Awareness, Understanding, and Action: A Conceptual Framework of User Experiences and Expectations about Indoor Air Quality Visualizations

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ABSTRACT

With the advent of new sensors and technologies, smart devices that monitor the level of indoor air quality (IAQ) are increasingly available to create a healthy home environment. However, little has been studied regarding design principles for effective IAQ visualizations to help better understand and improve IAQ. We analyzed Amazon reviews of IAQ monitors and their design components for IAQ visualizations. Based on our findings, we created a conceptual framework to explain the process of facilitating an effective IAQ visualization with a proposed set of design considerations in each stage. The process includes helping users easily understand what is happing to IAQ (*awareness*), what it means to them (*understanding*), and what to do with the information (*action*), which results in two outcomes, *knowledge gain* and *emotional relief*. We hope our framework can help practitioners and researchers in designing eco-feedback system and beyond to advance both research and practice.

Author Keywords

Indoor air quality; Peripheral Display; Design principles

CSS Concepts

• CCS → Human-centered computing → Interaction Design → **Interaction design theory, concepts and paradigms**

INTRODUCTION

Advancements in computing and sensor technology have enabled rapid access to an abundance of information about various facets of our everyday lives. This includes information about air pollution, one of the top 5 environmental risks to human health, which can seriously impact people's health, safety, productivity, and comfort [39]. Since people spend the majority of their time indoors, keeping indoor air quality (IAQ) clean and healthy is crucial for the quality of life. The indoor concentrations of some air pollutants, however, are often 2 to 5 times higher compared to outdoor concentrations [7]. A complicating matter is that people seldom recognize a worsening of their IAQ since many air pollutants, being colorless and odorless, are impossible to detect with unaided human sensors [8]. With the advent of new sensors and technologies, smart devices that monitor and visualize the level of IAQ are increasingly available in the market to help create a healthy home environment.

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Studies are scarce, however, regarding design principles for effective IAQ visualizations to help people better understand and improve their IAQ. Choosing proper design components in information visualization is central as these decisions will directly influence how users interpret the data [30] and make informed decisions reflecting accurate interpretation of the data, one goal of *persuasive design* [11]. Visualization is particularly important in understanding IAQ because laypeople often will not be able to understand the meaning of air quality sensor readings (e.g., What does $PM_{2.5}$ is 152 mean for my health? or how bad is my IAQ if AQI is 78?). IAQ visualization must effectively turn numeric air quality data into a meaningful representation of information so that users can easily understand what is happing to their IAQ *(awareness),* what it means to them (*understanding*), and what to do with the information (*action*).

As important as it is, we lack a systematic approach to design principles for IAQ visualization. While an emerging body of research has investigated the influences of monitoring IAQ on users' perception and behaviors, the primary focus has been on technical aspects of detecting, monitoring, and showing IAQ data and little about the design aspects of its visualization [25,27], with few exceptions [22,28]. This paper addresses this issue with an aim to develop design principles and guidelines for effective IAQ visualization.

In this study, we analyzed 1,447 user reviews of 7 IAQ monitors available on Amazon in the US to explore users' expectations and experiences with existing IAQ monitors. We then connected the findings from this analysis to design choices made in IAQ visualization on these devices to identify relevant design components to support such user expectations and experiences. Based on this work, we framed users' expectations and experiences with IAQ visualization into a conceptual framework as a proposed set of design considerations for effective IAQ visualization.

Our work builds on prior work by the HCI communities on eco-feedback systems [13] and persuasive technology [11]. We contribute to the HCI and design communities by offering practical design strategies and considerations for effective visualization of indoor environmental quality. We anticipate that a solid conceptual framework of IAQ visualization can provide a valuable means to help integrate the wealth of research in designing eco-feedback systems and beyond to advance both research and practice.

In the next section, we review related work in IAQ monitoring technologies, persuasive technology, and eco-feedback design. Next, we describe the details of our data collection and analysis. After we present a series of key findings from our data analyses, we introduce our proposed framework. We conclude by discussing the key implications this work has for using design to promote human heath, improve domestic well-being, and address sustainability issues.

RELATED WORK

Our work leverages and contributes to two domains of HCI and sustainable interaction design communities: persuasive technology [11] and eco-feedback systems [13]. In this section we review some of the related work in these two domains directly applicable to developing design considerations for IAQ visualizations.

IAQ Monitors as Persuasive Technology

Since research has explored the relationship between air pollution and negative effects on health and quality of life, HCI researchers have sought to provide viable ways to help people better understand IAQ and manage the possible health threats associated with poor IAQ. For instance, Kim et al. designed a standalone device for sensing and visualizing IAQ to improve awareness and understanding of indoor environmental quality [27], and Jiang et al. created a personal mobile sensing tool for monitoring IAQ [25]. The principle underlying the design of these systems is that self-monitoring is one of the most prevalent strategies to increase awareness and promote behaviors that have a positive influence on health and quality of life, called persuasive technology [11].

Persuasive technology is broadly defined as technology designed to change attitudes or behaviors of the users through persuasion and social influence, but not through coercion. The design of persuasive technology employs varied strategies for influencing behavior and activities by enabling self-monitoring and conditioning of relevant data [21]. Design strategies followed in persuasive design can be generally divided into (1) strong persuasion, in which information is provided about the extent to which a user's behavior is or is not sustainable [2], and (2) passive persuasion, in which information about consumption, waste or other broad impact effects are presented to the users, usually implicitly contextualized within the topic of sustainability [16]. HCI researchers and practitioners have increasingly studied and produced sophisticated devices to facilitate the persuasive power of computing technology to influence behaviors and enhance quality of life by tracking, monitoring, and visualizing health- and environment-related information on people's everyday lives [4,12,17].

One unique design consideration of persuasive technology is ambient awareness [26]. Systems for ambient awareness draw upon the histories of calm computing and ambient displays to construct systems intended to make users aware of some aspect of the sustainability of their behavior, or qualities of the environment associated with issues of sustainability [6]. The forms of ambient awareness systems vary from devices and physical artifacts [16] to visualizations [18] to instrumented environments [1]. These projects demonstrate two primary design tactics employed for ambient awareness: (1) making visible changes of environmental conditions based on different behaviors to prompt awareness; and (2) making visible (and aesthetically pleasing) desirable behavioral patterns and environmental statuses. Many persuasive systems adopted these design tactics to provide ambient awareness based on the idea that the information provided ambiently will persuade users to engage in pro-environmental behaviors [6].

Eco-Feedback Systems

Eco-feedback system refers to technology that provides feedback on people's behaviors with a goal of prompting pro-environmental behaviors and reducing environmental impact [13]. People often lack understanding of how their behaviors affect the environment (e.g., energy consumption, water usage), and eco-feedback through technology can help them better understand their own environmental impact. While IAQ monitoring systems are not the direct kind of eco-feedback systems, we consider them to serve the same goal of providing information on environmental conditions that influence and are influenced by human behavior with an aim to promote pro-environmental behavior and to reduce the harmful effects of a poor environment.

To maximize the transformative potential of information, visualization must be easy to understand, draw attention, and deliver information as close in time and place as possible [3]. Several works have addressed effective ways to design 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 [13]. A study of eco-feedback systems' user interfaces by Jain et al. introduced key design components, including historical comparison, normative comparison, rewards and penalization, incentives, and disaggregation [24]. We found these design components are relevant to designing IAQ visualization, and thus reflected on them with our findings in the findings and discussion sections.

Historical comparison
The historical comparison is to enable users to view a current environmental status relative to the past using a graph that displays information over periods of time (hours, days, weeks, months). By observing these graphs and recalling their activities, users can identify the reasons for the onset of an undesirable event and develop proper strategies to cope with the event. Several researchers have found that historical comparison is a key design component for eco-feedback interfaces (e.g., [5,47]).

Normative comparison (Sharing)
The normative comparison is to enable a comparison of one's data with others. It has been shown to persuade users to modify their behaviors to conform to social norms and thereby promote pro-environmental behavior [40]. Several studies highlighted that normative comparison is a key component of eco-feedback interface design (e.g., [27,33]). Researchers further demonstrated the potential of normative comparison in motivating pro-environmental behavior through competition and public perception [20,32,42,46].

Reward and penalization
The rewards and penalization approach is to provide users with the rewards for pro-environmental behavior and penalties for behavior harmful to the environment. A review of the literature supports the use of reward and penalization to encourage positive behavior and discourage negative behavior [23]. The importance of these design components is further supported by their use in real-time monitoring of environmental data, in which users are rewarded, for example, for electricity use during off-peak hours and penalized for the use during peak hours [18].

Incentives
Incentives can be both financial and non-financial awards for pro-environmental behavior, though their effectiveness is still under question. Some studies have shown that financial incentives are an effective design component to promote pro-environmental behavior [46], while others have shown that financial incentives do not provide sufficient motivation for users to become engaged in pro-environmental behavior [38].

Disaggregation
Disaggregation refers to design components that allow users to disaggregate integrated data into specific levels or granular categories. A review of eco-feedback studies confirmed the need for interface tools that draw a direct link between specific actions and the results from the actions [10]. Providing granularity and specificity would increase user's self-efficacy associated with behavior modifications [46]. Researchers have been installing individual sensors [23] or using eco-analytic tools that parse data to provide information regarding the impact of a specific behavior or environmental factor [13]. Because installing and maintaining individual sensors is difficult in residential settings, however, researchers have begun to turn their attention toward further developing and studying eco-analytic tools [24].

METHODS
Our approach is to qualitatively analyze users' product reviews of IAQ monitors on Amazon and then to thematically analyze design components of these systems, reflecting the review analysis. In the analysis, we sought to address the question: what are the reviewers' expectations and experiences when they interact with these devices? We constructed our conceptual framework based on an analysis of these expectations and experiences.

Data Collection
To determine proper IAQ monitors for review analysis, we first searched IAQ monitors available on Amazon in the US using "indoor air quality monitor" as a search query. Among the list of retrieved products, we chose those that meet the purpose of this study, based on three selection criteria: a device that (1) is stationary with a graphical display to visualize IAQ, (2) monitors at least three different types of air pollutants, and (3) has more than 30 customer reviews. These criteria led us to narrow the list down to 10 IAQ monitors. Next, we conducted a preliminary analysis of these 10 devices, primarily focusing on how these devices display IAQ information. From this analysis, the degree to which user engagement is required when interacting with a device (direct attention vs. peripheral awareness) has emerged as a significant factor to distinguish the type of IAQ visualization (See Figure 1).

Figure 1. IAQ monitors that require reading the numbers on a screen were placed on the right side of the spectrum, and those with a color panel allowing just a glance to check status were placed on the left side. The names of these devices are: NetAtMo, Awair Glow, uHoo, FooBot, Awair, Eve Room, AirVisual, Dylos, EG Air, and Temton (From left to right).

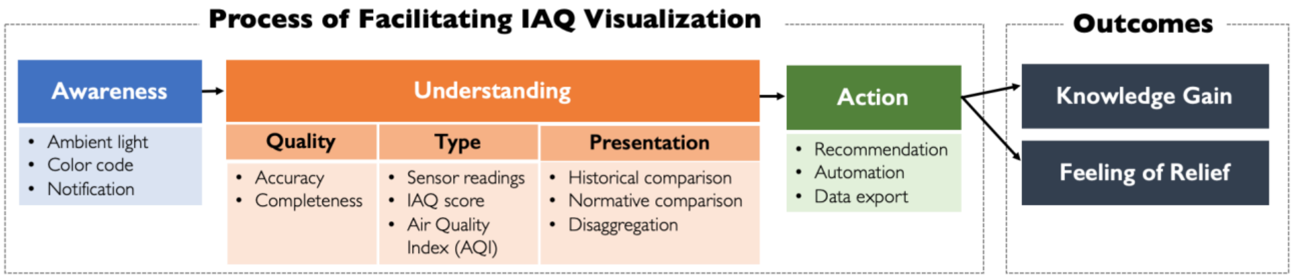

Figure 2. A conceptual framework to explain the process of facilitating effective IAQ visualization with a set of design considerations at each stage

Since our focus of research is an IAQ monitoring device as a type of persuasive technology, we dropped three devices that require direct attention to interact with them (on the far-right side of Figure 1). This led to a final list of 7 IAQ monitors for further data analysis. After we chose these, we visited the official website of each product and downloaded a product manual, pictures, introductory videos of the product, and a mobile app, if available.

Finally, we scraped a total of 1,447 reviews of these 7 devices available on Amazon in the US in June 2019 upon the terms and conditions of Amazon[1]. We chose to use Amazon's product review corpus for this study because customers' product reviews contain "product-centered experience data that puts the product in the center and integrated the product usage experience information from various different users" [31]. Content analysis of product reviews has been used to understand the opinions of a wider general public [43]. No identifying information about reviewers was collected.

Data Analysis

We analyzed Amazon's reviews using a thematic analysis to reveal patterns across data sets important to the description of a phenomenon and associated with our research question of understanding user experiences and expectations when using IAQ monitors. In particular, we applied both inductive and deductive approaches informed by grounded theory and other theory-driven qualitative analysis methods, such as thematic analysis [37,40]. That is, we inductively analyzed the data to allow for the themes to emerge, while we deductively analyzed emerged themes.

First, the reviews were checked to ensure that they were related to the actual experience of using the instruments. Thus, reviews that were short or un-descriptive (e.g., "good product" or "Don't buy it") were excluded from further coding. The remaining reviews (N= 1,257, 87%) were used for analysis. The first author engaged in line by line coding of the reviews. After the first iteration of open coding, further iterations included axial coding to consolidate codes under coherent groups. Through constant comparisons, these codes formed categories and core concepts that resemble a conceptual framework. We then applied the emerged themes to existing design components of the IAQ monitors to identify design components of each system compatible with the themes as a construct. Finally, the emerged theme was categorized with relevant constructs of design components and considerations. The final set of themes has become the analytical procedure through which users process IAQ information, and the final set of the constructs turned into design components and considerations of IAQ visualizations to realize each theme.

[1]https://s3.amazonaws.com/amazon-reviews-pds/LICENSE.txt

FINDINGS

Three distinct but closely interrelated themes emerged as a procedure by which users[2] process IAQ visualization, including *awareness, understanding,* and *action*. For each theme, several design components or considerations emerged as constructs of each theme to take into account when visualizing IAQ. Lastly, we identified two succeeding themes as outcomes of using IAQ visualization, including *knowledge gain* and *feeling of relief*. Consolidating all these, we propose a conceptual framework as a proposed set of design considerations for effective IAQ visualization (See Figure 2). Next, we explain each theme and associated constructs of our proposed framework in detail.

Awareness

Prior work has shown that people tend to lack awareness about how their everyday behavior affects the environment and vice versa, which poses an "environmental literacy gap" [13]. Other researchers have revealed that an increase in user awareness is an effective method of promoting behavior change [27,35]. Our findings echo these results by showing that users' first reaction to using an IAQ monitor was an increase in awareness about IAQ-related issues. Only shortly after using a device did people become mindful of improving their IAQ.

Since using it [the device] a few weeks ago, I've been more aware of the air I breathe and make a conscious decision to improve it by using a purifier and humidifier to regular air flow. (Review #143)

In improving people's awareness, a peripheral display was found to be a design component that is effective in

[2] "Users" in this section refers to Amazon reviewers of IAQ monitors we analyzed.

promoting users' engagement in IAQ without requiring much cognitive effort. Peripheral display refers to output devices that provide peripheral awareness, which is defined as "the amount of information shown by the display that people are able to register and use without focal attention" [36]. Peripheral display is an important application that allows users to be aware of certain information without being overburdened [45]. Our findings highlighted three design components of a peripheral display effective in enhancing peripheral awareness of IAQ, including *ambient light, color code,* and *notification.*

Ambient light

All devices in the left side of Figure 1 (toward peripheral awareness) adopted ambient light as a salient design component to provide the current state of IAQ peripherally. Particular design features of ambient light include a light strip encompassing the body of a device, covering one surface of a device with a glowing panel, or a dotted LED light (See Figure 3). Many users left positive comments about the effectiveness of ambient light in allowing easy engagement in IAQ.

The light on the top is sufficient to scan it quickly and see the general level for all the things it is testing and to keep us informed on our air quality. It makes it super easy to understand how things are going. (Review #34)

The fact that I don't have to be distracted by looking at my phone for another notification is really nice. I don't lose the context of whatever I'm working on but instead can quickly understand that I might need to open a window with a quick glance at the LED display. (Review #409)

However, there was a nearly equal number of complaints regarding ambient light being too disturbing and intrusive at night. Many users placed an IAQ monitor in a bedroom, and for them the feature of automatically increasing the intensity of ambient light due to the worsening of IAQ at night drew unintended focal attention, which consequently interfered with other, and probably more important, behavior, sleep.

I couldn't figure out to get the night light to work in my bedroom. It was always coming on for no reason, so this actually negatively impacted my sleep. This was moved into another room and is probably going to be returned. (Review #411)

I wish the nightlight LED were a warmer color, not the blue-white cold LED glow and could be turned completely off. I hate its light in my room. It's pretty annoying and bright. (Review #531)

To cope with this problem, some devices have adopted an automatic dimming feature based on the brightness of surroundings to prevent ambient light from being intrusive at night. Because people might not want to engage in IAQ when they are asleep, the device ought not to draw users' attention during sleeping. Automatic dimming turns out to be a simple yet effective feature that positively influenced user experiences. Even if ambient light is an effective means to arouse users' engagement when focal attention is not available, it is important to note that it can also negatively influence user experiences under certain circumstances. Adjusting the intensity of an ambient cue (brightness of light) based on the context is necessary to maximize positive user experiences and its usability.

I like that it [the device] automatically adjusts brightness based on ambient light. (Review #784)

I love the option to turn off the display automatically when it detects you've shut off the lights. (Review #901)

Figure 3. IAQ monitors with various forms of color-coded ambient lights for peripheral awareness

Color code

A color-coded theme based on the US EPA's Air Quality Index (AQI) [44] to visually represent the current level of IAQ was widely used as a simple way of implementing ambient light on a peripheral display (e.g., green/blue for good IAQ, orange for moderate IAQ, and purple for bad IAQ). Every device with an ambient light feature adopted the color-coded system to change the color of ambient light based on the level of IAQ. Most users were pleased with the simplicity, intuitiveness, and ease of use of color-coded ambient lights to apprehend their IAQ.

Now we're sitting in the green. It [the device] shows CO_2 levels and VOC levels with a green/amber/red light system that is easy to understand. (Review #81)

Notification

A peripheral display with color-coded ambient light is an effective way to keep users engaged with little to no conscious effort. On the other hand, the nature of peripheral awareness makes it difficult, if not impossible, to engage users when there is highly critical information a user needs to know but when users engage in other events. To overcome this problem, many devices implemented a notification feature to inform users of critical information when an abnormal IAQ event happens. Particular design features of notification we identified include playing a beeping sound, blinking LED light, and sending an alert notification to a mobile application. Many users counted on the effectiveness of notifications to keep themselves in the loop of monitoring IAQ.

The device sends me notifications to my phone when CO_2 level rises even before I can feel it as reduction of my performance, memory and concentration. (Review #1035)

We love the ability to get notifications when the AQI goes over a user-defined threshold, so we don't have to always check on it. (Review #945)

Understanding

Having an increased awareness of IAQ, users started to build informed intuition about specific IAQ situations, through understanding patterns of when peaks and valleys of indoor air pollution occur and what causes them. This confirms prior work that in-home displays with domestic environmental information promote households to better understand and engage in improving their indoor environmental condition [29]. Solving a problem requires knowing the problem exists. IAQ monitors enable users to understand IAQ problems that might not be recognizable otherwise. Three themes emerged as attributes of IAQ data that influence the understanding of IAQ information, including *data quality, data type,* and *data presentation*.

This helped me understand what I breathe and definitely changed some of my habits especially my hygiene. I never knew that CO_2 would go up really high at night when I sleep. (Review #48)

We didn't know that Glade and Lysol had high chemicals in them and were increasing the VOCs in our home. Also, we now feel much better knowing when it's a good day to be outside and when it is better to stay inside and play board games. (Review #732)

Because a form factor of an IAQ monitor is increasingly becoming a peripheral display focusing on supporting awareness with minimal visual cues (See devices on the left side of Figure 1), most detailed IAQ information is offered on an accompanying mobile application. At the same time, essential IAQ data are still being presented on a device, which we report in this section.

Data quality

While there are many definitions of data quality, data are generally considered high quality if it fits for the intended uses in operations, decision making, and planning. Unsurprisingly, we found that the quality of data is a foundational factor to establish users' understanding of IAQ. The majority of the negative reviews were complaints or dissatisfactions about the poor quality of IAQ data. Without high quality data, users lack confidence in the quality of information and may not trust it. Thus, assuring data quality is essential. However, data quality is not what IAQ visualization can directly control, as that lies with manufacturing of hardware. But it is still worth noting how users attempt to evaluate data quality so that designers can explore ways to visually aid users to appraise data quality.

We identified two aspects of data quality that contribute to understanding IAQ data. The first is **accuracy** of data. The most frequently mentioned complaints across all the reviews were about inaccuracy of IAQ data. Many users struggled to determine how accurate their IAQ data are, which led to distrust of IAQ information. Users simply had no means by which to measure data accuracy. Most users "guesstimated" the accuracy and some others purchased multiple IAQ monitors for comparison. While IAQ visualization itself cannot contribute to assuring or enhancing accuracy, it can provide an alternative means to help users approximate accuracy, via design components such as historical and normative comparisons of IAQ data, which will be discussed in the following section.

I want the sensors to be ACCURATE. It does not matter how cool the app for this is if the sensors are faulty. (Review #1043)

We will occasionally see spikes or drops in the numbers when nothing in the environment appears to have changed, which has made us question the accuracy. (Review #978)

The second aspect is **completeness** of data. Because air pollution is often caused by a combination of multiple air pollutants, users conclude that devices that monitor a wide range of air pollutants provide good quality data, and devices that monitor a limited number of air pollutants do not, which is true. While IAQ visualization cannot directly contribute to the completeness of IAQ data to monitor, proper IAQ visualization can effectively inform users with the types of air pollutants an IAQ monitor measures so that users can easily understand the scope of pollutants a device monitors.

This device will give you about 9 different air quality readings including temperature, humidity, carbon dioxide, CO_2, VOCs, and even dust levels. (Review #309)

I didn't know that it [the device] does not measure particulates, which are the component that really matters for smog or natural allergens (mostly). I am about to return it. (Review #781)

Data type

We identified three types of IAQ data that existing devices present in their IAQ visualizations. The most common type is **numerical sensor readings** of air pollutants. Most devices numerically presented readings of air quality sensors (e.g., CO_2 is 28PPM). Numerical readings, however, might not be effective as they require a significant amount of knowledge to interpret what the numbers mean and their influence on health (e.g., *"What does it mean to me if CO in my bedroom is 28PPM?" (Review #57)*). To improve interpretability and understandability of numerical

Figure 4. IAQ Visualization screens with various data types (left) and data presentations (right)

Air Quality Index (AQI) Values	Levels of Health Concern	Colors
When the AQI is in this range:	*..air quality conditions are:*	*...as symbolized by this color:*
0-50	Good	Green
51-100	Moderate	Yellow
101-150	Unhealthy for Sensitive Groups	Orange
151 to 200	Unhealthy	Red
201 to 300	Very Unhealthy	Purple
301 to 500	Hazardous	Maroon

Figure 5. A table of 6 AQI categories. (Image from http://www.airnow.gov)

presentation of IAQ data, many devices applied icons and color codes to convey contextual information along with the numbers (e.g., A fresh-leaf icon for good IAQ and a yellow frowning-face icon for poor IAQ. See Figure 4 left).

Another common type of IAQ data is **IAQ score**. Most devices presented a percentile of an IAQ score out of 100 to provide an overall rate of IAQ (See Figure 4 right). IAQ score is easier to understand than numerical sensor readings as the level of IAQ is presented on an absolute scale of 100, but it still poses problems of interpreting the formation of and the meaning behind the score. This problem can be solved by implementing a design component of disaggregation, which will be described later.

As far as the device's score goes, I don't know how to interpret it. I assume 90 is a better score than say 70, but I don't know what those numbers mean in absolute terms. If my score gets to 100 should I assume it's impossible the air could be improved? And what are the units? (Review #687)

The third type is **air quality index** (AQI), an index for reporting daily air quality, how clean the air is, and what associated health effects might be a concern (See Figure 5). EPA has established AQI with IAQ values, health concerns, and colors as national air quality standards by calculating five air pollutants: ozone, particles, carbon monoxide, sulfur dioxide, and nitrogen dioxide [44]. All devices we analyzed adopted AQI's colors as color codes for visual components such as an icon, graph, and ambient light, while other features of AQI (values and health concerns) were seldom used in IAQ visualizations. Consequently, AQI was never mentioned in the reviews and we assume that even active users may not know much about AQI. While users do not need to know what AQI is, it is important to develop skills to interpret different levels of air quality reflecting on one's health concerns, which is the gist of AQI. Designers can investigate innovative ways to further facilitate the components of AQI to convey IAQ information more effectively.

Data presentation

Proper representation of data is a key to information visualization to help users interpret the meaning of IAQ data. We identified three design components that can contribute to an effective visualization of IAQ data, namely *historical comparison, normative comparison,* and *disaggregation*. In fact, all these echo three key design components of eco-feedback systems' user interfaces [24].

First, **historical comparison** is a design component to provide a current IAQ status relative to the past using a graphical chart that displays information over periods of time. The graphical chart can be as abstract as a set of dots or as detailed as a combination of a color code, numerical sensor readings, and a timeline (See Figure 4 right). Historical comparison turned out to be an effective method to allow users to easily explore, track, and analyze the patterns of IAQ changes comprehensively and holistically.

Even more fun are the charts, lots of chart. You can plot almost any of the sensor readings, giving you simple trend analyses. You can custom create your own charts and take a look at the last week of whatever readings you choose. (Review #410)

The graphs really allow you to track your day. You can see spikes and reactions from the things you do. This has provided me the insight around why the air quality takes a dive and what pieces of the quality of air are taking a dive at certain hours of the day over others. (Review #689)

The second design component is **normative comparison** to compare one's IAQ with IAQ data of other places. Normative comparison is particularly useful to approximate the accuracy of IAQ data when users have no means to measure accuracy, as it helps compare the relative level of IAQ across places. When the level is significantly different from other places, people seek to discover the reason for this discrepancy (e.g., if it is due to inaccuracy of a device or if IAQ-degrading events happen). While there are air quality data of various places to compare with IAQ (e.g., outdoors, other rooms and households, and different cities), we found that most existing devices are limited to providing outdoor air quality for normative comparison and only one device provides a mechanism to compare IAQ data across other rooms and households. Designers can further explore more means to offer IAQ information across different places to implement effective normative comparison.

It has a fun feature that allows you to view the global air quality in a Google Earth like perspective. (Review #832)

It [the device] even lets me know when it is a little stuffy in my home that the outdoor air quality is good so I should open some windows. (Review #1022)

The last design component is **disaggregation**. It refers to design components that allow users to disaggregate aggregated information into specific levels or granular categories. It is particularly useful for devices that offer an IAQ score to help users better understand the meaning behind the score, such as what air pollutants constitute the score and how the score is calculated and updated. However, we did not find any design component to implement disaggregation among existing devices. Instead, we found a large volume of reviews complaining about lack of disaggregation, which ends up undermining understanding of IAQ information.

It says chemicals, but what chemicals? It did not specify what type of chemicals were in the air. I wish the device would break these down a little more so it's possible to know what major chemicals are in the air. (Review #67)

I'd like to know how frequently the sensors are read. It seems to update often but there's no "refresh" capability I could find and it's hard to tell precisely when it last took a reading. (Review #901)

Action

According to the literature, deeper engagement with the presentation of environmental conditions can encourage households to proactively change their behaviors to improve the condition [29]. Findings from our analysis support this in that users quickly took proper actions to lower indoor air pollution once they had a good understanding of their IAQ conditions. We identified three design components to help facilitate user action, including *recommendation, automation*, and *data export*.

We started opening the window a bit and snagged some new houseplants, and now both of us wake up more refreshed and feeling better. (Review #109)

This device was eye opening and completely changed some of my habits when it comes to aeration. I've also replaced my HVAC air filters to a higher level now and it takes care of dropping the $PM_{2.5}$ levels by simply turning on internal ventilation. (Review #871)

Due to a form factor of most IAQ monitors being a peripheral display with minimal visual cues, these design features were mostly offered through an accompanying mobile application, not on the monitor itself, which we report in this section.

Recommendation

Prior work showed that IAQ visualization can create a sense of powerlessness if users lack information to locate the source of poor IAQ or solutions for improving it [24]. To manage this issue, several IAQ monitors and their mobile applications provided relevant tips and recommendations for improving IAQ as actionable IAQ interventions when necessary. The reviews counted this feature to be most helpful in dealing with IAQ issues.

It provides incredibly detailed data, but no recommendations - it's up to you to figure out what to do with the data. I wish they gave you more tips for decreasing the chemical burden in the house. (Review #677)

The home screen gives advice or congratulates you on your air quality. I particularly like the helpful tips for fixing the air quality, like open door/windows or turn on filter, are really useful. It saves me time on having to research everything. (Review #681)

However, contents of some recommendations are limited to simple and generic suggestions (e.g., open/close window) due to a complexity of IAQ-related issues. To enhance the usefulness of recommendations, practitioners and researchers alike need to investigate and develop more actionable IAQ interventions and effective methods to convey such information.

I found the "tips" in the app to be a bit too simplistic. I wish the tips were a bit more explicit and individualized. (Review #510)

Some of the tips don't even make sense. It's August and it's telling me about buying a humidifier when it's 54%. (Review #589)

Automation

IAQ matters for quality of life, but it is not easy for households to always engage in and take action to improve IAQ. Thanks to smart home capabilities that are increasingly available in home appliances to automatically trigger actions under certain conditions, some newly released IAQ monitors are equipped with this capability to pair with other IAQ-related appliances, such as a humidifier, air purifier, and thermostat, to automate the management of IAQ. For instance, an IAQ monitor paired with an air purifier can trigger the air purifier to turn on if IAQ drops below a certain level. This feature would be an ultimate solution for action as it initiates actions without users' physical efforts. Probably because of this, users reviewing this feature were extremely positive about it for both effectively managing IAQ and reducing the burden of IAQ management. Complaints focused on its unfamiliarity and thus difficulty with interacting with it. Developing more user-friendly instructions and toolkits for automation setup can mitigate issues of lack of technical and informational support to facilitate this feature.

I set it up with IFTTT and made rules to control a smart plug that powers a humidifier, such that when the humidify is too low, the humidifier would be turned on automatically. Similarly, you can also setup rule to turn on the air purifier *when there's too much dust in the air. Very useful as I don't have to keep paying attention to it anymore! (Review #953)*

The beauty is that you can even automate that via IFTT and my Nest thermostat. Its ability to orchestrate other devices, such as my Nest thermostat have made it enjoyable to own rather than giving you data and requiring you to take action the device can do it on its own. The only issue I had was that it was not easy to figure out how to set it up. (Review #1278)

Data export

Some users turned out to be very proactive about monitoring IAQ. They did not passively consume the given IAQ information but wanted to actively engage in analyzing and making sense of IAQ data comprehensively and holistically. The historical comparison component might satisfy some of these needs, but these users were seeking to obtain and investigate richer IAQ datasets themselves. One simple way to implement this is to export/download the history of IAQ data, but among the devices we analyzed, no IAQ monitor provided this feature. Accordingly, users strongly requested a data export feature to meet such needs. Designers need to consider ways to implement this feature to enable deeper engagement in IAQ.

I do wish I could more easily save/download the historical data. It would be great if it did some more correlation of my historical data for me to draw some conclusions. (Review #371)

The only thing I don't like is the trends or historic data graphics, there is no way to download data and when you are in the day week or month views only show average data when it should be real data in the selected time period. The one week of data is informative but I'd like to see long term trends. (Review #396)

Outcomes

This section reports the outcomes we identified that users would enjoy in an IAQ monitor. These are not about design components but about tangible outcomes from using IAQ visualization. Nevertheless, it is still critical to consider them because they are ultimate goals that the provision of IAQ visualization should achieve. Consequently, these outcomes can give designers a clue of focal considerations when creating IAQ visualizations. Two types of outcomes emerged: informational gain of increased IAQ knowledge and emotional gain of feeling relieved.

Informational gain of increased IAQ knowledge

Prior work demonstrated that an increase in engaging in and understanding of IAQ dynamics leads to an increased knowledge about how the level of IAQ changes and what influences the improvement or worsening of IAQ [29]. Our findings confirmed it as users considered knowledge gain as a crucial benefit of using an IAQ monitor. Numerous users reported various types of information and knowledge associated with possible sources of indoor air pollution and interventions for poor IAQ they newly uncovered. This information turns into their own knowledge to cope with IAQ-related issues as part of their everyday behaviors.

It's interesting to see how the air quality changes as local humidity changes from a steamy shower, or with cooking a pot of pasta. When an extra person is in my apartment, I was surprised to see how much the level of carbon dioxide actually changes. (Review #533)

I finally know what air I am breathing in and out. After cooking CO_2 level increases and it alerts us to open windows for air circulation and turn on central fan through mobile app. Pretty neat. (Review #680)

Emotional gain of feeling relieved

As such, satisfying users' unmet informational need to understand the quality of indoor air is the primary goal of using an IAQ monitor. Then, using an IAQ monitor yielded an additional but invaluable outcome: users felt relieved from the concerns associated with poor IAQ. Users greatly appreciated being relieved of an emotional burden of worrying about IAQ, especially when a household has a child or someone who suffers from respiratory problems. Being well informed about the state of IAQ gave users reassurance about effective management of IAQ.

Keeping my IAQ monitor on all of the time and checking it occasionally allows my family to rest easy, especially with a toddler around the house. It gives me peace of mind being able to see what's in the air we're breathing. I feel much better now, obviously psychologically as well as physically. (Review #109)

I am relying on my IAQ monitor to see what categories are contributing to the effects of my allergies/asthma and can adjust my room settings to mitigate those effects. Feeling much relieved now. (Review #321)

DISCUSSION: DESIGN IMPLICATIONS

As a pervasive technology, an IAQ monitoring device can be an effective mechanism to promote people's engagement in managing and improving IAQ when it presents IAQ information *properly*. This paper sought to investigate what requires when designing IAQ visualizations for a proper presentation of IAQ information. Our findings echoed the importance of ambient awareness, the unique design component of persuasive technology to make users aware of qualities of the environment. Forms of ambient awareness systems vary, as we reviewed in the Related work section, but a design tactic to make changes in environmental conditions visible is most suitable for IAQ visualizations to prompt awareness. Since personal technologies are increasingly focused on aesthetic and minimalist aspects of design, it is important to make an IAQ monitor an "aesthetically pleasing display of information which sits on the periphery of a user's attention" [34]. In doing so, *ambient light* can be an important design component to ensure both usability and aesthetics. Thus, we suggest that it is essential to take into consideration *ambient light* as a key design component of IAQ visualization as an ambient display.

We found automation to be very promising for future design of personal technology as an increasingly popular feature of smart-home technology. While automation is convenient by enabling management of issues of concern without users' direct attention and action, it is important to balance the amount of automation and user engagement a technology offers. If a device requires no user engagement in managing a problem, it might be convenient for a while but will eventually negatively influence a user's knowledge of and cognitive abilities to understand the problem (e.g., not knowing what causes poor IAQ). Contrarily, if a device requires too much user engagement, a user might get burdened and overwhelmed by managing the problem. Thus, balancing automation and user engagement is another important design consideration.

Three constructs of the theme, *understanding > presentation*, in our framework were identical to three key design components of eco-feedback technology: *historical comparison, normative comparison,* and *disaggregation*. While it is not surprising that there is a substantial overlap between these two sets of design components since an IAQ monitor is a type of eco-feedback system, what is interesting is that two other design components of eco-feedback system, *rewards* and *incentives*, never emerged from our analysis. We assume that there are two possible explanations for missing these components in our findings: (1) IAQ information might be considered as technical data to analyze rather than behavioral/social data to play with for incentives or rewards; and (2) there might be no need for tangible incentives or rewards as the improvement of IAQ can be enough incentive or reward both physically and emotionally. For the first explanation, it is worth exploring ways to reshape a users' perception of IAQ information through a ludic approach [14]. For the second explanation, these missing design components actually offer great potential for expanding user engagement in IAQ when combined with other design components. For instance, historic and normative comparisons can further strengthen engagement and persuasion by coupling with relevant rewards and incentives. The question for designers is what relevant rewards and incentives to offer other than the information of IAQ improvement. Further investigation is needed to develop new design ideas about rewards and incentives for IAQ visualization.

Lastly, our analysis revealed only two types of outcomes: informational gain of increased IAQ knowledge and emotional gain of feeling relieved. However, this does not mean that these two outcomes are the only outcomes that the use of IAQ monitors would yield. Indeed, there might exist other outcomes that this study did not identify. For instance, prior works have shown people feeling powerless as a negative consequence of accessing quantified-self data [9] or sharing as an effective means for collaborative problem-solving of public health concerns [15], neither of which emerged in our analysis. That our findings miss these facets does not mean that such potential outcomes are not to consider, but instead demonstrate limited user experiences with existing IAQ monitors, at least not apparent in the product reviews. This evokes further discussion about a design space and opportunities to transform these under-realized outcomes into reality in the broader context of persuasive technology, including quantified self, public health, and healthcare technologies, in addition to the realm of eco-feedback design.

LIMITATIONS

This paper used Amazon's product reviews in the US to investigate how users respond to various design choices that off-the-shelf IAQ monitors implemented. Thus, our findings must be evaluated within the context of several limitations that product reviews have, including unknown demographics, cultural differences, and potential algorithmic biases and solicited reviews. The possibility of fake reviews is a particular concern as it would negatively impact the validity of data. We manually reviewed all 1,447 reviews to open code user feedback on various features of IAQ monitors and reported salient themes that emerged as the analysis progressed. While this process must have eliminated some outliers, we acknowledge that it is never perfect. Also, our findings might not provide the full picture since we only used the US data. The prevalence of asthma and other respiratory problems in the US alone, however, has led to a significant and long-lasting effort to improve IAQ. Further, we do not argue that our findings are applicable to other regions.

CONCLUSION

The advent of innovative computing and sensor technology made possible data-driven monitoring of everyday life. This paper reviewed one facet vital to quality of life, IAQ. By analyzing reviews of 7 IAQ monitors on Amazon and their design components for IAQ visualizations, we sought to provide design principles for effective IAQ visualization. Based on our findings, we created a conceptual framework to explain the process of facilitating effective IAQ visualization with a proposed set of design considerations in each stage. To the best of our knowledge, this paper is the first attempt to conceptually frame design considerations for IAQ visualizations. Expanding prior work on persuasive technology, this paper contributes to the HCI and design communities by offering design strategies for effective visualization of eco-feedback systems. We hope that our framework will provide a valuable means to integrate the wealth of research in eco-feedback system design and beyond to advance both research and practice.

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