Making Air Quality Data Meaningful: Coupling Objective Measurement with Subjective Experience through Narration

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ABSTRACT
Air pollution causes several million deaths every year. Increasing public awareness through the deployment of devices that sense air quality may be a promising step in addressing the problem; however, these wholly objective device measurements may not capture the nuanced and lived experiences people have with the air, which are often colored by perceptions, histories, imaginations, and the sociopolitical context in which people live. The gap between objective environmental *realities* and individuals' subjective *experiences* of the environment may make it difficult to form meaning from data, hindering the positive policy outcomes that they are intended to produce. To bridge this gap, we conducted a two-phase design fieldwork to obtain an empirical understanding of the rich contours of experiences people have with the air and outline design strategies in making air quality data meaningful.

Author Keywords
Air quality, environmental sensing, environmental representation, data narration, experience, sustainable HCI

CCS Concepts
•**Human-centered computing** → **Empirical studies in HCI;** *Interaction design theory, concepts and paradigms;*

INTRODUCTION
The World Health Organization estimates that outdoor air pollution causes over 4.2 million premature deaths each year worldwide, and that 91% of the global population lives in places where the air quality is worse than recommended standards [74]. Over the past decade, a convergence of low-cost sensing technologies and mobile networks presents opportunities for capturing air quality data to facilitate better monitoring of environmental change, promote public health, and assist efforts in sustainable urban planning [5, 18, 20, 37, 41, 50]. Building on this opportunity, researchers have explored strategies for collecting real-time data at high spatial resolutions revealing variations in air quality at the neighborhood or block level [56, 68, 75, 89]; examples include grass-root pollution tracking [19, 34, 41, 94], sensor-enabled mobile phones [47], hand-held monitors [49, 52, 91], sensing wearables [43, 46, 64], sensor modules on vehicles [5, 18, 53, 76, 85], or computational models [20, 37, 100]. The future is pointing towards a world where high-quality, high-resolution data on air quality will be increasingly available and accessible.

Figure 1. A participant maps places with good and bad air in her city.

However, there is a gap between our ability to generate fine-grained measurements of environmental *realities*, and our comparative lack of understanding of how people subjectively make sense of the air through their day-to-day *experiences*. In other words, while a new wave of technologies may reveal peoples' exposure to air pollutants at increasingly hyper-local scales, few works have investigated the full spectrum of peoples' lived-experiences with air pollution, and how these personal experiences affect and are influenced by individuals' subjective perceptions, histories, imaginations, and the sociopolitical context in which they live.

To paraphrase Dourish and Cruz, data do not speak for themselves; they must be narrated [33]. This work addresses the under-explored question of how to narrate environmental data to make them more meaningful. Inspired by previous work [5, 27, 29, 33, 60], we believe that to encourage pro-environmental behaviors through data, we must engage with peoples' lived experiences in our designs, incorporating the nuanced, contextual, subjective, political, and social experiences people have with the air. While we recognize that the boundary between objectivity and subjectivity may be blurry with each lying at one end of a continuum, and that environmental measurement can be subjective when it is narrated in service of political or economic interests, in this work we take a simplified view, treating environmental measurements as objective and peoples' lived experiences as subjective, as they typically fall at the opposite ends of an objectivity spectrum.

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We turn to a fundamental question: what does air quality mean to everyday citizens, and how do we make air quality data more meaningful through design? In pursuit of this inquiry, we conducted two phases of design fieldwork with residents in the greater Seattle area. In the first phase, we combined cognitive mapping with semi-structured interviews to establish an empirical understanding of the full spectrum of experiences people have with the air. We then moved on to explore possible strategies of making air quality data more meaningful through communities co-design workshops. Our results reveal that individuals have different modality preferences and some rely on multiple modes of perception simultaneously (e.g., drawing on the look, feel, temperature, and smell of the air) to perceive air quality. Reflecting on this, we suggest coupling objective measurements with subjective experiences to make environmental data more meaningful. We conclude by outlining possible design strategies for achieving so, including engaging with the sociotechnical context, encouraging reflection and speculation, and incorporating nonhuman stakeholders.

Our contributions are three-fold. First, inspired by the theoretical grounding that data should be narrated, we explore the question of how to make environmental data more meaningful through design. Second, we offer empirical insights into peoples' everyday experiences with the air and what air quality means to them. Finally, we outline both high level design strategies and specific design embodiments that aim at coupling objective environmental measurements with the subjective lived experiences of individuals.

BACKGROUND AND RELATED WORK

Situating this work in the broader context of facilitating change through design, we review existing work on environmental sensing and persuasive technologies. We highlight the need of moving from an objective, rigid representation of environmental data to one that attends to subjective experiences of the individuals and supports open-ended interpretations.

Air Pollution, Public Health, and the Environment

Air pollution is a major public health concern that impacts billions of people and causes millions of premature deaths each year [74]. Potential health effects of air pollution include increased risk of asthma, cardiovascular damage, impacts to the nervous system, and developmental risks to unborn children [45, 78, 79, 82]. High concentrations of air pollution around schools has been linked to increased child absence and poor academic performance [24, 73]. In addition, air pollution also threatens our fragile ecosystem [12, 16, 39, 70]. Sources of air pollution are both natural and artificial, including combustion, industrial and agricultural activities, wildfires, geological processes, and gasses from decomposing waste [2, 58, 84]. In urban environments, air quality varies significantly by location and time, influenced by factors such as terrain, traffic flow, human activity, land use, and weather [56, 75, 89].

Governments around the world have adopted scientific standards to measure pollutant concentrations in the air and communicate the associated health risks to the public. Such indices vary by countries in terms of how they are computed and which pollutants are taken into account [38, 48]. The Air Quality Index (AQI) in the United States tracks the concentration of ground level ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), coarse particulates (PM_{10}), and fine particulates ($PM_{2.5}$), and aggregates their respective concentrations into one numeric index representing the degree of public health risk [3]. Guidelines from the U.S. Environmental Protection Agency on AQI divide the full numeric scale into six coarse-grained, yet easy to interpret levels of risk: "good" (0–50), "moderate" (51–100), "unhealthy for sensitive groups" (101-150), "unhealthy" (151–200), "very unhealthy" (201–300), and "hazardous" (301–500) [3].

Environmental Sensing and Data Narration

The proliferation of personal devices, the expansion of wireless networks, the emergence of low-cost pollution sensors, and the rise of bottom-up initiatives have created a new paradigm in environmental sensing where city dwellers and the urban infrastructure can be activated to gather real-time data. Strategies for increasing the granularity of air quality data include leveraging existing network of mobile and wearable devices [26, 53, 59, 64], involving communities of actors [19, 34, 41, 50], mounting sensors on vehicles and animals [1, 5, 18, 96], building low-cost personal sensors [51, 91], combining various sources of data [42, 99], and developing computational algorithms and models [20, 100].

Following this thread, HCI researchers have also explored a wide range of strategies for visualizing air quality data, such as maps, heatmaps, graphs, charts, and numeric scales [41, 43, 47, 49, 53, 59, 100]. While data visualization renders environmental data legible to everyday citizens, there is still an enormous gap between the measured data and the felt life of individuals. The purely numeric scale of AQI, for example, exhibits little connection to our embodied experiences with the air. As Barone and Eisner argue, "what is hard to experience is a set of numbers. What is comparatively easy to experience is a set of qualities [7, p.xi]," we believe that overly reductive, arbitrary representations of rich environmental phenomena de-contextualizes users from real-life scenarios and obscure the relationship between personal behavior and environmental consequences [27, 29, 51, 62, 71, 80, 97, 98].

More recently, HCI researchers have explored more tangible forms of air quality representation to better connect real-world experiences with tracked results. For example, Hsu et al. recorded time-lapse videos to visualize temporal changes in smoke emissions from a coke plant. A thumbnail generator is embedded in the design to help local residents create animated smoke images as visual evidence of air quality violations for filing petitions to the government [42]. To increase community awareness and facilitate public discussions, Kim et al.'s design communicates concentrations of polluted gases through patterns displayed on a sensor-integrated t-shirt [46]. Following the strategy of broadcasting environmental data through expressive media, Kuznetsov et al.'s balloon installation changes colors to represents different levels of air pollution [50]. Very recently, Torres and Campbell used augmented reality to simulate contaminates in the air; their design helps bring awareness to the public by mapping pollutants that are invisible to naked eyes onto the real-world [93]. Common

across these explorations is that instead of offering a singular, prescribed representation of the environment, subjective experiences and personal goals play a major part in how an individual go about interpreting the data. In this way, data is democratized to support science discovery, civic participation, community advocacy, policy reform, and artistic expressions.

Inspired by these works, we break new ground in engaging with air quality by following Dourish and Cruz's theoretical framing that data "must be narrated—put to work in particular contexts, sunk into narratives that give them shape and meaning, and mobilized as part of broader processes of interpretation and meaning-making [33]." Focusing on sense-making, they note that data "makes sense only to the extent that we have frames for making sense of it," emphasizing the trajectories, temporalities, and cultural grounding within which data are embedded and must be interpreted. Our work employs ethnographic methods to explore these dimensions, and the question of how to narrate environmental data to promote public awareness, civic engagement, and sustainability [33].

Sustainable HCI and Persuasive Sustainability

In response to concerns about climate change, public health, and social equality, HCI researchers have committed to promote sustainability *in* (reducing the material impacts of products) and *through* design (encouraging sustainable behaviors and decisions) [11, 66]. Within the discourse of sustainable HCI, one major thread focuses on persuasive sustainability, which "involves efforts such as monitoring the state of the physical world; managing the direct and indirect impacts of large-scale human enterprises such as agriculture, transport, and manufacturing; and informing individuals' personal choices in consumption and behavior [66, p.19]." While curating and analyzing environmental and behavioral data provide useful insights to raise awareness and assist decision making, many have observed that persuasive sustainability holds the false assumption that "people are rational actors seeking to optimize activity based on what they know" [80, p.20]. Along this line, many have argued that works in persuasive sustainability often disconnect individual behaviors with the politics of space and infrastructure [14, 23, 29, 32, 61, 77].

In addressing these concerns, Brynjarsdottir et al. suggest supporting open-ended interpretation and reflection, allowing users to better establish the connection between data and their lived experiences [14]. In the context of sustainable agriculture, Liu et al. propose using the model of "working with" to replace the paradigm of control posed by persuasive sustainability [60]. Dourish suggests shifting the focus from "connecting people *to* their actions and their consequences" towards "connecting people *through* their actions and consequences" to support meaning making [32, p.7]. Recently, Rapp et al. propose looking beyond the quantified, behavioral manifestations of change to focus on changes that are internal and subjectively defined by the individuals [80]. Collectively, these works surface the need to account for subjective values, experiences, and felt lives to design for persuasion.

In the context of motivating pro-environmental behaviors, we see that challenges lay in representing environmental data in a way that is meaningful to everyday citizens. By meaningful air quality data, we suggest moving away from abstracting and discounting the heterogeneous day-to-day experiences people have with the air to a singular and arbitrary representation of the environment (e.g., AQI). Instead, we propose narrating environmental data by unpacking peoples' meaning-laden experiences with the air.

RESEARCH METHODS

Over the summer of 2019, we conducted two phases of design fieldwork in the greater Seattle area aimed at better understanding the contour of lived experiences people has with the air and air pollution. Our work is inspired by the tradition of ethnography to render the ordinariness "extraordinary and yet, recognizable [4, p.158]." In the first phase, we conducted individual interviews and cognitive mapping sessions to establish an empirical understanding of peoples' firsthand perceptions with the air. Informed by these sessions, we moved on to conduct community co-design workshops to explore design considerations on making air quality data more meaningful.

This work differs from previous studies on participatory sensing in the way that we did not have a fixed design embodiment or probe while engaging with the participants. Instead, to avoid imposing *a priori* beliefs or values of the researchers, we took an open-ended approach with the researchers being the "window to individual subjectivity and collective belonging [65, p.35]": the people whom we engaged with were not passive objects to be investigated but interlocutors who actively shape our understanding or air and air quality [90].

In considering how people might make sense of neighborhood scale air quality data, we recruited participants who live in the same parts of the city so their geographic experiences would overlap. We targeted two different areas of Seattle to also gather a diverse perspective—Capitol Hill, a dense and vibrant urban neighborhood in central Seattle, and Kenmore, a smaller suburban municipality just outside of Seattle.

In both locations, we posted on local civic forums and neighborhood social media groups; our recruitment strategy also varied slightly depending on the geography of the neighborhood. In Capitol Hill, we put flyers on community boards and street posts in dense public areas. In Kenmore, since there were few dense areas to post flyers, we worked with the local government who shared our study information to an email list of residents who were engaged about civic issues. Interested participants were directed to an online screening survey that collected their background information. In total, 179 participants responded to this screening survey, 116 of whom were from Kenmore and 37 were from Capitol Hill (others lived outside our two target area). Participants were selected based on their availability and to balance age and gender as much as possible. To mitigate sampling biases, the participants were subsampled to balance different degrees of awareness/concern about the air, which was self-reported in the screening survey.

In each session, people were given a $50 gift card for their participation. To situate our discussions closer to the community, interviews and workshops were conducted in public spaces within the participants' neighborhoods. Our study was approved by our Institutional Review Board.

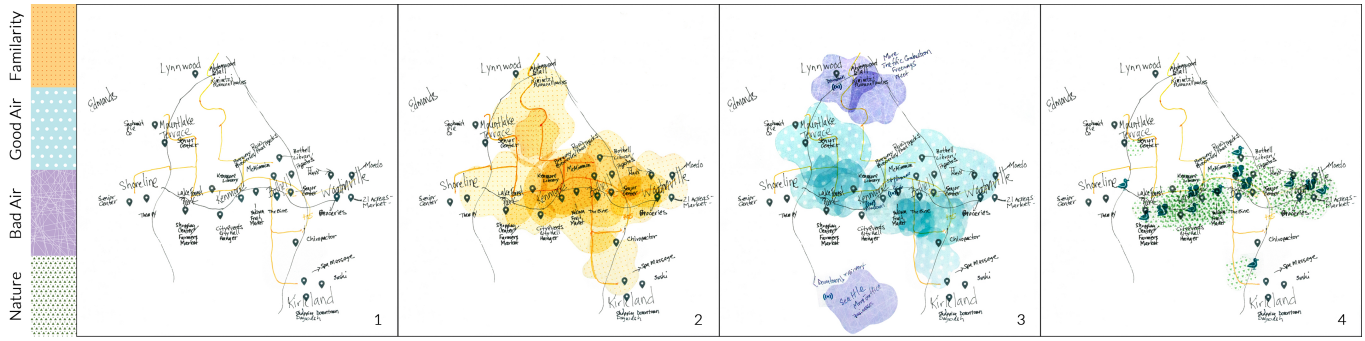

Figure 2. A cognitive map of Kenmore depicting four experiential layers: (1) A *base map* showing major roads, important places, landmarks, overlaid with *common routes*; (2) A *familiarity layer*, where darker regions indicate areas the participant is more familiar with; (3) An *air quality layer*, showing areas where they perceived there to be "good air" and "bad air," where darker regions indicate a higher intensity of perceived goodness or badness; and (4) A *nature layer*, indicating areas where the participant has observed "natural" areas, where darker regions again reflect the intensity of perception.

Cognitive Mapping and Participant Interview

We developed a semi-structured interview protocol and cognitive mapping toolkit to probe into the experiences, perceptions, memories, and folk-theories our participants might have about air quality. Each session lasted 90-120 minutes. The interview began with a discussion of the participant's background, including where they come from, how long they have lived in the neighborhood, and what other places they have lived in the past. Next, we conducted several rounds of cognitive mapping to sensitize the participants' tacit knowledge about the environment, including the built environment, their experience with natural spaces, and their perceptions about air quality in their neighborhood and beyond.

In using cognitive mapping, we were motivated by its strength in externalizing and visualizing aspects of non-verbal or spatial experiences that our participants may not be fully cognizant of *a priori* [10, 22, 50, 63, 72]. As Stanley Milgram writes, "a person may know many things about a city while not being aware that he possesses such knowledge [72, p.96]." Such is the case with perceptions of the air. On the one hand, air is a vital resource essential our very existence; on the other, air is such a ubiquitous part of life that people can be totally oblivious to it. In our study, cognitive mapping activities helped extract narratives that are "more personal and more closely tied to direct experience." [72, p.77]. To tease apart the complex web of relationships between people and their felt lives with the air and the environment around them, we created a tangible mapping toolkit that allowed us to visualize and explore different dimensions of peoples' experiences simultaneously, through a layered mapping technique.

First, participants were asked to draw the contours and boundaries of their neighborhood as they perceive it on a piece of 12" $\times$ 12" white card stock, mirroring traditional cognitive mapping methods [63]. We then augmented this base map with four additional layers that explore different dimensions of their experiences with their neighborhood: (1) common routes they take, (2) their familiarity with different parts of the city, (3) their perceptions of air quality, and (4) their experience with nature. Participants constructed and annotated each of these layers on transparent sheets of 12" $\times$ 12" acetate using markers, tape, icons, and translucent colored patterns printed in acetate in various shapes and sizes. These colored shapes were designed to be stackable to create splotches of varying opacity, which we used to create experiential "heat maps" that express the intensity of their perceptions. We used four colored patterns to map their *familiarity* with different areas (yellow), their perceptions of *good* (blue) and *bad* (purple) air, and their experiences with *nature* (green) (Figure 2). Participants were instructed not to "force" any of these relationships; for example, if they did not perceive any bad air in the region, it was perfectly fine to leave this layer blank.

Our interest was not in the particular details of maps people made, though they may be valuable artifacts for visual analysis in future work. Rather, we used the mapping to structure our conversation on subjective experiences with the air—discussions that may be difficult to approach purely verbally. By layering these semi-translucent maps on top of each other, we bring to the surface any relationships between the air and the environment that may have been latent. The maps also served as a boundary object [40], helping researchers and participants form a stronger connection over subtle concepts through our shared understanding of the local geography.

Throughout the mapping exercises, we guided the conversation with questions designed to provoke noticing through reflection. For example, to nudge the participants to reflect on their past and other people, we asked "*do you recall a time when yourself or the people around you were bothered by the air?*" Calling their attention towards their senses, we asked "*how do you come to notice the bad air? Do you see, smell, or feel anything different than usual?*" We also provoked reflection and speculation by making explicit comparisons, both spatially (e.g., "*If you had three to five air quality sensors, where would you place them on your map and why?*") and temporally (e.g., "*Do you think the air quality in your neighborhood changes throughout different times of a day or different seasons of a year? Is there any pattern that you noticed?*"). As many of the largest contributors to air pollution are a direct result of the day-to-day activities, we also tried to shift the participants' attention between environmental catastrophes and mundane experiences. We did so by going back and forth between interviewing and mapping to facilitate the participants engage in different modes of thinking and reflecting.

Community Co-Design Workshop

Participants of the workshop worked in groups of 3-4 to respond to our two prompts: (1) creating an image collage accompanied by short descriptions responding to the question, *"what does air quality mean to you?"*, and (2) selecting a target user and propose a design that makes air quality data *"meaningful"* to the user. Both prompts are designed to be open-ended, with no definitions given to encourage reflection and discussion. Each workshop session lasted 2 hours.

A variety of materials were given, including 52 images manifesting the various hypotheses people have with the air (both good and bad) we learned at the first study, 10 user profiles for the participants to choose as the target user of their design (they can also choose to create a new profile), 4 design inspirations representing different embodiment of environmental data (e.g., physical, digital, wearable, and system), pile of magazines rich in imaginary but varies in genre, and crafting supplies such as pens, glues, and scissors.

We also created a worksheet with questions that the participants answer to brainstorm and refine design ideas. Questions include: *"what is it," "how does it work,"* and *"what scenario best explains how the user interact with it."* The participants also answered a post-workshop online survey which encourages reflection on the design proposed by their own groups. This survey aims to capture individual values and concerns that might be backgrounded during group exercises.

Participant Demographics, Data, and Analysis

In phase one, we interviewed 12 participants: 6 from Capitol Hill and 6 from Kenmore. There were 7 females and 5 males, and their ages were approximately uniformly distributed across age groups, with two people in their 20s, two in their 30s, two in their 40s, three in their 50s, two in their 60s, and one in their 70s. In the second phase, we conducted two workshop sessions of 19 participants, with 8 people in the Capitol Hill session, and 12 people in the Kenmore session. There were 9 females and 10 males, and ages were diverse, skewing slightly older, with four people in their 20s, one in their 30s, three in their 40s, four in their 50s, six in their 60s, and one in their 70s. Cognitive mapping interview sessions were conducted in pairs by either the first and second authors or the first and third authors, and workshops were collaboratively led by the first and second authors.

We audio recorded the interviews and the independent group discussions at each table in the workshops. The 29 hours of audio were transcribed using an automated service,[1] and the transcriptions were reviewed and corrected collaboratively by the first and second authors. Following other works that engage with each participant's individual (possibly idiosyncratic) perceptions and experiential observations of a collective phenomenon, we analyzed the data through an Interpretative Phenomenological Analysis (IPA) [80, 86]. IPA offers us a framework for documenting and understanding a diversity of approaches and strategies people take to form meaning about the air, given their own personal life experiences. Transcriptions were reviewed independently by the first and second authors, and relevant quotations were thematically interpreted and coded. All researchers met frequently during this process to continually refine our understandings of relevant concepts as we made sense of the data, and the participants' experiences. Sampling people from a variety of age groups and sensitivities towards air quality enabled us to document a wide spectrum of backgrounds, experiences, and personal stories, that helped us contextualize each person's relationship with air and pollution.

[1] http://rev.com

Figure 3. Groups from our workshops in a co-design session exploring design scenarios for their target profiles.

RESULTS

To explore how technological interventions might make air quality data more meaningful, we focused on the lived experiences, tacit knowledge, and any folk-theories individuals have with the air and air pollution. In what follows, we present four themes that emerged from our empirical data. To highlight critical reflection, below we are more interested in *how* people make sense of air and air quality than how representative our participants are; we recognize that larger scale studies are needed to avoid faulty generalizations [65].

Sensory and Emotional Encounters

When asked to describe a moment when they or the people around them were bothered by the air, several participants referred to the regional wildfires in 2017 and 2018: "*I work on the 20th floor and I can see the smoke coming towards me, it's quite scary*" (P1), "*it was just grey and orange. it really was pretty thick and stagnant*" (P10), "*it was like apocalypse. You can't see the sky and you can smell the smoke. I feel like you're inhaling 10 cigarettes per minute. I can't really breath, the air is not coming in and out of my lungs... it feels like you're being suffocated in the city*" (P6).

The physicality of the air—its color, weight, taste, smell, and thickness—plays a major role in how people perceive pollution. Speaking of negative encounters with the air, one mentioned, "*it smells terrible, it's kind of sour, it's not smoky. It's a smell that kinda passes down your nose and launches into your... kinda your vocal cords and your throat... it is a... um, pungent smell and taste. I guess it's a combination, you can almost taste it* (P8)". Presence of air pollution is often perceived by unpleasant physical reactions such as watery eyes, running nose, headaches, chest pain, coughing, sneezing, and breathing difficulties. For participants with asthma or allergies, contaminants in the air can have serious physical impacts. One participant recalled smelling marijuana while at a traffic light:

We stopped at the light and the smell just came in... and I couldn't... like... I couldn't function... I had to pull into a parking lot and then I closed all the windows and put on the air conditioner. And then, um, I use my inhaler until I felt better so that I could drive. (P12)

Compared to bad air, good air seems to have less visual, tactile, and olfactory qualities; instead, participants described fresh air as something that just *feels* good: "*where I can walk and not be wheezing*" (P12), "*I can't feel it in my throat... it feels like it's clear in my head... it feels healthy*" (P10), "*it takes over your mind and then it brings all that peace... Peace is a mental thing but it is also a physical thing, and you don't notice it as much as you normally would*" (P8).

While all participants rely on sensory cues and physical reactions to detect the presence of air pollutants, some noticed that not all air pollutants are perceivable by human senses; some even spoke of an *"invisible danger"* of such toxins: "*you could stand on the street and be exposed to asbestos and not even know it. You know? cuz it doesn't have any... there is no taste, there's no odor, there's nothing... I can put a board with lead paint on it and you wouldn't know what it was*" (P11). Analogously, P8 described the danger of not being aware of air pollution using diabetes as a metaphor:

It's kind of like diabetes, you know? It'll kill you unless you take care of it... that's the same way with air quality. It'll kill you unless you're able to... and you might not even notice that it's happening.

While everyone may hold different subjective definitions about what should be considered an air pollutant—wildfire, traffic, marijuana, pollen, cigarettes, pet hair, car exhaust, bug spray, perfume, just to name a few—people's sensory perceptions play an important role in their overall awareness of the air. A person who pays little attention to the air under ordinary circumstances, may in an instant become acutely aware of it upon sensing something that feels "*wrong.*" When it comes to air quality, put simply, lack of sensory perception contributes to lack of awareness. Here we see both the potential and limitation of human sensory perceptions and subjective experiences.

The Relativity of Space and Time

We noticed that air quality is a relative concept with respect to space and time, and this relativity drives peoples' perceptions, awareness, and concerns about pollution. A workshop participant compared the air quality in Seattle with northern Italy where he grew up smelling pollution in the air, "*I'm actually glad that I'm here. Yes, we had the fires. The fires are bad, but I feel that it was still much better.*" Another remembered forest fire being an annual routine while he was living in Los Angeles: "*You get used to it... you wake up, you have ash on your car and everything. It's just like, oh, it's LA snow.*" Also, another former resident of LA, P6 remembered how bad the air was and blamed it as the cause of her dog's illness:

[My dog] had this horrible disease, Aspergillosis, he almost died. He was living with my parents in LA, and that's where he got the disease. I wonder if the air had something to do with it because I asked my vet in Seattle and they told me that they don't see a lot of that.

For those who have been living in the same neighborhood for an extended period of time, many observed that air quality worsened due to an increase in traffic, construction, and wildfire: "*When I first moved here... I can hike and walk and... not wheezing, I didn't have to use my rescue inhaler. Really wasn't that long ago when you think about it. Seven years, there's big, big changes*" (P12). A workshop participant resonated with this experience saying that she has witnessed a "*total change*" in Capitol Hill over the past 45 years. However, for some, the perspective of time revealed drastic improvements to the air in the region, largely driven by environmental regulations:

The air quality in the Seattle area is way better now than when it was prior to 1970. In 1970 at the base of Madison at 1st Ave in Seattle the asbestos in the air from car breaking exceeded the EPA standards at the time. Smell from the pulp mills in Tacoma, Everett and Puyallup was unbearable. Lake Washington, in 1970, was where all the raw sewerage from the Eastside was drained to. I could go on and on, but the bottom line is was have very good air quality (P11).

Because air is ubiquitous and omnipresent, not everyone is sensitized to stay alert: "*it's just something you live with... in levels of air contamination, I don't think people notice it because we live in the city with the toxins anyway*" (P8). Along this line, P6 recalled visiting her families in Hong Kong and Macau; even though her eyes constantly teared up because of polluted air, locals seemed to be desensitized to her:

It seems like they're used to it and only the visitors are talking about how bad air the air quality is. And it seems like people there, the main thing they say is it's fog. But I googled it and I found that it's actually air pollution.

When being asked to visually represent how air quality varies in the greater Seattle area using our cognitive mapping kit, two participants did not map any bad air, choosing only positive gradients within their mappings. Among them, P6 was comparing Seattle air with air in the other places where she has lived or visited. The other participant described how challenging going outdoors was for someone who was born with asthma, "*I've been in this area since 67... I can tell you that when I first moved here... you had to be careful where you went if you had asthma because it was bad*" (P11). He continued, "*from my point of view, the air, even with all those things going on, it was way better than it was in other places. In Los Angeles, you can't see across the street, I mean it was bad.*"

Theses narratives highlights both the importance of reflection in driving awareness and perceptions of the air, but also the subjectivity inherent in reflection, as each person's subjective comparison between space and time colors their perceptions of the present in unique and biased ways.

United We Stand

To understand what air quality means to people, as a warming up exercise, we asked all workshop participants to create a visual representation and a short description to communicate their perception of air quality. One participant cut out a black and white image showing people standing hand-in-hand by a

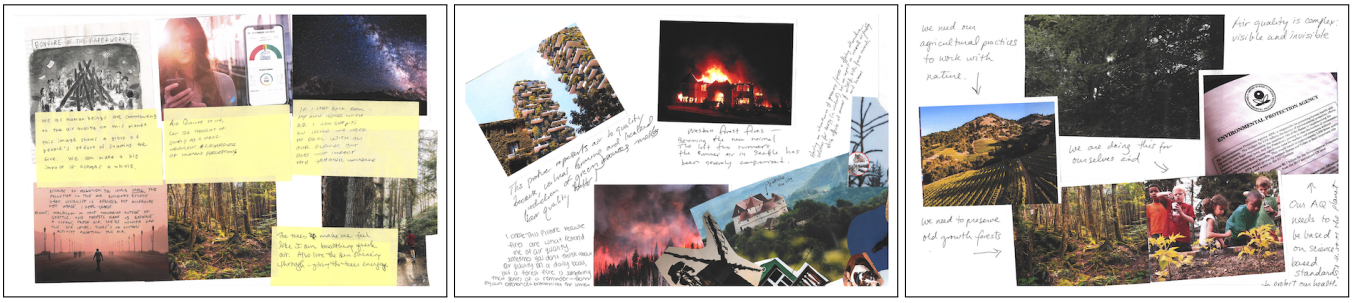

Figure 4. Three collages made by workshop participant groups answering the question "*what does air quality mean to you?*"

bonfire (see Figure 4, left). Her idea was that if humans made air pollution together, we can fix it together. In her words:

> *I feel like we can make a bigger impact when we work together. When I see this image, I see that these people, they probably make the bonfire... you know? like they gathered the woods as a group and then they're gonna get rid of the fire as a group. So it's kind of like a teamwork.*

There is a strong sense of "togetherness" in her narrative which, brings hope to a dark time. To others, the concept of togetherness is further extended to the relationship between humans, animals, and plants. One made a collage by gluing several images together, including a house, a castle in the forest, a windmill, a dog, a hawk, a pig family, and a lynx (see Figure 4, middle). The description went: "*having an abundance of greenery + offering alternative solutions for energy (i.e., windmill) has an impact on overall air quality which affects all members of wildlife, birds, farm animals, and humans*." Here, the sense of togetherness evoked both hope and responsibility.

Similarly, one workshop group had prolonged conversations on how humans and nature are interdependent. Starting from a photo of a vineyard: "*this is technology working with nature. I mean you can't grow crops without technology and being mindful of nature if it is for the long term.*" He continued,

> *How are bananas grown? Bees and birds do not pollinate bananas. Bats do, so you need bats, so you can't destroy the bats and their habitat and what they're eating, because other than that, you're not going to have bananas. It's like I grew a lot of vegetables and other plants. I grow things to bring in beneficial insects so they can pollinate my other plants... Everything has to work together. You just can't take one piece and say that's it.*

The collage this group made captured different aspects of air quality and exemplified (see Figure 4, right), in their words, how everything has "*to work as a whole.*" They chose a photo that depicts a forest because it was "*emblematic of the complexity of air quality*." They also included a photo of an EPA document: "*I like the idea of including the EPA because they have established science-based standards.... well, as the minimum standards for government is to keep us safe.*"

The image collages and narratives from our participants illustrate the notion of collaboration as an important pathway to address environmental crisis. Bringing the conversation back to the forest fires in the past two years, participants recollected how the fires in Oregon and British Columbia had drastic impacts on the air quality in the greater Seattle area, they said, "*you really can't put a blanket at the border and stop it... they [the fires] have no respect for borders anyway.*"

Science as The Bottom Line

When avoiding dirty air is not always an option for urban dwellers, many participants turn to science and technology to stay alert of what is happening in the environment. The value of equipping air quality sensors is specifically highlighted when pollutants are not perceivable by human senses: "*unless you up your little machines around and identify it, it's just something you live with*" (P8). P11 recalled that soldiers were all rationed cigarettes during World War Two and the Korean War until the 70s when scientists finally recognized that cigarettes were hazardous to human health. As a big advocate of science, he said,

> *Science is... helped us become more aware of what all these issues are. And you know, it takes people time to make this all happen. And then they start doing more research and find out things like creosote. Nobody knew that was hazardous. Asbestos, didn't know that was hazardous... all kinds of things like that. We just didn't know and they'd been around forever.*

Many who took part in the co-design workshop believed that more scientific data is needed to help us identify and avoid the unknown dangers. To do so, two groups of participants brainstormed strategies to help increase the granularity of air quality sensors. Among them, one group came up with the concept of a portable "array of sensors" that can be turned into a clip, a bracelet, or a docking station. Another group proposed an app that incentivizes users to deploy air quality sensors through a points reward system.

While everyone held positive attitudes toward science and technology, a few brought up that science can be limited in some scenarios. For example, complex issues like social justice and behavior change might not be answered just by putting a few sensors out in the environment. One participant wrote in his post-workshop survey, "being aware, is one thing. Doing somethings that might change the situation, is an emotional response to that stimulation" (P8). Another workshop participant took it to the extreme by role playing a volcano. He said, "*what about like... like a volcano, like a volcano doesn't care. And a volcano is going to make air pollution, but it doesn't see it as poor air quality...*" While this is a puzzling and unusual

narrative, we interpret his use of volcano as an analogy for those who do not care whether the air quality is good or bad. To paraphrase, this statement conveys that data is only relevant to people who care; for the rest, data is meaningless.

Our data suggest changing behavior requires more than awareness: some might simply have no means to choose between different options. For example, P5 told us that he won't change his commute route just to avoid air pollution, despite being concerned: "*I mean, air is just... I can't do anything about it... maybe I'll wear a mask? well, you just accept the reality... convenience of getting from point A to point B as fast as possible usually outweighs everything else... it's a sad but true.*" When asked to imagine a time when hyper-local air quality data is commonly available, he paused, telling us that he doesn't know what to do about that information:

> *If data starts coming out in the neighborhoods... um, I don't know... that could be a weird thing... Let's say you live in south Seattle and the air is bad... I'm not sure how that would affect that sort of stuff.* (P5)

These narratives suggest that while objective environmental data is imperative for improving air quality, designers must also embrace subjectivity in order to better understand people, their life experiences, and world views, if we ever hope to address such complex and "wicked problems" [15, 30].

DISCUSSION

There is rising world-wide concern regarding air pollution and other forms of environmental crises, to the point where civilization collapse and global extinction are plausible outcomes [55, 57, 92]. In response, an on-going body of research focuses on motivating sustainable behaviors through persuasive technology. In this section, we connect our findings to suggest opportunities and considerations for future research in sustainable HCI and environmental sensing, and to guide critical re-imaginings of environmental data representation to support sustainable behaviors through technological interventions.

Coupling Measurements and Experiences

In the context of measuring and communicating air quality, we have argued that *environmental data is not enough*, referring specifically to the data generated by electronic sensors that show objective (but possibly meaningless) representation of the air. First, such environmental data reduce the complexity of urban environment to a limited set of predetermined parameters according to the sensors' tracking capabilities. As our results suggest, such reductive measures fail to capture the contours of personal experiences with the air. In addition, environmental data needs to be situated and narrated to have meaning, but a purely numeric representation of air quality does not offer much for sense-making on its own.

While subjective experience plays a major role in constructing meaning about air and air pollution, subjectivity can also be limiting and misleading. For example, our study showed that while people often rely on sensory cues to detect pollution, toxins such as carbon monoxide, asbestos, or lead cannot be perceived by the human senses. Additionally, almost all participants explicitly associated good air with nature while describing pollution as being entirely human in origin.

> *[air pollution is] anything that doesn't come from quote-un-quote "nature." Um... so like pollen and things like that, I wouldn't consider pollution. Like that's normal. That's fine. I don't know if I would consider wildfires pollution cuz I do think they're natural that we do need a certain amount of that.* (P2)

However, poor air quality can have natural origins (e.g. smoke, pollen), revealing a disconnection between objective measurement and subjective experience. On the other hand, while objective measurements provide a ground truth that renders "invisible dangers" visible, purely objective designs may lack opportunities for meaning making that is essential for behavior change [6, 69, 80, 83]. Following this, we suggest coupling objective measurement and subjective experience to narrate air quality data. Our empirical data contains rich verbal and visual vocabularies people use to depict air. Some narratives and descriptions of wildfire included: *"smelt like burnt barbeque"* (P6), *"smelt like a campfire"* (P9), *"haze over"* (P7), *"thick and stagnant"* (P12), *"smoke rolling around"* (P1), *"grey and orange"* (P10), *"sky is red"* (P11), *"see lots of patients coming"* (P2), *"lung tightened"* (P3), *"tired and sluggish"* (P1).

One example of coupling objective measurements with subjective descriptions of air is to create a crowd-sourced system that collects verbal narratives or image collages to provide a more contextualized representation and embodied understanding of air quality. Conversely, another opportunity for future research is to understand how the subjective experience of the air might be informed by objective data from sensors. With rapid technological and design innovations in this space combining large-scale air quality data with corresponding fieldwork, we believe that we are not too far from answering this question.

Engaging with the Sociopolitical Context

Air quality is an immensely complex concern that touches on numerous facets of society including urban planning, transportation, economic development, policy, public health, sociodemographic, environmental sustainability, and others. These intricate, sociopolitical dimensions of air quality present a web of challenges that designers must grapple with if we are to push towards positive changes through design.

For example, during our study, we observed that while many participants believed that having high spatial resolution air quality data might help guide them to take protective actions, several participants noted that having the choice to avoid polluted air is a privilege. During the cognitive mapping activity, P1 nicknamed a bucolic area near a conservatory with its old-growth tree-covered streets as the *"old Capitol Hill."* To her, this is an area with *"rich people air,"* out of reach to the underprivileged. In fact, this idea of *clean air as a luxury* was pervasive throughout our interviews.

> *I'm inclined to believe that people who are much more economically challenged, this is going to be the last thing they're gonna think about. I know a lot of people that are homeless... um, they're not gonna think about this... they have other issues going on...* (P5)

These discussions emphasize the inherent spatiality of air quality, and the underlying politics and power dynamics that shape and control that spatiality [35, 67].

As the above examples illustrate, air quality is a "wicked problem" that is unlikely to be resolved through technical means alone [15], as there is no simple solution to improve the air, but rather a series of negotiations, trade-offs, and conflicts. During a co-design workshop, one participant reflected on her horrifying experiences with wildfire in previous years,

> *I was just dreading this upcoming Summer thinking that it would happen again. And then you feel sort of selfish because we're not having the fires, right, and I'm only seeing it from my little viewpoint. What about all those people losing their homes and who are closer to the fire?*

This narrative provides a glimpse into the opposite side of the tracks from areas of *"rich people air."* Many people don't have a choice but sleep on the streets during forest fires. Speaking to this, P2 recalled seeing a drastic increase in patients who suffered from home insecurity visiting the hospital during the wildfire period, "*because they can't crash in their cars.*"

Following Dombrowski et al. [30], we argue that air quality is a social justice issue that requires a new *"mode of knowing and relating, and sensitivities to inequality and marginalized voices"* [30, p.657]. While there is no easy answer considering the equity of having access to clean air, this did not stop our participants from designing for the underprivileged. During the co-design workshop in Kenmore, one group chose to design for "*an 'everyday person' who may not have the time and/or resources to pursue air quality technology on her own but should have access nevertheless.*" To design for someone who they considered to be "*busy and perhaps not affluent*", and "*maybe hearing impaired*" due to aging, they believed that the design should be affordable and effortless to use.

We call to shift our attention from an emphasis on technological progress towards strengthening commitments to ethics and politics [30, 32]. Attending to the sociopolitical context of air quality means to acknowledge the inherent tension and power differences both in society and in the technologies we build. For example, instead of showing AQI levels on a map without context, we can surface the inequalities in the production or and exposure to pollutants, or reveal how certain populations are more vulnerable to environmental realities while highlighting how changes in individual behaviors might have strong impacts to others. By enabling activism through design and designing for those who do not have a voice or the means to participate, all of humanity can benefit.

Encouraging Reflection and Speculation

We have argued that purely objective measurements of a quantified environment abstracts and decontextualizes air quality from the embodied, lived, and felt experiences people have with air, creating a barrier to forming meaning from data. One way of bridging this gap is to create systems that work *with* users [60] by creating designs that encourage self-reflection and open interpretation, instead of offering prescriptive views that might not reflect individuals' worlds [14]. But how exactly might we achieve that through design?

To begin, it is difficult to study implicit knowledge that an individual might not even be aware of, let alone be able to explicitly communicate. One of the main challenges we faced in understanding and unpacking the perceptions people have with the air was getting our participants to reflect and externalize—"to move through very vague, holistic, and bodily felt forms outward toward delineated and explicit symbols" [17, p.168]. Informed by critical qualitative methods and literature on reflection, our entire research protocol is designed to get people to reflect about the air [8, 17, 81]. During the interview, when our participants were asked to describe a moment when they or the people around them were bothered by the air, most started by talking about the regional wildfires happened in the past two years. With wildfires being such a catastrophic and alienating encounter for Seattle residents, this was not too surprising; but such extraordinary events are insufficient for understanding how perceptions and subjectivity are formed through everyday, mundane interactions with the air.

To elicit reflections on the seemly trivial incidences, our research protocol involved a wide range of stimulus as probing materials. We went back and forth between textual (survey, design descriptions, annotations), verbal (interview, group discussions), tactile (drawing, mapping, annotating, and designing), and visual (layering maps, narrating images, making collages, and sketching ideas) forms of communication, each medium serving as prompt shifting experiences in scale, time, location, meaning, and interpretation. During the study, many participants had an "aha" moment, in realizing their own hypotheses, biases, and (un)awareness: *"come to think about it, I think sometimes just the noise quality makes me perceive that air quality is worse"* (P2), *"I noticed that it felt fresher down there. I didn't notice that... come to think of it, but wasn't like I thought about it much while I was there"* (P10). The cognitive maps, image collages, and design worksheets were simultaneously boundary objects that help establish a shared understanding of the local geography and material enactments that encourage reflection-in-action.

In addition, our interview protocol also prompted participants to imagine and to speculate on air. During the interviews, we asked our participants hypothetical questions such as *"where would you place the sensors if we give you 3-5 of them?"*, *"what if the data tells you that the air quality in the forest is no better than in the city center?"*, and *"how does it make you feel if you learn that rich people have better air quality?"* These questions often made our participants pause and appreciate the complexity of air quality. In other words, our study showed that speculation plays a critical role in reimaging what a meaningful environmental representation might be.

Taking into account individual subjectivity, one strategy to design for speculation is to design for open interpretation. For example, inspired by the correlation between noise quality and air quality mentioned by P2, we can create designs that communicate air quality through acoustic representations, varying in tempo, timber, pitch, and volume. We suspect, designs that encourage multiplicity in meaning-making will make the user pause and puzzle; and it is through the process of speculation, attunement, and making connections between personal

experiences and environmental representation that an individual forms meaning from the data. Designs that employ an artistic representation of the environmental data help "evoking meanings, rather than denoting them [54, p.34]." If we avoid forcing a prescribed definition or authoritative claim onto how data should be understood, we might better engage people to form meaning from data in a personal way.

Incorporating Nonhuman Stakeholders

While many discussions centered around how air quality might affect the health of themselves and the people around them, several groups voiced concerns for the less-privileged, who "might be unable to voice their concern and need for care" [25, p.52]. In thinking of who is left in the current landscape of technological interventions, our participants reminded us to look around. Describing how she was bothered by the dusts generated from an on-going construction, P12 noticed that animals seem to suffer even more:

> *There's like bears running around on the golf course. There's coyotes, there's bobcats... there's all kinds of animals that I never saw seven years ago. You've got to go out to the woods if you wanted to see them. right? But they're being driven from their habitats.*

Within the community of sustainable HCI, there is an emergent thread of research that draws concepts in posthumanism, suggesting "de-centering humans" in design as a response to rising concern of climate change and environmental crisis [21, 28, 36, 55, 57, 61, 87]. By de-centering humans, the discourse of nonanthropocentric HCI does not suggest to simply negate humans; on the contrary, it is about foregrounding the sense of "togetherness," using our participants' words. We see observations reflecting the interdependency between human and nature throughout our empirical data. For example, almost all participants drew connections between good air and the presence of nature; arguing that protecting ecosystems and natural environment is necessary in bettering air quality. A group of workshop participants further brought out the notion of *"technology working with nature"* as the key for achieving long-term sustainability and well-being (see previous section). The notion of working *with* is important, pointing at a symbiotic relationships aiming towards mutual beneficial ends.

So how might we incorporate nonhuman stakeholders in reimagining environmental sensing? Of course, we can design *for* nonhuman animals and plants such as improving air quality in wildlife habitats or providing alerts to warn and evacuate fauna when forest fire occurs. However, feminist STS scholar Maria Puig de la Bellacasa reminds us that caring for the others is more than just an ethical concern but also involves interspecies relationship building and the transformation of the self. She writes, "thinking-with nonhumans should always be a living-with, ware of troubling relations and seeking a significant otherness that transforms those involved in the relation and the world we live in." [25, p.83].

Following Puig de la Bellacasa, the effort of thinking-with can be supported through the practice of defamiliarization, which involves shifting our attention to notice what matters to our nonhuman significant others [31, 95]. One way of doing so is through disengaging from our dominate model of knowledge production [9, 13]. For example, we can build cross species environmental sensing platforms that animals and plants are involved "in the creation and representation of our environmental commons." [44, p.219]. We have seen initiatives that leverage the mobility of birds to gather air quality data [96], designs that integrate mussels' high sensitivity to water pollutants to make legible environmental parameters that we have not known or could not yet measured [44], and works that couple biosensing and natural language processing techniques to enable two-way conversation between humans and plants [88]. Following this thread, we are no longer design *for* but design *with* nonhuman stakeholders. In fact, there is perhaps more for us to learn than to service. For example, to avoid oversimplifying the complex and ever-changing urban ecosystem to a few parameters, we can build computational models that learn from natural intelligence by observing, tracking, and understating how environmental data affect animals, plants, and microorganisms in the biosphere [44].

CONCLUSION

Through 12 semi-structured interviews and cognitive mappings sessions, and 2 community co-design workshops, we ground our research on the concept of data narration to reimagine environmental data representation and support meaning-making. We build on previous work in environmental sensing, but take an open-ended approach to studying how people perceive air quality using the full spectrum of their perceptions. We illustrate limitations of overemphasizing objective measurements or subjective experiences and outline strategies for making environmental data meaningful. The design directions include engaging with the sociopolitical context (to attend to issues of social justice and advocate change through design), encouraging reflection and speculation (to support open-interpretation and cultivate new sensory engagements), and integrating nonhuman stakeholders (to expand our current understanding of the environment). While we are still far from solving the environmental crisis, our study provides a critical re-interpretation of environmental representation and persuasive sustainability which helps us see challenges in a new light and ask better questions considering ways of moving forward.

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REFERENCES

[1] 2019. The Copenhagen Wheel. `http://senseable.mit.edu/copenhagenwheel/`. (2019). Accessed: 2019-9-12.

[2] European Environment Agency. 2019. Air Pollution Sources. `https://www.eea.europa.eu/themes/air/air-pollution-sources`. (2019). Accessed: 2019-9-15.

[3] U.S. Environmental Protection Agency. 2014. Air Quality Index: A Guide to Air Quality and Your Health.

https://www3.epa.gov/airnow/aqi_brochure_02_14.pdf. (2014). Accessed: 2019-9-10.

[4] Bob Anderson. 1997. Work, Ethnography and System Design. *The encyclopedia of Microcomputing* 20 (1997), 159–183.

[5] Paul M Aoki, RJ Honicky, Alan Mainwaring, Chris Myers, Eric Paulos, Sushmita Subramanian, and Allison Woodruff. 2009. A vehicle for research: using street sweepers to explore the landscape of environmental community action. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 375–384.

[6] Jeffrey Bardzell and Shaowen Bardzell. 2015. The user reconfigured: on subjectivities of information. In *Proceedings of The Fifth Decennial Aarhus Conference on Critical Alternatives*. Aarhus University Press, 133–144.

[7] Tom Barone and Elliot W Eisner. 2012. *Arts Based Research*. Sage.

[8] Eric PS Baumer, Vera Khovanskaya, Mark Matthews, Lindsay Reynolds, Victoria Schwanda Sosik, and Geri Gay. 2014. Reviewing reflection: on the use of reflection in interactive system design. In *Proceedings of the 2014 conference on Designing interactive systems*. ACM, 93–102.

[9] Genevieve Bell, Mark Blythe, and Phoebe Sengers. 2005. Making by making strange: Defamiliarization and the design of domestic technologies. *ACM Transactions on Computer-Human Interaction (TOCHI)* 12, 2 (2005), 149–173.

[10] Frank Bentley, Henriette Cramer, William Hamilton, and Santosh Basapur. 2012. Drawing the city: differing perceptions of the urban environment. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1603–1606.

[11] Eli Blevis. 2007. Sustainable interaction design: invention & disposal, renewal & reuse. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM, 503–512.

[12] Roland Bobbink, Michael Hornung, and Jan GM Roelofs. 1998. The effects of air-borne nitrogen pollutants on species diversity in natural and semi-natural European vegetation. *Journal of ecology* 86, 5 (1998), 717–738.

[13] Rosi Braidotti. 2017. Four Theses on Posthuman Feminism. In *Anthropocene feminism*, Richard Grusin (Ed.). University of Minnesota Press, Chapter 2, 21–48.

[14] Hronn Brynjarsdottir, Maria Håkansson, James Pierce, Eric Baumer, Carl DiSalvo, and Phoebe Sengers. 2012. Sustainably unpersuaded: how persuasion narrows our vision of sustainability. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 947–956.

[15] Richard Buchanan. 1992. Wicked problems in design thinking. *Design issues* 8, 2 (1992), 5–21.

[16] Andrzej Bytnerowicz, Kenji Omasa, and Elena Paoletti. 2007. Integrated effects of air pollution and climate change on forests: A northern hemisphere perspective. *Environmental Pollution* 147, 3 (2007), 438–445.

[17] Francis Phil Carspecken. 2013. *Critical ethnography in educational research: A theoretical and practical guide*. Routledge.

[18] Tusher Chakraborty, Taslim Arefin Khan, Mahmuda Naznin, Chowdhury Sayeed Hyder, and ABM Islam. 2016. What We Breathe As We Commute: From the Perspective of a Developing Country. In *Proceedings of the 7th Annual Symposium on Computing for Development*. ACM, 19.

[19] Ling-Jyh Chen, Wuulong Hsu, Ming Wei Cheng, and Hu Cheng Lee. 2016. LASS: A location-aware sensing system for participatory PM2. 5 monitoring. In *14th Annual International Conference on Mobile Systems, Applications, and Services, MobiSys 2016*. ACM.

[20] Xinlei Chen, Xiangxiang Xu, Xinyu Liu, Shijia Pan, Jiayou He, Hae Young Noh, Lin Zhang, and Pei Zhang. 2018. Pga: Physics guided and adaptive approach for mobile fine-grained air pollution estimation. In *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers*. ACM, 1321–1330.

[21] Rachel Clarke, Sara Heitlinger, Ann Light, Laura Forlano, Marcus Foth, and Carl DiSalvo. 2019. More-than-human participation: design for sustainable smart city futures. *interactions* 26, 3 (2019), 60–63.

[22] Justin Cranshaw, Raz Schwartz, Jason Hong, and Norman Sadeh. 2012. The livehoods project: Utilizing social media to understand the dynamics of a city. In *Sixth International AAAI Conference on Weblogs and Social Media*.

[23] Dana Cuff, Mark Hansen, and Jerry Kang. 2008. Urban sensing: out of the woods. *Commun. ACM* 51, 3 (2008).

[24] Janet Currie, Eric A Hanushek, E Megan Kahn, Matthew Neidell, and Steven G Rivkin. 2009. Does pollution increase school absences? *The Review of Economics and Statistics* 91, 4 (2009), 682–694.

[25] María Puig de La Bellacasa. 2017. *Matters of care: Speculative Ethics in More Than Human Worlds*. University of Minnesota Press.

[26] Srinivas Devarakonda, Parveen Sevusu, Hongzhang Liu, Ruilin Liu, Liviu Iftode, and Badri Nath. 2013. Real-time air quality monitoring through mobile sensing in metropolitan areas. In *Proceedings of the 2nd ACM SIGKDD international workshop on urban computing*. ACM, 15.

[27] Catherine D'Ignazio and Lauren F Klein. 2020. *Data feminism*. MIT Press.

[28] Carl DiSalvo and Jonathan Lukens. 2011. Nonanthropocentrism and the nonhuman in design: possibilities for designing new forms of engagement with and through technology. *From Social Butterfly to Engaged Citizen Urban Informatics, Social Media, Ubiquitous Computing, and Mobile Technology to Support Citizen Engagement* (2011).

[29] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. 2010. Mapping the landscape of sustainable HCI. In *Proceedings of the SIGCHI conference on human factors in computing systems*. ACM, 1975–1984.

[30] Lynn Dombrowski, Ellie Harmon, and Sarah Fox. 2016. Social justice-oriented interaction design: Outlining key design strategies and commitments. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. 656–671.

[31] Haraway Donna. 2008. When species meet. (2008).

[32] Paul Dourish. 2010. HCI and environmental sustainability: the politics of design and the design of politics. In *Proceedings of the 8th ACM conference on designing interactive systems*. ACM, 1–10.

[33] Paul Dourish and Edgar Gómez Cruz. 2018. Datafication and Data Fiction: Narrating Data and Narrating with Data. *Big Data & Society* 5, 2 (2018).

[34] Prabal Dutta, Paul M Aoki, Neil Kumar, Alan Mainwaring, Chris Myers, Wesley Willett, and Allison Woodruff. 2009. Common Sense: Participatory Urban Sensing Using a Network of Handheld Air Quality Monitors. In *Proceedings of the 7th ACM conference on embedded networked sensor systems*. ACM, 349–350.

[35] David Featherstone and Joe Painter. 2013. Spatial Politics. *Essays for Doreen Massey* (2013).

[36] Laura Forlano. 2016. Decentering the human in the design of collaborative cities. *Design Issues* 32, 3 (2016), 42–54.

[37] Daniela Azumendi Gongora, Juan Jose Diaz Baquero, Juan Felipe Franco, and Ivan Mura. 2018. Simulation to Predict Cyclists' Exposure to Air Pollution Along Bikeways. In *2018 Winter Simulation Conference (WSC)*. IEEE, 2387–2398.

[38] Sunil Gulia, SM Shiva Nagendra, Mukesh Khare, and Isha Khanna. 2015. Urban air quality management-A review. *Atmospheric Pollution Research* 6, 2 (2015), 286–304.

[39] Allen S Heagle, Denis E Body, and Walter W Heck. 1973. An open-top field chamber to assess the impact of air pollution on plants 1. *Journal of Environmental Quality* 2, 3 (1973), 365–368.

[40] Kathryn Henderson. 1991. Flexible sketches and inflexible data bases: Visual communication, conscription devices, and boundary objects in design engineering. *Science, Technology, & Human Values* 16, 4 (1991), 448–473.

[41] Yen-Chia Hsu, Jennifer Cross, Paul Dille, Michael Tasota, Beatrice Dias, Randy Sargent, Ting-Hao Kenneth Huang, and Illah Nourbakhsh. 2019. Smell Pittsburgh: community-empowered mobile smell reporting system. In *Proceedings of the 24th International Conference on Intelligent User Interfaces*. ACM, 65–79.

[42] Yen-Chia Hsu, Paul Dille, Jennifer Cross, Beatrice Dias, Randy Sargent, and Illah Nourbakhsh. 2017. Community-empowered air quality monitoring system. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 1607–1619.

[43] Ke Hu, Yan Wang, Ashfaqur Rahman, and Vijay Sivaraman. 2014. Personalising pollution exposure estimates using wearable activity sensors. In *2014 IEEE ninth international conference on intelligent sensors, sensor networks and information processing (ISSNIP)*. IEEE, 1–6.

[44] Natalie Jeremijenko and Hannah Dehlia. 2017. Natalie Jeremijenko's New Experimentalism. In *Anthropocene Feminism*, Richard Grusin (Ed.). University of Minnesota Press, Chapter 9, 197–219.

[45] Marilena Kampa and Elias Castanas. 2008. Human health effects of air pollution. *Environmental pollution* 151, 2 (2008), 362–367.

[46] Sunyoung Kim, Eric Paulos, and Mark D Gross. 2010. WearAir: expressive t-shirts for air quality sensing. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction*. ACM, 295–296.

[47] Yongsung Kim, Julien Eberle, Riikka Hanninen, Erol Can Un, and Karl Aberer. 2013. Mobile observatory: an exploratory study of mobile air quality monitoring application. In *Proceedings of the 2013 ACM conference on Pervasive and ubiquitous computing adjunct publication*. ACM, 733–736.

[48] Karolina Kuklinska, Lidia Wolska, and Jacek Namiesnik. 2015. Air quality policy in the US and the EU–a review. *Atmospheric Pollution Research* 6, 1 (2015), 129–137.

[49] Stacey Kuznetsov, George Davis, Jian Cheung, and Eric Paulos. 2011a. Ceci n'est pas une pipe bombe: authoring urban landscapes with air quality sensors. In *Proceedings of the sigchi conference on human factors in computing systems*. ACM, 2375–2384.

[50] Stacey Kuznetsov, George Noel Davis, Eric Paulos, Mark D Gross, and Jian Chiu Cheung. 2011b. Red balloon, green balloon, sensors in the sky. In *Proceedings of the 13th international conference on Ubiquitous computing*. ACM, 237–246.

[51] Stacey Kuznetsov, Scott E Hudson, and Eric Paulos. 2014. A low-tech sensing system for particulate pollution. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*. ACM, 259–266.

[52] Stacey Kuznetsov and Eric Paulos. 2010. Participatory sensing in public spaces: activating urban surfaces with sensor probes. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems*. ACM, 21–30.

[53] Jorge Lanza, Luis Sánchez, Luis Muñoz, José Antonio Galache, Pablo Sotres, Juan R Santana, and Verónica Gutiérrez. 2015. Large-Scale Mobile Sensing Enabled Internet-of-Things Testbed for Smart City Services. *International Journal of Distributed Sensor Networks* 11, 8 (2015).

[54] Patricia Leavy. 2015. *Method Meets Art: Arts-Based Research Practice*. Guilford Publications.

[55] Ann Light, Alison Powell, and Irina Shklovski. 2017. Design for existential crisis in the anthropocene age. In *Proceedings of the 8th International Conference on Communities and Technologies*. ACM, 270–279.

[56] Gang Lin, Jingying Fu, Dong Jiang, Wensheng Hu, Donglin Dong, Yaohuan Huang, and Mingdong Zhao. 2014. Spatio-temporal variation of PM2. 5 concentrations and their relationship with geographic and socioeconomic factors in China. *International journal of environmental research and public health* 11, 1 (2014), 173–186.

[57] Jen Liu, Daragh Byrne, and Laura Devendorf. 2018a. Design for Collaborative Survival: An Inquiry into Human-Fungi Relationships. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM.

[58] Jun Liu, Denise L Mauzerall, Qi Chen, Qiang Zhang, Yu Song, Wei Peng, Zbigniew Klimont, Xinghua Qiu, Shiqiu Zhang, Min Hu, and others. 2016. Air pollutant emissions from Chinese households: A major and underappreciated ambient pollution source. *Proceedings of the National Academy of Sciences* 113, 28 (2016), 7756–7761.

[59] Liang Liu, Wu Liu, Yu Zheng, Huadong Ma, and Cheng Zhang. 2018b. Third-eye: a mobilephone-enabled crowdsensing system for air quality monitoring. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 1 (2018), 20.

[60] Szu-Yu (Cyn) Liu, Shaowen Bardzell, and Jeffrey Bardzell. 2018. Out of Control: Reframing Sustainable HCI using Permaculture. In *Proceedings of the 2018 Workshop on Computing within Limits*. ACM.

[61] Szu-Yu (Cyn) Liu, Shaowen Bardzell, and Jeffrey Bardzell. 2019. Symbiotic Encounters: HCI and Sustainable Agriculture. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM.

[62] Dan Lockton, Delanie Ricketts, Shruti Aditya Chowdhury, and Chang Hee Lee. 2017. Exploring qualitative displays and interfaces. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. 1844–1852.

[63] Kevin Lynch. 1992. *The Image of The City*. MIT press.

[64] Balz Maag, Zimu Zhou, and Lothar Thiele. 2018. W-air: Enabling personal air pollution monitoring on wearables. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 1 (2018), 24.

[65] D Soyini Madison. 2020. *Critical Ethnography: Method, Ethics, and Performance*. Sage Publications.

[66] Jennifer C Mankoff, Eli Blevis, Alan Borning, Alan Borning, Batya Friedman, Susan R Fussell, Jay Hasbrouck, Allison Woodruff, and Phoebe Sengers. 2007. Environmental sustainability and interaction. In *CHI'07 extended abstracts on Human factors in computing systems*. ACM, 2121–2124.

[67] Doreen Massey. 1992. Politics and space/time. *New left review* (1992), 65–65.

[68] Helmut Mayer. 1999. Air pollution in cities. *Atmospheric environment* 33, 24-25 (1999), 4029–4037.

[69] John McCarthy and Peter Wright. 2007. *Technology as Experience*. MIT press.

[70] SB McLaughlin. 1985. *Effects of Air Pollution on Forests: A Critical Review*. Technical Report. Oak Ridge National Lab., TN (USA).

[71] Katherine Jane McLean. 2019. *Nose-first: practices of smellwalking and smellscape mapping*. Ph.D. Dissertation. Royal College of Art.

[72] Stanley Milgram. 2010. *The Individual in a Social World: Essays and Experiments*. Pinter & Martin.

[73] Paul Mohai, Byoung-Suk Kweon, Sangyun Lee, and Kerry Ard. 2011. Air pollution around schools is linked to poorer student health and academic performance. *Health Affairs* 30, 5 (2011), 852–862.

[74] World Health Organization. 2019. Ambient (outdoor) air quality and health. `https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health`. (2019). Accessed: 2019-9-10.

[75] Molini M Patel, Steven N Chillrud, Juan C Correa, Marian Feinberg, Yair Hazi, KC Deepti, Swati Prakash, James M Ross, Diane Levy, and Patrick L Kinney. 2009. Spatial and temporal variations in traffic-related particulate matter at New York City high schools. *Atmospheric Environment* 43, 32 (2009), 4975–4981.

[76] Eric Paulos, RJ Honicky, and Ben Hooker. 2009. Citizen Science: Enabling Participatory Urbanism. In *Handbook of research on urban informatics: The practice and promise of the real-time city*. IGI Global, 414–436.

[77] James Pierce and Eric Paulos. 2012. Beyond energy monitors: interaction, energy, and emerging energy systems. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 665–674.

[78] C Arden Pope, Douglas W Dockery, and Joel Schwartz. 1995. Review of Epidemiological Evidence of Health Effects of Particulate Air Pollution. *Inhalation toxicology* 7, 1 (1995), 1–18.

[79] C Arden Pope III and Douglas W Dockery. 2006. Health Effects of Fine Particulate Air Pollution: Lines that Connect. *Journal of the air & waste management association* 56, 6 (2006), 709–742.

[80] Amon Rapp, Maurizio Tirassa, and Lia Tirabeni. 2019. Rethinking Technologies for Behavior Change: A View from the Inside of Human Change. *ACM Transactions on Computer-Human Interaction (TOCHI)* 26, 4 (2019), 22.

[81] Donald A Schön. 1983. *The Reflective Practitioner: How Professionals Think in Action*. Routledge.

[82] Anthony Seaton, D Godden, W MacNee, and K Donaldson. 1995. Particulate air pollution and acute health effects. *The lancet* 345, 8943 (1995), 176–178.

[83] Phoebe Sengers and Bill Gaver. 2006. Staying open to interpretation: engaging multiple meanings in design and evaluation. In *Proceedings of the 6th conference on Designing Interactive systems*. ACM, 99–108.

[84] National Park Service. 2019. Where Does Air Pollution Come From? `https://www.nps.gov/subjects/air/sources.htm`. (2019). Accessed: 2019-9-15.

[85] Yoshinari Shirai, Yasue Kishino, Futoshi Naya, and Yutaka Yanagisawa. 2016. Toward On-Demand Urban Air Quality Monitoring using Public Vehicles. In *Proceedings of the 2nd International Workshop on Smart*. ACM.

[86] Jonathan A Smith and Pnina Shinebourne. 2012. *Interpretative phenomenological analysis.* American Psychological Association.

[87] Nancy Smith, Shaowen Bardzell, and Jeffrey Bardzell. 2017. Designing for cohabitation: Naturecultures, hybrids, and decentering the human in design. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 1714–1725.

[88] Helene Steiner, Paul Johns, Asta Roseway, Chris Quirk, Sidhant Gupta, and Jonathan Lester. 2017. Project Florence: A Plant to Human Experience. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 1415–1420.

[89] Adam A Szpiro, Paul D Sampson, Lianne Sheppard, Thomas Lumley, Sara D Adar, and Joel D Kaufman. 2010. Predicting intra-urban variation in air pollution concentrations with complex spatio-temporal dependencies. *Environmetrics* 21, 6 (2010), 606–631.

[90] Alex S Taylor. 2018. Ethnography in Ubiquitous Computing. In *Ubiquitous Computing Fundamentals*. Chapman and Hall/CRC, 217–250.

[91] Rundong Tian, Christine Dierk, Christopher Myers, and Eric Paulos. 2016. Mypart: Personal, portable, accurate, airborne particle counting. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1338–1348.

[92] Bill Tomlinson, Eli Blevis, Bonnie Nardi, Donald J Patterson, M Silberman, and Yue Pan. 2013. Collapse Informatics and Practice: Theory, Method, and Design. *ACM Transactions on Computer-Human Interaction (TOCHI)* 20, 4 (2013).

[93] Natalia Garcia Torres and Paulina Escalante Campbell. 2019. Aire: Visualize Air Quality. In *ACM SIGGRAPH 2019 Appy Hour*. ACM.

[94] Umbrellium. 2020. Tackle Air Quality in Neighbourhoods Together. `https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health`. (2020). Accessed: 2020-4-18.

[95] Thom Van Dooren, Eben Kirksey, and Ursula Münster. 2016. Multispecies StudiesCultivating Arts of Attentiveness. *Environmental Humanities* 8, 1 (2016), 1–23.

[96] Adam Vaughan. 2016. Pigeon patrol takes flight to tackle London's air pollution crisis. `https://www.theguardian.com/environment/2016/mar/14/pigeon-patrol-takes-flight-to-tackle-londons-air pollution-crisis`. (2016). Accessed: 2019-9-12.

[97] Pawel Wargocki and David P Wyon. 2017. Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. *Building and Environment* 112 (2017), 359–366.

[98] Xiaojing Zhang, Pawel Wargocki, Zhiwei Lian, and Camilla Thyregod. 2017. Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance. *Indoor air* 27, 1 (2017), 47–64.

[99] Yu Zheng, Licia Capra, Ouri Wolfson, and Hai Yang. 2014. Urban Computing: Concepts, Methodologies, and Applications. *ACM Transactions on Intelligent Systems and Technology (TIST)* 5, 3 (2014).

[100] Yu Zheng, Xiuwen Yi, Ming Li, Ruiyuan Li, Zhangqing Shan, Eric Chang, and Tianrui Li. 2015. Forecasting fine-grained air quality based on big data. In *Proceedings of the 21th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*. ACM, 2267–2276.