

inAir: Sharing Indoor Air Quality Measurements and Visualizations

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ABSTRACT

This paper describes *inAir*, a tool for *sharing* measurements and visualizations of indoor air quality within one's social network. Poor indoor air quality is difficult for humans to detect through sight and smell alone and can contribute to the development of chronic diseases. Through a four-week long study of fourteen households as six groups, we found that *inAir* (1) increased awareness of, and reflection on air quality, (2) promoted behavioral changes that resulted in improved indoor air quality, and (3) demonstrated the persuasive power of sharing for furthering improvements to indoor air quality in terms of fostering new social awareness and behavior changes as well as strengthening social bonds and prompting collaborative efforts across social networks to improve human health and well being.

Author Keywords

Air quality, health, sensors, sustainability, persuasive technology, domestic technology, environment, iPhone.

ACM Classification Keywords

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

General Terms

Design

INTRODUCTION

In the past several years, a growing body of scientific evidence has indicated that indoor air pollution within homes and other buildings can be worse than the outdoor air pollution in even the largest and most industrialized cities. For example, the California Air Resources Board estimates that indoor air pollutant levels are 25-62% greater than outside levels [4], and the United States Environmental Protection Agency's (EPA) Total Exposure Assessment Methodology study revealed that levels of about a dozen common organic pollutants were found to be 2 to 5 times higher, and occasionally more than 100 times higher, inside homes than outside regardless of whether the homes were located in rural or highly industrial areas [34]. What makes

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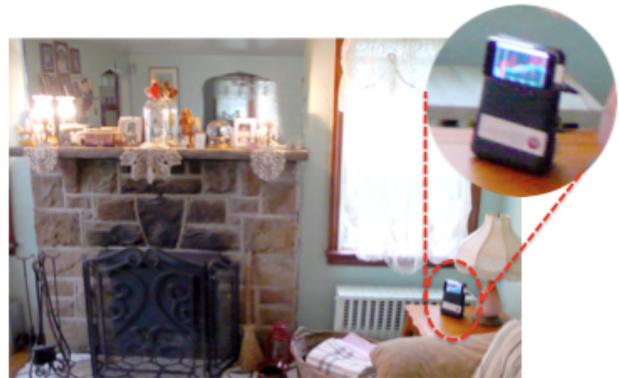


Figure 1. *inAir* system standing on a living-room side table.

these numbers more significant is that we spend by far most of our daily lives indoors. We work, eat, sleep, and spend time with loved ones in enclosed environments. EPA statistics indicate that people in the US spend 65 to 90 percent of their time indoors [33]. Thus, for many people, the health risks may be greater due to exposure to air pollution indoors than outdoors. According to the World Health Organization (WHO), indoor air pollution is the eighth most important risk factor for disease, responsible for 2.7% of the global burden of disease and 1.6 million deaths due to chronic respiratory disease per year [35].

There are three primary sources of indoor air pollutants: (1) products and chemicals we bring into and use in the home, (2) everyday activities and household routines such as cooking and heating, and (3) appliances and materials used to build and decorate our homes. Surprisingly, common household activities, even those efforts undertaken by people to improve indoor air quality, in fact often degrade the overall air quality of these spaces. For example, cooking with a gas burner or lighting a fireplace emits carbon monoxide particles and dust into the air, laser printers give off toxic chemicals [16], and cleaning sprays contains various chemicals. Personal care products further contribute to poor indoor air quality and are often causes of dizziness, nausea, allergic reactions, and even cancer [34]. Tobacco smoke contains a complex mixture of over 4000 compounds, more than 40 of which are known to cause cancer, and many are strong irritants [30].

Clearly there are numerous factors that threaten to degrade indoor air quality. However, people are often completely unaware of these issues since air quality is difficult to

sense, understand, and interpret. There are three main factors that contribute toward people's misunderstanding of indoor air quality. First, people are not aware of how their various indoor activities affect the overall air quality of their environment. Second, it is very difficult with human perception to detect the changes in air quality since many air pollutants are invisible and impossible to detect with human senses. Lastly, existing indoor air quality sensors (e.g., smoke detectors) report only binary data triggered by a threshold condition such as safe or unsafe.

With the emergence of ubiquitous computing technologies in homes, offices, and schools there is an opportunity for such technologies to play a primary role in improving the quality of indoor environment by measuring, visualizing, and helping people better understand indoor air quality. In this paper, we present *inAir*, a tool to measure, visualize and share indoor air quality (see Figure 1). By providing a mechanism to compare measured air quality across places, we expect that it can help educate people and motivate changes in behaviors for improving indoor air quality when the levels vary across locations [25].

In the next section, we provide the explanation of a primary pollutant measured by our system, particulate matter. Then, we provide a review of related work in issues related to health and technologies. Next, we describe the design and implementation of the system, *inAir*, and the details of a domestic deployment study. We present a series of key findings from our qualitative studies and data analyses. We conclude by discussing the key implications this work has on sharing, persuasive technologies for human health, improved domestic well-being, and sustainability issues.

AIR POLLUTANT: PARTICULATE MATTER

While a range of hazardous toxins and pollutants are typically measured when a home is purchased such as mold, radon, asbestos, and lead, they vary slowly over time. We wanted to measure an indoor air pollutant that not only poses a serious health risk but also is clearly linked to indoor activities. There are two primary candidates: Volatile Organic Compounds (VOCs) and particulate matter. VOCs are emitted from many indoor sources such as paint and carpet backing. However, an even greater health risk is posed from the millions of tiny airborne particles called *particulate matter* [28].

Particulate matter, also known as particle pollution or PM, is a complex mixture of extremely small particles and liquid droplets. PM is made up of a number of components, including acids such as nitrates and sulfates, organic chemicals, metals, and soil or dust particles. PM is one of the most critical health threats contributing to the development of health hazards such as respiratory problems, heart disease, asthma, and lung cancer [36]. It is also closely linked with human activities such as cooking, cleaning and ventilation. It is an airborne mixture of microscopic solid particles and liquid droplets made up of a number of components, including acids such as nitrates and sulfates, organic chemicals, metals, and soil or dust particles. Those can be inhaled and trapped in various parts

of the respiratory tract. Exposure to fine particles, those between 0.5 and 2.5 microns, poses a great risk particularly to people with heart or lung diseases and older adults. Healthy people also may experience temporary symptoms from exposure to elevated levels of particles. In fact there is no threshold level below which exposure to particulate matter is deemed safe to human health. Even long-term exposures to low levels of particles is known to decrease lung function in asthmatics and children, increase respiratory stress, and exacerbate cardio-respiratory diseases leading to an increase in illnesses and deaths.

RELATED WORK

Our work leverages previous research on indoor air pollution and human health [9,22], persuasive technologies [11] and citizen science [2,27]. For example, Jones described the relationship between indoor air pollution and health by examining indoor air pollutants and those causes and effects on human health [15]. McCormack *et al.* specifically focused on revealing the impact of indoor particulate matter on childhood asthma [21], and Mølhave investigated the relation between indoor air pollution with volatile organic compounds (VOCs) and human health [23]. Residential homes and schools are the major places where levels of indoor air quality have been scrutinized [8]. Such research linked the causes of pollution with effects on health but rarely offered solutions for people to deal with those problems. Our work aims to provide a tool that can support people to understand and cope with health threats.

While there have been a number of efforts to deploy computing technologies to measure and raise awareness of outdoor air pollution [2,13], there has been little work addressing indoor air quality with respect to human health in the domain of human computer interaction. Researchers have recently started to explore the role of technology for healthier everyday life under the category of citizen science or sustainability. For example, Ballegard *et al.* designed healthcare technology for everyday life using participatory design methods [3], the Participatory Urbanism project tried to sense and improve urban air quality by participation of everyday citizens [27], Niemeyer *et al.* developed a series of networked public air pollution sensors for use within a game context [24], and Hooker *et al.* designed an electronic street sign to visualize urban air quality [13].

There has been research on exploring the effect of persuasive power of computing technology to influence behaviors and enhance health by sharing lightweight health-related information with others in a close tie. For example, researchers have developed mobile applications that share step counts to encourage a healthier lifestyle [6,29], leverage social networks to motivate individuals to reduce ecological footprints [20], employ instant messaging systems to share health related contextual information [31], and develop a system to share healthy-eating experiences to support healthy eating habits [12]. Similarly, we believe that *sharing* the indoor air quality information across a social network will improve awareness of indoor air quality

and persuade people to change their indoor behaviors and activities for better health and domestic well being.

Our work builds on these efforts and provides contributions across a combination of four themes for HCI: (1) particulate matter as a primary pollutant, (2) continuous expression of measurement to motivate awareness and behavior change in households, (3) leveraging sharing of air quality data between homes and individuals, and (4) design strategies for indoor health and well being. Our work explicitly extends our prior research in indoor air quality [18] by focusing on the role of sharing in such systems for promoting awareness and motivating behavior changes.

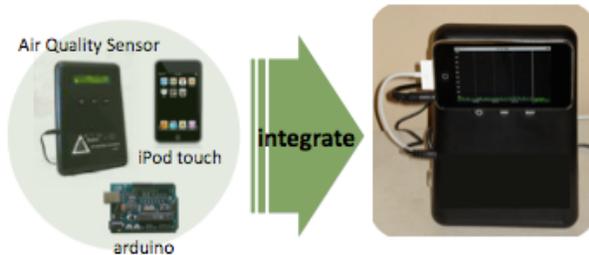


Figure 2. components of the system (left) and the integrated system, *inAir* (right)

SYSTEM DESIGN AND IMPLEMENTATION

We designed and implemented *inAir*, a system to measure, visualize, and share indoor air quality. The prototype consists of three parts: a sensor to measure indoor air quality, a processor to gather the measured data, and a platform to manage the gathered data such as storing, transmitting and visualizing. To measure indoor air quality, we used a commercialized air quality monitor. To gather the measured data, we transplanted an AVR-based Arduino inside the air quality monitor. The Arduino is also connected to an iPod Touch. The iPod Touch was used to process, visualize, and wirelessly transmit the data. Integrated all together, *inAir* is implemented as a stationary platform to visualize both measured and shared indoor air qualities across locations (see Figure 2).

Air Quality Sensor

A DC1100 air quality monitor manufactured by Dylos[®] is used to measure the level of an indoor pollutant, particulate matter [10] (see Figure 2 left). We decided to use the DC1100 air quality monitor because it is commercially available, low-cost, and factory calibrated. The DC1100 air quality monitor continuously counts the number of tiny airborne particles as small as 0.5 microns in size.

Data Processor

We integrated an AVR-based Arduino inside the air quality monitor to process and reformat the air quality data from the DC100 for the iPod Touch. The Arduino reads data from the air quality monitor at regular intervals and transfers it to an iPod Touch that is connected via an audio jack. The DC1100 is capable of reporting particle counts in a wide range of intervals. Balancing accuracy and usefulness, we tuned the DC1100 in our study to report data every 15 seconds. The Arduino encodes the data into a

series of modulated audio tones like a modem. These tones are then read by the iPod Touch via the microphone port.

Communication and Visualization

The *inAir* application uses standard Wi-Fi networking to send collected air quality data to, and to receive others' shared data from the our central server in real-time. Also, it serves as a platform for producing visualizations of the local and remote air quality datasets.

For data visualization, the *inAir* screen is divided into two regions (see Figure 3). The left side of the screen is used to render a line graph representing the particle count over the past four hours. The graph shows data for not only the local sensor but also data from other households in one's social network during the sharing mode. It represents such datasets using different colors for each user. We used one to three line graphs based on the mode of the study, either the single mode or the sharing mode, and the number of people in the study groups. Since the air quality data is gathered every 15 seconds and the size of the screen is relatively narrow to plot every single data point onto the screen (480 pixels in width), we averaged data gathered for every 5 minutes into a single point by which the line graph updates every 5 minutes. The right side screen is used to visualize the current number of airborne particulates as bar charts. The bar charts update every 15 seconds. In the single mode, it displays three consecutive data points for the previous 15, 30, and 45 seconds. In the sharing mode, one for each home's latest reading was shown. The screen visualizes the number of airborne particulates as small as 0.5 microns in size. Environmental statistics for clean air are given as total particle mass per volume. Since we do not know the mass or exact chemical composition of the particles we are measuring, we did not map the particle counts directly into a "healthy" or "unhealthy" scale. Instead, we report out graphically the particle counts along the y-axis using a linear 0-1000 scale where, as explained to participants before the study, in practice values under 200 are typically considered as "very clean" and over 700 "very poor".

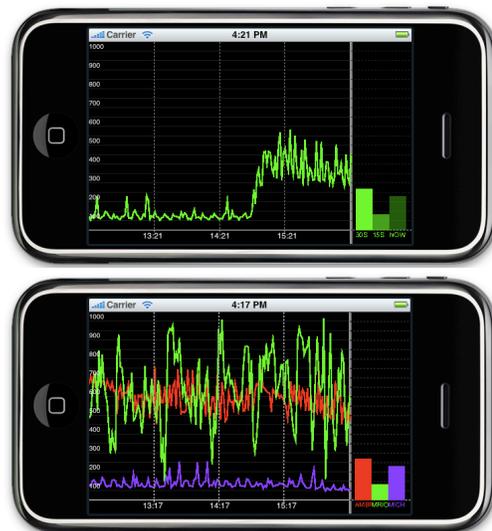


Figure 3. *inAir* screen for single-user (upper) and for sharing mode (lower)

Website

Since the application does not support access to data beyond the previous 4 hours, we created a website to enable users to revisit and explore their entire dataset at any time (See Figure 4). By clicking a certain date in a calendar a user can zoom into the air quality graph for that day. Access to each user's full dataset was controlled via a password known only to each participant.



Figure 4. *inAir* website showing 24 hours of data of one of the participants. The two spikes in the graph correspond to 7am (breakfast) and 8pm (dinner) at the left/right respectively.

METHOD

We gathered both qualitative and quantitative data from the study. Ethnographic data collected from three interviews were used to understand cognitive and behavioral effects of *inAir*, while the numeric levels of measured air quality in participants' homes were logged to analyze changes in air quality across each phase of our study. In the remainder of this section, we describe our method in detail.

User Study

We designed and conducted a home deployment study to evaluate the effectiveness of our system and the value of sharing in the context of real domestic living situations. The study consisted of two modes, a single-user mode and sharing mode each of which lasts two weeks. Participants were introduced to the system and informed how it works and what it measures. Participants were asked to select a public area in their homes to locate *inAir*. To observe the effect of having a shared view, both types of sessions were undertaken by study participants as within-subjects. To minimize the Hawthorne effect, we randomized the order of study phases: half of the groups started the study by single-user mode followed by sharing mode two weeks later, and the other half conducted the study in a reversed order. The study lasted for four weeks in total.

Study participants

Six groups of 14 people were recruited to participate in the study via local Craigslist. At first, we recruited 6 individual participants and asked them to invite either one or two more people in their close social networks to participate in the study with them. All participants were required to live in different houses and have wireless network connections at their homes. Two groups consisted of 3 members (referred as A and D) and the rest groups consisted of 2 members in

each group (referred as B, C, E, F). Since the device is located at public area in the house, all residents were able to access to the device. Group A, B, and C conducted a study starting with a single-user mode and switched to a sharing mode, and Group D, E, and F did by the reversed order.

Group A

The participant (referred as A1) in Group A invited a friend of hers and her mother-in-law (referred as A2 and A3 respectively) both of who live within 5 miles from each other. Participant A1 is a 28 years old working wife living with a husband in a two-story house. Participant A2 is a 28-year-old working mom living with a husband and a two-year-old daughter in a two-story house. Participant A3 is a 57-year-old retired teacher living with a husband and her 86-year-old mother in a single-story house, and the only smoker in her family smoking indoors.

Group B

The participant (referred as B1) in Group B invited a friend of his (referred as B2). Participant B1 is a 64-year-old retired electrician living with his wife in a three-story house, and Participant B2 is also a 62-year-old retired teacher living with his wife in a single-story house. Both households have frequent visits of their children and grandchildren in their houses.

Group C

The participant (referred as C1) in Group C invited a friend of hers (referred as C2). Participant C1 is a 27-year-old graduate student sharing her apartment with her roommate. Participant C2 is a 24-year-old graduate student in the same program as Participant C1 living in an apartment by herself.

Group D

The participant (referred as D1) in Group D invited her two neighbors next door (referred as D2 and D3). Participant D1 is a 35-year-old working mom living with a husband and two daughters in their ages of 3 and 4. Participant D2 is a 29-year-old single working mom living with a 3-year-old daughter. Participant D3 is a 28-year-old working mom living with a husband and her 2-year-old son. All participants live next door each other.

Group E

The participant (referred as E1) in Group E invited her mother (referred as E2). Participant E1 is a 21-year-old college student sharing her apartment with a boyfriend in downtown area. Participant E2 is a 51-year-old florist living in a single-story house with a husband in a suburban area, approximately 20 miles away from her daughter's place.

Group F

The participant (referred as F1) in Group F invited a friend of his (referred as F2). Participant F1 is a 24-year-old graduate student sharing a four-story house with three other housemates. Participant F2 is a 28-year-old graduate student in the same program as Participant F1 living in a two-story house with a wife and his baby just born after the three weeks of the study.

Interviews

To understand cognitive and behavioral effects of *inAir*, we conducted semi-structured interviews in the study. Three interviews were conducted during the study: a pre-study, an in-between, and a post-study interview. The overall goal of the interviews is to determine how a system is being used, what kinds of activities users are engaging in with the system, and whether the overall reactions are positive or negative [1]. A pre-study interview was conducted right after that *inAir* was installed at participants' places to assess their general knowledge and understanding of air quality and human health. Two weeks after the study started, we revisited participants' homes and conducted an in-between interview while changing the mode of the application either from sharing to single-user mode or vice versa. The goal of the in-between interview was to understand how participants had integrated *inAir* into their lives, and to gather feedback about behavioral changes resulting from real-time indoor air quality data. Four weeks after the study started, we revisited participants' homes and conducted a post-study interview to find out any differences between single-user mode and sharing mode, and to discuss possible design ideas for data visualization. In the design discussion session, participants were shown various paper mockups using different themes for visualization such as a numerical, shape bubbles, a color map, and iconic virtual digital pets. Based on the order of the study, questions about the effect of sharing were added in either an in-between or a post-study interview. The purpose of additional questions regarding sharing was to understand how sharing indoor air quality data with others affected awareness of their indoor air quality and arouse any change in behavior. Each interview lasted between 30 minutes to an hour, and all interviews were voice-recorded and transcribed.

Qualitative Data Analysis

We analyzed our interview data using a grounded theory approach [32]. Our approach includes a process of open coding, axial coding, and selective coding.

Open Coding

In the first step of our data analysis, we conducted open coding where we identified and coded concepts that are significant in the data as abstract representations of events, objects, happenings, actions, interactions, *etc.* The example below explains how one participant in our study learned that "motorcycles" negatively affected indoor air quality. This response is coded as "factors to worsen air quality".

"Every time [factors to worsen air quality] motorcycles [factors to worsen air quality] go up or down on the highway, it spikes. It becomes worse than normal regular spikes. I can hear them passing by." (Participant F2)

Throughout the open coding process, a total of 41 loosely connected concepts were created.

Axial Coding

In the second step of our data analysis, we categorized the related concepts created by open coding into higher conceptual phenomena using axial coding. Phenomena in a grounded theory refer to repeated patterns of events,

happenings, actions, and interactions that represent people's responses to the problems and situations. For instance, "increase in awareness" is a phenomenon that represents a pattern of increased awareness about the relationship between changes in air quality and causal factors people obtain from air quality visualization. "Factors to worsen air quality", for example, is one of open coding concepts categorized to "increase in awareness". Our axial coding resulted in a total of seven categories.

Selective Coding

In the last step of our data analysis, we followed the selective coding process to assemble our conceptual phenomena extracted from axial coding into a single storyline. The goal of this step is to integrate all concepts into a single storyline throughout building relationships across phenomena. We employed diagramming among several methods to facilitate selective coding.

Quantitative Data Analysis

To find out changes in the level of air quality, we analyzed the collected air quality data. Since the raw data was not normally distributed, a logarithmic estimate of the data that were normally distributed was used instead. We analyzed data using linear least squares fit. First, the entire dataset alone was analyzed to find out if having visualized air quality information itself affects household activities and hence results in changes in the overall indoor air quality over time. We also measured the effect that sharing air quality data visualizations had in altering overall changes in indoor air quality. To do this, the user variable was randomized and the dates of the study and the study mode (a single-use and sharing mode) were used as independent variables. These separated data sets for each participant were analyzed repeatedly to find out if sharing has any effect on changes in the level of indoor air quality in specific households.

FINDINGS

In our analysis, we distinguished two core categories designating the usefulness of the system, *Engagement in the system* that leads to *Increase in Awareness*: more engaging in the system, more awareness about the level of indoor air quality and its relationships to activities. *Sharing* plays a significant role in maintaining engagement in the system by providing emotional, entertaining, and comparative aspects to users. Our analysis revealed that an increase in user awareness promoted direct changes in behavior when the sources of the problem were apparent and solvable. However, *inAir* also aroused feelings of powerlessness and concern particularly when the source of the problem was unknown or no solutions were provided. This evidence argues for the incorporation of design elements that provide feedback about not just poor air quality but, equally important, its probable causes and proposed solutions strategies. Next, we describe each category in detail.

Engagement in the System

In general, user engagement on the system has a large correlation with system success [14]. Our study revealed that *inAir* was easy to interpret and unobtrusive so that

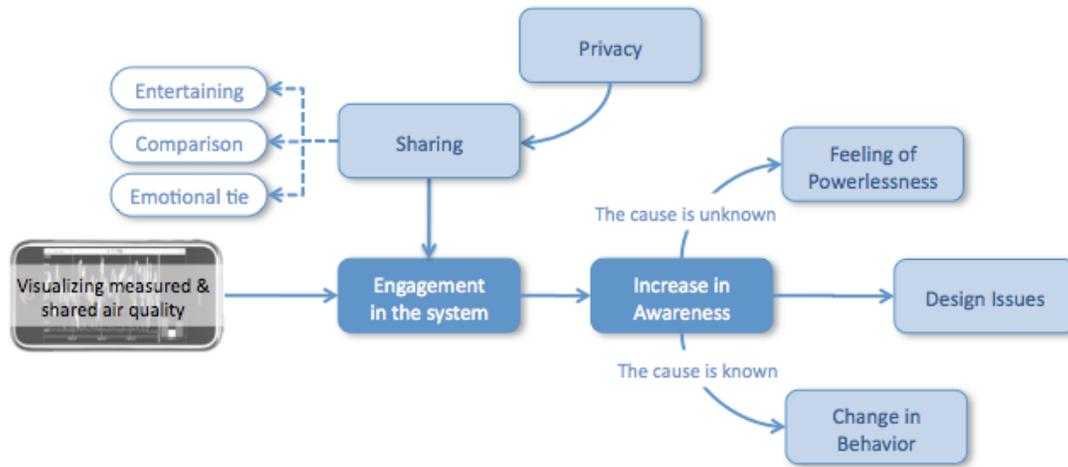


Figure 5. A diagrammatic model of out findings. Visualizations of measured and shared air quality was (1) easily engaged so that (2) increasing awareness about indoor air quality. Increased awareness prompted (3) changes in behavior when the cause is traceable but caused (4) feeling of powerlessness when the cause is unknown. Meanwhile, (5) sharing helped people to engage in the system, and (6) privacy was less of an issue because personal air quality is not considered private.

people easily engage in using it. For easier access, all participants voluntarily located *inAir* where they could easily glance at it such as on a shelf across the living room, next to the TV station, or on a side table. Users most commonly reported glancing at the *inAir* visualization unintentionally whenever they passed by it as if checking the time on a clock or looking at a mirror with no purpose.

"We placed the sensor there [on the side table in a living room] because we spend a lot of time here reading, exercising, and playing with our grandchildren. I don't know how often or why to see it. I just look at it as it is there. (Participant B2)"

Meanwhile, there were a certain types of events that people expected to see an actual change in indoor air quality such as cleaning and cooking. In such cases, participants examined the graphs intentionally after the events happened to confirm expected changes in air quality [26].

"I noticed that it does not mind a vacuum so much... [I] checked [it] whenever I was done vacuuming. I thought it would not like it very much. (Participant E2)"

Because of the novelty effect, we anticipated the possibility of decrease in engagement in the system as time elapses. However, most participants mentioned that the degree of engagement was not decreased over the entire study period. Our analysis revealed two reasons for consistent engagement: (1) low effort to engage with *inAir*, and (2) a prompt for curiosity and speculation of others by variations and fluctuations in air quality from other homes [12].

"I guess the frequency I check the graph has not changed much since four weeks ago because it is just peeping over it. Nothing is hard to do it. (Participant A2)"

Increase in Awareness

Before the study, participants had some understanding of their indoor air quality (e.g., how good their air quality might be, and by what air quality gets poorer or better). Being able to assess the numeric representation of indoor air quality increased awareness and knowledge about indoor air pollution and its relationship with indoor

activities. Also, noticing changes in air quality gave a prompt to think further about the potential causes of poor air quality and how to improve it. The patterns of which participants speculated on the causes and the solutions varied from self-reasoning to talking to other residents or to discussions with other participants. Participants reported discovering a great number of factors that affect indoor air quality that they did not expect (e.g., running a dishwasher, motorcycles passing by, applying cleaning products on hot surfaces, the next-door neighbor moving-out, and an upstairs neighbor's running on a treadmill). Overall, people expressed relief and satisfaction about their indoor environment when it measured their typical air quality as static and clean, while showing concerns towards poor air quality. In summary, our analysis shows that *inAir* provided more opportunities to think about indoor air quality and health related issues.

"I knew what things I do affect my air quality before using it. For example, I knew that grilling salmon worsens air quality. But I did not know how long it lasts. Now I know how long I have to keep the window open to get back. (Participant C2)"

"I noticed that whenever we do things on the stove, it goes up. I boiled water the other day and it gets real high. It was strange. My oven has a flat top range and I clean that everyday because it was so easy to clean. Just spray and wipe it, and done. Windex or whatever the spray I have... Oh, it might be the cleaning spray residue. (Participant A1)"

"You can tell when I vacuumed with my Dyson. It does drop out when I run a Dyson. It feels awesome to see that money spent for my Dyson was actually worth it. (Participant D1)"

Meanwhile, knowing the level of air quality in one place inspired participants to question the air quality of other nearby or frequently visited places: parents cited concerns in schools or pre-schools while full-time employees were worried about their offices and work environments. Several participants also mentioned a desire to know the air quality inside their cars in which cases the concern was focused on the effects of carpeting and air conditioning.

“Inside my car is interesting to measure [air quality] when the air conditioner is on and especially when my 5-day-old baby is in there. (Participant F2)”

Also, our system’s direct comparison of air quality across locations raised concerns about the relationship between indoor and the overall outside air quality in a region.

Feeling of Powerlessness

The lack of tools to locate the source or solutions of the problem caused some participants to feel powerless to affect any positive change in their air quality. There were a number of reports about irregular spikes when no one was at home or when everyone was asleep. We also received comments concerning the difficulty both in locating the cause of indoor air pollution and in taking action to improve indoor air quality. Because the system shows only the level of indoor airborne particles, users often struggled to connect a change in the level with the cause. This difficulty resulted in feels of powerlessness and frustration. In severe cases this problem led to distrust or ignorance of the *inAir* system. While our system was designed to provide helpful and informative information in improving domestic health and well-being, several people commented on how such a system also could place an extra burden on home life by presenting yet another thing to worry about (*e.g.*, air quality and all the new complex issues they must now be concerned with). However, unlike other types of public health hazards that are often beyond the control of an individual (*e.g.*, nuclear power, outdoor air quality, pollen, groundwater chemicals, *etc*), participants considered domestic air quality as a personal territory within their control and maintenance [28]. These desires to locate the cause of poor air quality, to learn proper methods of solving problems, and to improve the overall air quality were a major concern of participants.

“Often I saw very high spikes in the graph even though nothing was going on or nobody was at home. I really wanted to know what caused those. Just seeing the result without knowing its cause is helpless. (Participant D1)”

“I will not reduce the number of times I fry an egg even if it worsens air quality. What I need to know is how to recover poor air quality or make my air quality better. (Participant C1)”

Changes in Behavior

In general, the levels of indoor air quality in our participants’ homes were fairly clean and static except when cooking or unusual activities were occurring, and in Participant A3’s place where had the highest indoor air pollution level because of her indoor smoking. One direct finding from our analysis was that knowing the current level of indoor air quality was a strong factor in motivating people to alter their behavior to improve air quality. This was especially true when *inAir* reported poor air quality.

“When I see the spike in the graph, first I open the window, and sit down to think what caused it. (Participant B1)”

“I told my wife ... how [breathing] unhealthy food-burning smoke is as [bad as] eating burned food is after I saw the crazy jump in his [participant B1] graph by burning cheese. Since then, my wife is more careful about not to burn food when cooking. (Participant B2)”

“We bought a few plants for our living room last week. You could buy an ionizer or something but I do not know how well that works. (Participant D3)”

We expected enhancement in the quantitative level of indoor air quality when people alter their behavior to improve indoor air quality. Unfortunately, our data analysis did not show any significant change in the level of indoor air quality across the entire study period. Neither did we see any significant effect of sharing in the improvement of air quality. We speculate two reasons for this finding: first, overall indoor air quality across our study sites was fairly clean, and second, seasonal or other external factors might exist to affect the overall air quality measurements.

One interesting finding is that Participant A3’s (the indoor smoker) indoor air quality improved significantly during the sharing mode than the single-user mode. Participant A3’s air quality was significantly poorer than others and it was relatively easy to locate the major source of air pollution – a lit cigarette. We cannot claim this case to be generalizable because it was only one sample showing such a pattern. However, it brings up a new hypothesis in visualizing indoor air quality: visualizations that expose significantly higher levels of air pollution when compared to other shared locations can be a compelling factor in motivating overall improvement in air quality at such sites. This is consistent with studies where it is shown that people are heavily influenced by the behaviors and actions they expect or know others to be performing [5].

Sharing

Sharing is an effective mechanism to trigger positive activities by social influence [6,17]. Our analysis also supported persuasive power of sharing. Shared air quality data played an important role in understanding the relative level of air quality across people. When the level is significantly different from others, people collaborated to discover the reason for this discrepancy. It appeared that this high variation was a primary motive in prompting for solutions, discussing best methods, and drawing from mutual knowledge and experience. People were similarly concerned about other participants when they observed significantly worse levels than normal air quality readings.

“One day I saw a huge spike in my son’s graph [Participant A1] that was up high for last a few hours. It was around noon and they must have been out to work. I started to worry about thinking like catching a fire in his house or something. I called my daughter-in-law and found out that it was my son who was off work and repainting their garage. (Participant A3)”

“I saw a huge spike on his [Participant B2] graph a few days ago. That was unusual so that I called him. He said he had burned cheese. We were laughing about how poor we are when our wives are not around. (Participant B1)”

Having access to shared indoor air quality also provided a lightweight awareness of others and an increased feeling of connectedness. Besides directly commenting on the air quality itself, participants also engaged in shared datasets with ludic elements of play, curiosity, and wonder. Participants incorporated the datasets into jokes about poor

air quality in others' homes and speculated on the imagined activities of others based on the graphs.

Indoor smoking plays a significant role in our study and merits a detailed analysis. One of our study participants, Participant A3 was a heavy smoker for 40 years who smoked a pack of cigarettes a day regularly in her living room. Visualizing and sharing the effect of her smoking on air quality dramatically affected her thoughts and attitudes towards smoking. We perceived the changes in her thoughts over the course of our study as reflected across her three interviews – before having the visualization of air quality, before sharing data with others, and after sharing data. (This group started the study with a single-user mode.)

Before having the visualization: *“I have smoked more than 40 years. I have no reason to quit.”*

After having single-user visualization: *“It was different from knowing how bad it is and seeing how bad it is. Sometimes you need smack in the face. It shoots up when I light the cigarette.”*

After having shared visualization: *“It was affecting my denial over the smoking. It is too predominant. Nothing else made air worse than smoking. Cooking, vacuuming, lighting a fireplace... Nothing! My air quality is like ten times worse than others. I am not feeling comfortable anymore with smoking.”*

For Participant A3, sharing measurements of her extremely poor air quality across her social network evoked a series of introspective thoughts on her own smoking habit. At the conclusion of the study she referred to her own smoking using words such as *embarrassed, bothered, offensive, aggravating, and cumbersome*. Moreover, two other participants in participant A3's group mentioned effects of monitoring the extreme fluctuations in Participant A3's graph. A significant result of our study was the reactions of Participant A1's husband to viewing Participant A3's air quality graph. Participant A1's husband was a light outdoor smoker who quit after seeing the extremely poor air quality at his mother's home from her (A3's) indoor smoking.

“My husband quit smoking and it has been two weeks. He said that seeing how bad the air quality was in her mothers' place influenced him to finally quit. (Participant A1)”

“Even just looking at huge ups in her graph [participant A3] was scary. It is like sitting in a room filled with toxic chemicals. I won't take my daughter near smokers at all. (Participant A2)”

“Now, I am trying to smoke outside. I feel guilty for my husband and mother. We now see how long my smoking toxins last in here. [I] feel bad thinking that they inhale it. (Participant A3)”

Privacy

Overall, air quality data was not regarded as personal or private information that felt inappropriate or awkward to share. Every participant in our study justified their answers to this by explaining that they think air quality data does not contain any personal information and thus they do not feel that sharing such data with anonymous people compromise privacy. While we find this result encouraging for future environmental data sharing, it is likely that participants did not reflect on the full range of privacy issues involved (e.g., tracking home occupancy, exposing “unclean” homes, etc).

Design Issues

After living with the *inAir* air quality visualization system for several days, people started to search for a holistic view of the data such as a pattern or average level over time. Also, after gaining awareness about the connection between air quality and indoor activities, people began to draw their attentions to improving long-term changes in air quality. Typically they attempted to link their routines to variations in indoor air quality. Since most people did not stay home all day, time played a significant role in furthering the need participants to construct a holistic view rather than to interpret the directly available fine-grained information.

“It would be helpful to see a larger snapshot of time because then I could actually look at the patterns like when my husband has to take the trash out. (Participant D2)”

“I do not really care about the fine granularity like what happened within this hour. I think I am looking for trends. I do not have time to examine every single spike. (Participant F1)”

Throughout the design discussion sessions about data visualization in the post-study interview, we found different preferences in design by different populations. Parents with young children valued simplicity and easy interpretation as the most important factors in order to teach children how to read the data. They commented on the current version of visualization as *scientific* and preferred alternative designs we presented such as a gauge, color map, or iconic virtual pet. Seniors valued aesthetics as one of the most important factors since it helped provide or fit into their home “decoration”. This age group regarded the current version of visualization as *clinical*, preferring ambient bubble and abstract designs. Finally, younger participants such as students preferred the original visualization, the graph, describing it as simple and intuitive.

IMPLICATIONS

We believe this work has several implications for people designing persuasive technologies for the visualizing and sharing environmental data aimed at promoting healthy living and behaviors. Our work also makes contributions within an important new research of area of HCI involving and addressing environmental issues.

Visualizing Air Quality Improves Awareness

Our study proved that simple visualizations of otherwise inaccessible or humanly undetectable information such as indoor particle counts can play a significant role in increasing peoples' awareness and understanding of air quality, the environment, and human health. This finding suggests that technology can indeed play an important role in helping further public awareness and knowledge of environmental issues and should be exploited whenever possible in designs. More importantly, it argues strongly for further research into ubiquitous technologies to support public awareness of health and environment related issues.

Data Sharing Can Persuade Behavior Change

We evidenced that sharing with simple graphs can persuade people to change their behaviors to improve their level of air quality and health. People evaluate the quality of their

measured states not only by absolute values but also through relative comparisons over time and to others. We observed conditions, particularly where data differed significantly between members, when data sharing played an important persuasive role in promoting changes to the improvement. Thus, we confirm finding from previous research that a simple technology can be just as persuasive at sharing information as a complex, highly accurate technology [6,17]. Since sharing has such a strong effect, it can play a central design role in any persuasive systems. Also, since sharing mechanism already exist or are easy to integrate into existing systems, sharing can be one of the first design elements in any persuasive systems.

Linking Data to Causes and Solutions is Important

Showing people air readings is less effective when people feel powerless to understand its cause or to take action to change it. While a perfectly knowledgeable system may be currently technically infeasible, a system that provides remedial assistance in terms of high probability suggestions for causes of a measured problem would go a long way toward furthering the air quality education and literacy of individuals. Similarly, providing suggestions for actions that can be taken to improve one's air quality and health should be incorporated into future designs. Also, providing additional knowledge linking causes to actual human physiological effects, medical health data, and long-term symptoms and effects would put a more human face onto what is admittedly a data-centric view of the data.

Visualization Preference Differs across Populations

As is the case in many designs, the preferred choice differs across various population demographics. Respecting and understanding the needs and goals of such groups can help drive the selection of the design or visualization that most successfully communicates the demographics' desired need. In many cases it means that the correct design is actually a flexible design, capable of a range of representations.

Accuracy and Interpretation of Data Is Critical

We evidenced the strong effects of shared visualizations of environmental data. We observed how it raised awareness about the phenomena of air quality, aroused a desire for further information, and motivated changes in behavior to improve human health. By visualizations of the measured air quality, people felt either safe or worried, and altered their behaviors based on their perception of the information. While this is mostly good, the problem is that such systems do not convey any legibility information such as the sensor's range, accuracy, resolution, operating characteristics and parameters, *etc.* Exacerbating the problem, users view the visualization on what appears to be a highly sophisticated technological system making the user more prone to believing and interpreting the results with a much higher degree of accuracy than they likely should. Future systems may be able to avoid this problem by incorporating some design elements that invite questioning of the data accuracy without sacrificing sensor credibility and effectiveness [26]. Researchers have an ethical obligation to be cautious in developing technologies with

data measurement and visualization that when misconstrued can lead to detrimental results on human health, the economy, or environment. While researches should feel free to explore a wide design space, they should remain conscious of the implications of their choices.

Environmental Data Is Regarded as Non-Private

Although our study measured personal air quality, participants viewed this data as publicly sharable data. Users did not regard it as private because it did not included specific personal information. This presents us with a much richer design space for developing persuasive technologies that utilize environmental data such as air pollution, noise level, water quality, or electricity consumption for the improvement of our everyday living and environment. However, as pointed out earlier, there are indirect privacy issues that result from sharing personal environmental data. There is an increased obligation on the designers of such systems to make users more aware of these concerns.

CONCLUSION

Our research goal was to understand how to raise awareness and promote positive changes in indoor air quality. To that end, we created a system, *inAir*, to measure, visualize, and share real-time local air quality information with others. From a four-week long user study, we found that our system provided a usable and lightweight mechanism for people to learn and reflect on indoor air quality *in situ*. We saw direct evidences of an increase in awareness of, reflection on air quality, and changes in behavior to improve air quality. We also discovered that sharing data within a social network motivates people to arouse positive changes toward their air quality, and to strengthen social relationship. In particular, we evidenced significant behavioral changes in a smoking participant's group after sharing air quality information with others. While these are encouraging results, we also found evidence that *inAir* created a sense of powerlessness by failing to provide information to help locate the source of the problem or suggest recommendations for improving air quality.

Our work has contribution to the field of HCI research for health and environment in three ways. First, there has been very little research investigating how visualizations of environmental information in domestic settings affect people's behaviors and awareness. Our study shows that visualizations of a domestic environment arouse positive reactions with enhanced knowledge for better domestic wellbeing. Second, our work demonstrates new design territories for the application of persuasive technologies. Even a simple graph with sharing mechanism is effective both in prompting collaborative effort to improve the current state and in strengthening social bonds. Lastly, the finding that personal environmental information is not regarded as private opens up new design opportunities across a range of personal environmental sensing research landscapes on the one hand, while stressing the responsibility of designers to recognize and arouse possible problems and risks unknown by users on the other hand.

Overall, *inAir* was successful in raising awareness and motivating behavioral changes to improve indoor health with respect to air quality. We are hopeful that our work can motivate future research regarding health and environmental issues by empowering everyday people to learn, understand, improve, and broaden their awareness of the environment for improving health and wellbeing.

FUTURE WORKS

We plan to develop techniques to provide more information to help people discover and solve the possible causes of poor air quality, provide suggestions for solving problems, and relate readings directly to health and diseases. Also, we will incorporate other air quality sensors into our design and develop more expressive visualizations to further understanding of the design territory for such a system.

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