inAir: A Longitudinal study of Indoor Air Quality Measurements and Visualizations

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ABSTRACT
Indoor air quality (IAQ) is important for health as people spend the majority of time indoors, and it is particularly interesting over outdoor air because it strongly ties to indoor activities. Some activities easily exacerbate IAQ, resulting in serious pollution. However, people may not notice such changes because many pollutants are colorless and odorless, while many activities are inconspicuous and routine. We implemented *inAir*, a system that measures and visualizes IAQ that households appropriate and integrate into everyday life. The research goals of this work include understanding the IAQ dynamics with respect to habitual behaviors and analyzing behavioral and quantitative changes towards improving IAQ by the use of *inAir*. From our longitudinal study for four months, we found that *inAir* successfully elicited the reflection upon, and the modification of habitual behaviors for healthy domestic environments, which resulted in the significant improvement of IAQ.

Author Keywords
Air quality; health; sustainability; domestic computing.

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

INTRODUCTION
Exposure to unhealthy environmental conditions is known as one of the causes for numerous chronic diseases. Among those, air pollution and its effects on health have been researched extensively over past several decades [13]. In particular, the health effects of air pollution cover a wide variety of respiratory problems including allergies, asthma, hypersensitivity reactions, airway infections, chronic obstructive pulmonary disease, and even lung cancer [41]. Also, there is mounting evidence of severe health threats from polluted air on the vulnerable population: exposure to air pollution has long-term effects on cardiovascular development in children, and the elderly are particularly vulnerable to air pollution. As such, it is important to maintain good air quality standards in order to promote a higher quality of life, protect health, and reduce the costs associated with respiratory and chronic disease. Concerns over the health effects of IAQ are of particular interest as people spend the majority of time indoors. Perhaps the most predominant indoor environment in this regard is the residence where people eat, sleep, and spend time with their loved ones. The typical person in the United States spends between 58% and 78% of his or her time in the home, and the percentage for vulnerable populations such as the elderly and the young is even higher, reaching up to 100% [42]. Consequently, the health risks associated with IAQ far surpass problems related to outdoor air pollution [29].

Contrary to a common perception about air quality, the air pollution level indoors is in fact often higher than polluted outdoor air [43]. Modern buildings are more airtight than older buildings from added insulation, caulking and weather-stripping for thermal comfort. While such efforts might make indoor environments comfortable, they also contribute to the creation of an unhealthy breathing environment where pollutants linger, easily accumulate, and become highly concentrated [24]. A variety of factors and their relationships determine the level of air pollutant concentration including the volume of air contained in the indoor space, the rate of production or release of pollutants, the rate of removal of pollutants via reaction or settling, the rate of air exchange with outside the atmosphere, and the outdoor pollutant concentration [27]. While not impossible to calculate the approximate level of indoor air pollution given such complexity, actual human exposure to pollutants is even more difficult to quantify because an individual's behaviors and activity patterns vary [18].

The primary cause of indoor air pollution is gases or particles released into the air from a wide variety of sources including building materials and furnishings; deteriorated, asbestos-containing insulation, wet or damp carpets, and furniture made of pressed wood products; heating and cooling systems and humidification devices; outdoor sources permeated into the home such as radon, pesticides, and outdoor air pollution; combustion sources such as oil, gas, kerosene, coal, wood, and tobacco products; and products for household cleaning and maintenance, personal care, or hobbies [21]. Surprisingly, several indoor activities

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Figure 1. inAir located on a TV tabletop in a living room

of ours, even some aimed at making indoor environment healthier, often degrade air quality. 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 [37]. Personal care products contribute to poor IAQ and are often causes of dizziness, nausea, allergic reactions, and even cancer [42]. Frequent use of household cleaning sprays may be an important risk factor for adult asthma [45]. 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 [24]. Even high temperature and humidity can increase concentration of some pollutants.

However, it is challenging to identify causes of air pollution and to measure the level of air quality indoors. First, it is difficult to estimate air quality condition through bare human sensors like eyesight or smell because many air pollutants are colorless and odorless. Even if the human nose is able to notice some pollutants by odor, it is hard to detect the changes in air quality promptly and accurately because it so quickly becomes accustomed to smell. Several off-the-shelf instruments exist to monitor IAQ. However, most commercialized instruments simply monitor the level of a particular air pollutant, or a few, without offering further information about sources or the complex dynamics of pollutants. Efforts are still underway to enhance technical abilities to identify air contaminants and their sources, to measure pollutants that exist in indoor environments, and to improve IAQ.

Since many indoor practices are tightly correlated to IAQ, we assume that indoor breathing condition can be improved if indoor activities are changed to an air-clean direction [16]. Using an existing sensing technology as a mediator to reflect habitual behaviors with regard to IAQ, households could understand the effects of habitual behaviors on IAQ and might voluntarily change their daily routines accordingly. The central assumption of this work is that the provision of IAQ visualizations would raise awareness about the effects of habitual behaviors on IAQ, and thereby helps households make rational decisions to modify habitual behaviors towards an environmentally sustainable direction [44]. We hope that simple technologies likes *inAir* can help educate people with the effects of habitual behaviors on indoor environments, and engage them in the efforts towards healthy living and everyday well being.

This work explicitly extends our prior research in IAQ [25], focusing on how households appropriate and integrate *inAir* into everyday lives to produce a healthier living environment. The primary contribution of the prior work was the study of fourteen households as six groups to demonstrate the persuasive power of sharing IAQ to increase awareness and promote behavioral changes. For this work, we used the same hardware from our previous work, upgrading the visualization with information such as a range of IAQs within neighbors, outdoor air quality (OAQ) and temperature. Also, the relationship among participating households was changed from a group within social network in the prior work to strangers, and the study duration was substantially increased from four weeks in the prior work to four months. The primary contribution of this work is the study showing improvement in IAQ, and our qualitative analysis of the behavioral changes that remained consistent over the study period.

AIR POLLUTANT: PARTICUATE MATTER

While a range of different hazardous toxins (*e.g.,* mold, radon, asbestos, and lead) and pollutants are typically measured when a home is purchased, these vary over time. We wanted to measure a 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 (PM).

VOCs are emitted from many indoor sources such as paint and carpet backing. However, millions of tiny airborne particles, called Particulate Matter [35], pose an even greater heath risk. Particulate Matter, also known as particle pollution, or PM, is a complex 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/dust particles. Indoor activities like cooking, cleaning, lack of ventilation, *etc.*, comprise the major sources of PM.

PM is one of the most critical threats contributing to the development of health hazards such as respiratory problems, heart disease, asthma morbidity, and lung cancer [45]. They 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 PM is deemed safe to human health. Long-term exposure to low levels of PM is known to decrease lung function in asthmatics and children, increase respiratory stress, and to exacerbate cardio-respiratory diseases leading to an increase in illnesses and deaths. As such, exposure to PM is strongly associated with increased morbidity and mortality, suggesting that sustained reductions of PM indoors should result in improved life expectancy [35].

RELATED WORK

Our work leverages previous research on indoor air pollution and human health [9], persuasive technologies

[12] and citizen science [11]. Jones examined indoor air pollutants and the causes of and effects on human health, to describe the relationship between indoor air pollution and health [24]. McCormack *et al.* particularly examined the impact of indoor Particulate Matter on childhood asthma [28], and Mølhave revealed the relationship between indoor VOCs level and health [26]. Residential buildings and schools are the places that have often been scrutinized for levels of IAQ [8]. Such research links the causes of air pollution with the effects on health but rarely offers either a means to measure air pollution or solutions to deal with those problems. Our work aims to provide a simple tool to help people understand the IAQ dynamics upon habitual behaviors to cope with possible health threats.

While there have been great efforts to deploy computing technologies to measure and raise awareness of outdoor air pollution [xx,xx], little work has addressed IAQ with respect to human health in the field of human computer interaction. Efforts to build a sensor to monitor IAQ are fledging [23]. Researchers have started to explore potential roles for technology to foster healthier everyday life. For examples, Ballegard *et al.* designed healthcare technology for everyday life using participatory design methods [3], the Participatory Urbanism project sought to sense and improve urban air quality through everyday citizens [32], Niemeyer *et al.* developed a series of networked public air pollution sensors to use within a game context [30], and Hooker *et al.* designed an electronic street sign to visualize urban air quality [20]. Some research efforts sought to use technology as a tool to empower and engage households with habitual practices for environmental sustainability, but most focus on consuming behaviors like water usage or energy consumption [7] with little attention on healthy living environment or IAQ.

The concept of everyday practice has been considered crucial to understanding the dynamics and reasoning behind human behaviors in psychology and behavioral economics. Recently, HCI researchers expanded their focus to everyday contexts, raising questions about the rational choice approaches and current understanding of the complex dynamics of human behaviors. For example, Pierce et al. illustrated the ways in which people make choices are unconscious and habitual within everyday practices rather than based on conscious rational reasoning [34]. Also, Strengers demonstrated water consumption as a rational and individual decision-making process as part of social practices [40]. As such, everyday practices, situated activities within a cultural understanding of social norms reflecting daily routines [33], are considered crucial to the design of eco-feedback technologies. Meanwhile, our work focuses on habitual behaviors, routine tasks that a person undertakes without engaging in self analysis [6].

People often lack in understanding how their behaviors affect the environment. Eco-feedback through technology can help them better understand it. To maximize information's transformative potential, visualization must be easy to understand, draw attention, and deliver information as close in time and place as possible [5]. Several works have addressed effective ways for the design of eco-feedback visualization. For example, Froehlich *et al.* argued the importance of considering what behaviors a design is hoping to motivate as well as motivation technologies when designing eco-feedback technology [14]. Spagnolli *et al.* also drew out design principles for eco-feedback design: the provision of near-real-time feedback; a support for social engagement; ensuring the system usability; acknowledging behaviors in the household that affect the larger community [39].

SYSTEM DESIGN AND IMPLEMENTATION

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

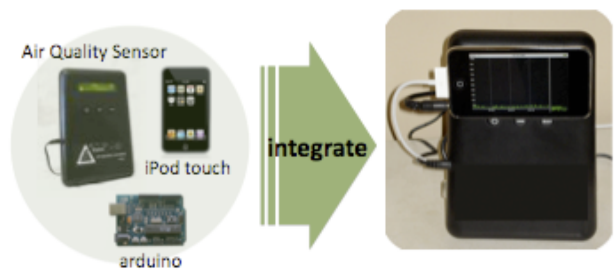

Figure 2. Components of the system (left) and the integrated system, *inAir* (right)

Air Quality Monitor

A DC1100 air quality monitor manufactured by Dylos© was used to measure the level of an indoor pollutant, Particulate Matter (see Figure 2 left). We selected a DC1100 air quality monitor because it is commercially available, low-cost, and factory calibrated. A DC1100 continuously counts the number of tiny airborne particles as small as 0.5 microns in size per cubic meter.

Data Processor

We integrated an 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. A 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 data into a series of modulated audio tones like a modem. These tones are then read by the iPod Touch via microphone port and decoded to numeric data.

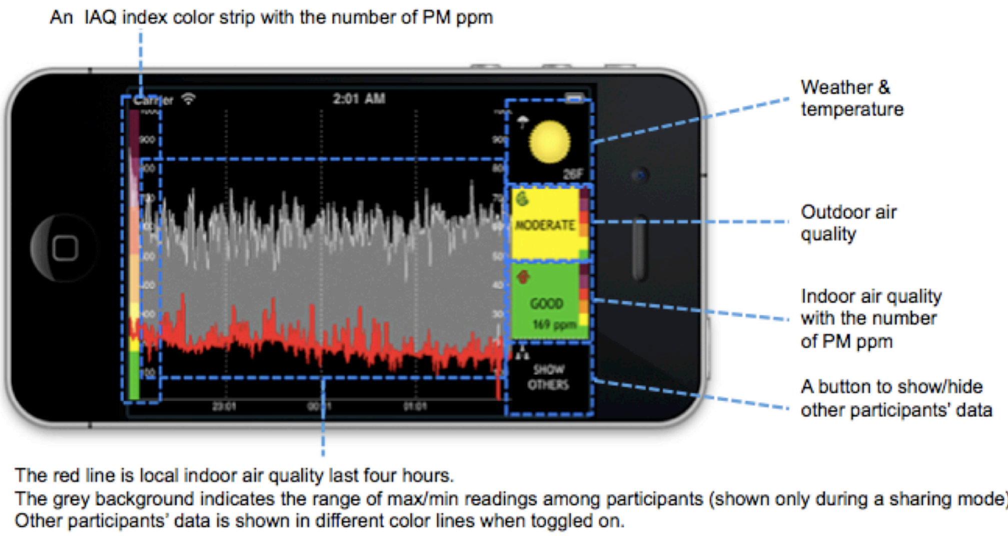

Figure 3. Data visualization in a sharing mode when other data is toggled off

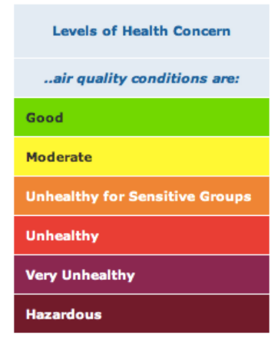

Figure 4. Air Quality Index

Data Visualization

The *inAir* application runs on an iPod Touch and uses a standard Wi-Fi network to send collected data to, and to receive others' data from a central server in real-time. The iPod Touch also serves as a platform for visualizing local and remote air quality dataset. To illustrate the data, we adopted a line graph format with the vertical axis being air quality level and the horizontal axis being a lapse of time. The interface consists of two regions: the main graph area and a set of auxiliary information on the right (see Figure 3). The main area of the screen is used to render a line graph representing particle counts over four hours. There are two modes of data visualization: a single-user and sharing mode. In single-user mode, the graph displays only its own data, and in sharing mode a user can choose to display either a single line from the local sensor or multiple lines in different colors from all participants. Additionally, the display renders a grey area in sharing mode, which represents the range of data from all participants.

Vertical axes on both sides of the screen scale from 0 to 1,000 which indicate the count of PM. The horizontal axis unit is time, and the plot area is divided into four horizontal sections with dashed lines, each representing one hour. On the left-most end of the screen, we also displayed a vertical color strip of air quality index (AQI). AQI is the national air quality standard in the United States established by the US EPA to indicate how clean the air is in color conveying potential associated health effects. For example, green indicates satisfactory air quality with little or no risk; while purple indicates hazardous air quality (see Figure 4). Data is collected every 15 seconds, but the screen is narrow to plot each data point (480 pixels in width). To address this we averaged data for 5 minutes into a single point, and updated the graph every 5 minutes.

On the right corner of the screen, we arranged three additional data blocks and one button vertically. On top, a weather icon with temperature (°F) is displayed. Below, OAQ is shown in text on a colored background. The OAQ data is retrieved from AIRNow database by zip code in a JSON format. AIRNow is a service developed by EPA and multiple agencies to provide easy access to real-time local air quality conditions to the public. Below is an IAQ read from the local sensor. While the line graph provides the trend of IAQ over time, it is hard to check immediate changes as the graph updates every 5 minutes. This block updates when new data is read (every 15 seconds) to show immediate changes of IAQ. Additionally, this block displays particle counts in ppm. We expect that a user could collate IAQ with outdoors by comparing these two adjacent color blocks. The same AQI is applied to the backgrounds in these two blocks. Colored backgrounds would support users in identifying air quality from a distance. At bottom is the button to plot other participants' data, or hide it if the screen becomes too busy from several lines of data. This button is active only in sharing mode.

METHOD

We conducted a longitudinal home deployment study for four months and collected both qualitative and quantitative data. Numeric air quality levels were logged to analyze quantitative changes in IAQ across modes of the study and by time lapse. The interviews focused on how *inAir* affected the awareness of IAQ dynamics with habitual behaviors and exploring the negotiation process between healthy indoor environments and indoor activities.

User Study and Participants

The study consisted of two modes, a single-user and sharing mode, each of which lasted two months. In total, the study ran for four months. To observe the effects of a shared view, we relied on within-subjects design, meaning that all participants undertook both sessions. To avoid ordering effects, we randomized the order of study modes: half of participants started the study in single user mode followed by sharing mode two months later, and the other half conducted the study in a reversed order.

Six households were recruited via flyers posted at local libraries and grocery stores in urban Pittsburgh. In 2012 Pittsburgh has ranked as the third most polluted for short-term particle pollution [1], which is a cause for a raising concern about air quality among residents. There were several requirements to participate in the study. First, the house must have a wireless network connection. Second, households had to share ordinary, regularly scheduled family activities (*e.g.,* we excluded dorm-type housing, single-resident households, and shared apartments). All the recruitment criteria were on the flyer.

We asked participants to place *inAir* in a public area in the house so all members of a household could easily access it. Household A, C, and F conducted a study starting with single-user mode and switched to sharing mode afterwards, and B, D, and E did the reversed order. To aid in recruitment, we offered all households $160 ($40 per month) as compensation for their time and effort.

Household A

The family members include a full-time working husband (a 38-year-old accountant) and a stay-at-home wife (32 years old) with a one-year-old infant and a dog. The house is two stories with three bedrooms. The family has been living in this house for four years. They placed *inAir* on a table between the kitchen and the living room.

Household B

The family members include a full-time working husband (a 41-year-old entrepreneur) and a part-time working wife (a 38-year-old jewelry designer) with two children, aged 8 and 6, and a dog. The wife was diagnosed with breast cancer and recovered after a surgery two years ago. The house is three stories with five bedrooms. The family has been living in the house for less than one year. They were still repairing the house and addressing issues like cracks in the floor. They placed *inAir* on a living room table.

Household C

The family members include a husband working from home (48 years old) and a full-time working wife (a 47-year-old lawyer) with a 5-year old daughter and a dog. The house is two-stories with five rooms. They placed *inAir* on a shelf between a living room and a dining room.

Household D

The family members include a full-time graduate student husband (32 years old) and a stay-at-home wife (30 years old). The house is a two-bedroom apartment on the first floor. The husband stays at home most of the time to work in his study. They have been living in this apartment for two years. They located *inAir* on a shelf in the living room.

Household E

The family members include a retired husband (62 years old) and part-time a working wife (52 years old) with a cat. The house is two stories with four rooms. While only two of them live in this house, they have frequent visits from their adult children who live nearby, and they babysit their grandchildren three times a week in this house. They have been living in this house for over twelve years. They located *inAir* on a shelf in a dining room.

Household F

The family members include a full-time working husband (a 34-year-old teacher) and a stay-at home wife (34 years old) with two children, aged 6 and 3. The house is three stories with four bedrooms. This household grows and eats almost all food at home, including vegetables, cheese, flour, milk, *etc*. They have been living in this house for over five years. They located *inAir* on a shelf in a living room.

Interviews

Five interviews were conducted: a pre-study, three in-between, and a post-study interview. The overall goal of the interviews was to determine how *inAir* was used, what kinds of activities users performed with *inAir*, and whether the overall reaction was positive or negative. All household members were asked to participate in interviews. Interviews employed an ethnographic approach, allowing extended and discursive conversations with family members as a group.

We conducted a pre-study interview immediately following the installation of *inAir* in participants' homes to assess their general knowledge and understanding of air quality and human health. We revisited participants' homes at the end of every month (three times in total) to conduct in-between interviews. At the second in-between interview after two months lapsed, we changed the mode of *inAir* either from sharing to single-user mode or vice versa. The goal of in-between interviews was to understand how participants had integrated *inAir* into their lives, and to gather feedback about behavioral changes resulting from real-time IAQ data over time.

After four months, we conducted a post-study interview to discover differences between single-user and sharing mode and to discuss the overall effects of *inAir*. Based on the order of the study modes, questions about the effect of sharing were included in either an in-between or post-study interview. The purpose of additional questions regarding sharing sought to uncover how sharing IAQ data affected awareness of IAQ and behavioral changes. Each interview lasted about an hour, and all interviews were audio recorded and relevant portions transcribed.

Quantitative Data Analysis

The raw data of IAQ measures was not normally distributed (clustered close to zero with a long tail at the high end because the level was mostly low and steady), so a logarithmic transformation of data was used to address this. We measured the effect of sharing air quality data using one-way ANOVA. To do this, the user variable and study mode (single or sharing) were used as independent variables. Separated data sets from each participant were analyzed repeatedly to see if sharing has any effect on reducing indoor air pollutants. We also analyzed data using repeated measures ANOVA and linear least squares fit to see changes in IAQ over the study period. To do this, the user variable was randomized, and timestamp and study phase (first or second) were used as independent variables.

Qualitative Data Analysis

We analyzed our interview data using a thematic analysis to reveal patterns across data sets that are important to the description of a phenomenon and are associated to a specific research question. The themes become the categories for analysis.

First, we used open coding to identify and code concepts that were significant in the data as abstract representations of events, objects, happenings, actions, interactions, *etc*. Next, we categorized related concepts, created during open coding, into themes. A theme is a pattern emerged within data. Lastly, we assemble the themes into a single storyline to integrate all concepts into a single storyline through building relationships across themes.

FINDINGS

Our analysis reveals that IAQ significantly improved over the duration of the study. We also found that *inAir* allows householders to easily reflect upon the relationship between their habitual behaviors and IAQ. In what follows, we describe our findings in detail.

Quantitative Analysis

Our analysis showed no difference in IAQ between households who could see how other households were performing and single user households. Using an ANOVA to compare sharing vs. single-user mode we found no significant difference ($p = 0.453$). For the remainder of our analysis we did not separate out these conditions.

We next calculated the mean IAQ in the first and second two months of the study (first vs. second phase). The difference was large (128 *vs* 100) and significant on a repeated measures ANOVA with a Greenhouse-Geisser correction ($F(1,5)=10.663$, $p = 0.022$*).

To further understand the possible causes of changes to IAQ over time, we looked at the most common correlation of IAQ to OAQ. As shown in Table 1, OAQ was better (lower) than IAQ by a factor of 2-3 and varied very little during the study (mean of 41 in the first half and 43 in the second half). Thus, it is unlikely to be responsible for the large changes in OAQ that we found. This is unexpected since a number of studies documented a high positive correlation between OAQ and IAQ. For example, Hoek et al. found a high positive correlation of $PM_{2.5}$ outdoors and indoors [19] and Baek et al. showed a strong correlation between indoor and outdoor levels of vehicle-related pollutants such as PM, CO and NO [2].

Although OAQ cannot fully explain the changes we observed, we did find a correlation between OAQ and IAQ We found the negative correlation between air qualities indoors and outdoors. We ran a simple linear regression model fit. Three variables were used as predictors: timestamp, OAQ and temperature. The result shows that there are statistically significant correlations between the normalized value of IAQ and all three predictors. OAQ had the most significant positive correlation to IAQ ($\beta = 0.201$, $p<0.0005$**), followed by temperature ($\beta = 0.141$, $p<0.0005$**). Timestamp also had a statistically significant negative correlation ($\beta = -0.110$, $p<0.0005$**), meaning that IAQ has improved over time.

Table 1. Mean air qualities indoors and outdoors [1]

Month	Mean IAQ	Mean OAQ
Jan ~ Mar	128.14 (SD=167.38)	41.10 (SD=12.916)
Mar ~ May	99.94 (SD=132.174)	42.79 (SD=13.546)

To summarize, our data show a large and significant change in IAQ over the course of the study. Since changes in OAQ alone do not explain this, we turn to the qualitative data next for further insights.

Qualitative Results

We observed that increased awareness of this relationship prompted participants to modify their practices to better indoor air, leading to a decrease in indoor air pollution. Meanwhile, contrary to the findings from our previous work, sharing data among people with no standing social relationship had little influence on the use of the system.

Domestication of New Technology

Metaphorically, we can observe a domestication process when a user integrates new technologies into the structure of daily routines [4]. We found that people easily assimilated *inAir* into their daily lives.

User engagement with the system has a large correlation with system success [22]. Our study revealed that *inAir* was easy to interpret and unobtrusive so that people could easily engage with it. Participants most commonly reported glancing at the screen unintentionally whenever they passed. Householders acquired general knowledge about their overall level and dynamics of IAQ from *inAir* over the first several days to couple weeks. Because they had never accessed such information before, most participants were very interested in looking at the changes of IAQ in the beginning of the study. People were surprised when their expectations about how their practices affected IAQ proved incorrect. They frequently went out of their way to check *inAir*'s graph out of curiosity.

Once they were accustomed to the air quality dynamics, participants' interest translated into a routine, deeply integrated into their everyday lives [3]. Householders developed a habit to checking air quality periodically in a daily routine such as after cooking, when returning home, or every morning. All participants stated that this habit lasted until the study was over. The introduction of new technology often produces a *novelty effect* that biases the results of observations and studies of its usage and value to participants. While our study was not devoid of such effects, the longitudinal nature of the study (4 months) and the more habitual daily usage patterns of *inAir* by our participants, are indicative of a greatly diminished novelty effect in our study.

[1] The scales for air pollution levels indoors and outdoors are different (IAQ: particle counts per cubic meter from 1 to 1,000, OAQ: EPA standard air quality index from 1 to 500) so that those cannot be directly compared each other.

"Whenever I come back, I glance over at it to see if there were any spikes while we were out. Started probably about a week after I had this. I think now I have a habit to check it." – Household D

"My interest was definitely the highest when I first saw it. But it is still interesting. I think it became a routine to check it." – Household A

The aesthetic appearance of the device is important to how successfully it is integrated into the fabric of households. If a device is not attractive enough, it is often concealed and loses its power to communicate [17]. Participants were mostly pleased with the appearance of *inAir*. People especially liked an iPod Touch and its application interface, including the graph, while noise from the fan attached at the back to circulate air in and out of the sensor was identified as the most disturbing factor of the system.

"I wish it (the hardware) would be another color than black. But it is still fine as it's not bulky, and the iPod looks techy, neat, and modern. Who complains about the design of iPod?"- Household E

Reflecting Habitual Behaviors on Indoor Air Quality

Understanding habitual behaviors is crucial to sustaining everyday health and well being [14]. Indoor activities can be a major source of indoor air pollution, but people often underestimate these practices because these are inconspicuous and mundane [36]. *inAir* provides an air-quality footprint from indoor activities on which people can reflect their practices in relation to changes in IAQ. Since many indoor activities are included in daily routines, householders spotted the activities that increased or decreased air pollution even though *inAir* only visualizes the historic and current air quality flow. This knowledge then led participants to consider performing further actions to improve IAQ. Participants discovered cooking and cleaning to be the most predominant sources of air pollution. They intentionally examined the graph after these activities in order to confirm expected changes in air quality [31]. After learning the relationship between air quality and activities, participants tried to trace the exact source of air pollution. Overall, the use of *inAir* significantly increased the awareness of IAQ. Before the study, participants had some understanding of their IAQ (*e.g.,* how good their IAQ might be, and why air quality becomes poor). Accessing the numeric representation boosted awareness and knowledge about IAQ and its relationship with indoor activities.

"Every time we turned the stove on, it spiked. I cook all the time, and it was disturbing to see what you do everyday causes poor air quality. You can't stop cooking. So we researched the best surface to cook on among iron and ceramic pots." – Household F

"It jumps whenever I run a vacuum. I have a good vacuum cleaner with a HEPA filter in it. So it was a little surprising to me. It's because of air turbulence surged by the vacuum?" – Household C

"I knew ventilation helps clean the air but wasn't sure how long I had to keep my windows open. This (inAir) tells me when it is okay to close them." – Household E

Aside from cooking and cleaning, several other practices were reported to cause degradation in air quality. Participants reported that most indoor activities affected IAQ in some degree, and they were surprised that many activities rarely associated with air quality actually affected it. These findings inspired householders to become more engaged in and even change some habitual behaviors [34].

"We often light candles at dinner. I was surprised that lighting candles makes spikes. That reminded me of my friend's visit. She asked to turn off them as she had asthma." – Household E

"This (inAir) even picks up when we walk around in the morning. Now I know many other things that I didn't expect could worsen my air, and started to pay more attention to it. " – Household D

"I assumed when you burned stuff then that's bad, but didn't realize that even regular cooking makes it go up." – Household A

There were occasions when the graph spiked for no apparent reason, making it impossible to link the spike to specific activities. In our previous studies, people actively talked to other participants to share knowledge and discuss the possible causes of mysterious peaks as they were within strong social bonds [25]. In this study, however, participants deliberated these anomalies on their own because they did not have such a relationship with other participants. Interestingly, participants in this study rarely complained about the unknown spikes, while participants in previous studies reported the mysterious peaks as the most frustrating aspect (only one participant commented about unknown spikes in this study). We assume that the difference was caused by the study durations: previous studies lasted 2 to 4 weeks; this study was conducted for 4 months. Participants in short-period studies tended to pay more attention to sudden changes in air quality. However, when the study period is relatively long, *inAir* is woven into a daily routine so that activities become a trigger to check IAQ, which normalizes the mysterious peaks.

inAir provided two additional statistics: OAQ and weather. Participants used these as a supplementary index to estimate and better understand the changes in IAQ since OAQ and weather are possible indoor air pollutants. Comparing IAQ with these figures allowed participants to better understand and deeply engage with the IAQ dynamics.

"I always compared inside with outside. Outside there's tons of pollutants, damp mold, etc that come into my house. Outdoor, I can't do much, but indoor I can." – Household B

" I was interested if rain affects our air. When it rains a lot, the air quality seems to be very good. I was thinking maybe that's because rain suppresses all the particles in the air. "- Household E

Altering the Process of Habitual Behaviors

Awareness is a crucial component for behavioral changes [4], and the result of our study confirmed this. *inAir* caused householders to pay more attention to IAQ. Increased awareness was accompanied by efforts to improve air quality. Some efforts were immediate single actions (*e.g.,* changing filters). Other efforts became part of habitual behaviors. Unlike behavioral changes for environmental sustainability (*e.g.,* reducing energy consumption), daily practices are non-negotiable. For example, we cannot reduce the frequency of cooking even if we are aware of the negative effects it has. In this study, participants incorporated additional activities into habitual behaviors to improve air quality. For example, running a fan while cooking became a necessity, not an option.

"I was surprised the first time I saw this (inAir) because the average level seemed to be so high. So we went out to get a better furnace filter right after we had this. A couple of days after changing the filter, the level dropped down." – Household A

"It convinced my wife to turn on the fan. She freaks out when she sees the jumps. Now she pays more attention to turning it on, as she knows how dramatic it is if she doesn't use it." – Household C

inAir gradually extended users' attention from certain activities that had the primary effect on air quality to every indoor activity. They began to reflect most indoor activities against its effect on air quality. We argue that the use of *inAir* generates a new habit of considering IAQ with regard to habitual behaviors.

"Air quality is something you don't think about in general. I think this (inAir) is a reminder when you need to make the air better. People don't think about it, assuming it healthy." – Household E

"I think from an education point it became a real enforcement. It really made us understand and talk about a couple of issues. The fan goes on every time we're cooking now, and I watch it a little bit more when I run the sweeper or other things. " – Household D

Sharing and Privacy Concern

One significant difference between this and our past studies is that sharing had little influence on engaging participants in either *inAir* or air quality. In our previous work, we conducted a study in which participants shared their IAQ within a close social network such as distant family members or friends [25]. Its result showed that sharing not only increased engagement in air quality but also strengthened social bonds among participants through collective discussions and knowledge sharing. Meanwhile, in this study participants were interested in comparing their IAQs to others during the early phase of sharing mode because the air qualities in other places allowed participants to determine whether theirs was relatively 'good' or 'bad'. When they noticed that their air pollution level was relatively lower, participants were satisfied and legitimized small fluctuations in their air quality [39]. In the opposite case, participants felt guilty and blamed.

"I checked others because it helps to determine if it's because of outside or only in my house when I see spikes " – Household B

"Ours was the worst all the time, and I felt bad and guilty. Even the kids asked why we were so high." – Household F

However, their interests in other houses waned quickly because participants did not have any relationship with one another. They were not provided with any information about other houses. Having acquired a general understanding about the relative level of their air quality, participants quickly turned attention to their own IAQ. Some participants even told us that others' data became nothing but a distractor from fully focusing on their IAQ because there was nothing for them to do even if they saw high spikes from others.

"It was interesting to see others in the beginning, but I lost interest quickly. The voyeur was fun but doesn't do a lot because I have no idea what is going on there. Who knows if they are having a party with a log fire or three fireplaces?" – Household C

"I thought I would miss sharing. But didn't. I am now more into ours. Before, I was distracted by others. "- Household B

Nobody raised a privacy concern in sharing even though data was shared with strangers. We assume that this is not because there is no privacy issue, but because people are not aware of possible privacy threats when exposing it to others. Since changes in air quality reflect indoor activities, it could be used as an indicator when householders are at home. When we explained possible misuse cases, participants agreed it was a privacy threat. However, all participants consented to share data, as it did not provide any identifying information.

"I thought air quality was not personal to keep private. But, I now am a bit worried. You could tell when you are at home by looking at it. But I guess it's fine as long as anonymized."– Household D

Summary

To summarize, a simple visualization of IAQ appears to have helped to improve IAQ and increasing habitual behaviors and awareness. While we cannot rule out the possibility that this is due to a Hawthorne effect, we designed the study to minimize experimenter involvement. It is also possible that some other unexplored variable affected the IAQ. However the most likely explanation (the connection to OAQ) cannot explain the magnitude of the change we saw. Finally, it is possible that a novelty effect is at play here, however the length of the study helps to offset this, as does the qualitative data presented.

DISCUSSION

People often assume that improving IAQ would demand significant effort and money, such as installing a good quality furnace filter or running a cutting-edge air purifier. While those efforts certainly improve it, small efforts in a mundane life can also affect IAQ because occupants and their activities within a building are often a major source of indoor air pollution. However, many daily practices are unconscious or habitual rather than the result of rational decision-making [34], and there is little public awareness about adverse respiratory effects of indoor activities [45]. Our study demonstrates *inAir* as an effective visualization tool that illuminates otherwise invisible IAQ condition. *inAir* provides an air-quality footprint from indoor activities, allowing people to reflect on habitual behaviors and the changes in IAQ and thus, raising awareness and altering routines in accordance with improving IAQ.

Literature shows that deeper engagement with the presentation of domestic environmental conditions can promote feelings of empowerment among householders [17], and in-home displays with information, either real-time or historic, help households understand and manage their behaviors through changed habits [10]. Findings from our work support this, as we observed that *inAir* significantly increased awareness of IAQ and prompted behavioral changes towards healthy indoor environments. Contextualizing feedback could further increase eco-friendly behavior and increase awareness (*e.g.*, [15]).

While participants actively engaged with *inAir* throughout the entire study period, we noticed that participants' interaction with *inAir* changed over time. During the early phases, interest was the main prompt to interact with it. Participants randomly checked *inAir* without any particular scheme or routine. Noticing a spike triggered an action: when participants saw peaks, they actively traced possible sources of changes and performed immediate actions to mitigate the condition. This pattern illustrates that the short-term use of *inAir* effectively increases households' attention to and engagement with IAQ. During this phase, participants built knowledge of the IAQ dynamics with regard to habitual behaviors.

Then, over time, participants gradually changed the way they interacted with it from a sporadic action to part of a daily routine, such as after waking up, while cooking, or when coming back home. In this phase, participants altered their practices based on conscious rational reasoning rather than from an unconscious and habitual reiteration. This illustrates that *inAir* successfully integrates into the fabric of everyday life and becomes a mirror to reflect the effects of daily indoor activities against air pollution.

The prevalent reaction to poor IAQ was to increase ventilation. Ventilation is a simple and effective way to remove air pollutants and dilute the concentration to acceptable levels. However, the determination of exact required ventilation rates or durations is seldom possible [38]. *inAir* is well suited to notify people of the need for ventilation and help gauge the appropriate duration. Also, OAQ helps households determine a right time for an influx of outdoor air. With *inAir*, ventilation becomes a simple and effective way to improve IAQ. The decrease in air pollution over the study period verifies its impact on domestic environments.

Contrary to our assumption that sharing would help better estimate and evaluate IAQ, we observed that sharing had little influence on either participants or the quantitative level of indoor air pollutants. This also opposes the findings from our previous work where sharing IAQ within strong social ties had a significant influence on participants. This difference stems from the different types of participant relationships. This study allowed access to anonymous individual houses' air quality without further knowledge about them, while the data was shared within a strong social network in the previous work.

When shared within social bonds, showing poor air quality to others becomes a social pressure and motivator to improve the condition. Moreover, others became a resource for better understanding the IAQ dynamics through collective discussions and knowledge sharing. However, it was merely voyeurism when shared within parties without personal relationship. This implies that sharing can be a powerful mechanism if the benefits are well explored, and the proper parties are selected to share data.

CONCLUSION

Our work focuses on designing an open, persistent presentation of IAQ that households integrate into their everyday lives for a healthy living environment. The central assumption of this work was that the provision of IAQ visualization would raise awareness about the effects of indoor activities on IAQ, and thereby empowers households to make a rational decision to steer habitual behaviors towards an environmentally sustainable direction.

To that end, we created a system, *inAir* that measures and presents IAQ. From the first of its kind four-month long field study, we found that *inAir* provided a usable and lightweight mechanism for households to reflect their everyday activities on air quality in homes. We saw direct evidences of *inAir* being smoothly integrated into everyday lives and increasing awareness of, and reflection on air quality. Motivated by *inAir*, householders altered their routines and habitual behaviors for healthier living conditions. Such efforts resulted in the significant improvement of IAQ (the average drop in our study from phase one to phase two was about 25% over 4 months). In combining qualitative data pointing to habitualized changes, our results are far stronger than any equivalent longitudinal study.

From these findings, we argue that conscious awareness of habitual behaviors with regard to IAQ can improve indoor environments, and a simple presentation mechanism might be sufficient for changes. While these are encouraging results, we also found that sharing is not an effective means of support when the data is shared among strangers.

Our work makes three contributions to HCI research for health and sustainability; there has been little research on how visualizing environmental information in domestic settings affects awareness and behaviors; our work emphasizes that understanding habitual behaviors is crucial to promoting positive changes toward a healthy daily life; our work proposes new design territories for technologies to reflect habitual behaviors upon domestic environments. We hope that our work motivates future research on health and environmental issues by empowering people to understand, improve, and broaden their awareness of surroundings.

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