", P7), and simplicity (*e.g.*, "keep it simple, red, yellow green", P10).

Awareness and Action

Generally, participants did not see a need to share the data unless it negatively impacted them ("If it directly affected me or my children or them being in school… and I was presented with that information I would say yes we need to do something about this", P9), or if they were interested in "proving" a specific point ("if I was trying to do something… monitoring whether or not something needed to be adjusted, or if there was some negative effect on the environment", P8). In many cases, participants saw sensor placement as a message in itself, for instance alerting stores to provide "clean wipes near the [shopping cart] handle" (P9) or "to remind people if you can bring a q-tip with you

Figure 5. Homeless sensor placements: exhaust at gas station (top left), chemicals at McDonalds (top right), exhaust at bus stop (bottom left), dust near construction site (bottom center), pathogens at bathroom faucet (bottom right).

maybe or wipes…. Use antibacterial before you start typing" (P10, regarding dust and pathogen sensor near shared computer). Participants indicated that if they did discover unsafe sensor readings, they would first alert other parents through a school assembly, meeting or website, or a "datasheet to give the parents in a parent packet" (P9). While participants were also willing to talk to store managers, school principals and recreation center director, they had limited confidence in higher-order authorities ("I wouldn't have much faith in the city, its not a priority", P10, "so much apathy", P8). Lastly, participants noted that the study itself raised their awareness ("It really did make me think about the environment", P9), specifically in the context of exhaust and bacteria ("now I carry more antibacterial soap", P10).

Homeless

We recruited 5 homeless participants through a local shelter: three completed the entire study and two did not show up for the second interview. Participants indicated that they communicate by phone (4 owned cellphones, 1 used a payphone). They indicated that during their day-to-day life, they spend time in spaces that help them find employment ("all over the city looking for jobs", P11), as well as downtown, parking lots, libraries, local amusement park, foodbank, grocery stores, restaurants (Wendy's, McDonald's, etc), and the casino. Most participants identified the library as an ideal public space: "it's quiet" (P10 & P12), "they have al lot of books there, they have a lot of knowledge" (P14), and "there's people there that you can mingle with" (P15). The most disliked spaces were public bathrooms "cause they're always dirty" (P10), or places with "too much noise and drinking" (P12). While participants have not previously considered environmental sensing, they voiced several concerns: P11 was annoyed by sidewalk conditions ("they just spent 2 million dollars putting sidewalks in and then they go and plant trees… the roots get big and they buff up the concrete"), P14 commented on bus exhaust ("these buses going past, and all this smoke- just inhaling the smoke and stuff, I think about that kinda stuff every day", P14), and P13 was worried about cleanliness in restaurants ("in restaurants the people are not clean… gotta be more careful about who you hire, know who's dealing around the kitchen, working around food and stuff- the person has to look clean also").

Sensor Usage and Placement

The pathogen sensor was most commonly used, with participants' explanations hinting at general public health concerns: in public bathrooms (at CVS, McDonald's, Hilton Hotel) because "there's like a lot of people there and there's restaurants there too" (P12), in a bus because "a lot of people sayin they're getting sick this week so I'm wondering- cause people are on the bus a lot together" (10), in the homeless shelter dorm, on children's toys at a doctor's office, door handles, and floor of common area in the shelter. Participants also placed combinations of exhaust, smog and dust probes throughout bus stops ("I picked the bus stop cause lots of people are always there", P12) near cars, and on street poles and fences, focusing on construction sites and heavy traffic streets.

In addition participants placed a chemicals probe at a gas station ("You get that smell of gas real bad, some gas stations is real bad, cause I smelled it when I was walking by that's why I did it", P10) and McDonalds (because the nearby sewer gutter "stunk", P11), and a dust probe on window sills. P12 also placed the noise sensor on garbage cans: "it make a lotta noise- when you put something in that loud sound kinda scare you sometimes. I think they should pad it on the inside". In addition, P11 wished the set included a 'pollution' sensor, defining pollution as "trash garbage in the river, all the crap that floats by". He explained: "I really coulda done a lot with pollution in vacant lots, in vacant houses", emphasizing that "junkyard, barges and coal mines" often "drain down into the river".

Expression and Authorship

Participants did not feel at all self-conscious about placing sensors in public, as P10 explained: "people looked at me funny I didn't feel awkward though. I just said I was doing a study", P12 said: "I didn't feel uncomfortable", and P11 even involved his friends who appeared in numerous pictures ("I asked friends to hold the thing [probe] up", P11). Sensors were a 'good size', but participants preferred more visibility ("it should maybe light up") to draw attention to "people's health". P10 commented: "I think it's a good size cause it didn't interfere with anything, but if they blink yea that would be good… if they blinked like even if they were on just to let you know they were on they were blinking". More concretely, P12 suggest posting 'notes' or 'signs' indicating if pollution levels were too high: "put something overheard in the bus stop that says it". Participants wanted simple displays on the sensors as well: "some kinda signal that the air quality is not up to par" (P12), for instance, P11 suggested "a certain color to identify by color code", and P10 proposed "flash red then text your phone".

Awareness and Action

Two of the participants noted that the study heightened their sensitivity to environmental factors. P10 "noticed a lotta dust and stuff", while P12 was more watchful for germs: "I gotta be careful put something in my hand open the door without touching it". Participants were compelled to share sensor data with the general public, especially younger people "it's really important to share with kids, I think" (P12). However, they indicated that their first response to harmful sensor readings would be to "get outta there" (P10) or "move for sure" (P11). For sensors placed near business (*e.g.*, CVS, McDonald's, etc) P10 and P11 suggested also talking to the manager or owner, but did not know whom to contact on a larger scale (eg, "I"d report it to.. what's it called, department of something?", P10- regarding smog downtown; "write down the license plate number and um…talk to a policeman maybe", P12- regarding excessive car exhaust). P11 felt that "there's nothing to do about it [sensor data]", comparing the

government to a "whirling dervish" that "won't change anything". More specifically, P11 was disappointed with the city's attempts at infrastructure: "infrastructure here is shit. Look at the stadiums and arenas they built, that's not infrastructure". Hence, for him, being able to sense factors such as chemicals or germs would only "empower" him in the sense that he could ask for a "free cup of coffee" or other "small things" in places where the readings were harmful.

DISCUSSION

Given the challenges of implementing and deploying working sensing systems in the real world, we highlight the advantages of our approach, which leverages non-working sensor probes. The use of probes (instead of real sensors) allowed us to engage with four diverse communities without the overhead of troubleshooting technical difficulties, or the financial losses associated with damaged or stolen equipment. More importantly, this method enabled us to abstract from specific environmental data and explore broader concerns as voiced by each group. Rather than reacting to a particular sensor value, participants were invited to think about how factors such as germs, exhaust, smog, etc. play into public spaces throughout their everyday lives. Our findings reveal a wide range of values, environmental concerns and sensor appropriations across the four studied communities, and we now discuss the motivations for collecting data and community expressions.

Motivations for Participatory Data Collection

Participants across all four communities wanted to use sensors to ensure personal health and well-being, most strongly exemplified by bicyclists who wanted to monitor most of the factors wherever they biked. At the same time, participants also demonstrated concern for their respective communities: students (most community-driven) placed sensors throughout libraries, seating areas and lounges where other students spend prolonged periods of times; parents simulated monitoring pathogens or exhaust in locations visited by other children and parents (community center, bathrooms, playground, etc.); homeless were worried about bathrooms and restaurants used by their community; and one bicyclist (P5) wanted to leave sensors in parks or trails where other people bike. In addition, both students and homeless (along with the parents community) expressed a concern for children, wanting to monitor pathogen levels near schools or on toys at a doctor's office. Students, parents, and homeless were also interested in the 'garbage', chemicals and pathogens in the general water supply, suggesting a broader interest in the general public.

Expressions

All four groups commented on a need to compare sensor data against an acceptable standard, suggesting ways of informing the user when dangerous levels were detected. Participants emphasized abstracting from raw numbers and visualizing information in terms of colors, graphs or sound alerts. Interestingly, community differences emerged in the desired sensor visibility. Parents, and homeless were most proactive: feeling confident about putting sensors in public locations, they requested bigger, brighter, "blinking" sensors, and prominently placed probes where others would notice them. While students also expressed the desire to draw attention to the sensors, they were less comfortable with the act of placement— positioning sensors further away from crowds and feeling more awkward at the beginning of the study. Not surprisingly, bicyclists, who tended to interpret sensors as instruments of personal monitoring suggested that they should "blend in" or appear to officially "belong". This view is in part motivated by bicyclists' mobile relationship with urban space: they are less likely to stop and look public sensors while biking, preferring to access data through a website or cellphone. Lastly, expressions across all four communities were curbed by a fear of sensor theft, loss or damage, hindering participants from leaving the probes unattended, and inspiring "higher" placement on less reachable surfaces.

DESIGN IMPLICATIONS AND FUTURE WORK

Our findings emphasize participatory place-based sensing not merely as a passive act of measurement, but as a powerful resource for community-wide expressions and activism. We argue for public sensors as mediums for 'projecting' stakeholders' concerns into the public sphere and exposing ('tracing') the circumstances that have led to the current state. As such, sensors offer the potential to become instruments of defiance and transformation of space, leading to community-wide awareness, togetherness, and ultimately- the construction of active 'publics'.

Sensing as Engagement with Space

Our findings show that sensing, even in the abstract form of non-working probes, inspires people to reconsider and engage with public space. Some spaces afford similar concerns across communities: parents, students and homeless all placed the pathogen probe in public bathrooms, and across all four communities, participants attached exhaust and noise probes onto street poles at busy intersections, or on bus stops. Other spaces, however, evoke different interpretations. A homeless participant placed the noise probe on a trashcan, while parents and students commonly saw this as a site for pathogen sensing, and while all four groups routinely attend grocery stores, only parents placed a pathogen probe onto store counters and shopping carts. Reflecting on sensor placement as an act of demarcating a place to be sensed shifted participants' perceptions of spaces: they became more aware of dust at construction sites or germs on door handles, ("I noticed more dust and stuff", "I started carrying more antibacterial", etc.) The interplay between community values and spatial affordances leads to different interpretations of public space across communities, suggesting that there is no 'one size fits all' universal sensing system. Instead, future technologies must tailor to specific community interests and needs, supporting participatory sensing as an approach for *community-based* engagement with public surfaces.

Environmental Data as Social Currency Within and Across Communities

Our participants discussed 'sensor data' as an artifact that can be shared, broadcast, or articulated within and across communities. For parents, this information served as a tool of community togetherness: they wanted to share data with other parents, presenting it through school award ceremonies, children's sporting events, school websites, etc. Homeless participants wanted to anonymously broadcast this information to the general public by making the sensors more visible, or conveying the information through notes and flyers. The homeless participants' uncertainty about how to contact authority figures, as well as their disappointment in the government at large suggests that they might hope to leverage the general public's reaction to the data— rather than personal activism— as a means of changing the environment. Perhaps by showing passengers that a bus contains germs or by proving to pedestrians that exhaust levels are harmful, the homeless hope to incite public activism that they themselves do not feel empowered to partake in. Lastly, students used the data as a boundary object to negotiate dialogues with policy makers. They suggested presenting it directly to local officials and authorities to subvert or break down existing power structures and initiate change.

These findings suggest environmental data as a social currency- a potential for parents to act together with other parents, for homeless to speak to and incite action from the general public, and for students to negotiate for change with the policy makers. Future research can therefore focus on output modalities to engage stakeholders beyond the traditional charts, graphs and colors. For tighter-knit groups such as parents, visualizations can serve as tools for community togetherness, facilitating data exchange between members to inspire bottom-up activism that reflects community concerns. Moreover, sensor data can be presented as a boundary object to facilitate discussion of issues across groups and with policy makers. For instance, interfaces can open opportunities to broadcast personal concerns in ways that appeal to the general public, who in turn can serve a as an intermediary between the stakeholders (*e.g.*, homeless) and the government. For more politically active communities such as students, new technologies could empower direct communication between citizens and policy makers through mechanisms that provide feedback.

Sensing as Active Transformation of Space

The act of placing a sensor is a public statement: the presence of a sensor broadcasts a citizen's concern about a particular space. Parents used pathogen probes to draw public attention to dirty toilets, the possibility of lice on theatre seats or bacteria on un-emptied trashcans. Bicyclists placed exhaust probes in parks and bike lanes to raise questions about the impact of surrounding traffic on air quality. Students put chemical probes near sewers to highlight possible contamination of the water supply. In placing sensors throughout their daily routines, participants physically labeled each space with specific concerns. The intentional act of tagging an area as a candidate for high exhaust, smog or pathogen levels not only reflects participants' perception of this space, but also provokes the space itself, restructuring the relationship between this environment and the public. Further research can explore the impact of these 'tags': does an exhaust sensor reroute foot traffic, or does it signify a safer, cleaner area because of the in-place monitoring? Rather than being mere instruments to gather input, sensors become an active output modality just by virtue of their presence. Place-based sensors thus provide design opportunities for articulating stakeholders' relationships with urban spaces and potentially transforming these spaces to reflect the more preferable states of the world they desire.

CONCLUSION

We deployed sensor probes to explore participatory place-based sensing across four urban communities. Our findings reveal the act of placing physical sensors as a point of reflection and engagement with space, suggesting environmental data as social currency within and across communities. By embodying unique community values, future sensing and visualization systems can serve to broadcast stakeholders' concerns, negotiate dialogues with policy makers, or bring communities together, thereby facilitating the creation of cohesive 'publics' and serving as instruments of political, social, and environmental change.

ACKNOWLEDGEMENTS

We thank our participants for their insightful feedback, and Will Odom and James Pierce for their help with this work.

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