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Sensing the invisible: Understanding the perception of indoor air quality among children in low-income families

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ABSTRACT

Indoor air pollution is a leading indoor environmental risk factor, especially to individuals already at risk, such as children in low-income families. While studies have shown that occupants' perceptions plays a significant role in improving indoor air quality (IAQ), little is known about how at-risk, low-income populations perceive and engage in IAQ. In this paper, we sought to understand how low-income families, especially children, perceive and assess IAQ. Findings show that the air quality of the indoor environment is perceived and assessed primarily through sensory responses relating to perceived comfort or discomfort, such as a sense of smell, visual cleanliness, and thermal comfort. We discuss how our findings could be applied to the future design of persuasive IAQ monitoring technologies.

1. Introduction

Indoor air pollution is an important determinant of health, as people in modern societies spend the majority of their time indoors, over 65% being in their own residence [1,2]. Indoor air pollution in low-income households is of particular concern as these households suffer disproportionately from poor air quality. Studies have shown that ambient air pollution is higher in low-income neighborhoods and lower in mid- to high-income neighborhoods in the United States [3,4]. It is well-established that infiltration of outdoor pollutants indoors contributes to indoor pollution. Correspondingly, health risks associated with poor air quality are not randomly distributed in the population but inversely correlated to socioeconomic status [1,2]. For example, levels of air pollution are consistently associated with asthma development and morbidity among children [5], and asthma rates are four times higher than the national average among the children who reside in metropolitan census tracts where approximately 30% of the residents are below the US federal poverty guidelines [6].

Researchers, policymakers and professionals have invested in interventions to improve residents' health by enacting building codes and developing guidelines designed to improve air quality indoors [7]. However, implementation and adherence to voluntary strategies, and even mandated ones, may depend on the extent to which people perceive indoor air quality (IAQ) as a critical issue. Prior work demonstrated that an increase in occupants' perception of IAQ is one simple but effective means to improve IAQ [8,9]. The Health Belief Model also posits that improved perception of health-related problems plays a significant role in promoting behavior change for positive health outcomes [10]. Because indoor human activities are often a primary source of indoor air pollution, behavior change, which can be predominantly motivated by the increased awareness of IAQ issues, can lead to significant improvement in IAQ [11].

Poor indoor air quality is a universal issue of concern across socioeconomic groups, but special attention is warranted for resource-deficit populations, as existing solutions might not be affordable or applicable to them. While various efforts have been made to increase perception and awareness of IAQ as a means to encourage people to improve the quality of their indoor environments (e.g., [4,12,13]), little is known about how low-income families, and children in particular, perceive and assess IAQ and make corresponding adjustments to their lifestyles and behavior. Therefore, the objective of this paper is to understand how children in low-income households perceive and assess IAQ as a first step toward designing a persuasive IAQ monitoring tool that incorporates the needs and perspectives of families of low socioeconomic status. We are particularly interested in how children engage in IAQ issues as we hypothesize that parents in low-income families may overlook or deemphasize the importance of IAQ due to insufficient financial, physical, and emotional resources to allocate to it, while children, who are not only highly vulnerable to air pollution but also highly influenced by education, may take a critical role in exerting a positive influence on IAQ in their households.

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The key contributions of this work are: (1) to understand perspectives that children in low-income families have in perceiving and assessing indoor air pollution; and (2) to engage a low-income population that has been overlooked in the design of a persuasive IAQ visualization technology that better incorporates their perspectives. This work advances an HCI approach informed by theories of environmental and behavioral psychology [14,15], cognizant of "everyday practices" as a means to design more effective interventions for quality of life. The focus of this work is on everyday practices of *perceiving and assessing* IAQ.

2. Background

2.1. Indoor air quality and health effects

Air pollution has been recognized as the fifth leading cause of death worldwide [16], and multiple air pollutants are considered carcinogens [17]. A growing body of scientific evidence indicates that indoor air pollution within homes and other buildings can be worse than outdoor air pollution even in the largest and most industrialized cities. For example, the California Air Resources Board estimates that indoor air pollutant levels are 25% to 62% greater than outside levels [18], and the United States Environmental Protection Agency's study revealed that levels of about a dozen common organic pollutants were found to be 2- to 5-fold higher, and occasionally more than 100-fold higher, inside homes than outside, regardless of whether the homes were located in rural or highly industrial areas [1,2].

In particular, IAQ agents have been implicated in asthma onset and morbidity [16,19]. Studies have found strong associations between elevated levels of particulate matter, one of criteria air pollutants, and cardiovascular disease [20]. According to the World Health Organization, indoor air pollution is responsible for 2.7% of the global burden of disease and 3 million premature deaths due to chronic respiratory disease per year [21].

Human exposure to indoor air pollutants is due to many factors, including building characteristics and conditions, family lifestyles, occupants' behaviors and indoor activities, and availability of information and means to remediate known indoor air quality problems. Indoor sources of pollutants are intermittent, as in the case of particulate matter caused by cooking or use of combustible materials such as burning incense and smoking [9,22]. Occupants may use active ventilation systems, if available, such as building exhaust ventilation fans to decrease particle concentrations indoors, along with the operation of windows, when air pollution levels indoors are higher than outdoors [11]. Conversely, these ventilation systems along with leaks in the building envelope and open windows when the pollution outdoors is high permit the transmission of outdoor pollutants indoors, which may result in occupants living in highly polluted indoor environments.

2.2. Low-income households and IAQ

Research suggests that, on average, families need an income of about twice the federal poverty threshold to meet their most basic needs [23]. Families living with incomes below this level—$48,016 for a family of four with two children in 2015 in the United States—are generally referred to as low-income [24].

Studies demonstrate that air pollution significantly affects children's health. For example, the lung capacity of children living in environments with polluted air can be reduced by 20%, which is similar to the effect of growing up in a home with exposure to secondhand cigarette smoke [6]. Also, asthma and related respiratory symptoms are significant health threats to children in low-income households, as the approximately seven million children in the United States with asthma are living in a household below the national poverty level [25].

Since each home is a fairly unique microenvironment due to the great diversity of potential indoor pollutant sources and indoor human activities, it is important to understand how occupants respond to their indoor environment. This study specifically focuses on very low-income urban households because poverty is a crucial barrier to preventing or reducing poor health caused by indoor environmental hazards [26] and because, unfortunately, urban poverty is on the rise.

While studies have reported on the effect of socioeconomic status on IAQ, few studies have explicitly examined how low-income households, and especially children in low-income families, perceive and assess IAQ. One exception is a study done by Patton et al. which evaluated how occupants' indoor activities living in low-income green buildings influence the level of particulate matter, taking into account indoor behaviors as opening windows, using window air conditioners, smoking, cooking, and burning incense or candles [9]. While participants in these studies were asked to assess IAQ, less emphasis was placed on how they perceive and assess IAQ.

2.3. Persuasive technologies for IAQ monitoring

The research on persuasion in Human–Computer Interaction generally builds on psychological research focusing on the understanding of human behavior [27]. The rationale behind the design of most persuasive technologies for eco-feedback is that people lack awareness and understanding of how their behaviors have an impact on the environment: Providing proper information can influence the psychological and behavioral factors shaping everyday practices and motivating associated decision-making [28]. Associated research further seeks to characterize this "everyday practice" of a target population as data-rich repositories for the design of persuasive technologies and other interventions [14,15]. This includes consideration of imagery and other representations as a precursor to everyday practices [29,30] whether efficacious or maladaptive.

Traditionally, IAQ measurements have been carried out using sophisticated and expensive equipment. In the past few years, however, there has been an explosion of low-cost IAQ sensors entering the market. Technologies are being developed not only to measure IAQ [26,31] but also to raise awareness of indoor air pollution and to foster healthier everyday practices through persuasion, called persuasive technology. Persuasive technology refers to the products designed to "persuade by giving a variety of social cues that elicit social responses from their human users" [27]. The design of persuasive systems to increase awareness and promote behavioral changes is increasingly recognized as an important topic in HCI pertaining to human well-being and health behaviors [12,32,33], and many such interventions have shown statistically significant effects on health-related behavior (e.g., [34]). Examples in the context of IAQ include a design of indoor air quality monitoring devices [35], the Participatory Urbanism project seeking to improve urban air quality through everyday citizens [36], gamified public air pollution sensors [37], and an electronic street sign designed to visualize urban air quality [38]. In particular, a range of visualization mediums has been explored for their effectiveness and persuasiveness (e.g., numeric graphs [13,36] and abstract representations [13,39,40]). Froehlich et al. reviewed the literature on existing eco-feedback technology where they identified important considerations for designing eco-feedback systems, including the level of granularity of the presented data, the ability to make comparisons, and the creativity of visual design among other factors [14].

While interactive computing technologies have been designed to promote increased public engagement in indoor air pollution

Table 1
The number of workshop participants per session.

Session	Child	Caregiver
1	3 girls, 1 boy	3 mothers, 1 grandmother
2	2 girls, 5 boys	5 mothers
3	2 girls, 3 boys	3 mothers, 1 father
4	3 girls	2 mothers, 1 father
Total	10 girls, 9 boys	14 females, 2 males

issues, little effort has been made to involve low-income families, children in particular. This paper directly tackles this issue by exploring how low-income families and their children perceive and assess IAQ to benefit future design of persuasive technologies for IAQ monitoring.

3. Methods

Our data collection and analysis occurred through a participatory workshop as a means to gain input from those whose voices often are excluded from the design process. This approach allowed us to tap into low-income households' direct experiences with air quality perceptions and management.

3.1. Study site

The workshop was conducted with current residents of an affordable housing community in Elizabeth, New Jersey, a city with a high concentration of vulnerable, low-income families. Elizabeth is a city in the Greater New York metropolitan area, home to the Port Elizabeth marine terminal, one of the busiest ports in the country, and adjacent to the Newark Liberty international airport. The study site is bifurcated by the New Jersey Turnpike, the sixth most heavily traveled highway in the US. Altogether, Elizabeth is the city with some of the worst air pollution in New Jersey [41], resulting in a high prevalence of chronic respiratory diseases in the area, such as asthma [42].

The study site was built in 1938 and it is home to approximately 750 residents whose annual household income is below 30% of the area's median income level (i.e., $19,800 for a 1-person household, $22,600 for 2, $25,450 for 3, and $28,250 for 4). As of 2016, 69% of the residents were African–American with 73% of households being single-parent households (predominantly female), according to the community's database (obtained via email communication with the site's owner, a housing authority).

3.2. Participants

Through recruitment flyers distributed on site and by word-of-mouth during on-site summer camp programs, we recruited caregivers with at least one child between 7 and 12 years old. In this study, a caregiver is defined as a person responsible for the primary care of and upbringing of a child, such as parents or grandparents. We recruited only those children who could possibly read. A total of 16 caregivers and 19 children were recruited (see Table 1). All but two caregivers were women, and their ages were between 24 and 51 years old (average age = 31; SD = 8.42). For the children, there were 9 boys and 10 girls (average age = 8; SD = 1.36), and all but 2 children were between 7 and 9 years old. 15 families were African–American, and one family was Latino; all were fluent in English.

3.3. Study esign

At each of the four workshops, two researchers were present. Each workshop was divided into four sessions: an icebreaker, a guided discussion about IAQ containing an educational component about IAQ, demonstrating an IAQ monitor, and a hands-on design activity session.

Before beginning the main activities, we convened an icebreaker session to build a sense of community and common purpose across participants. First, we explained the purpose and the process of the workshop in detail to the participants and encouraged questions regarding the workshop. All participants introduced themselves with their names and ages. Consent was attained from caregivers on behalf of themselves and their children, permitting participation in the workshop and also video recording and photographs; children additionally gave their verbal assent.

After the icebreaker, one of the researchers gave a presentation about IAQ (see Fig. 1). The presentation slides were created and curated to prompt discussion and then convey information about IAQ to school-level children based on IAQ educational material developed over the course of two HUD (Department of Housing and Urban Development) grants (see Fig. 2 for an example slide). Prompted topics included: what is IAQ; what makes IAQ good or bad; why IAQ matters; and how to keep indoor air clean and healthy. Before any educational materials were presented, participants were asked to share their thoughts on the topic. To this end, we constructed this component of the workshop as a combination of open-ended discussion followed by a structured tutorial for two purposes: (1) learning about the participants' current perspectives and thoughts on IAQ, and (2) conveying to participants actionable information about IAQ. This component of the workshop lasted about ninety minutes.

At the end of this session, we introduced AirVisual, an indoor air quality monitoring device that measures $PM_{2.5}$ (particles with a diameter less than 2.5 μm) and CO_2 concentrations, and checked the level of IAQ of the workshop room together. AirVisual uses various visual cues, including a bar graph with Air Quality Index colors, numeric readings of $PM_{2.5}$ and CO_2 concentrations, and icons with different facial expressions, to visualize the level of air pollution (see Fig. 3). The Air Quality Index (AQI) is an EPA's index for reporting air quality in a meaningful way, designed to be used by the public so that they can easily understand air pollutant levels. AQI has been widely used to represent air quality and shown to be an effective means for the general public to understand IAQ [1,2]. We used AirVisual due to its availability to researchers. This and most of other existing IAQ monitoring devices have similar visual components to display AQI and a numerical reading of air pollutant concentrations on a display or via an app. AirVisual has no particular significance, and any other IAQ device could have been used. In the study participants were prompted to share thoughts and feedback reflecting on IAQ of the workshop room and the graphical interface of AirVisual.

Finally, participants, and especially children, engaged in a hands-on design activity session. They were given paper, crayons, colored pencils, and markers. We asked them to express their thoughts on our questions as sketches (see Fig. 4). The questions related to main topics of the prompted discussion conducted earlier including, "What do you think a space with poor IAQ looks like?" or "How would you get rid of dirty air?"

At the end of the workshop, pizza and drinks were served, the caregivers and children were thanked for their help, and compensation for participation was provided.

Fig. 1. An IAQ tutorial session.

Fig. 2. A sample slide used for prompted discussion.

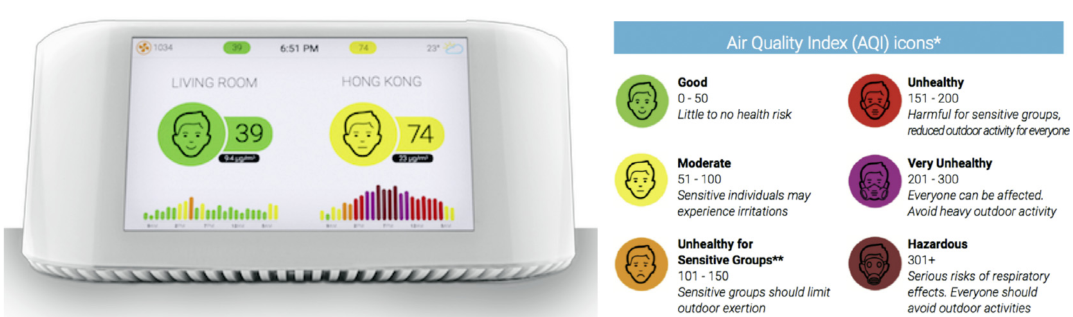

Fig. 3. AirVisual, an IAQ monitoring station that uses colors, graphs, numbers, and icons to visualize IAQ (left) and the AQI icons with different facial expressions (right).. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Design activity sessions: Children drew sketches using pen and paper.

3.4. Data analysis

The video recordings were transcribed and analyzed by the research team using inductive thematic analysis to reveal patterns across data sets, informed by a Grounded Theory approach [43,44]. Our approach included a process of open coding, axial coding, and selective coding.

In the first step of our data analysis, we conducted open coding where we identified and coded concepts that are significant in the data as abstract representations of events, objects, happenings, actions, interactions, etc. The example below shows that one participant thought of bad smell when asked about bad air quality. This response is coded as "smell". Throughout the open coding process, a total of 43 loosely connected concepts were created.

> *"Bad air quality is like* ***[smell]*** *something that stinks that comes from your pants* ***[/smell]***."
>
> (Participant C8)

Next, we categorized the related concepts created by open coding into higher conceptual phenomena using axial coding. These phenomena in grounded theory refer to repeated patterns of events, happenings, actions, and interactions that represent people's responses to the problems and situations. For instance, "perception of air quality" is a phenomenon that represents a pattern of what people perceive of when thinking about air quality. "Smell", for example, is one of the open coding concepts categorized to "perception of air quality". Our axial coding resulted in a total of seven categories. Lastly, we followed the selective coding process to assemble our conceptual phenomena extracted from axial coding into a single storyline. Through this step, we integrated all concepts into a single storyline throughout building relationships across phenomena.

4. Findings

Overall, we found that our participants do not have much interest in or knowledge about IAQ in general. When they perceive and assess IAQ, they rely exclusively on sensory responses relating to olfactory, visual, and thermal comfort to determine the quality of the indoor environment. In what follows, we describe our findings of how our participants perceive and assess IAQ in detail.

4.1. General perspective about indoor air quality

According to the EPA, the indoor environment could have pollutant concentrations 2- to 5-fold higher than our outdoor environment, and, in some cases, the pollutant concentrations indoors have been found to be 100-fold higher than outdoors [25]. However, when we asked to compare the quality of air indoors and outdoors, most participants said that they think air quality indoors is always better than outdoor air quality.

> *"Air in my house is good because there's less germs and dirt inside than outside".*
>
> (Participant C9)[1]

Perhaps such perception exists because the participants assume that air pollutants come exclusively from outdoors; when we asked about possible sources of indoor air pollution, they pointed to outdoor objects, such as rusty pipes, dirt, litter, car, bikes, and pets. In fact, this is incorrect, because many pollutants affecting the IAQ are the result of sources, systems, and human behaviors inside buildings, including inadequate ventilation, emissions due to cooking and heating, and chemicals and particulate matter from candles and other household products.

> *"Pets are outgoing so they like to run around a lot. And all the dirt from outside, it'll come inside and then it runs around and it (the dirt) can fly off from it (pets) and go in the air".*
>
> (Participant C14)

[1] In the quoted responses, C refers to a child participant, and P refers to a parent/caregiver participant (e.g. C9 is a quote made by the ninth child participant, and P3 is by the third parent participant).

In addition, the perception that outdoor pollutants could infiltrate the indoor environment through windows has led to the conclusion that windows should never be used to minimize indoor air pollutants.

"That's like nasty air on the outside and like good air inside and you open your window and nasty air outside, some of that air may come in to your house".

(Participant C3)

"When you open one window, don't you have pollutants come in it?"

(Participant P5)

"You should keep your space closed so that not everything can transfer from outside to inside because dirt is coming into a house through these windows."

(Participant C8)

Consequently, participants indicated uncertainty and reluctance to use windows for ventilation given their understanding that the quality of outdoor air in their neighborhood is poor and that opening windows would permit infiltration of polluted air from outdoors. Such comments point to a sensible behavior only when the outdoor air pollution is indeed high while keeping the windows closed all the time, in fact, deprives the residents of clean and fresh air when the outside conditions are favorable.

Regarding health effects of air pollution, irritation of nose or throat and the corresponding coughing and sneezing were mentioned. Whereas, chronic health effects due to air pollution, such as respiratory diseases, heart disease, and cancer, or mental, behavioral and neurological disorders were never mentioned.

Whereas, we found that neither children nor caregiver participants thought that his or her indoor behaviors could become a source of indoor air pollution. This perception resulted in putting either no effort or inadequate effort into improving IAQ.

Because most participants have not thought much about IAQ in general, they have not done much to safeguard or improve their IAQ either. When we asked about the things they (can) do to improve IAQ, activities or objects relating to cleaning and deodorizing were mentioned, such as broom, duster, vacuum, mop, towel, bleach, Swiffer, Lysol, candles, and air freshener.

"If you don't wash the dishes it starts to have a smell to it and make air quality bad".

(Participant C1)

"I use candles and air fresheners all the time, all day".

(Participant P2)

Other than cleaning a room, keeping things organized, and using scented candles and air fresheners, neither caregiver nor children participants had any further ideas about ways to keep IAQ clean and healthy. We asked participants to sketch anything related to their needs or requirements for keeping IAQ "clean and healthy", but participants did not draw much in response to this request.

4.2. Sensory responses as a primary way of assessing indoor air quality

It is difficult to assess air quality through bare human sensors such as eyesight or smell because most air pollutants are colorless and odorless at typical indoor concentrations. Therefore, human sensors are not a reliable means to measure IAQ. However, we found that participants rely heavily on their sensory responses, including a sense of smell, sense of air temperature (thermal comfort), and visual cues (cleanliness of space) to perceive and assess IAQ. This propensity is likely not unique to people in low-income households but universal across people in different socioeconomic status. However, it is still important to investigate the experiences of people in low-income households so that their perspectives are fully incorporated into the future design of persuasive IAQ monitoring technologies.

4.2.1. Sense of smell

we found that smell is the most prevalent sensory response to perceive and assess air quality, which confirms previous findings [32,45]. When we asked to compare air quality indoors and outdoors, one caregiver participant responded:

"There are different smells outside than inside".

(Participant P5)

When we asked to describe places where air quality is not good, places and terms relating to unpleasant odors were mentioned, including the public bathroom, school bathroom, school bus, garbage, trash, basement, attic, gym, along with smelly cheese, stinks, and stench.

"Bad air quality is like something that stinks that comes from your pants".

(Participant C8)

"When you are in a dirty room… like dirty clothes and like really smelly and it stinks".

(Participant C12)

"A school. It (school) smells musty".

(Participant C3)

"Sometimes I can smell that somebody is smoking in the backyard".

(Participant C10)

Consequently, caregiver participants reported that they use scented candles and air fresheners frequently to keep their houses smelling nice and "clean". Such perception is often promoted by various household product manufacturers, as air fresheners are a $10 billion business worldwide [46]. However, scented candles, incense, and air fresheners, including the ones advertised as green and organic, in fact, emit particles or their precursors, and/or volatile organic compounds (VOC), and their negative health effects have been recognized [9,47]. When we explained this to our participants, many caregiver participants were surprised and asked how to keep the air clean and smelling nice without using candles and air fresheners.

"I use them (candles and air fresheners) all the time. I keep the candle burning all day to make my indoor air smell good and fresh. What shall I do?"

(Participant P2)

4.2.2. Thermal comfort

Thermal comfort is defined as "the state of mind that expresses satisfaction with the thermal environment" [48]. While thermal comfort is an important factor in determining overall indoor environmental quality, affecting productivity and health of building occupants, it is different from IAQ because thermal comfort is affected primarily by air temperature and humidity. Many participants, however, did not recognize the difference between thermal comfort and IAQ and assessed IAQ based on perceived thermal comfort.

"In the summer outside it's very hot so the air is heavy".

(Participant C3)

When we asked the participants to describe what IAQ in other places was like on the day of the workshop, the participants described it reflecting mostly on air temperature, such as air quality being bad when the air temperature is perceived as too high. Similarly, when we asked to describe what they thought of IAQ in the workshop room, most answers were related to air temperature (The workshops were conducted during several hot 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 C1)

"It was really hot today. We were outside so the air was really heavy and it smelled contaminated".

(Participant C2)

"Air is nice and cool in here [the workshop room] because of an air conditioner".

(Participant C4)

4.2.3. Visual cues

Unsurprisingly, we found that visual cues are considered important when identifying the source of indoor air pollution and assessing IAQ. When we asked to think about good air quality, participants mentioned objects and terms related to nature and the environment, including butterflies, flowers, grass, greenness, bright colors, shiny, and clean.

"Air is nice and clean when the plants and grass are greener".

(Participant C13)

"It's very bright and air is clean outside because of the Sun. It's colorful outside"

(Participant C9)

"My hypothesis is that when the air is dirty, it's not as bright".

(Participant C8)

Also, children participants assumed that air pollutants would be something that piles up like dust at the corner of a room or that stays afloat by the ceiling. When they were prompted to imagine what air pollutants would be like, they mentioned a surface covered with dust, such as old books, attics, and basement. One child drew a bedroom and a bathroom where the corners of furniture and household objects are "contaminated with air pollutants" – marked in green color (see Fig. 5), and another child drew a house with air pollutants that are infiltrated through a window and float by the ceiling (see Fig. 6).

Another important visual cue when assessing IAQ is the cleanliness (or tidiness and organization) of a space. Children participants considered air quality to be good when the indoor space was clean and organized. Therefore, cleaning was mentioned as a major existing practice that they perform to improve IAQ. For example, one child drew his bedroom being disorganized with toys on a floor to represent a room with bad IAQ and being organized without any toy on a floor to represent a room with good IAQ (see Fig. 7).

"Air quality in my room gets bad when it is messy"

(Participant C12)

4.3. Feedback on the AirVisual display

At the end of the prompted discussion session, we showed AirVisual, an indoor air quality monitoring device, to participants to get feedback about its visualization of IAQ measurements. None of the participants had used any indoor air quality monitoring device before, but they quickly engaged with the device once we introduced it to them. Caregiver participants instantly asked questions about how to interpret the display, such as meanings of different colors and numbers. They said that the number did not make much sense to them because they did not know what the numbers mean and how to interpret them in relation to IAQ. In addition, some participants reported that they did not understand what different colors in a visualization meant in relation to IAQ.

Interestingly, none of the participants noticed the presence of icons with different facial expressions, or at least did not make any comment on it until we drew their attention to it. When we asked the participants about their reaction to the icons, they said that it was not intuitive for them to understand what an icon means in relation to IAQ. Participants did not recognize that the facial expression of an icon would change by the level of IAQ. This was different from our expectation as we expected the IAQ visualization mechanism of AirVisual to be easy and intuitive enough for our participants to interact with. We hypothesize it might be because our participants used the device only for a short period of time whereas the icon changes when IAQ readings, presented as AQI, go from one range to another; this change rarely occurs in a room within a short period of time, especially when there no obvious introduction of pollutants as was the case during our sessions. This leads to a need for a further study to investigate how different visualization components of a device's interface would affect a user's interaction with and perception of air quality issues in a short-term and a long-term usage period.

5. Discussion: Design implications

The design of persuasive systems to increase awareness about environmental factors and to promote behavioral changes for health and wellness is increasingly recognized as an important topic in HCI. However, graphical representations of air quality are predominantly by means of visualizing concentration levels of particular pollutants using an Air Quality Index (AQI) with color-schemed graphs and numerical values (e.g., [13]). This approach may not be intuitive enough for most people, including resource-deficit populations with little knowledge and engagement of IAQ. Our findings suggest several graphical themes relating to sensory responses that can be used to visualize IAQ as a supplement to AQI, which conforms to the existing literature that illustrated "abstract representation" of environmental data can enhance the effectiveness and persuasiveness of information presentation [40]. 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 thermal or olfactory cues such as "hot weather" and "toilet" can be used as abstractive

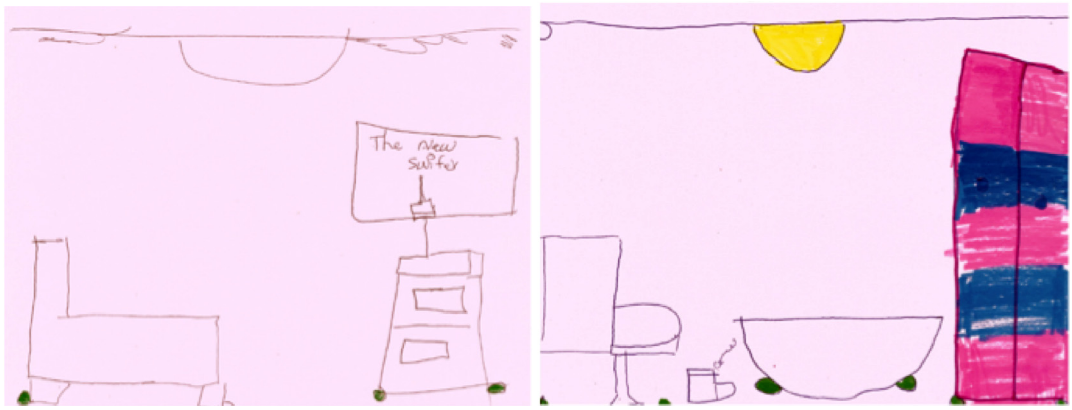

Fig. 5. Sketches of a bedroom (left) and a bathroom (right) where perceived air pollutants are marked with green color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. A sketch of a house with bad IAQ by Participant C8.

visualization themes to represent 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). This way, the current practices of perceiving IAQ can be directly reflected toward interpreting the IAQ visualization, which likely will help people with little interest and knowledge about IAQ to easily understand the current state of IAQ without the need for further explanations or education. Similarly, other themes for abstract representation of IAQ can be adopted from indoor activities that have significant correlation to IAQ, such as opening/closing windows, smoking, cooking, and burning candles [9]. These themes can be used not only to represent the underlying meanings of the level of IAQ (e.g., a display visualizing an animated person who smokes to indicate that AIQ is extremely poor), but also to provide actionable behavioral interventions for IAQ improvement (e.g., a display visualizing an animated icon of opening windows to promote when AIQ is poor). This contributes to extending Froehlich's design considerations for eco-feedback systems [14] by adding the ability to associate a physical event and its virtual representation in a meaningful way. We intend to perform future research that will incorporate the findings into our design and development of more expressive visualizations for IAQ monitoring technologies, and further our understanding of the design territory for such systems.

Also, thermal comfort was found to be a significant factor in determining the perceived condition of air quality indoors. Therefore, it would make sense to inform and educate residents using visualizations not only about IAQ parameters, such as the concentration levels of particular pollutants, but also about comfort factors such as humidity and temperature indoors. Visual tools informing how temperature and humidity could affect indoor air pollution also should be considered for an IAQ visualization component.

In addition, our findings regarding how children perceive and assess indoor air quality may inform local authorities and policy makers in implementing targeted outreach campaigns, education programs, and policies to protect low-income households against the detrimental impacts of IAQ.

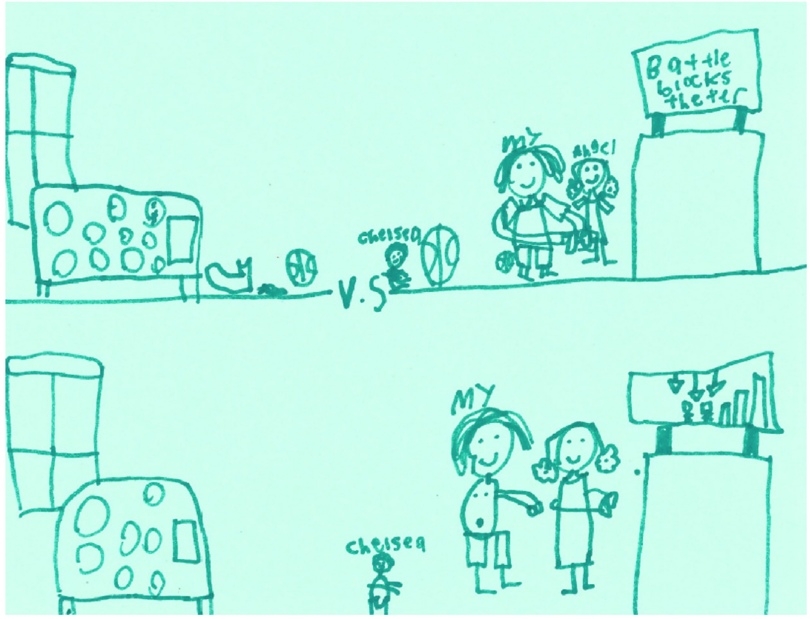

Fig. 7. Sketches of a bedroom that is perceived to have bad IAQ (top) and good IAQ (bottom) by Participant C12.

6. Conclusion

Indoor air pollution is an important threat to health and quality of life. Various stakeholders are increasingly concerned about the quality of the indoor environment, including IAQ, which often results in top-down approaches, such as building codes or voluntary guidelines. Relatively little effort has been made to understand how low-income households, and especially children, engage with, perceive, and assess IAQ in a bottom-up fashion. What is needed is empirical knowledge to produce effective interventions that encompass the needs and perspectives of this population, who, beyond the lack of basic financial resources, may additionally struggle to access, assimilate, and implement actionable information.

To our knowledge, this work is the first study that explored how children in low-income families perceive and assess IAQ. The findings demonstrate that IAQ is primarily perceived and assessed through sensory responses related to perceived comfort or discomfort, such as a sense of smell, visual cleanliness, and thermal comfort. Based on these findings, we discuss design implications for future IAQ monitoring technologies. In the long term, we hope our efforts can shed light on future research that can engage and encourage low-income households to learn, understand, and improve their health and well-being and broaden their awareness of their indoor environment.

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Conflict of interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work. For full disclosure statements refer to http://dx.doi.org/10.1016/j.ijcci.2018.12.002.

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