inAir: Measuring and Visualizing Indoor Air Quality

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ABSTRACT
Good indoor air quality is a vital part of human health. Poor indoor air quality can contribute to the development of chronic respiratory diseases such as asthma, heart disease, and lung cancer. Complicating matters, poor air quality is extremely difficult for humans to detect through sight and smell alone and existing sensing equipment is designed to be used by and provide data for scientists rather than everyday citizens. We propose *inAir*, a tool for measuring, visualizing, and learning about indoor air quality. *inAir* provides historical and real-time visualizations of indoor air quality by measuring tiny hazardous airborne particles as small as 0.5 microns in size. Through user studies we demonstrate how *inAir* promotes greater awareness and motivates individual actions to improve indoor air quality.

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Sustainability, air quality, domestic computing, health

ACM Classification Keywords
H.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Design, measurement.

INTRODUCTION AND MOTIVATION

We typically spend 90 percent of our time indoors eating, sleeping, working, cooking, and spending time with our loved ones [6]. Yet, some of our activities degrade the environmental quality of these spaces. For example, cooking with a gas burner or lighting a fireplace emits carbon monoxide particles and dust into the air, and laser printers give off toxic chemicals [8]. To make indoor spaces clean and amenable, we apply various cleaning products in our environments that contain chemicals such as phthalates, Bisphenol A, and Triclosan. These products are designed to make our lives clean, healthy, and safe; however, long-term exposure to such chemicals can cause significant chronic health problems like asthma and allergies [14]. Household cleaning agents and personal care products further contribute to poor indoor air quality and are often causes of dizziness, nausea, allergic reactions, and even cancer [6]. While most people think indoor air quality is better than outdoor, indoor air quality is typically twice to five-times *worse* than outdoors [6]. This misconception is likely due to the effort people put into enhancing indoor air quality with chemical products while those often worsen it.

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Figure 1. *inAir* located in a living room.

We posit three problems in people's understanding of the relationship between indoor air quality and indoor activities: first, people are not aware of how their activities affect the quality of their environment. Second, people cannot detect the changes in air quality since particles are invisible. Lastly, common numerical representations of indoor air quality are hard to evaluate. Ubiquitous computing technologies designed for homes, offices, and schools are ideally positioned to play a primary role in helping measure and visualize environmental data to promote improved human health.

In this paper, we present *inAir*, a tool to measure and visualize indoor air quality (see Figure 1). We hope that future ubiquitous technologies such as *inAir* will promote a awareness and understanding of indoor air quality, elucidate the effects of human activities on indoor pollutants, and lead to improved human health and well being.

MEASURING AIR QUALITY: PARTICULATE MATTER

Regular indoor air monitoring is typically confined to smoke and carbon monoxide detectors. However, these devices report only binary data triggered by a threshold condition (*i.e.* safe or unsafe). In our design we present a visualization of continuous indoor air quality to residents. While mold, radon, and carbon monoxide, which are measured when a home is bought, are hazardous to humans, 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 and can reach counts 1000 times greater than outside [6]. However, an even greater heath risk is posed from the millions of tiny airborne particles called *particulate matter*.

Particulate matter is the primary cause of indoor air quality problems contributing to the development of health hazards such as respiratory problems, heart disease and lung cancer [6]. 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 dust. Those can be inhaled and trapped in various parts of the respiratory tract. Exposure to fine particles between 0.5 and 2.5 microns poses a great risk particularly to people with respiratory problems and older adults. Healthy people also may experience temporary symptoms from exposure to elevated levels of particles. *inAir* is designed to measure these hazardous particles as small as 0.5 microns in size.

RELATED WORK

Our work leverages previous research on indoor air pollution and human health [11], and citizen science [4]. Jones described the relationship between indoor air pollution and health by examining indoor pollutants and those causes and effects on human health [8], and Meredith *et al*. specifically focused on revealing the impact of indoor particulate matter on childhood asthma [10]. Works in all the fields above have focused on unearthing the relationship between causes of pollution and effects on health without any solution for lay people to deal with those problems. Our work aims to provide a solution that can support people to understand and manage with possible health threats.

While there have been a number of efforts to deploy ubicomp technologies to measure and raise awareness of outdoor air pollution [1,7], there has been little work addressing indoor air quality with respect to human health in the domain of ubiquitous computing or 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 [2] and the Participatory Urbanism project tried to sense and improve urban air quality by participation of everyday citizens [12]. Meanwhile, we focus on using technologies to measure and assess indoor air quality for healthy *domestic* environments. Whitesell's work is similar to our work in that both try to address ways of using technologies to increase awareness of indoor air quality [13]. The major difference is that Whitesell addressees various image processing challenges while our focus is more directly centered on the human perception, usage, and experience of the technology.

There exist a few off-the-shelf indoor air quality monitors for home on the market. For example, Dylos produces a monitor to measure indoor particle pollution levels, and CO2Meter manufactures indoor CO and CO^2 monitors [5,3]. Since it is factory-calibrated and measures the level of particulate matter accurately, we decided to utilize a commercialized sensor, a Dylos monitor, by improving its data visualization to be more user-intuitive.

SYSTEM DESIGN AND IMPLEMENTATION

We designed and implemented *inAir,* a personal tool for sensing and evaluating indoor air quality to improve awareness and understanding of indoor air quality. *inAir* consists of three parts; a commercially available air quality sensor, an iPod Touch and an arduino micro-controller. A Dylos air quality monitor, a commercial air quality sensor, is used to measure particulate matter. It counts the number of particles larger than 0.5 microns within a cubic meter of air. Attached to the sensor is an iPod Touch used to render the visualizations of the measured indoor air quality. The arduino translates the serial communication from the air quality sensor into an audio signal sent to an iPod Touch.

An iPod Touch screen is horizontally divided into two parts (see Figure 2) showing a historical view of the previous 24 hours (left: line graph) and the most recent values (right: bar graph). The line graph is updated with a data point consisting of the average of the 15-second sensor readings from the past 20 minutes. To the right, we integrated a bar graph updating every 15 seconds making it easier for current activities to be linked to air quality variations. The screen can visualize the number of airborne particulates from 0 to 1000 labeled in y-axis. In this particular study we did not provide a contextual mapping of the data (*i.e.* good, poor, hazardous) and instead focused on the cause-effect relationships between the relative visualization of the data and the change in awareness, knowledge, and actions of participants.

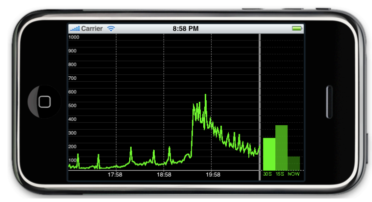

Figure 2. iPod Touch Screen

We also created a web version that enabled visualizing the full set of data over multiple days. This allowed people to easily revisit air quality data beyond the 24-hour range by clicking on a specific date in a calendar and to log text descriptions of various indoor activities as linked with the air quality data. We expected that the daily air quality graphs augmented with the activity diary logging would help participants improve their knowledge about the relationship between activity patterns and indoor air quality.

USER STUDY

We deployed and evaluated *inAir* in a two-week home deployment study. Five households were recruited in total from local Craigslists.org. Study participants were given *inAir* to use in their homes at their convenience for 2 weeks, and we interviewed them before and after the study. Three of the households consisted of a husband and a wife, another household consisted of a husband, a wife, and a seven-week-old infant, and the other household consisted of a husband, a wife, a six-week-old infant, and a grand-mother. All of the wives acted as the primary participants in the study. We visited each participant's home to set up and provide them basic information on the use and functionality of *inAir*. Participants positioned *inAir* themselves in a place where it could be easily observed (*e.g.*, next to a bed or on a living room shelf). Participants were not asked to do anything specific with *inAir* during the study except to look at the screen whenever they wanted. They were asked to visit the website at least once a day to keep a daily log of their activities. At the end of two weeks, we revisited participants' homes and conducted a post-study interview to understand their experiences living with *inAir*.

We used semi-structured interviews for the pre- and post-study interviews. The purpose of the pre-study interview was to understand participants' general perception and knowledge about air quality and health. The purpose of the post-study interview was to find out the effect of having visualized information about indoor air quality on changes in participants' perception and knowledge about air quality and health, and on changes in their behaviors. We asked open-ended questions in five categories: engagement, awareness, changes in behaviors, privacy, and design factors. The results are described in the next section.

RESULTS

In this section, we report qualitative findings from our field study. We focus on effects of visualized indoor air quality on users' awareness, perceptions and changes in behavior regarding indoor activities and health. We did not conduct a quantitative analysis due to the short period of the study.

Engagement

Most participants said that *inAir* was not obtrusive so that they could easily engage in using it. Participants used *inAir* in two distinctive ways; to glance over the *inAir* screen unintentionally when they passed by the device, and to check how their current activity was affecting indoor air quality. The location of the display played a significant role in engaging with the system. For example, a participant who placed *inAir* on the shelf across their kitchen stovetop engaged with it more than a participant who located *inAir* on a table behind a couch. The stovetop participant intentionally checked *inAir* frequently when in the kitchen.

> *"I checked if there was any change in air quality whenever I cooked because I could easily see it by raising up my head. My 7-week-old baby was here too. So I tried not to make air quality poor when I cook. Attaching the sensor onto a fridge door would be another good place to locate it." (Participant C)*

Another participant who placed *inAir* right next to her bed also highly engaged in using it but unintentionally.

> *"The sensor was next to my bed. So I looked at it whenever I passed by. It was unintentional. I think now I have a habit to check air quality in a bedroom when I come in. (Participant B)"*

Awareness

Participants had a general sense of their indoor air quality such as how good their air quality might be, and when air quality gets poorer or better. Being able to assess the quality of their indoor air increased their awareness and knowledge of the relationship between indoor activities and indoor air quality. All participants agreed that *inAir* provided opportunities to think and talk about their indoor air quality and health related issues. Also, noticing changes in air quality gave participants a prompt to think further about what caused poor air quality and how to improve it.

> *"In the past I [was] concerned about it because this house is old and we live in a basement level, but not so technically. After using this, I can see the amount of particles. I think now I am more concerned about air quality. (Participant B)"*

> *"My husband has allergies. So we are keen at air quality. After we had the device, we often talked about high spikes on the air quality graph that means bad air quality. We are actually considering installing new ventilation system. (Participant A)"*

> *"A washing machine and a drier are over there (close to where inAir is located). I noticed air quality got poor when I run those. That was something I have never thought. I guess the cleaning detergent is the source of poorer air quality? (Participant E)"*

> *"I noticed the air quality graph surges up around 6PM every night. After wondering why for days, I realized that 6PM is when my neighbor upstairs comes back from work with 3 kids. Kids keep running across our ceiling, well, their floor. Now I guess it is not only about the noise issue any more. (Participant B)"*

> *"My grandma smokes. Because of my 6-week-old daughter, she now smokes in a basement only. She used to smoke here (in the living room where inAir was placed). But still, when she smokes downstairs, I see rising in numbers on a graph. (Participant D)"*

Also, participants wanted to have more information about other air pollutants or indicators besides particulate matter.

> *"I heard that oxygen level is another indicator of air quality. I wish this device could measure it as well. (Participant E)"*

> *"Because my husband is allergic to pollens, sometimes I hesitate to open the window. It will be great if the sensor can show the level of pollens in air. (Participant A)"*

> *"When we first moved to this house, we detected radon emission at the basement. Even if radon is not detected anymore, we rarely use the basement. Can you add a radon sensor? (Participant D)"*

> *"I wonder how the air quality differs over seasons. In winter, we use a heater. In summer, we use an air conditioner. And in spring and fall, we keep opening windows. (Participant C)"*

Some participants also mentioned that obtaining only the level of air quality was not helpful enough. They wanted to have information about what causes change in air quality, how bad the current level of air quality is to their health, and suggestions for improving it.

> *"I am not sure how much it actually affects my health even though it says the air quality is poor. I have lived in this house for 21 years and haven't got any problem. Yes, I cannot feel if BAD means real bad to my health. (Participant D)"*

Changes in Behavior

Realizing the current level of indoor air quality motivated several participants to alter their behavior and perform activities to improve air quality especially when *inAir* reported the air quality as worse than they expected.

“I checked the air quality every morning and opened the window when air quality is poor. I think sometimes the heater over night makes air quality poor. Even if I do not have that any more, I will keep opening the window every morning. (Participant B)”

“I was surprised by how poor the air quality becomes when I deep-fry. After knowing that, I always turn on the range hood when I deep-fry. (Participant C)”

We also found out that users sometimes felt powerless in controlling air quality, which urges us to further research ways to provide more information regarding air quality.

“Sometimes I had no idea what to do to improve air quality. When it is cold outside, I’d rather have poor air than being cold.”(Participant A)

“I sometimes noticed very poor air quality even though there was nobody. I wonder what causes it and want to fix it. But without knowing the cause, I could not fix it. (Participant E)”

“As it only shows my air quality is bad without any clue, sometimes I felt frustrated. There was nothing I could do except opening the window. Right, opening the window is the only thing I know and do for better indoor air quality. (Participant B)”

Privacy

Sharing information is one effective way to compare data. We wondered to what degree participants considered their air quality data personal or private. Across all of our participants we found air quality data to be considered public and that they would readily share it with others.

“Air quality does not include any of my personal information. That is why I do not mind showing my place’s air quality to others, even to strangers. (Participant D)”

Design Factors

Participants expressed a desire for *inAir* to provide a more direct mapping of the visualized data to health effects and also to help interpret the overall air quality (*i.e.* good, poor, hazardous). Also, participants mentioned that they checked the 24-hour history of air quality using *inAir* less frequently. Instead, they used the website to see the changes in air quality for the day or earlier. Then, they used *inAir* to check how their current activities affect air quality. This usage pattern suggested us to redesign the interface from a graph with imperceptible updates to a more dynamic representation over a smaller time window.

CONCLUSION

Our initial research goal was to understand how to raise awareness and promote positive changes in human health as related to indoor air quality. 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 evidence of an increase in awareness of, and reflection on air quality and health. More strikingly, we observed several examples of changes in behavior and activities to improve indoor air quality as a direct result of visualized data from our system. While these are encouraging results, we also found evidence that *inAir* created a sense of powerlessness by not having information to locate the source of the problem or recommendations for improving air quality. Some users expressed desire for *inAir* to display data about other pollutants and in other locations. Overall, *inAir* was successful in raising awareness and motivating changes in behavior to improve indoor health with respect to air quality. We are hopeful that our work can be useful towards motivating future ubicomp research that can empower everyday people to learn, understand, and improve their health and wellbeing and broaden their awareness of their environment.

FUTURE WORK

We plan to conduct a quantitative analysis of activity and air-quality logs to identify activities that correlate with reduced air quality. Encouraged by our results we are also exploring several new directions for *inAir*. First, we plan to study further the persuasive power of sharing indoor air quality across existing social networks. We are also interested in developing techniques to help people discover the possible cause of poor air quality, provide suggestions for solving problems in air quality, and relate readings directly to human health and diseases. Finally, we plan to incorporate other air quality sensors into our design and develop more expressive visualizations to further our understanding of the design territory for such systems.

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