Environmental Protection and Agency: Motivations, Capacity, and Goals in Participatory Sensing

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ABSTRACT
In this paper we consider various genres of citizen science from the perspective of citizen participants. As a mode of scientific inquiry, citizen science has the potential to "scale up" scientific data collection efforts and increase lay engagement with science. However, current technological directions risk losing sight of the ways in which citizen science is actually practiced. As citizen science is increasingly used to describe a wide range of activities, we begin by presenting a framework of citizen science genres. We then present findings from four interlocking qualitative studies and technological interventions of community air quality monitoring efforts, examining the motivations and capacities of citizen participants and characterizing their alignment with different types of citizen science. Based on these studies, we suggest that data acquisition involves complex multi-dimensional tradeoffs, and the commonly held view that citizen science systems are a win-win for citizens and science may be overstated.

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Citizen Science; Environmental Sensing.

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H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
In environmental research, *citizen science* [29] is frequently touted as a means for both "scaling up" academic research and increasing lay engagement with scientific issues and practice. Involvement of non-professionals in scientific inquiry is seen as a way to refocus research productively on issues of societal concern [13,39]; educate citizens about science [6,51]; and benefit scientific practice through the use of citizens to collect measurement data and local knowledge [10,12,42].

Two particular approaches to citizen science have received the bulk of attention in computing research: supporting *expert amateurs* (including institutions like the Audubon Christmas Bird Count [47]) and facilitating *community action* (e.g., *street science* [13]). The Christmas Bird Count is a coordinated wildlife survey conducted by bird hobbyists around the world, whereas community action campaigns involve non-expert community residents in the process of characterizing local environmental conditions. The expert amateur approach resonates with many long-standing themes in HCI/CSCW research and has led to work on tools for open knowledge communities, collaborative visualization, and structured discussion. This work has also spawned a variety of general-purpose platforms like Sensr [31], Ohmage [48], and ODK [26]) intended to support a wide range of data collection activities by expert amateurs. Similarly, the community action approach resonates with recent themes in sensor network research [2] and has led to work on infrastructure for participatory mobile sensing (e.g., [39,44]).

However, an early focus on generalizable research – notably, on infrastructure for collaboration and data collection, things that computing research does well – risks losing sight of some of the particulars of citizen science as it is actually practiced. Such efforts often overlook: (1) the behavioral **motivations** of citizens to contribute to particular environmental causes, (2) the **capacity** of citizens to participate in activities necessary to a meaningful scientific campaign, and (3) the **alignment** of technologies with the ultimate goals of the collective scientific effort.

These issues become particularly salient when we consider that the design of infrastructure for related domains such as crowdsourcing is typically predicated on narrowing and simplifying participants' roles to reduce the impact of human variability on the data "product." This attitude is mirrored in the literature on citizen science, which is filled with comments to the effect of "scientists who design research projects have to write study protocols that take citizen scientists into account…protocols should limit what citizen scientists are asked to do" [10] and "the public doesn't know how to handle complex equipment" [5]. Do such design goals, as practically justified as they might be, match what "the public" wants to achieve?

In this paper, we consider the experience of citizen science from the perspective of the citizen participants. Our goal is to inform the design of participatory sensing systems. The analysis here draws on qualitative design fieldwork comprised of an interlocking series of citizen science

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projects conducted over the course of the past eight years. This involved three years of concentrated engagement, including four user studies and technological interventions, followed by intermittent observation over the following five years. Based on this extended engagement, we seek to unravel the assumptions resulting from uncritical adoption of *expert amateur* and *community action* viewpoints as well as the straightforward application of tropes from social media and sensor networks.

We begin with a background on citizen science and provide a framework for citizen science genres. Next, we describe the goals and methods of our studies. Drawing on our fieldwork, we present findings on participants' motivations in environmental action and participants' individual and collective capacities for citizen science. We then discuss how these align with different types of citizen science. We conclude with a discussion of the practical tensions among various goals in the design of participatory sensing systems.

BACKGROUND

In the computing literature, critiques of citizen science have tended to highlight the very limited involvement of citizens in science practice – especially in the popular areas of participatory sensing [17,19] and crowdsourcing [40]. However, the term is being actively applied to an even wider range of environmental science and natural history activities[1]. One documentary study [54] divided projects into primarily scientific (physical or virtual) or systemic (action/monitoring or education), but follow-on survey research [55] showed that ¾ of projects examined basically gave equal weight to science, action/monitoring and education. In this section, we describe archetypal work that has been classified as citizen science, noting variation in the degree of agency afforded to citizen-participants.

For the purposes of our discussion, we divide observational scientific practice using a linearized model of scientific method [24], a model in which a set of goals, ideas and hypotheses drive a study design (*preparation*); a set of study protocols are executed (*data collection*); and the resulting data set is analyzed and related back to the original ideas (*post-collection*). This is a caricature, as science practice typically proceeds in a more ad hoc, iterative manner [9,12,24]. Our main motivation is to separate data collection from the steps before and after it.

[1] Notable online citizen science projects appear in a number of disciplines, such as molecular biology (e.g., FoldIt, http://fold.it). However, environmental observations are still predominant—for examples, see project registries at http://citizenscience.org and http://scistarter.com. While platforms like Zooniverse (http://zooniverse.org) run crowdsourced image labeling and transcription projects in a variety of scientific domains, environmental observations also make up the majority of their efforts. To keep the domain-specific content of this paper manageable, and because the main focus of this paper is on participatory sensing, we limit our discussion to the environmental sciences and focus on on-the-ground activities rather than online participation.

Citizen Science: Origins and Genres of Practice

There are many genres of citizen science, and the ideas underlying them have a long history [20,47]. For example, Shirk et al. [45] categorize five genres of participation in citizen science research ranging from purely "contractual" research in which communities contract professional scientists, to "collegial" in which citizens conduct research independently with varying degrees of outside affirmation or recognition. These distinct genres can be seen as arising from two main historical threads – one with the primary goal of using citizens to facilitate science, and the other subordinating science to citizens' political goals.

Citizen <u>Science</u> – Facilitating Scientific Agendas

The now-widespread use of non-professionals for data collection [10,20,42] is the best-known form of what we might call the *expert collectors* genre. The pre- and post-collection work of study design and data analysis remain in the control of professional scientists, and the role of citizens is carefully defined and constrained to maximize the scientific utility of their labor. The Christmas Bird Count is an oft-cited example of this, yet it also highlights the fact that such work can require considerable domain expertise (recognizing birds) even if that expertise is not that of professional science (analyzing data) [51]. To encourage participation, web-based tools for data submission now commonly include online community tools (e.g., [1,32]).

Inspired by the popularity of projects like the Christmas Bird Count, computing researchers are creating crowdsourcing-style projects for environmental research. The availability of wirelessly connected mobile computing devices and inexpensive sensors has driven a great deal of recent research in mobile participatory sensing – the organized collection of sensor data using personal mobile devices [2]. A typical *sensing citizens* vision assumes a scale trade-off – i.e., high spatiotemporal data coverage will result from the mass participation enabled by cheap platforms and sensors, and that coverage can make up for limitations imposed by an ad hoc, de-skilled data collection process as well as those resulting from the use of cheap sensors [28]. A sensing citizens perspective is often applied when participant tasks can be usefully constrained, for example an effort in which participants execute clearly defined tasks to track chlorine usage [30].

<u>Citizen</u> Science – Enabling Collective Agendas

A different thread of work has been inspired by action research in the social sciences. The primary objective here is to effect changes in local conditions as opposed to the construction of (academic) scientific knowledge.[2]

[2] Other common forms of citizen participation in change processes include participation in the representative electoral processes, formal policy-setting processes, or informal agenda-setting processes [49]. In the latter two forms, activities may be epistemically scientific (requiring access to scientific resources and expertise), but they may also focus on identity politics or even be explicitly subversive [8].

What we will call *community research* takes many closely related forms [56], such as participatory research in the social and health sciences [34] and street science in the environmental sciences [13]. The scientific resources and professional scientific training available to community activists is generally limited, so data often takes the form of qualitative local knowledge instead of quantitative measurements. One path to address this limit involves local youth as *student scientists* who learn about conventional science practice and become aware of environmental issues (e.g., [25]). Another path is to enroll community members as *citizen scientists* with the specific aim of creating new knowledge, data products that are good enough to use in policy/regulatory arenas (e.g., [37,39]). Obviously, these paths increase the involvement of participants in conventional science practice.

Technologists, artists, and activists are hybridizing community research with the same crowdsourcing ideas that inspired participatory sensing. What we call *community reporting* resembles community research in that it uses participatory sensing data in a qualitative way to raise environmental or political awareness within communities (e.g., [17,35,44]). However, the intensity, duration, and capture of local knowledge tend to be reduced.

Similar ideas and language (e.g., participation, science) are used in all of these genres. However, the disparate sources and influences of these ideas – including the recent ability to scale them using crowdsourcing and sensing technology – result in quite different emphases in terms of the data collected, and also impact how the data can be applied.

Ideal Types of Data-Centric Practice

Detaching these various genres of citizen science from their specific origins and goals for a moment, it is helpful to arrange them into an ideal type [53] system (Figure 1) based on their goals and approaches to data collection. (These ideal types are meant to be analytically useful, as opposed to thoroughly descriptive or precisely definitional.)

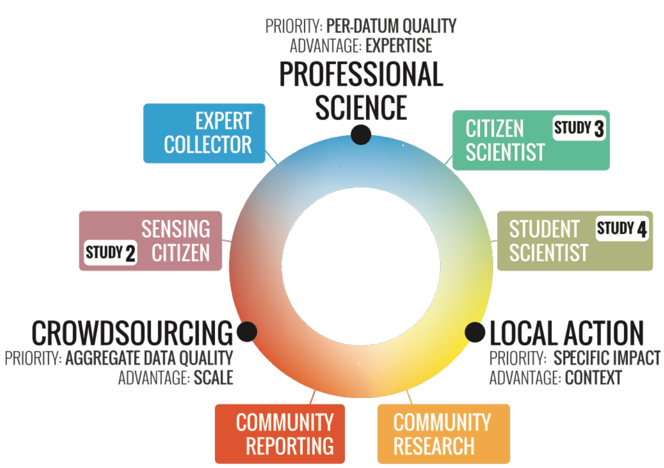

Figure 1. Different types of data-centric community and science practice. Studies 2-4 show the focus of our fieldwork.

When all portions of a study are handled by professionals, we might simply call this first ideal type *professional science*. The primary goal of data collection in professional science is quality – not just maximizing the accuracy and minimizing the uncertainty of measurements, but characterizing their limitations, reproducibility and traceability. Strategies for achieving such goals include developing detailed technical knowledge of the measurement apparatus, careful construction of study protocols, and thorough documentation.

Economic realities and geographic constraints have long incentivized professional scientists to try to use amateur labor, which shares with *crowdsourcing* the key goal of maximizing the usable labor captured from participants. Crowdsourcing also shares the strategies of extreme division of labor and task standardization. Participant agency tends to be limited to the willingness to participate and work for the benefit of science practice. In particular, because of the difficulties of involving non-professionals in pre- and post-study practices, participation is often limited to data collection (whereas the goals and potential uses of the data are typically driven by study design).

A third ideal type of science-oriented activity might be called *local action*. The primary goal here is to effect change in local conditions. Participant agency is an explicit part of the activity – community goals, not those of scientific practice, drive what the project aims to achieve.

Overlaying our citizen science genres into this ideal type system (Figure 1) allows us to both consider the seemingly disparate goals of the projects and participants, and illustrate common tensions between them.

STUDIES

Our analysis draws upon post-hoc reflection on a series of four studies with interlocking goals and timelines. All four engagements centered on local air quality monitoring in a dense urban community in northern California. We chose to focus on air quality specifically because it represents a situated, locally relevant environmental problem with the potential to engage and impact a diverse set of contributors. At the same time, accurate and comprehensive air quality monitoring still presents a number of scientific, technical, and coordination challenges [50].

We began with background research on individual motivations for engaging in environmental action. We then collaborated with a local environmental justice NGO on a series of focused interventions. After these engagements concluded, we continued to informally track the progress of the NGO's efforts over the following five-year period.

Research Questions for HCI

In considering the design space of technology to support variations on "citizen science" (and in particular mobile participatory sensing), we explore two research questions.

The first question is, *What drives people to engage with participatory efforts, and what actions and outcomes are* *meaningful to them?* Engagement in environmental action of any kind is a process [58]. As one survey [18] notes, HCI sustainability research frequently considers the role of persuasive interfaces, social influence, and individual motivations for personal sustainability choices. Further, work has been done on motivations for online participation in citizen science [36]. However, exactly what kinds of meaningful outcomes motivate participants to pursue collective activities like citizen science (and how these interact with their abilities) is not yet well understood.

The second question is, *What are productive ways for citizens to participate?* As suggested in the previous section, different citizen science genres involve varying degrees of effort, formal scientific knowledge, attention to detail, etc. Understanding the realistic limits of citizen participation informs the requirements for technology intended to facilitate citizen science. Many different technologies for participatory sensing and collaborative analysis have been proposed. Some are highly appropriate when the goal is primarily to collect data to facilitate scientific purposes, whereas others are more appropriate when the goal is primarily to serve local residents.

Field Studies

Our field research can be grouped into four studies according to primary research focus and methods. The participants, tasks, and situations differed across studies, allowing us to observe variations in citizens' motivation to participate, their role in data collection and other aspects of science practice, and the types of sensing technology involved. In the three studies involving scientific practice, we participated in planning, execution and surveyor debriefs as well as providing enabling resources (e.g., equipment, technical assistance, funds for surveyor compensation). However, the goals and specific questions of the work itself were driven by our partners' agendas.

All phases of the fieldwork were qualitative. We took detailed field notes during interviews and other interactions. We recorded all formal interviews, meetings and workshops, transcribing relevant segments. At various points over the course of the projects, we performed affinity clustering on the text corpus and iteratively identified and refined emergent themes [7]. The analysis procedure reported here extends the detailed process described in several of the individual field studies [22,57].

Study 1 – Concerned Citizens

To investigate the motivations of individuals who were engaged in environmental action, we conducted exploratory fieldwork in the San Francisco Bay Area over a period of 7 months in 2008. This exploratory study did not involve a technical intervention and, unlike the other three studies, was not tied to a particular genre of citizen science. We conducted formal in-person interviews with 14 participants and informal phone and in-person interviews with approximately 30 additional stakeholders. Participants were selected for interest or involvement in environmental action around air quality. Almost all participants were adults, at a variety of life stages, with a balanced number of male and female participants. Interviews were semi-structured and lasted between 1.5 and 3 hours. The informal interactions followed an open-ended format and varied greatly in length.

Study 2 – Sensing Citizens

To understand more about citizens grappling directly with technical questions, we then engaged with a local environmental justice NGO, the Environmental Indicators Project (EIP). Founded by grassroots activists, EIP has conducted community-based participatory research (CBPR) [34] for many years [14]. EIP is perhaps most widely known for a series of campaigns in which it collected observational ("survey") data on particulate matter emitted by diesel trailer-trucks operating in local residential neighborhoods [38], resulting in a health risk assessment and emissions inventory at the state level [16] and increased monitoring at the air district level [21].

The Sensing Citizens study focused on the collection of air quality data by community surveyors using chemical sensing technology. This pilot study (conducted by approximately 10 surveyors over a 4-month period in 2009) employed wireless sensor platforms developed by the Common Sense project [22] (Figure 2-left) that geolocate and record measured levels of three EPA criteria pollutant gases (CO, NO_2, O_3) using two different off-the-shelf chemical sensor technologies. These devices require no user intervention and, indeed, participants were not required to do anything specific except recharge the devices at night. As such, this was an example of the sensing citizens genre described in the previous section. In both this study and the Citizen Scientists study below, we followed EIP's existing practices for surveyor recruiting (using snowball sampling complemented with local advertising) and incentives.

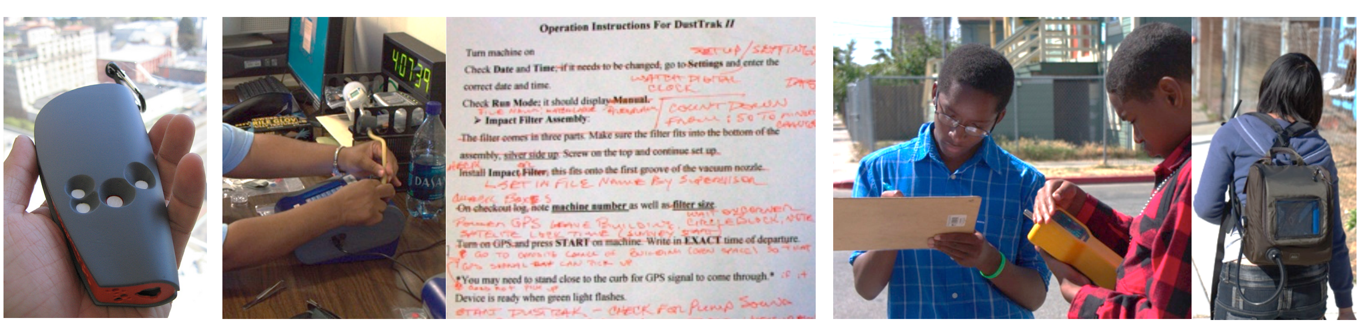

Figure 2. *Left*–The gas sensor developed for the Sensing Citizens study. *Center*–Calibration and evolving documentation during the Citizen Scientists study. *Right*–Sensing activities conducted during the Student Scientists study.

Study 3 – Citizen Scientists

While the Sensing Citizens study with chemical sensing devices provided valuable usage data, engaging EIP's staff and community surveyors in deeper scientific investigation required that we shift to EIP's main pollutant of interest, particulate matter (PM). As a result, subsequent campaigns involved off-the-shelf portable aerosol monitors (DustTrak II, Model 8530; TSI Inc.) that log continuous particulate matter readings in the same units as EPA NAAQS (i.e., mg/m^3). Unlike the Common Sense devices, these monitors require considerable operational and administrative attention including maintenance, calibration, manual data management, and record-keeping (Figure 2-center).

In this engagement, data was collected by approximately 20 community surveyors over a period of two years from mid-2009 through mid-2011. Data collection was somewhat intermittent, with the exception of a focused round of approximately 100 shifts during two weeks in February 2010. Surveyors typically carried the monitors for hour-long shifts, walking one of six routes designed by EIP staff. Surveyors and EIP staff frequently reviewed the data in a visualization tool developed by the researchers. In addition to participating in initial orientation and training, some surveyors participated in an EIP capstone workshop and visualization focus groups [57]. The greater involvement of EIP staff and surveyors in the technical aspects of this process makes this an example of the citizen scientist genre.

Study 4 – Student Scientists

To study a third common citizen science genre, we collaborated with an NSF-funded high school science enrichment program, the East Bay Academy for Young Scientists (EBAYS). From a technical perspective, this was fairly similar to the Citizen Scientists study (EIP's request, photo and SMS annotation capabilities were added), but the surveyor population was radically different in terms of their demographics (high school students as opposed to immediate community members) and motivations (curriculum enrichment as opposed to community interest).

In this final engagement, two dozen student surveyors and six instructors collected data using PM sensors over a period of six months during 2010 (Figure 2-right). This initiative including a concentrated summer program in which EIP was actively involved (for example, training the students and instructors in the use of the equipment). The data collection was contextualized with lectures on environmental science and environmental justice as well as data analysis sessions. The students participated in individual interviews, and researchers acted as participant-observers during data collection and analysis. All student surveyors gave final presentations, and some presented their results in a poster session at a national scientific conference.

As the studies progressed, EIP leveraged its extended network to proselytize the work, garnering attention from regulatory agencies and high-ranking government officials, significant press, and numerous requests from other communities who want to conduct similar work. When our research team transitioned to other activities in mid-2011, EIP and EBAYS continued the Citizen Scientists and Student Scientists work, and EIP also began conducting training sessions for other community groups across the country. As of 2016, both groups were still actively engaged in these activities.

WHAT DRIVES PARTICIPATION?

In this section, we discuss participants' motivations for conducting various types of citizen science.

Drive for Personally Relevant Information

The predominant driver of interest for concerned citizens was clearly the desire to gather personally relevant information. Personal health issues (or threats of potential future health issues) triggered concern about air quality.

> "People who have children who have asthma and get more concerned about it, or they're sick themselves and they're concerned about it, that interest makes them want to join a group or find out more about the issue." – *David[3], Concerned Citizen*

> "I used to go walking. There were some days I thought I wasn't going to make it home. I'd just get so short of breath." – *Linda, Concerned Citizen*

Participants were eager to get information about how to minimize their exposure. For example, they wanted to receive recommendations for walking routes or driving routes with the lowest potential exposure. Accordingly, while participants had some willingness to collect or view data for more abstract scientific purposes, they were more compelled to gather and view data that was immediately relevant to their own lives. They wanted data about the specific locations in which they personally spent time and about the pollutants with the greatest relevance to their health. For example, they had greater interest in collecting data about particulate matter than in collecting data about ozone or carbon dioxide.

> "For me, I would just be interested in my own local [air quality]."
> – *Ethan, Concerned Citizen*

Therefore, while concerned citizens were highly motivated to carry devices to collect data about their own exposure, they were not necessarily motivated to collect data that was most strategic from a scientific perspective. Further, their needs may not be met by technical approaches that collate data from a large number of low-accuracy sensors; because people spend the bulk of their time in a few locations where multiple sensors may not be available, conventional instruments that take highly accurate individual samples may be most appropriate for health-focused data.

Although they shared the concerned citizens' interest in personally relevant information, community and educational organizations were more flexible about location and type of data than the individual citizens. As discussed further below, EIP wanted to gather a fairly broad data set

[3] All participant names are pseudonyms.

for exploratory purposes, and funding opportunities played a significant role in guiding their focus. EBAYS' predominant interest was educational, so they were somewhat agnostic to the type and location of data.

Interest in the Environment, not Environmental Science

The community and educational organizations had a desire for citizens to gain an understanding of scientific process and principles, for example so that they could meaningfully participate in community meetings with scientific agencies. However, individual citizens made it clear that their interest in the environment was not necessarily the same as a desire to develop competence in environmental science. Some people may become engaged in the scientific process, but many do not. Participants were typically satisfied by learning about fairly general information and by gaining "awareness," and they tended to be largely uninterested in conducting scientific activities beyond simply collecting data. For example, participants wanted to learn what pollutants they might be exposed to.

> "I don't know what's in the air. That's why I wanted to do this. So that I could learn." – *Jake, Surveyor*

> "All three of my children have asthma, so from that perspective, I wanted to know what was in the air. Not only that—I'm allergic to something out there in the air… So I really would like to know what's hit me..." – *Loretta, Survey Team Leader*

However, participants were less engaged in analyzing or interpreting data. Many did not know, and were not particularly interested in learning, what the numbers meant.

> "What's 2.1? … See, those numbers wouldn't mean a thing to me." – *Abigail, Concerned Citizen*

> "From sensor to sensor, pollutant to pollutant, this one's bad at a hundred and fifty parts per billion, this one's bad at eighty parts per billion, this one's at nine parts per million (laughs) … they could care less." – *Ethan, Concerned Citizen*

Participants such as the surveyors seemed happy to assume that someone else (an expert) would take the data and do something meaningful with it. They were satisfied by "playing their part" by collecting the data, and were not generally inclined to engage with it.

> "Once they receive the data that we give to them, they test it. They know what it is." – *Desiree, Surveyor*

> "[Collecting data] made me feel like I was doing something for Oakland… I think I'm making a difference, and I feel better about myself." – *Darius, Surveyor*

Rather than seeking to explore the data, participants were more interested in being provided with higher-level interpretations that explained their exposure in terms of health effects or "normal" conditions, contextualizing their experience without requiring them to have specific technical knowledge. Overall, participants tended to seek narrowly defined roles as data collectors and assume that (anonymous) experts would fill all other functions.

Awareness, Education, and Advocacy

Citizen science rhetoric often suggests that citizens will leverage the data they collect to take effective political action. However, while participants were convinced that collecting data was useful, they were often vague as to how it would be used. Participants' immediate inclination was to use data to raise awareness among community members, a goal that was also shared by EIP.

> "The most important thing is get it out to the community and the residents who live in these areas who might not be aware." – *Desiree, Surveyor*

> "It's really hard to educate people about environmental issues because they just immediately want to get defensive... But if you provide them with something like this that's engaging, it's graphic, it's factual… then they start to sort of care and they start to sort of understand..." – *Claire, Concerned Citizen*

In practice, this awareness raising was fairly successful in both the Citizen Scientists and Student Scientists studies.

> "I've learned, since I started participating and doing the air study… how small the particulates are that can go through your lungs… pollutants there in the air that I would never have thought about that are entering my body and my children's body." – *Desiree, Surveyor*

> "I talk a lot about it when I'm out and about [collecting data]. People are always asking us what we're doing… and you go into a whole scenario about explaining what you're doing it for and why. It's another way to draw people into what we do, by letting them see us doing it." – *Loretta, Survey Team Leader*

However, participants were somewhat hazy about how this community awareness would be helpful. We attended one community action workshop in which the moderator specifically led a session to educate participants about using data for advocacy, because it did not generally occur to participants to interact with policy makers, and they did not know how to approach this process. Even though the community and educational organizations had a deeper understanding of the political advocacy process, using data in advocacy was not necessarily an immediate goal for them either. The initially desired impact of citizen science was in many ways educational rather than environmental.

> "Another mission of ours is to have students develop problem-solving skills as well as critical thinking skills… They can then utilize those same skills to try and solve problems in their own lives or in their own communities." – *Ben, Science Teacher*

WHAT IS PRODUCTIVE?

As we saw in the previous section, a key motivation for citizens is to answer questions about environmental conditions and the potential effects on community, family and personal health. However, when moving from general information to professional science or community advocacy, additional goals become relevant, and the procedures by which data is collected and managed become critical for its potential use. In this section, we discuss our experiences with citizens and consider their capacity to productively gather and use data in various conditions.

Relevance of "Scientific" Conduct for Non-Scientists

One of the touted benefits of citizen science is that citizens can effectively donate their time and effort, amplifying the efforts of professionally trained scientists. But is it always possible to execute "science" without professional training?

Professional science assumes that "data" is far more than the raw measurements. For reproducibility, data collection procedures and equipment must be recorded, as well as measurement conditions. For analysis and presentation, these factors become part of uncertainty estimates. In professional science practice, all of this is considered as part of study design – it would not make sense, for example, to use equipment and procedures that would be unable to measure the phenomena of interest.

In spite of its non-scientific origins, community advocacy turns out to involve similar concerns. Because advocacy generally occurs in a governmental setting of one kind or another, data-backed arguments are typically presented in terms of standards set by existing laws, which are in turn framed in terms of relatively conservative scientific standards [37]. A key rhetorical strategy is to present citizen data as the product of "good science" [5], meaning that its methodological credibility must be high enough that results cannot be *immediately* dismissed by technical experts.

Hence, while data intended for personal use might be collected using arbitrary methods, data intended for use in scientific or advocacy settings is far more valuable if it is collected and managed according to conventional protocols. To give an example of such a protocol, the technical procedures for our student-scientist study might be summarized in a scientific journal publication as follows:

> Surveyors carried photometric aerosol monitors (DustTrak II Model 8530; TSI Inc., Shoreview, MN) with a 1Hz sampling rate and air flow calibrated each day to 3.0L/min (Model 4146; TSI Inc., Shoreview, MN). Monitors were fitted with TSI impactors (size-selective inlets) with designed 50% cut-points at 2.5μm ($PM_{2.5}$) at 3L/min. The monitors' internal clocks (used to timestamp logged readings and which required manual setting) were re-set at every shift using an NTP-based wall clock. Surveyors walked one of three routes specified by EIP, with positions logged by GPS at 1Hz (AGL-3080; Amod Ltd., Taipei, Taiwan). Monitors were carried using custom backpack cases, with air sampled from the surveyor's breathing zone using 1m conductive silicone rubber hoses (TSI p/n 810688, TSI Inc., Shoreview, MN) attached to the inlet. All monitors were within annual factory calibration against ISO 12103-1:1997 A1 test dust. Local PM characteristics were obtained using the monitor's built-in sampling port and 2-piece, 37mm cassettes loaded with 2μm PTFE filters (SKC p/n 225-308 and 225-27-07; SKC Inc., Eighty Four, PA) at an effective internal flow rate of 2.0L/min. Gravimetric analysis (ALS DataChem Labs, Salt Lake City, UT) applied NIOSH 0500 procedures including field blanks. Readings were manually downloaded from the DustTraks and submitted (with GPS logs) to a system that performed basic quality checks and automatically uploaded data into a database. At pre-selected street intersections, particle count readings were taken at 0.3, 0.5, 1, 2, 5 and 10μm using a multi-channel optical particle counter (Model 983, Fluke Corp., Everett, WA).

Executing these procedures is not simply mechanical and requires considerable technical and administrative attention to detail.

Operations and Maintenance

In our experience, citizens found it highly challenging to develop procedures and documentation for their activities. In the Citizen Scientists study, researchers wrote initial procedures, a customized user manual, and checklists, and trained EIP staff in the use of these. The researchers then encouraged EIP to adapt the procedures and documentation to reflect their specific needs and practices as the work unfolded. This task was delegated to EIP's survey team leader, who had a strong preference for the oral tradition. (As is common in environmental justice communities, many EIP staff and volunteers had had limited opportunities for formal education.) She quickly appropriated the technical procedures and made minor modifications, such as reordering maintenance steps for increased productivity. However, months passed with little progress on the documentation, and necessary information about data provenance was not being recorded. Some EIP staff understood the significance of this (for example, in order to receive funding from the EPA or even provide data as input for EPA decision-making processes, an organization must demonstrate that they have followed extensive EPA quality assurance requirements [23]). EIP staff appealed to the researchers to verbally interview the survey team leader and update the documentation (daily log sheets, etc.) to reflect the new practices that had emerged (Figure 2-center).

> "I didn't do my reading. I just learned the system… It's not really hard to use… I'm trying to figure out which ways to do it faster." *– Loretta, Survey Team Leader*

> "This is a really big problem in a culture where there isn't better than a sixth-grade education and people don't have any technical knowledge or understanding… It's great if [she] learns how to do this, but there's no documentation. She memorized it because she made you tell her 55 times. Tell me every day until I learn it. Well, that's great, but what about the next person?" – *Alex, Community Organization Leader*

In many ways, the citizens and students were highly capable of executing day-to-day procedures. Initial mastery of the technical procedures was rarely a problem when the procedures were codified in advance. For example, EIP staff was competent at charging and calibrating equipment, changing filters, and modifying device settings.

> "It's just a really great experience for the young people and as well for policymakers in the government to see that young people are capable of doing this kind of work and that anyone can really do this work." – *Ben, Science Teacher*

> "The mechanics of data collection... they [the students] were competent at that... But they didn't always understand why they were doing what they were doing." – *Connor, Science Teacher*

However, as is common in tedious work, sticking rigidly to protocols is difficult – especially with an intermittent volunteer population. We saw considerable "practical drift" ([46], p. 194) between the written procedure and collection practice. In some instances, critical metadata was not recorded, GPS data was not collected in conjunction with the air quality data, etc. Volunteers did not always reliably handle mundane tasks such as charging devices nightly.

> "Badge #10 was not charged… (surveyor took some antihistamins [sic] and fell asleep early)." – *Survey log, Sensing Citizens study*

> "Now we have to worry about quality control… we have to keep correcting them on their process and procedure, and that's just going to be a reality of working with volunteers who are doing this one hour a week." – *Alex, Community Organization Leader*

Additionally, some administrative aspects were difficult. For example, many of the EIP staff were not experienced in using computers, so tasks such as saving data with agreed-upon filenames (specified to contain necessary metadata) were challenging and error-prone. As a result of various procedural errors, approximately half of the first 100 shifts were unusable. EIP responded by paying greater attention to learning and enforcing the procedures, and later data collection was more successful.

Monitoring and maintaining complex equipment over the longer-term was challenging for the citizens, as it required a certain level of understanding of its principles of operation. While the researchers encouraged them to become more involved and grow their competence in this area, and the survey team lead was alert and did occasionally notice potential problems, overall they had little interest in deepening their understanding of the equipment. In the end they relied almost entirely on the researchers to ensure the equipment was in good operating condition.

In summary, participants executed day-to-day operations well (when they made it a priority to follow the protocols). However, they relied heavily on the researchers for procedures and documentation, as well as longer-term maintenance and troubleshooting – sometimes because these were not organizational priorities, and sometimes because participants did not yet have the requisite skills. In practical terms, this means that without expert intervention the data being collected might not be considered credible. In fact, according to EIP, the Citizen Scientists study would probably not have been conducted without heavy participation from outside researchers.

Sensitive to these concerns, EIP articulated that the work was more complicated than they had anticipated, often expressing a strong desire for the type of equipment in the Sensing Citizens study (equipment that required minimal operation and maintenance, and no interaction with data files), which they came to call "passive" equipment. Such equipment was unfortunately not an option, as consumer-grade particulate matter sensors (like AirBeam [3] or the Air Quality Egg [4]) had not yet come to market, and the need to measure PM dominated other concerns. However, on other occasions, the same EIP staff also expressed concerns about such passive equipment – noting that it might compromise engagement and undermine their educational goals. They were eager to participate fully and did not want the researchers to "dumb things down". Ultimately it became clear that the ideal technology would involve active participation and learning, but not too much. Ideally, new opportunities for participant involvement would lie in the zone of proximal development [52] and build on participants' existing knowledge and capabilities.

> "This citizen data gathering has to be completely passive or it's never gonna work!" – *Alex, Community Organization Leader*

> "It can be done much more easily than the way we do it, but we choose not to simply treat a volunteer or a student as a pack mule… We want them to learn something…" – *Alex*

> "In a sense, I don't want it to be fully automated. I want it to be an accessible process that doesn't take me a month and a half to teach someone… walking that line between automation and engagement is an important one, because you know we could have dogs carrying the thing around the neighborhood if all we want to do is collect data." – *Alex*

Aligning Study Design, Execution, and Goals

Approaches like CBPR or street science [13] posit that the community has latent questions – that local knowledge can be elicited and converted into both questions with a scientific formulation as well as influencing the reformulation of scientific questions in non-scientific form when appropriate. However, it may be hard to get people to articulate local knowledge. For example, the environment and residents of our target community are both over-studied. Some have posited that urban sensing may cause people to lose hope [15]. But, in fact, even without such sensing, members of the community have had so many people tell them things are wrong that it becomes difficult to elicit specific formulations.

> "Polluted, everything is polluted. Soil is polluted, water is polluted… The air is polluted. Everybody has asthma. It's all sooty. Starting from that, what would we need to know for them to ask a more specific question?" – *Alex, Community Organization Leader*

Hence, one must not only offer data but must also offer a specific course of action [5]. This can elicit more focused concerns – for example, particulate matter as opposed to environment or even air quality.

Even after hypotheses were posed, participants found it difficult to design a study plan that would yield data relevant to the hypotheses. Sometimes this was due to practical considerations such as the limits of volunteer schedules. For example, community members, the Air District, and a local atmospheric chemistry professor all provided EIP guidance about the times at which it would be most productive to collect data (e.g., the times of day the particulate matter levels were highest). However, volunteers were not readily available at those times, so EIP routinely collected data at times that were less valuable from both the scientific and community perspectives. Further, individual concerns can overtake organizational priorities. For example, one of the EIP staff had a personal interest in illegal dumping. She was attracted to this issue because it was concrete (unlike air quality) – one could easily identify misbehavior, report an offender to the city, etc. Accordingly, she significantly modified the data collection plan in the Student Scientists study such that the students refocused much of their effort on taking pictures of trash in the neighborhood, rather than gathering air quality data.

Participants also found it difficult to align their expectations of the data with the nature of the data being collected. For example, when EIP was designing a study plan, they articulated goals such as showing spatial variation in particulate matter levels or generally exploring the data to see what phenomena emerged. However, the study plan resulted in data that was geographically and temporally sparse (limited locations, inconsistent times of day, etc.), and from a scientific perspective this data was ill-suited to answer their questions. Despite receiving expert input expressing grave reservations about this approach, they were highly optimistic that if they just pushed forward collecting data, eventually they would have "enough".

> "I think the great value here is creating a tool which over time can either in an organized way or a random way accumulate tons and tons of data… it doesn't matter in a sense where [volunteers] go, how long they stayed there, what they did, the data is coming together. And eventually we have a picture that represents the cumulative experience of the community."
> *– Alex, Community Organization Leader*

The reality on the ground was that these campaigns were often "data first, questions later", personal interests and availability of volunteers often trumped focused agendas, and the data collection method was often poorly suited to the data collection goals. Accordingly, the resulting data was of limited use from all perspectives, being poorly suited to answer either scientific *or* community questions.

Leveraging the Data

Many citizen science projects expect citizens to not only gather data, but to explore and use it as well. However, such activities may be more difficult and less common than traditionally assumed. In all of our studies that involved data collection, citizen groups made relatively little progress in leveraging the data. Previous research has often proposed collaborative visualization [27] and its associated discussion tools are as means to focus and direct citizen activity [33,57]. Our research team provided the participants with user-friendly, custom tools, but the limitations of the tools and the limitations of the computer and analytic skills of the participants were both challenges.

Participants in the Citizen Scientists and Student Scientists studies gradually converged on the following types of analysis: (1) noticing the "baseline" level for a given day (e.g., "today was mostly 17s but yesterday was mostly 6s"); and (2) noticing where "spikes" (i.e., high PM values) occurred and inferring that locations with repeated spikes might be hotspots. Much focus in citizen science environmental monitoring is on hotspots, and it is indeed recognized that research is needed because the health effects of hotspot exposure are not well understood [11]. Searching for hotspots was fun and engaging – for example, one participant reported that PM levels were elevated near a taco truck. However, while participants had a number of theories about possible explanations for elevated levels and captured contextual information about potential sources during surveys, little progress was made on reproducing data or modifying study design to further investigate problem areas or provide credible evidence of causes.

In addition to their own analyses, EIP and EBAYS drew on a member of the research team to assist with analysis. Ultimately, participants presented preliminary data in some venues, but usually framed it as an example of what might be possible with these methods rather than an actual result.

ALIGNING SCIENCE WITH PARTICIPANT MOTIVATIONS

We now consider the alignment of participant motivations and capabilities with the ideal types of citizen science. Framing narratives from these ideal types suggest that: (1) citizens will play a role in the scientific process – designing studies and analyzing data (*professional science*), (2) citizens will collect the types of data that are needed, in the locations where data is needed (*crowdsourcing*), and (3) citizens will take action and use the data that is collected for advocacy (*local action*). We argue that while our participants had some natural interest in performing these duties, their predominant interests lay elsewhere (at least initially). However, participants' interests were often sufficiently aligned with the desired science outcomes that carefully designed interventions could still leverage them.

Professional science. As described in our findings above, participants had moderate motivation to participate in data collection and limited motivation and capacity to participate in pre- and post- data collection tasks such as study design and data analysis. Individuals may appear disinterested in specific processes and analyses ("low incidence of public engagement in research tasks outside of data collection, management, and analysis" [55]), but their individual and collective motivations are generally still rooted in the (anticipated) relevance of the findings. Capacity for data collection was mixed, but our experience has been that complexity of the equipment itself is perhaps the least of problems. Although individuals may have limited ability to do infrequent complex tasks (as when regulatory workers observe that "citizens can't use complex equipment" [5]), with training they can successfully execute detailed processes [37]. While volunteers often have limited time, attention, and skills, most did in fact execute well when correct procedures and attention to detail were clearly established and reinforced.

The most serious capacity issues related to complex problems and "big picture" thinking – identifying and troubleshooting issues with complicated equipment, designing effective procedures and study plans, ensuring that data aligns with goals, analyzing data, etc. Individuals may not be very good at formulating questions or understanding how to answer them, but that does not mean they do not have their own interests. These interests tended not to be abstract intellectual curiosity or emotional engagement with the environment (as posited by prior research [39]), but were instead concrete and personal.

Crowdsourcing. Citizen participants were capable of performing the extensive data collection envisioned in this narrative, but were not always motivated to do so. Participants were primarily interested in collecting personally relevant data, and had limited incentives to gather data for aggregation or general scientific purposes.

Local action. As noted earlier, participants were not generally motivated to take action (although the organizations were more interested in doing so). Moreover, both the participants and the organizations had fairly limited capacity to leverage the data for advocacy. However, while individuals may not understand precisely how data can be used in science or policy, they were also not entirely comfortable delegating to the scientists which outcomes the data should serve.

As hybrids of the ideal types, most of citizen science genres presume that citizens will readily embrace tasks that are more complex than those our participants tolerated. Designers may want to carefully target a very narrow band of activity (with just the right amount of participation and learning) so that citizens' can "do" science and advocacy with relatively low investment and barriers.

IMPLICATIONS FOR DESIGN

Past research has suggested that the main opportunities for design for citizen science are tools for data-sharing (e.g., [41]) and collaborative sensemaking (e.g., [33]). Given the discussion above, we believe that more basic systems-level questions inevitably play a large role in the viability of participatory sensing systems. From a technical perspective, an ideal sensing system would involve no user intervention (ideal ease-of-use) and would provide individual readings that would be perfectly accurate, precise and repeatable. Yet, in practice, sensing technologies are imperfect, which creates tensions between the goals of the various data-centric practices. As a result, organizers, designers, and scientists must be cognizant of participant motivations and tailor systems and processes accordingly–sometimes in ways that look different from stereotypical formulations of citizen science.

Designing for Professional Science

High per-measurement (datum) quality typically requires higher-cost equipment and/or higher skill on the part of data collectors. As we saw our Citizen Scientists study, both requirements tend to result in fewer measurements. As we have seen, this can lead to reduced spatial and temporal coverage, which can make analysis difficult and reduce participant motivation. As a result, where research must rely on distributed data collection to deliver high-quality data, systems should be designed explicitly to guide and incentivize consistent collection procedures. Tracking provenance and process, supporting in-situ validation, and encouraging participant awareness of analyses can all help ensure data quality remains high [43].

Designing for Crowdsourcing

In theory, a massive data collection campaign can achieve all goals, since large numbers of lower-quality measurements could approximate a more accurate sensing system. However, using this approach, failing to reach a critical data density will also result in a failure to meet all other goals. As we have seen, citizens who spend time and effort to take physical measurements tend to be concerned with the environment around them – their families, their immediate neighborhood, etc. If the measurements taken around the surveyors' areas of interest are very sparse, they may have little value. Even with denser coverage, aggregated measurements may not produce good estimates if sufficient spatial coverage is not achieved. In either case, local action goals will not be met, and meeting science goals will be challenging. This suggests that networks of low-accuracy sensors carried by volunteers (like those deployed in the Sensing Citizens study) may not be an ideal solution for large-scale collection. Instead, resources might be better spent developing low-cost, high-accuracy, fixed sensors, and building dense sensing networks that can meet the needs of both individuals and scientists.

Designing for Local Action

Because environmental problems usually arise from proximity to industrial activity, the citizens involved in action campaigns typically have lower average income and education levels than stereotypical "expert amateurs". As a result, action organizations often value science activities as opportunities for education and community engagement. Given the challenges associated with obtaining high-quality and high-coverage data via citizen collection, citizen action campaigns may benefit from alternative models that reduce the dependency between data collection and engagement. Rather than relying on citizen participants to gather essential baseline data, these organizations may be better off collecting data via other means, and creating opportunities for public participation on top of that data.

CONCLUSION

In this paper, we have examined the citizen science experience from the perspective of citizen participants. Drawing on four interlocking qualitative studies and technological interventions, we have identified a number of ways in which citizen motivations, capacity, and goals are poorly aligned with scientific agendas. The reality on the ground was far from the commonly held view that citizen science systems are a win-win for citizens and science. Rather, data acquisition involves complex multi-dimensional tradeoffs, and efforts that fail to consider these tradeoffs can result in data that is not useful to either citizens or science. We illustrated these tradeoffs with a framework of citizen science genres, which can inform priorities for intervention and invention. In light of these findings, technologies and participatory methods that can bridge the gap between citizen and scientific stakeholders represent a promising goal for citizen science research.

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