Designing to Engage Children in Monitoring Indoor Air Quality: A Participatory Approach

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ABSTRACT
Indoor air quality (IAQ) is especially important for children because they are more susceptible to the deleterious impacts of poor air quality compared to adults. While devices to monitor IAQ are increasingly available, these are designed primarily for adults, and little attention has been paid to their potential use by children. This paper describes an effort to engage children directly in the design of an IAQ visualization interface for children. In engaging children in participatory workshops, we found that they rely heavily on visual, olfactory, and thermal cues to perceive and assess IAQ. Reflecting on these findings and based on design principles for technology for children, we created and tested child-friendly interface prototypes for IAQ visualization. Based on children's input, we designed a final set of visual interfaces that will be implemented in the IAQ monitor. The next study will test and deploy the monitor in the real world.

Author Keywords
Indoor air quality; children; participatory studies

CSS Concepts
• **Human-centered computing~Human computer interaction (HCI)**; *Empirical studies in HCI*

INTRODUCTION
Indoor Air Quality (IAQ) refers to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants [34]. A substantial body of scientific evidence indicates that indoor air could be more polluted than the outdoor air, including in the largest and most industrialized cities [33]. Other research indicates that people spend approximately 90% of their time indoors [35]. Given the potentially high pollutant concentrations indoors and the amount of time we spend indoors, the risks to health from exposure to air pollutants indoors might be greater than risks from exposure to air pollutants outdoors.

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Children and their health are of particular concern when it comes to poor indoor air quality. Not only do they spend the majority of their time indoors, but they also are most susceptible to the effects of air pollution. Their lungs are still developing, and they breathe in greater volumes of air per body mass compared to adults [14].

Off-the-shelf devices to monitor IAQ enable users to monitor IAQ and take actions to manage it. Research has shown that simply being aware of IAQ levels can positively motivate behaviors to realize better IAQ [21]. Most existing IAQ devices, however, are not designed specifically with children in mind, and their interfaces to visualize IAQ are not optimized for interaction with children. If the interface is designed without regard for users' cognitive and other abilities, it can cause confusion and other deficits in how information is understood and acted upon [8]. Because the needs, skills, and expectations of children differ drastically from those of adults, a technology designed for adult users can be difficult for children to use and embrace [11]. This study investigates design considerations to best convey IAQ information to children, with the ultimate goal of creating an IAQ monitor optimized for children's use in monitoring and improving IAQ.

To accomplish our research objective, we conducted two complementary studies with children. First, we conducted participatory workshops in which we involved children as *informants* to participate in the design process for IAQ visualization, to express their opinions, and to determine how they would like to interact with IAQ visualization [11]. The findings from this study showed that children rely heavily on sensory perceptions, including visual, olfactory, and thermal cues, to indicate their perception of IAQ [22]. Using these findings and reflecting on design principles for children's technology [6], we created a set of child-friendly interface prototypes to visualize IAQ and provide relevant, actionable interventions to improve it (e.g., opening windows to let in cleaner air). Next, we conducted focus groups in which we involved children as *testers* [10] to try out our interface prototypes and to express opinions and suggestions for their improvement [10]. Finally, we used this input from the *testers* to develop a final prototype interface to visualize IAQ.

This work contributes to our growing understanding and practice of involving children in the process of designing technology for children. Our study demonstrates a robust design process in which children play critical roles as both *informants* and *testers* to capture the child's perspectives as a guiding principle when designing technology for children. This process provides children's insight into the design of the IAQ visualization interface, explains children's challenges in understanding IAQ, and evaluates the interactivity and designs of interface prototypes. To the best of our knowledge, this work is the first study that investigated how children perceive and assess IAQ to create child-friendly interfaces for IAQ visualization. We are hopeful that our work motivates future HCI research to engage children in designing technology for use by children.

BACKGROUND

Devices to Monitor IAQ as Persuasive Technology

Traditionally, IAQ measurements have been conducted by experts using sophisticated and expensive equipment. Recently, there has been an increasing availability and capability of low-cost IAQ monitoring devices that offer great potential for effective monitoring and analysis of IAQ. Many of these tools are developed not only to measure IAQ (e.g., [5,19]) but also to raise occupants' awareness of indoor air pollution and promote healthier everyday practices (e.g., [20,21]) as a form of persuasive technology [13]. Using these tools, laypeople can monitor and evaluate IAQ and then take action to improve their indoor environmental conditions.

Persuasive systems refer to systems to promote positive attitudes or behaviors of the users through persuasion and social influence, but not through coercion. Such systems have been increasingly recognized as an important topic in the HCI community pertaining to wellness, quality of life, and health-related behaviors (e.g., [20,28]). A variety of visualization techniques and components have been explored to investigate the effectiveness and persuasiveness of these systems (e.g., [1,27,29]), and many persuasive systems have shown a positive influence on health-related behaviors (e.g., [15]). As such, personal computing and sensing technologies have been designed to promote engagement in health-related issues. However, little effort has been made to include children who have their own likes, dislikes, curiosities, and needs that are not the same as adults [9]. This study tackles this issue by directly engaging children in the design process to elicit their preference to design IAQ monitoring tools reflecting how children perceive and assess IAQ.

Designing Technology for Children

Children increasingly use computing technologies for their education and entertainment. Given the greater exposure of children to these technologies, it is imperative to design them taking into account children's abilities, interests, and developmental needs [17]. Complicating matters is that no design is suitable for all age groups of users, and most software and applications for children are developed by adult designers, who may not be sufficiently familiar with children's skills and preferences [18]. At best, the resulting applications may not be child-friendly; at worst, they may inhibit the intended task. Clearly, designers should develop software based on the target users' cognitive abilities and consider children as a special group when children are the primary users of the software [2].

A growing body of literature discusses children, technology, and human-computer interaction issues. Early discussions focused primarily on the impact of new technologies on children as learners rather than on the role of children as developers of learning technology [23,30]. Since the late 1990s, discussions have included children as design partners, with active involvement from initial brainstorming experiences to final evaluation phases [7,9]. In 2002, Druin introduced a new concept: the creation of applications by children for children. Druin suggested that children can play critical roles in various ways throughout the design process: as *users* who use the applications or devices and comment on them; as *testers* who try out the prototype and make suggestions to improve it, or simply express opinions; and as *informants* who participate in the design process, to express opinions, to determine how to interact with the device and the result obtained [11]. Since then, researchers in the HCI and child-computer interaction communities have involved children as active partners in the design of technology for use by children (e.g., [3,12,16,31,36]).

As part of this effort, Chiasson and Gutwin produced a catalog of design principles for technology for children [6]. They categorized design principles based on three areas of children's development: cognitive, physical, and social/emotional. Cognitive development is the mental and intellectual growth of a child; physical development is the development of motor skills; social development involves forming relationships with others, and emotional development is a child's ability to understand, regulate, and express their own feelings.

Cognitive Development

- Literacy: Most interfaces designed for adults assume that users are proficient readers with fairly extensive vocabularies. Young children, however, have not reached this proficiency level. Thus, text may not be an effective means of displaying information for children. Visual or audio cues prove more valuable, as long as the information presented is clear and age appropriate.
- Feedback: Children expect to see the results of their actions immediately. If nothing happens after their input, children may repeat their actions until something occurs.
- Imagination: Children are good at playing with a metaphor and readily immerse themselves in pretend situations. Metaphors are useful design factors as children expect the on-screen objects to behave as they would in real-life.
- Concreteness: Children expect their actions to have a direct effect on their environment. For this reason, input devices should have direct mappings to the actions on the screen, and abstractions need to be used with care as they are not intuitive for many younger children.

Physical Development

- Motor Skills: Children's motor control skills develop over time. Thus, typing can be an obstacle for younger children. Touch screens offer a simple alternative to other input devices for those whose motor skills are not yet fully developed.
- Tangibility: Children enjoy playing with tangible objects. Thus, simply having a computerized, tangible device to interact with can lead to valuable exploration and learning for children. Especially, direct manipulation through tangible devices can enhance children's understanding and interpretation of information.

Social/Emotional Development

- Motivation and Engagement: Many systems for children aim to teach or provide practice with particular skills. Thus, the value provided by the systems can be achieved when children engage in the task at hand. Several means of motivating children in the use of computer systems have been noted, including embedding fun features, providing animated digital agents, and offering intrinsic and extrinsic rewards.
- Social Interaction: Social interaction is an important part of children's lives, and technology can encourage and facilitate this interaction with other children from around the world. To support children's social interaction, technology and interaction with it need to follow social conventions and meet their expectations.

METHODS

We drew upon the concepts outlined by Druin [11] and Chiasson and Gutwin [6] when designing a series of participatory studies of the design process with children aged seven to twelve years. We targeted this age group because children in this age range exhibit a range of physical, social, and mental skills appropriate to technology development [11]. This study was reviewed and approved by the institutional review board. Consent was attained from caregivers on behalf of the children, permitting participation in the study, video recording, and photographs. Children additionally gave their verbal assent. Monetary compensation for participation was provided to caregivers at the end of the study.

Study I. Children as *informants*: Participatory Workshop

As a first step, we positioned children in this study as *informants* to harvest their contributions as to how they would like to interact with IAQ visualization. This approach allowed us to tap into children's direct experiences with their perceptions, assessment, and management of IAQ.

Study site and participant recruitment

Participants were recruited among the residents of an affordable housing community in Elizabeth, New Jersey, a city with poor air quality [24] and a high prevalence of chronic respiratory diseases such as asthma [25]. Through distributing recruitment flyers on-site and by word-of-mouth during on-site summer camp programs, we recruited 19 participants aged between 7 and 12 for 4 workshop sessions (average age = 8; SD = 1.36, See Table 1). Eighteen children were African American, and one child was Latino.

Session	Participant	Average age
1	3 girls, 1 boy	8.1
2	2 girls, 5 boys	8.2
3	2 girls, 3 boys	8.7
4	3 girls	9.0

Table 1. Workshop participants per session

Data collection

The participatory workshops were conducted at a community meeting room of the housing community. A workshop consisted of three sessions: a guided discussion about IAQ, a session to demonstrate and try out an existing IAQ monitor, and a hands-on design activity session. After explaining the purpose of the workshop, participants introduced themselves with their names and ages. Next, a researcher gave a presentation about IAQ comprised of two components. First, a researcher prompted a discussion among participants about IAQ by asking questions, such as "*What does IAQ mean to you?", "What do you think makes IAQ good/bad?", "Why does IAQ matter?"* and *"How do you maintain good IAQ?"*. At the end of each question, we presented related educational material about IAQ (e.g., sources of poor IAQ, its effects on health, and solutions to improve IAQ). These activity components had two purposes: (1) to gain insights about the participants' current perspectives and thoughts on IAQ, and (2) to provide them with actionable information about IAQ.

We then measured the level of IAQ in the workshop room using an AirVisual, an IAQ monitoring device that measures $PM_{2.5}$ and CO_2 concentrations. AirVisual employs various visual cues to present the level of air pollution, including a bar graph with colors, numeric readings of $PM_{2.5}$ (i.e., particles smaller than 2.5 μm) and CO_2 concentrations, and icons with different facial expressions (see Figure 1). We used AirVisual due to its availability to researchers. This and many other existing IAQ monitors have similar visual components to present air pollutant concentrations. AirVisual has no particular significance, and any other device could have been used. Participants were prompted to

Figure 1. AirVisual, an IAQ monitoring device that employs colors, graphs, numbers, and icons to present IAQ (https://www.airvisual.com)

share their thoughts and feedback on the IAQ of the workshop room and the graphical interface of the AirVisual.

Finally, participants engaged in a hands-on design activity in which they were given paper, crayons, coloring pencils, and markers to visually express their thoughts on our questions as sketches (See Figure 2). The questions related to the main topics of the prompted discussion, including, *"What do you think a space with good/poor IAQ would look like?", "What would happen when IAQ is poor,"* and *"How would you get rid of dirty air?"* We asked the participants to draw sketches to answer these questions visually.

Figure 2. Design activity sessions in which children drew sketches about visualizing IAQ using pen and paper.

Data analysis

Audio of the video recordings was transcribed and analyzed using inductive thematic analysis to reveal patterns across data sets, including open coding, axial coding, and selective coding [4]. We first conducted open coding to identify and code concepts that are significant in the data as abstract representations of events, objects, actions, interactions, etc. Next, we categorized the related concepts created by open coding into higher conceptual phenomena using axial coding. These phenomena refer to repeated patterns of events, happenings, actions, and interactions that represent people's responses to problems and situations. Last, we followed the selective coding process to assemble our conceptual phenomena extracted from axial coding into a single storyline by building relationships across phenomena. Due to the small sample size and narrow distribution of ages, we did not quantitatively analyze data by age groups. Using the themes and concepts identified by our *informants* and reflecting on the design principles for technology for children [6], we created 4 sets of IAQ interface prototypes (See Figure 5).

Study II. Children as *Testers*: Focus groups

Next, we conducted a series of focus groups as a means to understand how children would perceive and interact with the interface prototypes for IAQ visualization we created using input from Study I. We positioned children in this study as *testers* because they tried out the prototype and made suggestions to improve it. The purpose of this study was to learn how children interact with the interfaces of IAQ visualization and to apply their preferences into the design of a final product. This approach allowed us to tap into children's direct perception, preference, and understanding of the prototypes.

Study site and participant recruitment

Participants were recruited among the residents of an affordable housing community in Trenton, New Jersey, a city with below-average air quality [33]. For recruitment, we worked closely with a local community development corporation that serves this community. The manager first identified potential participants from a pool of their outreach program participants, contacted a caregiver of each participant to ask if they were interested in participating in the study, and sent us the contact information of those who agreed. Then, we contacted each party to confirm their participation. We held 4 focus group sessions with 14 participants aged between 7 and 12 (average age = 9.6; SD = 1.5, See Table 2). Ten children were Latino, and four were African American.

Session	Participant	Average age
1	2 girls, 1 boy	10.6
2	2 girls, 2 boys	8.6
3	3 girls, 1 boy	9.0
4	3 girls	9.3

Table 2. Focus group participants per session

Data collection

A focus group comprised two sessions: a prompted discussion about IAQ and a group discussion session to elicit feedback about the interface prototypes of IAQ visualization. First, a researcher gave a presentation about IAQ to prompt a discussion about the IAQ. The procedure and topics of a prompted discussion were identical to those of Study I. Next, the participants were shown each of the interface prototypes in a random sequence both on a presentation slide and by providing a paper copy. Then, participants were asked to share their interpretation, preference, thoughts, feedback, and suggestions for the improvement of each prototype. We randomized the order of presenting the prototypes to mitigate possible order effects bias.

Data analysis

Similar to Study I, audio recordings were transcribed and analyzed using inductive thematic analysis to reveal patterns across data sets, through open coding, axial coding, and selective coding [4]. In the first step of the open coding process, significant themes were captured. Next, our axial coding grouped similar themes into categories. Last, we followed the selective coding process to assemble conceptual phenomena extracted from axial coding into a single storyline. Through this step, we integrated all concepts by building relationships across phenomena. Again, we did not

Figure 3. Focus group sessions where children provide feedback about different prototypes for IAQ visualization

analyze data by age groups due to the small sample size and narrow distribution of ages.

RESULTS

Study I: Unraveling children's perspectives about IAQ

It is difficult to assess air quality through bare human senses such as eyesight or smell because most air pollutants are colorless, odorless, and invisible to the naked eye at typical indoor concentrations. Therefore, human physical sensors are not a reliable means to measure IAQ. The findings from Study I, however, demonstrated that our participants rely heavily on their sensory perceptions, including a sense of smell (olfactory comfort), air temperature (thermal comfort), and visual cues (cleanliness of space) to perceive and assess IAQ, regardless of whether these perceptions are specifically related to IAQ or to broader indoor environmental quality (IEQ) issues.

While smell at times might be misleading about IAQ status, the smell was found to be the most prevalent sensory perception that children use to describe and assess IAQ, confirming previous findings [33]. When we asked participants to describe places where air quality is not good, places and objects relating to unpleasant odors were mentioned, including bathroom, garbage, trash, basement, attic, smelly cheese, along with tobacco and other sources of stink and stench.

> *"Sometimes I can smell that somebody is smoking in the backyard. That makes air quality bad." (Participant A10)* [1]

Thermal comfort was another sensory perception that our participants used to assess IAQ. Thermal comfort is defined as "the state of mind that expresses satisfaction with the thermal environment" [2]. While it is an important factor in determining overall IEQ, thermal comfort is considered part of IAQ as it is dictated by air temperature and humidity and not by the presence of particular air pollutants. For our participants, however, thermal comfort was an important indicator of IAQ. When we asked them to describe what they thought of IAQ in the workshop room, participants' answers were related to the air temperature in the room. Similarly, when asked to describe what the IAQ was in places other than the workshop room during the same day, participants described it reflecting mostly on air temperature, such as indoor air quality is bad when the air temperature is high. The workshops were conducted during several hot and humid days in the summer, which may have affected the participants' perception of heat and hot weather on IAQ.

> *"The sunrise during the day heats up the ground. That's why in summer the air pollution becomes worse because of the Sun." (Participant A1)*

> *"It was really hot today. We were outside so the air was really heavy and it smelled contaminated… Air is nice and cool in here the workshop room because of an air conditioner." (Participant A4)*

Last, visual cues were commonly used to identify the source of indoor air pollution and to address IAQ. When we asked them to think about good air quality, participants mentioned objects and terms that are related to nature and the environment, such as flowers, grass, and butterflies.

> *"Air is nice and clean when the plants and grass are greener." (Participant A13)*

> *"It's very bright and air is clean outside because of the Sun. It's colorful outside." (Participant A9)*

While cues such as green plants and the bright sun might not be directly related to IAQ, they do provide useful indicators that such symbols could be used to visually indicate IAQ, especially where children are concerned.

Also, the participants suggested that air pollutants would be something that piles up like dust in the corner of a room or that floats near the ceiling. It is an astute observation as dust in the air contributes to the dust on the floor. When children were prompted to imagine what indoor air pollutants would look like, they mentioned surfaces covered with dust, such as old books, attics, and basements – again an astute perception based on the settling of airborne particulate matter. One child drew a bedroom and a bathroom in which the corners of furniture and household objects are *"contaminated with air pollutants"* – marked in green color (see Figure 4 left), and another child drew a house with air pollutants that infiltrated through a window and float near the ceiling (see Figure 4 center).

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[1] In the excerpts, "Participant A#" refers to the #th interviewee of a participatory workshop, and "Participant B#" refers to the #th interviewee of a focus group.

Figure 4. Sketches of a bedroom in which perceived air pollutants are marked with green color (left); A sketch of a house with bad IAQ (center); Sketches of a bedroom perceived to have bad IAQ and good IAQ (right).

Another important visual cue when assessing IAQ was the cleanliness, tidiness, or organization of a space. Participants considered IAQ to be good when the indoor space was clean and organized. Consequently, cleaning was mentioned as a major existing practice that they would perform to improve IAQ. For example, one child drew a disorganized bedroom with toys on the floor to represent a room with bad IAQ and an organized room without any toys on the floor to represent a room with good IAQ (see Figure 4, right). A more detailed discussion of this study and the results can be found in [22].

> *"Air quality in my room gets bad when it is messy." (Participant A12)*

Design Considerations from Study I

The findings from Study I suggest several graphical themes relating to sensory perceptions to be used for IAQ visualization. For instance, a strong perceptual correlation of good air quality with visual cues such as "green plant and grass" or "clean and tidy room" and bad air quality with olfactory cues such as "trashcan" and "toilet" can be used as a metaphor to visually present the underlying meanings of the level of IAQ (e.g., a display visualizing a mock-up indoor space with different levels of tidiness and amount of dust depending on the level of IAQ).

At the same time, we have to be cognizant that those images do not represent the actual IAQ, but rather the sensory perception of IAQ by the participants, and that they might have a different meaning for a different group of children. Thus, there is a risk that such visualization might provide children with incorrect or even misleading conceptual models about IAQ since some of these metaphors are in truth not correlated with IAQ (e.g., thermal comfort has no direct relation to the level of air quality) or even represent sources of air pollutants (e.g., scented candles that provide satisfying smell will, in fact, worsen air quality due to emission of very fine particulate matter).

A possible solution to mitigate this problem is to use children's propensity for perceptual and visual metaphors in designing visual interfaces. Such interfaces should have objects and concepts familiar to children and be related to IAQ, such as opening/closing windows, smoking, cooking, and burning candles [27]. These themes can be used not only to represent the underlying meanings of the level of IAQ (e.g., visualizing an animated person who smokes to indicate that IAQ is extremely poor) but also to provide actionable behavioral interventions for IAQ improvement (e.g., an animation of opening windows to improve IAQ if outdoor air quality is good).

Using Input from Study I to Design initial Interface Prototypes

Based on the findings from Study I and reflecting on the design principles for children's technology [6], we created four sets of prototypes that visualize IAQ on a mobile device (a tablet or a smartphone wirelessly connected to an IAQ sensing unit) by adapting to the ways in which children perceive and assess IAQ. Reflecting the design principles by Chiasson and Gutwin [6], we used the following five criteria as a baseline of prototype design: minimizing the use of text (*literacy),* adopting physical metaphors (*imagination)* using familiar objects (*concreteness)*, providing immediate feedback on actions (*feedback),* and facilitating direct manipulation (*tangibility*) in creating prototypes. Each prototype consists of three conditions to present different IAQ status, such as poor, moderate, and good IAQ. The prototypes for moderate and poor IAQ provide an icon or an object to further explore the possible causes of indoor air pollution and the actionable solutions for children to improve IAQ. Two prototypes were designed as playful versions, and the others were designed as scientific-looking visualizations.

Prototype A: A metaphor of smell and visual cues

Prototype A focuses on visualizing IAQ using a metaphor of sensory perceptions relating to unpleasant smell (a trash can) and visual exaggeration of air pollutants. In addition, a window is added to illustrate the condition of air quality outdoors. As a playful prototype, this prototype depicts a child as the main character to be affected by IAQ, either expressing happiness when IAQ is good and feeling suffocated when IAQ is not good. When IAQ is poor, a trash can full of garbage appears with a blinking red background. Clicking the trash displays a speech balloon to explain the possible causes of indoor air pollution and the actionable solutions to improve IAQ (See Figure 5, top left).

Figure 5. Prototypes for graphical visualization of IAQ: Prototype A. Illustrating a child with dirty room (top left); Prototype B. Illustrating room organization (top right); Prototype C. Bar graph of IAQ using emoji characters (bottom left); Prototype D. Providing a direct comparison of air quality indoors and outdoors (bottom right)

Prototype B: A metaphor of visual tidiness

Prototype B focuses on visualizing IAQ by illustrating a room with various objects to present different levels of tidiness/organization. For instance, a room is well organized when IAQ is good, and the room becomes cluttered with items such as a shelf with disorganized books, a toy, garbage, and spilled water left on a floor, and dead leaves dropping from a flowerpot when the IAQ is poor. In addition, a window is added to illustrate the condition of air quality outdoors. As a playful prototype, this prototype depicts an adult as the main character to react to IAQ, such as mopping or organizing shelves. When IAQ is poor, a blinking orange icon shows up. Clicking it displays a speech balloon to explain the possible causes of indoor air pollution and the actionable solutions for children to improve IAQ (See Figure 4, top right).

Prototype C: A horizontal bar graph of IAQ with emoji

As a scientific-looking visualization, Prototype C focuses on visualizing IAQ using emoji characters on a horizontal bar strip as a direct presentation of IAQ that many existing IAQ monitors use. An emoji is a graphic symbol that expresses concepts and ideas pervasively used in mobile communication and social media [26]. The emoji has been proven to be an effective visual element to communicate with children about contextual meanings of information (e.g., [32]). We adopted emojis because it helps break the language barriers since meanings of symbols are easily understood regardless of the level of literacy and language. Furthermore, images tend to have more appeal than text. In this prototype, the emoji makes a smiley face when IAQ is good, and it frowns when IAQ is poor. In addition, the color of a horizontal bar strip gradually changes from green to purple to illustrate the level of IAQ: green color is associated with good IAQ and purple with bad IAQ. These colors correspond to the AQI color scheme adopted by the US EPA [34]. A lamp icon shows up when IAQ is not good, and clicking it displays a speech balloon to explain the possible causes of indoor air pollution and the actionable solutions for children to improve IAQ (See Figure 5, bottom left).

Prototype D: Comparing air quality indoors & outdoors

Prototype D focuses on visualizing IAQ as a direct comparison to air quality outdoors using colors. This prototype was initially created based on the sketch in Study I that visualizes air pollutants inside a house (see Figure 4, center) and then further developed to this version. Following the AQI color scheme, the colors of indoors and outdoors change according to the current level of air quality indoors and outdoors (e.g., indoor space is colored with green when IAQ is good, orange when IAQ is moderate, and purple when IAQ is bad). As a scientific-looking visualization, we incorporated vertical strips that many existing IAQ monitors use to indicate the current level of air quality indoors and outdoors. A button icon shows up to indicate the possible causes of indoor air pollution and the actionable solutions for children to improve IAQ (See Figure 5, bottom right).

Study II: Children's Feedback on the Interface prototypes

Overall, the focus group participants responded positively to all of the prototypes. Most participants did not have any difficulty interpreting the meanings of each prototype and expressed positive feelings about interacting with the prototypes. Participants appreciated graphical elements of the prototypes, such as metaphors that behave as they would in real life, interactivity, such as a button/icon to click and play, and the minimum use of text, all of which confirmed the design principles for children's technology [6].

> *Prototype B: "It's pretty simple to understand. I mean, click the green dots to learn ways to learn tips to keep it that way. When you have bad air quality, you can't open the window because the tree is dead." (Participant B1)*

Across different prototypes, color, the most dominant form of a visual element, was reported to be most effective for children to understand the underlying meanings of the level of IAQ. We applied a conventional color scheme of green being good, orange being moderate, and purple being bad to corresponding levels of IAQ; such a scheme made it intuitive for the children to interpret the meanings of pictorials.

> *"It's easy. The green one is good, the orange one is kind of good, and the red one is super bad." (Participant B12)*

> *"Most children will understand what the different colors mean. Red is bad, and green is good to go." (Participant B8)*

Relating to this, several participants recommended making graphical representations more apparent to make it easier to understand the meanings. Examples include changing the tone of color to more vivid or darker and exaggerating the shapes of on-screen objects.

> *Prototype B: "If it's bad, make the dots a little darker. If it's moderate, you can make it maybe half the leaves on the tree fall off, some of which are visible on the ground. And, for green make the leaves on the plant a little bit greener." (Participant B3)*

In terms of preference, there was no unanimous choice of a preferred interface prototype; rather, different prototypes were preferred for different reasons. Both prototypes A and B focused on illustrating the interior of a house using metaphors associated with sensory perceptions. The primary difference between these two prototypes is the main character and its role in the prototypes. In Prototype A, a child, who is of similar age to the participants, is the main character, and he is passively influenced by IAQ either positively or negatively. Whereas in Prototype B, an adult is the main character who actively responds to poor IAQ to improve it by organizing a room. While both prototypes were easily understood and well received by all participants, participants had different emotional reactions to them. In prototype A, they seemed to have empathy with the boy character because of his suffering from poor IAQ or blamed the boy for not doing things to improve IAQ. With Prototype B, they felt as if they were playing a virtual game by interacting with the character.

> *Prototype A: "He (a character) is covering his nose and his mouth, like it prevents him from breathing the bad indoor quality… I'm guessing those are very clear for children to understand. So, they can alert their elders when they see this". (Participant B2)*

> *Prototype A: "I think it's telling us he (a character) is being lazy and not taking the trash outside. So it's basically his fault that the indoor air quality is bad… He's too lazy so he won't clean it." (Participant B10)*

> *Prototype B: "Instead of a kid in the other interface, there is an actual room with a cleaning lady or a mom*

in this interface. And I guess I can click the dots to make the lady to clean the room and to clean the air. It will be fun playing with her!" (Participant B4)

Prototype C retained an emphasis on the main character but used an emoji as an entity to visually narrate contextual information about IAQ. Most participants expressed strong comfort and ease interpreting the meanings of the illustration through the emoji characters in Prototype C.

Prototype C: "The air is good because the face is smiley, right now. It's easy." (Participant B2)

Prototype C: "Yeah, it (emoji) is happy. So I'm happy too. I've got good air." (Participant B10)

Different from the other three prototypes, Prototype D did not employ any character to visually narrate the context. Instead, it employed a metaphor of a house with distinct colors to illustrate a direct comparison of air qualities indoors and outdoors. Our participants found it very easy and intuitive to understand, and chose this prototype as their favorite due to its simplicity, comparability, and concreteness.

Prototype D: "It's probably the easiest. It really is easy, because the house says your room is bad and that the outside air is good. And, I guess it's more easier for people that have a hard time. I don't know. I guess that's all I have to say". (Participant B2)

Prototype D: "I like it. It's pretty good. The air quality in your room is worse than the air quality outside. That's easy. To improve the indoor air quality try these actions. It's pretty good, actually. It's easiest to understand for children". (Participant B14)

Overall, we did not receive any suggestions for improvement or modification of our prototypes except making graphical representations more apparent to make it easier to understand their meanings. Participants reported all prototypes to be easy, simple, and intuitive enough for young children to understand the current level of IAQ and actionable information to perform to improve IAQ. We attribute this result to our effort to actively involve the primary stakeholders, children, in the design process, as *informants* to express opinions and to determine how to interact with IAQ.

Design Considerations from Study II

Two salient design considerations have emerged from the findings of Study II. First, the main character that graphically narrates the meanings of information might determine the emotional, experiential, and contextual interpretation of information. In our initial interface prototypes, we had three different types of characters: a reflective self (a child in Prototype A), a third-party character (an adult in Prototype B), and an iconic character (emoji in Prototype C). While a more nuanced understanding of each character and its influence is needed through further studies, our observations and discussions with the participants imply that it is crucial

Figure 6. A set of final prototypes for graphical visualization of IAQ for children

to properly design the properties and the characteristics of the main character in order to convey the meaning of IAQ and to provide positive experiences of interacting with the visual interface. Second, the use of appropriate colors and graphical metaphors determines the efficacy of a system. In our prototypes, we appropriated a variety of on-screen objects and color codes as both a metaphor of the situation and a concrete expression of abstract concepts with an aim to make it intuitive for children. Our observations and discussions with the participants confirmed that these visual elements are indeed crucial in supporting children to reason about and interpret the meanings of the visual interface.

Final Interface Prototypes

Reflecting on the feedback from Study II, we created the final version of the IAQ visualization interface to implement in an IAQ monitor for children. The final design is a modified version of Prototype D that employs a metaphor of a house with distinct colors to illustrate a direct comparison of air quality indoors and outdoors (see Figure 6). Based on the input from Study II, we chose and modified Prototype D as a final set of visual interfaces that will be implemented in the IAQ monitor. In the final design, we applied more vivid colors to visualize air quality indoors and outdoors, used an image of a cat as a new main character that embraces characteristics of both a human and an emoji to narrate the meaning of IAQ, and applied both a concrete object (a vertical bar strip indoors) and an abstract metaphor (background image outdoors) to indicate the levels of air quality indoors and outdoors.

DISCUSSION

Children can play an important role in bringing about positive changes in our lives if they are provided with a means to assess and respond to a situation. While this study investigated the context of IAQ, we believe our findings provide insight into a wider domain of wellbeing, healthy living, and environmental sustainability (e.g., exercise, healthy eating, energy/water saving). First, our findings highlight that children have their own ways of understanding the world around them regardless of whether or not those ways are correct. For instance, our participants associated hot air with poor air quality, which is not always true. This implies that incorporating children's perspectives into the design should involve a compromise between two approaches: while it is important to identify children's ways of understanding the world and turn them into design factors, the presented information must be factually accurate. Misperceptions can be corrected by employing design cues that are appropriate for children, thereby further leveraging the design by children for children approach of this study. Second, our findings show that children tend to perceive and process information differently depending on who delivered it (e.g., a reflective self, a third-party human, an iconic character). While further investigation is needed to gain a more nuanced understanding of different characters and their influence, a narrating medium to deliver the information should be carefully crafted to yield desired outcomes.

Last but not the least, our findings and design implications must be evaluated within the context of study limitations. Our recruitment approach, which relied on a convenience sample, resulted in a gender imbalance in Study II, which runs the risk of compromising its generalizability. Future studies might seek to examine gender differences in children's perspectives and design preferences.

CONCLUSION

Poor indoor air quality is harmful to everybody, but children are of particular concern because they are more vulnerable to its negative health effects. While off-the-shelf IAQ monitoring devices are increasingly available to help people keep informed about their IAQ, little effort has been made to create such devices with children in mind. Empirical knowledge is needed to produce effective interventions that encompass the needs and perspectives of children, who, beyond the lack of basic understanding of IAQ, may additionally struggle to access, assimilate, and implement actionable information.

Our study demonstrates a robust design process in which children play critical roles as both *informants* and *testers* to capture their perspectives as a guiding principle in the design of technology for children. This process provides children's insight on the design of the IAQ visualization interface, explains their own difficulties in understanding IAQ, and evaluates the interactivity and designs of prototypes. All of our interface prototypes were well received, we believe, because we directly engaged children in the design process both as *informants* to express opinions and to determine how to interact with the device, as well as *testers* to try out the prototypes and make suggestions for improvements. To the best of our knowledge, this work is the first study that investigated how children perceive and assess IAQ and the first study that created child-friendly interfaces for IAQ visualization. We are currently developing a working system with the final design prototype that provides persuasive and expressive visualization of IAQ for children. As a next step, we plan to deploy the system in the real world to investigate the effects of a child-friendly IAQ visualization on children's understanding of and engagement with IAQ. We hope our work motivates future HCI research to further engage children in the design process for the successful design of technology for children.

SELECTION AND PARTICIPATION OF CHILDREN

Thirty-three children, aged 7 to 12 years old, participated in this work consisting of two studies. For Study I, nineteen participants were recruited by distributing recruitment flyers in a local affordable housing community and by word-of-mouth during the community's summer camp programs. For study II, fourteen participants were recruited from attendees of a local community development corporation's outreach program. Both organizations worked collaboratively with the research team and provided explicit permission for recruitment activities. All participants were protected under the study's IRB approval. Consent was attained from caregivers on behalf of the children, permitting participation in the study, video/audio recording, and photographs. Children additionally gave their verbal assent. Finally, all personally identifiable data was removed to protect the children's anonymity.

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