

# From Invisible to Actionable: Augmented Reality Interactions with Indoor CO<sub>2</sub>

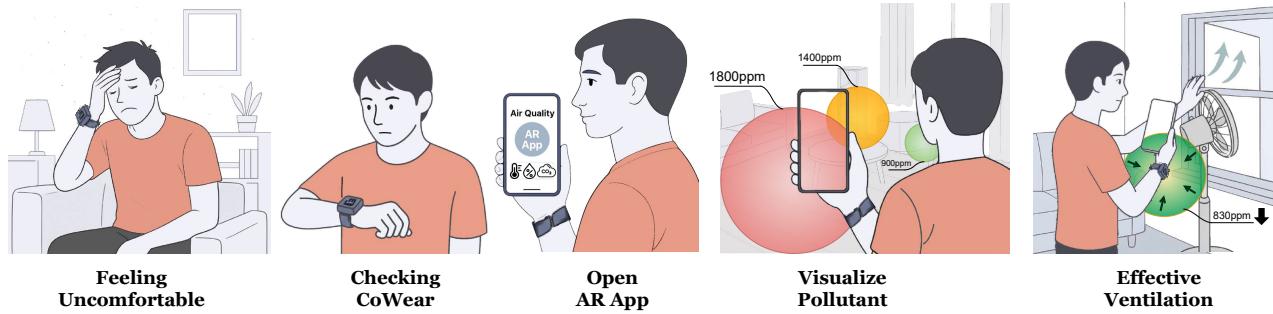
Prasenjit Karmakar  
prasenjitkarmakar52282@gmail.com  
IIT Kharagpur  
India

Manjeet Yadav  
p25cs0011@iitj.ac.in  
IIT Jodhpur  
India

Swayanshu Rout  
22it3057@rgipt.ac.in  
Rajiv Gandhi Institute of Petroleum  
Technology  
India

Swadhin Pradhan  
swapradh@cisco.com  
Cisco Systems Inc  
USA

Sandip Chakraborty  
sandipc@cse.iitkgp.ac.in  
IIT Kharagpur  
India



**Figure 1:** Our system enables actionable awareness of indoor air pollution using augmented reality (AR). (1) When feeling uncomfortable indoors, the user (2) checks the CoWear wrist-wearable sensor to monitor real-time air quality. (3) By launching the AR app, the user can (4) visualize invisible CO<sub>2</sub> pollution as color-coded, spatial bubbles overlaid in their environment. (5) Guided by these visualizations, the user employs effective ventilation strategies, such as directing airflow toward high-CO<sub>2</sub> zones, and immediately observes reductions in pollutant concentration for healthier indoor air.

## Abstract

Indoor carbon dioxide (CO<sub>2</sub>) can rapidly accumulate to form invisible pollution *hotspots*, posing significant health risks due to its odorless and colorless nature. Despite growing interest in wearable or stationary sensors for pollutant detection, effectively visualizing CO<sub>2</sub> levels and engaging individuals remains an ongoing challenge. In this paper, we develop a portable wrist-sized pollution sensor that detects CO<sub>2</sub> in real time at any indoor location and reveals CO<sub>2</sub> bubbles by highlighting sudden spikes. In order to promote better ventilation habits and user awareness, we also develop a smartphone-based augmented reality (AR) game for users to locate and disperse these high-CO<sub>2</sub> zones. A user study with 35 participants demonstrated increased engagement and heightened understanding of CO<sub>2</sub>'s health impacts. Our system's usability evaluations yielded a median score of 1.88, indicating its strong practicality.

## CCS Concepts

- Human-centered computing → Ubiquitous and mobile computing systems and tools; Visualization; Interaction design.

## Keywords

Augmented Reality; Pollution visualization; Interactive Games; Wearables

## ACM Reference Format:

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## 1 Introduction

**Motivation.** Air pollution remains one of the most pressing environmental and public health challenges of our era. While outdoor pollution has received significant attention in HCI through work on sensing, visualization, and community engagement [27, 29, 30, 41, 43, 45, 66], the indoor context is comparatively underexplored, despite evidence that indoor air quality can be equally or more harmful [20]. Pollutants such as VOCs, CO, CO<sub>2</sub>, and other indoor

gases impair respiratory and cognitive function [55]. Yet, most remain invisible, odorless, and unperceived by occupants. Given that people spend up to 90% of their time indoors [52, 76], raising awareness and enabling actionable strategies for indoor air quality is a crucial challenge for HCI.

Despite the well-documented health effects of indoor pollutants, most occupants are unaware of and lack the means to monitor their immediate exposure. Traditional sensing approaches typically rely on static monitors placed in fixed locations. However, these monitors are difficult to deploy at dense spatial scales and often fail to provide information that is personally meaningful to the occupant. This limitation creates a disconnect between *sensing* and *actionable awareness*. In contrast, wearables offer a promising alternative by moving the sensing closer to the individual, allowing user-centric real-time measurements of personal exposure [34, 46].

When combined with Augmented Reality (AR), wearable data can be visualized *in situ*, anchored to the user's immediate surroundings, and embodied perspective [7, 49]. AR on mobile devices has emerged as a powerful medium to enhance human perception of the environment and support new forms of interaction [10]. Prior research demonstrates the broad applicability of AR: from enabling interactions with 3D depth maps [18], supporting digital literacy among older adults [35], and facilitating shopping [1, 6], to assisting navigation in unfamiliar smart spaces [14]. More broadly, AR has been used to promote environmental sustainability through immersive and situated awareness experiences [11, 15, 57, 69]. By integrating invisible environmental data with everyday perception, abstract sensor readings can be transformed into situated and interactive visualizations. Coupling these pathways enables users not only to monitor continuously, but also to interpret invisible pollutants and take action.

**Objective.** In this paper, we focus on carbon dioxide ( $\text{CO}_2$ ), a pollutant often overlooked in everyday discourse but associated with significant health risks. Elevated concentrations above 1000 ppm can impair cognition, while levels exceeding 2000 ppm cause headaches, nausea, and reduced attention [8, 59, 73]. Prolonged exposure at such concentrations can also contribute to *hypertension*, a condition of excessive  $\text{CO}_2$  in the bloodstream that is particularly dangerous for older adults and individuals with respiratory conditions such as chronic obstructive pulmonary disease (COPD), obesity-hypoventilation syndrome, or asthma, who already have compromised gas exchange [16, 75]. Even healthy individuals may experience dizziness, sleepiness, or reduced work performance when exposed to sustained indoor  $\text{CO}_2$  levels above recommended thresholds [3, 17, 21].

Indoors,  $\text{CO}_2$  accumulates due to human respiration, cooking and combustion, with accumulation patterns shaped by room size, ventilation, and occupancy. This means that common environments such as *office spaces, conference rooms, classrooms, or basements* can easily reach concentrations associated with headaches, drowsiness, and impaired decision-making if fresh air supply is insufficient [3, 21]. *Kitchens and indoor gyms* are also high-risk, as cooking and heavy breathing rapidly generate additional  $\text{CO}_2$  in confined spaces. Industrial or recreational environments such as *breweries and wineries*, where fermentation produces large amounts of  $\text{CO}_2$ , pose occupational risks of acute hypertension and even unconsciousness if

ventilation is inadequate [56]. Air conditioning is not always effective in mitigating these build-ups [70, 79], leaving users dependent on informed ventilation strategies. Consequently, in this paper, we examine how AR interactions can render  $\text{CO}_2$  perceptible and contextualized within a user's immediate environment, and how such visualizations can be made actionable – nudging individuals to intervene and experiment with mitigation strategies in real time. By doing so, this work extends AR from environmental awareness to situated actionability, bridging sensing, visualization, and interaction in everyday health contexts.

**Proposed Solution.** We begin with a mixed-mode prestudy survey of 140 participants to assess awareness and behavioral practices around indoor  $\text{CO}_2$ . We find that while many participants acknowledge  $\text{CO}_2$  as harmful, few have measured it personally, and most lack knowledge of safe thresholds or effective ventilation strategies. Echoing prior studies on localized " $\text{CO}_2$  bubbles" around occupants [19, 26, 54], our pilot experiments confirm that  $\text{CO}_2$  accumulates unevenly and can persist in corners unless actively dispersed. To address this gap, we design and implement *CoWear*, a wrist-worn  $\text{CO}_2$  sensor integrated with a smartphone AR application. The system visualizes localized  $\text{CO}_2$  concentrations as color- and size-coded AR bubbles that users can place, observe, and interact with (Figure 1). Through these interactions, users can both monitor their personal exposure and experiment with actions, such as opening windows or directing airflow, to mitigate  $\text{CO}_2$  hotspots. We evaluate *CoWear* with 35 participants across semi-controlled and in-the-wild contexts. Through AR-mediated visualization, we demonstrate that indoor air quality can be improved not only as a result of improving awareness, but also as a result of informing timely and targeted ventilation interventions. In addition, the system also supports play-like, interactive interactions, highlighting the broader potential of AR for situated environmental management.

**Contributions.** In this paper, we contribute to the HCI community by advancing the development of interaction techniques that allow invisible pollutants to be perceived, situated, and made actionable. Specifically, our work offers:

- (1) **Human survey to assess awareness about personalized  $\text{CO}_2$  exposure.** We present a mixed-mode pre-study survey with 140 participants, combining online and offline responses. The survey reveals significant gaps in public understanding of  $\text{CO}_2$  as an indoor pollutant, misconceptions about ventilation strategies, and a strong demand for more intuitive visualization methods. It is these insights that underpin the design requirements for our system and underscore the role of HCI in bridging awareness gaps.
- (2) **Design of a wearable (*CoWear*) with a smartphone AR interface for personalized  $\text{CO}_2$  visualization.** We introduce *CoWear*, a low-cost wrist-worn prototype that continuously monitors personal  $\text{CO}_2$  exposure, integrated with a smartphone-based AR application. Through the use of dynamic, color-coded AR bubbles, our system becomes a multi-modal HCI interface that translates sensor data into situated, embodied experiences that facilitate environmental sensing and interaction.

- (3) **Developing a single-player AR game for pollution awareness and mitigation of CO<sub>2</sub> bubbles.** Extending the AR interface, we design and evaluate a game mechanic where users actively interact with CO<sub>2</sub> bubbles through ventilation strategies (e.g., opening windows, directing airflow). The game not only enhances user engagement but also demonstrates how playful interaction modalities can motivate behavior change for healthier indoor environments. We validate this approach with 35 participants across semi-controlled and in-the-wild settings, demonstrating effectiveness and usability.

## 2 Related Work

We review related work in two areas: (i) studies on the impact of CO<sub>2</sub> as an indoor pollutant, and (ii) research on pollution measurement, visualization, and interactive methods for environmental awareness.

### 2.1 CO<sub>2</sub> as an Indoor Pollutant

Several studies have identified that CO<sub>2</sub> can negatively impact decision-making at concentrations as low as 1000 ppm [4, 63]. However, both home and bedroom environments can contribute to significant CO<sub>2</sub> exposure [36], with individuals spending nearly one-third of their life sleeping [8] and more than 60% of their time in homes. In particular, for bedroom, CO<sub>2</sub> levels may exceed 2500 ppm when doors and windows are closed [24, 71], although lower CO<sub>2</sub> concentrations in bedrooms improves the sleep quality [36]. Notably, air conditioning (AC) systems also influence personal CO<sub>2</sub> exposure, as CO<sub>2</sub> tends to concentrate at lower heights due to its density. Sedentary office work can similarly result in higher CO<sub>2</sub> levels, as static air and limited occupant movement create conditions where individuals may re-inhale their exhaled CO<sub>2</sub> [26]. Studies have shown that CO<sub>2</sub> bubbles from personal respiration can average around 1200 ppm, compared to 650 ppm in surrounding indoor air under normal ventilation conditions [26]. Thus, a comprehensive understanding of personal CO<sub>2</sub> exposure requires measurements near the inhalation zone.

### 2.2 Pollution Measurements and Visualization

Several studies [48, 77] have shown the utility of static electrochemical and BAM (Beta Attenuation Monitor) sensors to measure the concentration of indoor air pollutants (i.e., CO, CO<sub>2</sub>, VOC, PM<sub>2.5</sub>, etc.). In addition, dashboards [30, 40] and alert systems [66] from the measurements to provide actionable recommendations to the user. Pollution data visualization is traditionally achieved through time-series plots and 2D representations overlaid on satellite imagery. For instance, Chen *et al.* [13] introduced a method for visualizing air quality data collected from fixed reference stations across China using Google Earth. While such representations are adequate for data visualization, they often fall short in terms of user engagement, as they are presented through static dashboards or mobile applications [34, 51].

Recent studies have highlighted advancements in visualization techniques, such as dynamic and interactive dashboards or user-driven suggestions, which can significantly enhance user engagement with data. For instance, Lindrup *et al.* [42] demonstrated how physical representations of data could improve understanding

of the environmental impacts associated with food consumption. [38] reported user experience and awareness of indoor air quality based on data visualization in the in-built display of the sensor. [41] designed a data visualization platform to extract possible spatiotemporal transport patterns from large-scale pollutant transport trajectories. [47] deploy a modular, shape-changing, configurable display for climatic awareness in the workplace. Another example, *AirSense* [22], can automatically identify pollution events, pinpoint the sources of pollution, and offer valuable suggestions for improving indoor air quality. Unlike outdoors, indoor pollutants can be distributed non-uniformly and persist only in specific spatiotemporal instances, making static sensor deployment challenging. Several studies [22, 78] have proposed mobile handheld or wearable sensor solutions to better approximate the spatiotemporal pollution distribution of indoor environments.

### 2.3 Immersive Visualization for Environmental Awareness and Actionability

Notably, AR is rapidly becoming the new medium through which users can understand and interact with their surroundings innovatively and meaningfully by enhancing their perception of the environment and objects. Several studies have utilized AR visualization to improve awareness and decision-making. For instance, a game-based learning tool, *EscapeCampus* [11], simulates an AR escape room to increase students' (11-16 years old) awareness of the 17 sustainable development goals of the United Nations. Saßmannshausen *et al.* [62] created an AR visualization for citizens to contribute design ideas for urban planning, where building projects and environment changes are visualized. Studies [5, 61] also helped customers choose by utilizing AR to overlay nutrition facts and comparative data with online and in-store products. Jin *et al.* [35] develops an AR support tool for learning smartphone applications, particularly in improving digital literacy among older adults.

Moreover, AR visualization has been proven effective in persuading users to take proactive actions. For instance, Schaper *et al.* [65] developed a persuasive mobile AR app that teaches the recycling process of each type of waste. Assor *et al.* [7] introduced ARwavs, an AR waste accumulation visualization representing waste data embedded in users' familiar environment. ARwavs yields stronger emotional responses than non-immersive waste accumulation visualizations and plain numbers. Mittmann *et al.* [50] introduced an AR smartphone-based collaborative game that facilitates improved social interactions among students. Recent studies have utilized AR to visualize air quality data. For instance, [49] visualized outdoor air pollutants in an AR scene with real-time data from nearby air quality monitoring sites. Katsiokalis *et al.* [37] overlayed real-time data with AR to provide citizen awareness of outdoor air and noise pollution data. Chae *et al.* [12] explored mobile AR systems to visualize air conditioner airflow and temperature changes. However, a few studies have investigated AR applications for indoor pollution visualization and interaction.

### 2.4 Interaction Design for Environmental Awareness and Actionability

Our research is also connected to the growing work on games and gamification. Recent literature has seen a surge in publications

exploring the use of games across various domains [2, 9, 33, 58]. For example, the gamified application AXO [33] was designed to teach preteens about recycling by engaging them in sorting and identifying common household waste to protect a chain of islands. Simultaneously, Prophet *et al.* [58] developed an application where air quality is symbolized by the growth of a virtual tree, with users interacting via augmented reality to care for the tree based on local air quality. Similarly, Feldpausch-Parker *et al.* [23] created an educational game to enhance students' understanding of the impacts of CO<sub>2</sub> emissions, while Albar *et al.* [2] emphasized game-based learning to foster environmental sustainability awareness among children. Similarly, CityOnStats [72] employs a 3D game-like environment where users can explore and interpret air quality data through various visual cues, catering to diverse user preferences. Furthermore, the work by Relvas *et al.* [60] underscores the importance of raising awareness about air pollution. Their study introduces "Problems in the Air," a Unity-based game designed to educate players about air pollution through interactive gameplay.

## 2.5 Open Challenges and Hypothesis

Although prior work has established CO<sub>2</sub> as a significant indoor pollutant and developed methods for measuring individual exposure, these efforts largely stop at data collection. Invisible phenomena such as personal CO<sub>2</sub> "bubbles" remain difficult for occupants to perceive or interpret, leaving a critical gap between sensor readings and everyday experience. In contrast, visualization and gamification techniques have been effectively used to foster awareness of environmental issues such as outdoor air pollution. Yet, we still lack an understanding of how best to bridge *invisible environmental data* with everyday perception through interactive means. We approach this challenge by expanding the role of AR beyond environmental awareness toward situated actionability. Physical properties of CO<sub>2</sub> (e.g., diffusion, accumulation, persistence) lend themselves to embodied representation in AR. Our aim is to connect abstract sensing data, situated visualization, and interaction into a coherent pipeline that enables users not only to perceive their personal CO<sub>2</sub> environments but also to act upon them in everyday contexts [2, 7, 11]. Accordingly, we hypothesize:

**H1. Lack of CO<sub>2</sub> Pollution Awareness.** Occupants may be aware of CO<sub>2</sub>'s general health impacts but often lack knowledge of concrete remedies. We hypothesize that making CO<sub>2</sub> exposure *visible and situated* at a personal scale can improve awareness of effective preventive measures.

**H2. From Awareness to Actionability.** Beyond raising awareness, we hypothesize that AR visualizations of CO<sub>2</sub> exposure will nudge occupants toward concrete actions, such as engaging with ventilation systems, windows, or other devices, to reduce concentrations. Prior research demonstrates that AR can scaffold in-situ decision making and proactive behaviors [7, 50, 65], particularly when immersive data visualizations are tightly coupled to everyday contexts [39, 61].

## 3 Prestudy Survey and Motivational Experiment

Hypothesis H1 aims to determine the perception and awareness of communities on indoor pollution in general and CO<sub>2</sub> exposure

in particular. For this purpose, we designed a pre-study survey questionnaire with the following objectives.

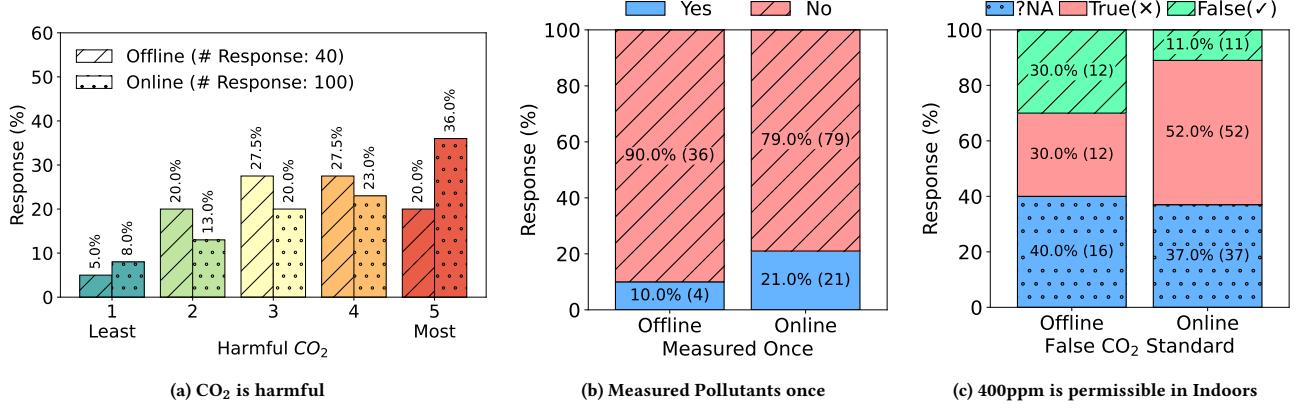
- O1.** How experienced are the participants in measuring pollutants, like CO<sub>2</sub>, at a personal scale, like at their homes?
- O2.** Are participants aware about the CO<sub>2</sub> standards and its impact?
- O3.** What is participants' perception of ventilation's role in indoor pollution, particularly CO<sub>2</sub> exposure?
- O4.** What is the participants' perception about improving their awareness level for breathing healthy air indoors?

### 3.1 Survey Methodology

We have conducted a mixed-mode pre-study survey with two groups of participants – offline and online participants. Using a one-sided one-sample proportion test for awareness and experience with null-hypothesis proportion ( $p_0$ ) 0.40, and expected true proportion ( $p_1$ ) 0.25 (i.e., small-to-medium effect, Cohen's  $h = 0.32$ ), with statistical significance ( $\alpha$ ) 0.05 and 80% power, the required sample size is  $N \approx 61$  respondents (normal approximation). In the pre-study survey, we collected a total of  $N = 140$  responses. The offline participants ( $N = 40$ ) were recruited from the university campus and further chose to volunteer for the entire study at its different stages (system performance and testing, as we discuss later in Section 5). The online responders ( $N = 100$ ) are more diverse. For online participation, we have broadcast the survey questionnaire through social media, public forums, and emails to targeted groups/communities. The survey questionnaire contained four significant sections – (1) general demographic information including age, gender, location, profession, family income, house type, number of members in the family, history in the family about pollution-related diseases, etc., (2) general awareness on indoor pollution (7 questions), (3) understanding about the type, spread, and harmfulness of indoor pollutants (7 questions), and (4) perception on counter-measure to reduce indoor pollution (10 questions with a rating 1–5). The offline survey participants were mainly university students and faculties, aged between 20–38, with 82.5% male and 17.5% female. We have received online survey responses from 30 different cities over 4 countries – Germany, India, the UK, and the USA. The online participants were aged between 17–60, with 75% of males and 25% of females. Most of the online participants were from within the 20–30 age group, representing 55.4% of the total participants; the 30–40 age group accounted for 24.1%, while 14.4% participation was between 40–50 years old. The remaining participants (6.1%) were more than 50 years of age. Among these online participants, 46% were from urban areas, 34% were from suburban areas, and 20% were from rural backgrounds.

### 3.2 Observations

**3.2.1 Experience with Pollution Measurement.** As per Figure 2a, around half of responders (i.e., 47.5% in offline, and 59% online) think that CO<sub>2</sub> is harmful. However, when it comes to measuring these pollutants in their personal indoor spaces, only 10% offline and 21% online responders have experience with pollution monitors and measurements, as shown in Figure 2b. Overall proportion ( $\hat{p}$ ) 0.178 (95% CI: 0.115 – 0.242, z-statistic  $-5.35$ ,  $p < .01$ ) indicates



**Figure 2: The responders of the prestudy (a) agree that CO<sub>2</sub> is harmful, but (b) most of them have never measured indoor pollutants. (c) Awareness about indoor pollutants – response to a false statement about indoor CO<sub>2</sub> standards.**

that most of the responders who think CO<sub>2</sub> is harmful have never actually tried to measure their exposure level.

**3.2.2 Awareness and Ventilation Strategy.** We observe that the majority of the responders (i.e., 87.5% offline and 85% online) are aware that indoor gatherings increase CO<sub>2</sub>. However, as depicted in Figure 2c, we observe that most of the responders are unfamiliar with permissible CO<sub>2</sub> limits in indoors (i.e., only 30% in offline and 11% in online were correct) with overall proportion ( $\hat{p}$ ) 0.164 (95% CI: 0.103 – 0.225, z-statistic  $-5.69$ ,  $p < .01$ ). Notably, a significant number of survey participants were not able to answer the facts related to indoor pollutants like CO<sub>2</sub> and the strategy to mitigate them from indoor spaces under different situations. For example, most of the participants, both from the offline and online survey, believed that split AC can ventilate pollutants, contrary to the observations made in existing studies [70, 79]. To improve energy efficiency, the split AC recirculates the cold indoor air rather than injecting outside fresh air. Thus, the inside polluted air is not ventilated unless an embedded ventilation system with the AC exists.

To analyze this further, we asked how the participants would ventilate the CO<sub>2</sub> in a family gathering. Interestingly, we observed that 27.5% offline and 33% online responders proposed an ineffective solution (i.e., turn on split AC or ceiling fan). Further, 57.5% offline and 31% online responders get confused and propose a solution that might be effective for reducing CO<sub>2</sub> but would waste resources (i.e., turn on AC and open the windows at the same time). 7.5% offline and 23% online responders could choose an effective method (i.e., turn on the ceiling fan and open the windows while keeping the AC off); however, opening up windows can increase other pollutants like particulate matter (e.g., PM<sub>2.5</sub>) if the outdoor is heavily polluted (e.g., for cities like Delhi, Hotan, Dhaka, etc.). Only 7.5% offline and 13% online responders proposed a safe and effective approach (using electric window ventilation or an exhaust fan). Overall proportion ( $\hat{p}$ ) 0.114 (95% CI: 0.061 – 0.167, z-statistic  $-6.9$ ,  $p < .01$ ) of effective and safe ventilation approach in the survey indicates that due to less understanding of the indoor pollution dynamics, most responders

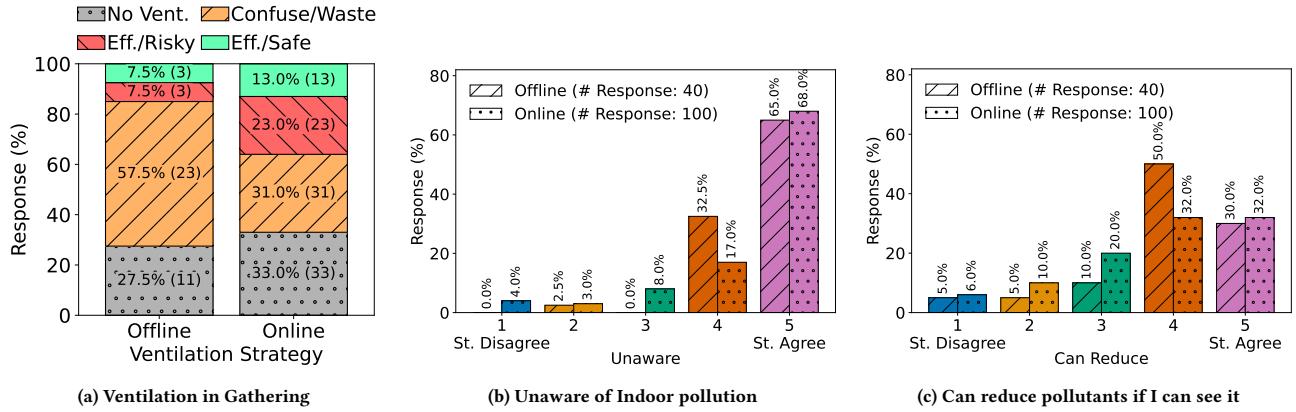
may not be able to mitigate indoor pollutants like CO<sub>2</sub> in an efficient way.

**3.2.3 Can Visualization Help?** As shown in Figure 3b, most of the respondents in the mixed-mode survey agree that there is less awareness about indoor pollutants among the general population, whereas only 0.06 (95% CI: 0.019 – 0.101, z-statistic  $-7.95$ ,  $p < .01$ ) of the overall proportion ( $\hat{p}$ ) disagrees. Moreover, 80% of offline and 64% of online responders think that they can reduce the pollutants if they can see them, as shown in Figure 3c, indicating the importance of a visualization method for indoor pollutants to improve awareness among the general population, fostering adequate ventilation, healthier, and happier indoors. Based on this prestudy that validates H1, we next discuss our observations from the pilot experiment to understand the indoor CO<sub>2</sub> dynamics to design effective data-driven visualization.

### 3.3 How do we actually manage CO<sub>2</sub> in Indoors?

We conducted a pilot study to investigate key physical behaviors of CO<sub>2</sub>, including spreading, trapping, and lingering, to inform data-driven visualization in personal indoor spaces. The study took place in a  $15 \times 10 m^2$  office containing 10 cubicle workstations (cubicle height: 5 m), two ceiling fans, two pedestal fans, a window ventilator, and a split AC. We deployed pollution sensors at three heights across 9 spatial locations (Figure 4). During the experiment, the ceiling fans and split AC remained off; only the pedestal fan and window ventilator were selectively operated.

As occupancy increased, localized CO<sub>2</sub> accumulation formed around active workstations (Figure 4a), with concentrations rising proportionally to the number of occupants (Figure 4b). CO<sub>2</sub> levels were consistently highest at table height, compared to floor or ceiling measurements. Once all sensors exceeded 1400 ppm, the window ventilator was activated (Figure 4c). After occupants left, CO<sub>2</sub> levels decreased, particularly at ceiling height and central room regions; however, persistent elevated concentrations remained in corner cubicles at table height, forming localized *personal CO<sub>2</sub> bubbles* [26, 54] exceeding 1200 ppm (Figure 4e). Activating the pedestal



**Figure 3:** (a) Effectiveness of different ventilation methods in a family gathering, as perceived by the responders. (b,c) Perception of the responders on (b) the fact that the general population is unaware of indoor pollution and (c) their confidence in reducing the pollution through a visualization method. The survey indicates the need for effective pollution visualization, like an AR-based solution.

fan near one such bubble significantly reduced local accumulation (Figure 4f). These CO<sub>2</sub> bubbles grow quasi-statically [19] and may remain trapped in corners unless dispersed by directed airflow.

### 3.4 Personified, Situated Visualization and Actionability

Central to our approach is the concept of *personified CO<sub>2</sub> bubbles*, representing an individual's localized exposure zone. Capturing these highly dynamic and spatially heterogeneous bubbles typically requires dense networks of static CO<sub>2</sub> sensors, as demonstrated in our pilot study (see Fig. 4). However, such infrastructure is costly, immobile, and poorly suited to evolving environments or personal routines. In contrast, a wrist-worn CO<sub>2</sub> sensor travels with the user, enabling high-resolution, personalized exposure monitoring at lower cost and with greater flexibility. Real-time wearable data allows AR-based visualization of evolving CO<sub>2</sub> bubbles at meaningful physical locations and heights, transforming abstract sensor values into situated, perceptible risks. This spatial anchoring supports rapid identification of hotspots and encourages exploratory mitigation actions (e.g., directing airflow, opening windows). Immediate visual feedback, such as bubble shrinkage following ventilation, not only improves comprehension but also reinforces confidence and sustained engagement. We argue that AR serves as a bridge between *risk location*, *affected user*, and *effective action*. The following sections detail the wearable prototype and AR platform.

## 4 Prototype Design and Study Procedure

On the basis of the pre-study survey and the pilot experiments, we design a visualization and interaction methodology to mitigate high concentrations of CO<sub>2</sub> (i.e., bubbles). We consider the following design goals to build the prototype.

- D1.** To design a personal wrist-wearable prototype that can effectively measure CO<sub>2</sub> concentration in real-time at a personal indoor space.

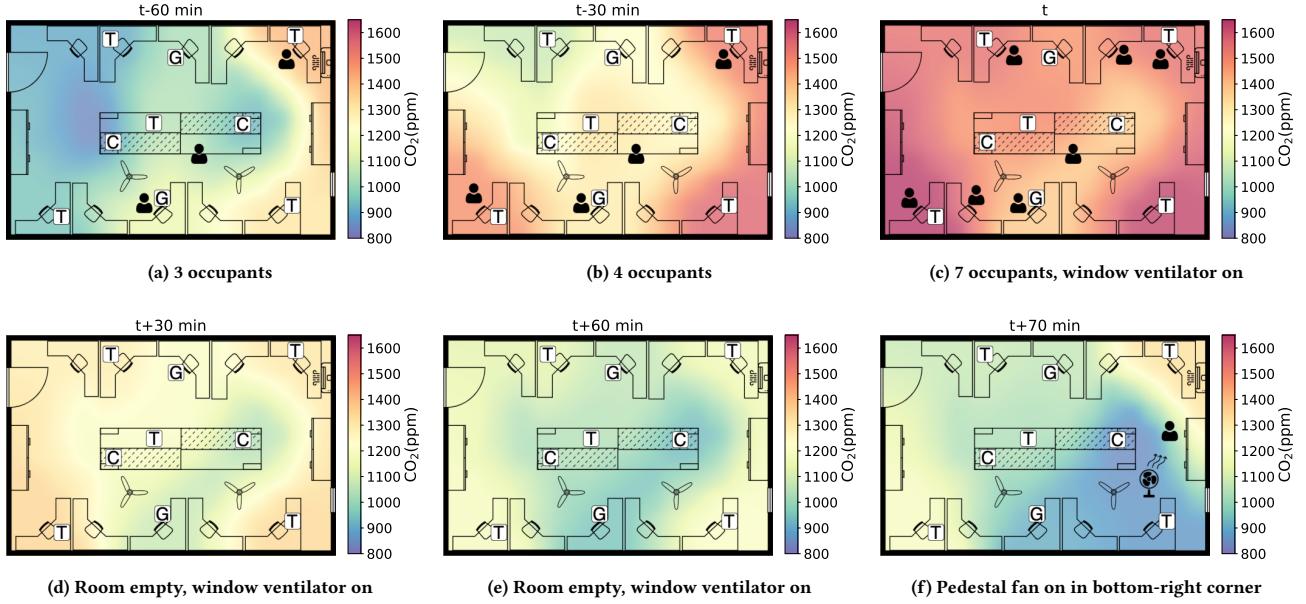
**D2.** To design a smartphone-based AR gaming application with two sub-objectives: (1) visualizing the CO<sub>2</sub> bubbles in a personal space while displaying their severity in real-time, (2) interacting with the CO<sub>2</sub> bubbles through directed actions, like turning on the window ventilator, opening the window, directing airflow towards the bubble, etc., to reduce their severity. We discuss these in detail below.

### 4.1 CoWear Wrist-wearable Sensor

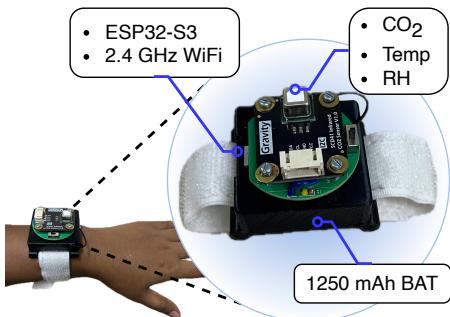
We developed a wrist-wearable module named *CoWear* to sense personalized pollution exposure of the user. *CoWear* is equipped with *Temperature*, *Humidity*, and *Carbon Dioxide* (CO<sub>2</sub>) sensors [67] along with a 1250 mAh battery, enabling day-long power backup with only two hours of recharging time. Notably, wrist-wearable works best because of the following reasons: (1) the participants can move their hands to check the varying CO<sub>2</sub> exposure around them, (2) wrist-wearables are lightweight and provide a comfortable and robust solution compared to other commercial wearable pollution monitors available in the market like Atmotube Pro<sup>1</sup>, a neck-wearable or AirSniffle<sup>2</sup> that needs to be carried explicitly. For developing *CoWear*, we use the ESP32-S3 chip as the on-device processing unit that packs a dual-core Xtensa 32-bit LX7 microcontroller with 2.4 GHz Wi-Fi (802.11 b/g/n) capabilities. The connectivity board is a two-layer printed circuit board (FR4 material). This wearable uses a 3D printed shell (PLA+ material) to package the sensors and battery. Table 1 details the overall specifications of the *CoWear* wrist-wearable. The microcontroller periodically measures CO<sub>2</sub> at a 5-second interval. The measurements are transmitted to client devices over HTTPS GET queries via the wireless channel with a latency of 58.76 ( $\pm 5.32$ ) ms. Next, we describe the smartphone AR app that visually grounds real-time pollution data over the indoor space.

<sup>1</sup><https://atmotube.com/atmotube-pro> (Accessed: February 3, 2026)

<sup>2</sup><https://www.airsniffle.com/> (Accessed: February 3, 2026)



**Figure 4:** CO<sub>2</sub> distribution at various locations of a room at different heights. [G] represents ground height, [T] represents table height, and [C] represents ceiling height. The CO<sub>2</sub> concentration increases over time with the occupancy level of the room without ventilation (i.e., window ventilator is turned on at time  $t$ ) - (a) three-person occupancy at  $t$ -60 minutes, (b) four-person occupancy at  $t$ -30 minutes, (c) seven-person occupancy at  $t$ , maximal CO<sub>2</sub> concentration of 1635 ppm in bottom-left corner, window ventilator is turned on for ventilation. Occupants leave the room. CO<sub>2</sub> distribution when the room is - (d) ventilated for 30 minutes, (e) ventilated for 60 minutes. We observe that CO<sub>2</sub> accumulates and gets trapped in corners of the room at source height (i.e., occupants, table height). Lastly, (f) Turned on the stand fan from the bottom-right corner towards the top-right corner, reducing accumulated CO<sub>2</sub> in the bottom-right corner. Thus, targeted airflow can reduce trapping of CO<sub>2</sub> in specific areas of the room (e.g., corners).



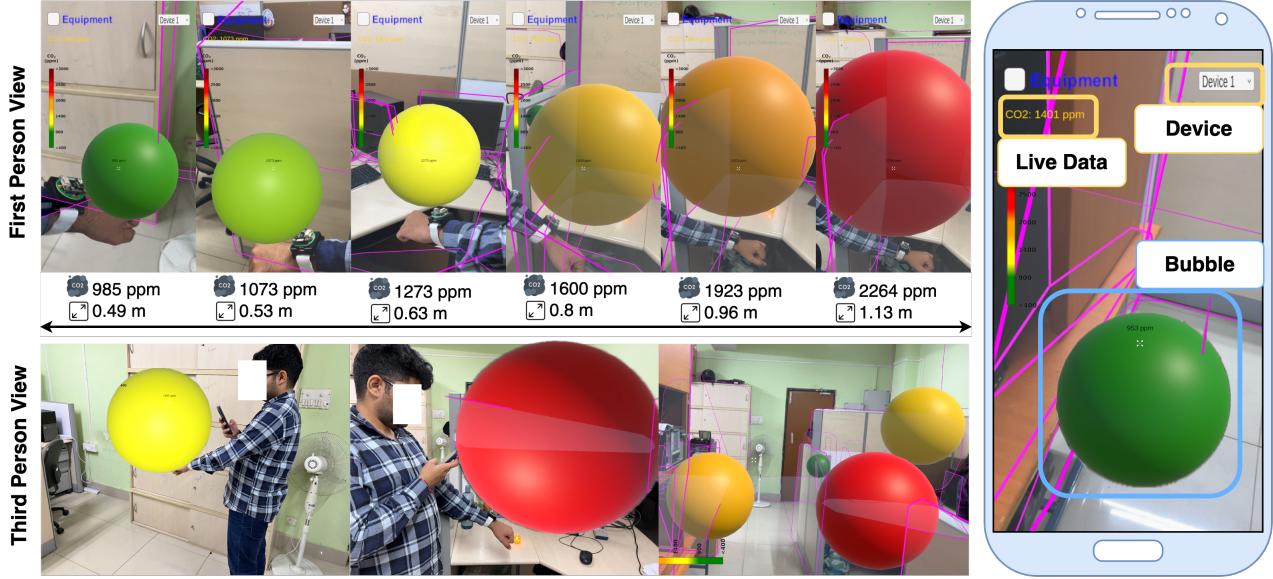
**Figure 5:** CoWear wrist-wearable.

## 4.2 Smartphone Augmented Reality (AR) Interactions

We developed an AR application that visualizes indoor CO<sub>2</sub> concentration with virtual bubble objects based on our observations from Section 3.3. The app has three key features: spatial anchoring, personified pollution visualization, and real-time AR interactions with pollutants. The app helps to understand indoor pollution hotspots as follows.

**4.2.1 3D Spatial Anchoring.** The app creates a relative 3D coordinate system for the indoor environment using the Unity3D Plane Manager library. By detecting planar objects and walls in the environment, the app provides spatial anchoring for tracking virtual objects' location and size, regardless of the smartphone's location. To place objects at any location, the user must scan the entire indoor space at the start of the app. Although this is an essential step, modern smartphone cameras (e.g., Apple iPhone 13 Pro in this study) allow us to scan an entire space in minimal time.

**4.2.2 Personified Pollution Visualization with CoWear.** The AR app is coupled with CoWear wrist-wearable – the wearable measures user-centric CO<sub>2</sub> exposure at any location of the indoor space. The AR app visually anchors the CO<sub>2</sub> data by allowing the user to spawn representative AR bubbles that vary in terms of color and diameter with the sensor readings at any particular location. A smaller, more greenish bubble represents a lower CO<sub>2</sub> concentration. Typical outdoor 400 ppm, CO<sub>2</sub> is represented as a green 0.2m bubble. Whereas increased CO<sub>2</sub> reading leads to yellow and then red bubbles in a continuous spectrum. An unhealthy high CO<sub>2</sub> reading of 3000 ppm indoors is represented as a red, 1.5m bubble. The bubbles placed in different pollution scenarios are shown in Figure 6. The users must align their hand to co-localize the CoWear wrist-wearable and the



**Figure 6: Augmented reality application - green bubble represents less CO<sub>2</sub> concentration, relatively larger yellow bubble represents moderate CO<sub>2</sub> concentration, and the largest red bubble represents more than 2000 ppm CO<sub>2</sub> concentration. The bubbles' color and diameter vary according to the sensor readings (i.e., 400 ppm ⇒ green, 0.2m bubble, and 3000 ppm ⇒ red, 1.5m bubble).**

**Table 1: Overall specifications of CoWear wrist-wearable. Typical conditions represent 25°C, 50% RH, 1013 mbar ambient pressure.**

System Specification	
Microcontroller	Xtensa®32-bit LX7 Clock 80–240 MHz
PSRAM+Flash	8MB+8MB
Connectivity	Wi-Fi 2.4 GHz
COM Latency (ms)	58.76 ( $\pm 5.32$ )
Avg Power (W)	0.244 @3.7V
Battery (mAh)	1250
Dimensions (mm <sup>3</sup> )	42×49×18
Weight (g)	50

Sensors		Operational Details				
		Range	Repeatability	Response Time		Yearly Drift
CO <sub>2</sub>	Condition			Preheat	Poll	
	Accuracy	$\pm 40$ ppm + 5 % value	$\pm 10$ ppm	90 sec	5 sec (periodic samples)	0.25% RH
Humidity	Condition	0% RH – 95% RH	Typical	120 sec	0.03 °C	$\pm 0.8$ °C
	Accuracy	-10 °C – 60 °C	$\pm 0.4\%$ RH	120 sec		
Temperature	Condition	-10 °C – 60 °C	Typical	120 sec	0.03 °C	$\pm 0.8$ °C
	Accuracy	$\pm 0.8$ °C	$\pm 0.1$ °C	120 sec		

AR bubble such that the bubble represents the local pollution concentration. The user must stay near the AR bubble ( $\leq 1\text{m}$ ) to notice the change in the bubble's color and size with the accumulation or ventilation of the pollutants.

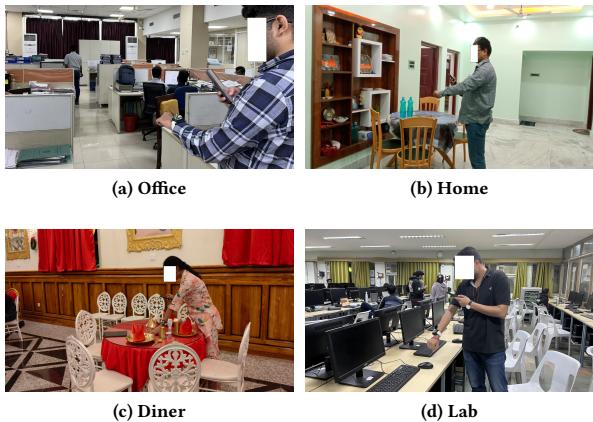
**4.2.3 AR Interactions with the Pollutants.** CO<sub>2</sub> sources, such as cooking, candles, and indoor gatherings, form CO<sub>2</sub> bubbles in the indoor environment. Candles produce CO<sub>2</sub> steadily, creating CO<sub>2</sub> bubbles around it. Cooking food generates a significant amount of pollutants due to the fire. Baking soda-based food items (i.e., cakes and fried foods) produce CO<sub>2</sub> even when heated in an induction oven. Additionally, small indoor gatherings cause significant CO<sub>2</sub> accumulation in that area due to the respiratory emission of the occupants, as shown in our pilot experiment on how to manage indoor CO<sub>2</sub> in section 3.3. Subsequently, CO<sub>2</sub> bubbles get trapped at various corners of indoor spaces unless they are removed through external airflow. The user places the representative CO<sub>2</sub> bubbles using the AR app and reduces the bubbles with these tools and available ventilation equipment, such as ceiling fans, pedestal fans, open windows, and window ventilators. For instance, the user may use the hand fan to direct airflow towards the window ventilator

or the opened window, observing a gradual shrinkage and color shift in the AR bubble with a reduction in CO<sub>2</sub> concentration in the indoor location. With these AR bubbles, users can identify areas of accumulation or potential pollution sources. In addition, bubble shrinkage can be monitored to confirm effective ventilation of the indoor space.

### 4.3 Study Conditions and Setup

We have evaluated the system in both semi-controlled and in-the-wild settings. The semi-controlled experiments were conducted in two office rooms. In-the-wild experiments are conducted in office, household, diner, and lab environments. Next, we discuss the semi-controlled and in-the-wild setting in detail.

**4.3.1 Semi-controlled User Experiments.** We have taken two scenarios for these experiments: (i) a large office room (R1) with multiple windows, fans, and window ventilators, and (ii) a relatively small office room (R2) with only one window, fan, and window ventilator. The large room is  $5\text{m} \times 8\text{m}$  ( $40\text{ m}^2$ ), and the small room is  $3\text{m} \times 5\text{m}$  ( $15\text{ m}^2$ ). For the semi-controlled experiments, we ensure the formation of CO<sub>2</sub> bubbles in specific areas of the room by placing CO<sub>2</sub>



**Figure 7: In-the-wild experiment conditions - (a) Working office, (b) Home with multiple rooms, (c) Diner, (d) Lab environment. The participant must first identify the dynamic pollution sources to effectively ventilate CO<sub>2</sub>.**

sources (i.e., candles, heated baking soda, and indoor gatherings) in designated parts of the room. The participants act independently to figure out the bubbles and execute their ventilation strategies to reduce CO<sub>2</sub> concentration.

**4.3.2 In-the-wild User Experiments.** We have conducted uncontrolled in-the-wild user experiments in a working office, household, diner, and lab environments, as shown in the Figure 7. The pollution sources in these environments are dynamic and depend on the other occupants and their activities (e.g., cooking, burning, gathering). For instance, in a diner, CO<sub>2</sub> bubbles can increase when the diner staff decides to put up candles at each table or serve on hot plates (like sizzlers). Moreover, CO<sub>2</sub> can accumulate in the corner of the office or the lab due to gathering. Therefore, the participant must find instances where CO<sub>2</sub> bubbles are formed with the *CoWear* wrist-wearable and the AR app. Subsequently, they can employ effective ventilation strategies to mitigate the accumulated CO<sub>2</sub> bubbles from the space.

#### 4.4 Participants

We conducted an a priori power analysis to determine the minimum sample size required for our within-group mixed/augmented reality study. Following the guidelines for AR/MR experimentation [53], we adopt recommended effect size thresholds of 0.40 (small), 0.81 (medium), and 1.55 (large) for Cohen's *d*, and 0.17 (small), 0.33 (medium), and 0.54 (large) for Cramer's *V*. We power our analyses such that the intervention is likely to elicit medium to large effects. For the Welch's t-tests, detecting a medium-to-large effect (Cohen's *d* > 0.81) at 80% statistical power and significance ( $\alpha$ ) 0.05 requires a minimum of 15 participants. Similarly, for categorical comparisons using  $\chi^2$ -tests, detecting large (Cramer's *V* > 0.54) to medium (Cramer's *V* > 0.33) effects requires at least 17 to 45 participants, respectively. From [53], which summarizes proceedings of CHI from 2019 to 2023 for effect sizes, within-group studies typically include 28.5 median participants (AR/MR-specific range: 7–40, median 20).

Based on this, we have recruited 35 participants through a call for volunteers during the offline prestudy survey.

Most of the participants were undergraduate and graduate students. Therefore, most of them are accustomed to playing smartphone games and are used to wearing smartwatches. Their age ranges from 20 to 48 years ( $\mu = 25.11$  years,  $\sigma = 6.23$  years). 30 (85.7%) of the participants are identified as male, and 5 (14.3%) as female. Most of the participants already have fair experience with smartphone games. Two participants play smartphone games every day. Seven participants play weekly. Five participants play monthly at least once. Moreover, 12 participants reported that they play smartphone games rarely. However, 9 participants do not play smartphone games. The participants have limited or no prior experience with smartphone AR games.

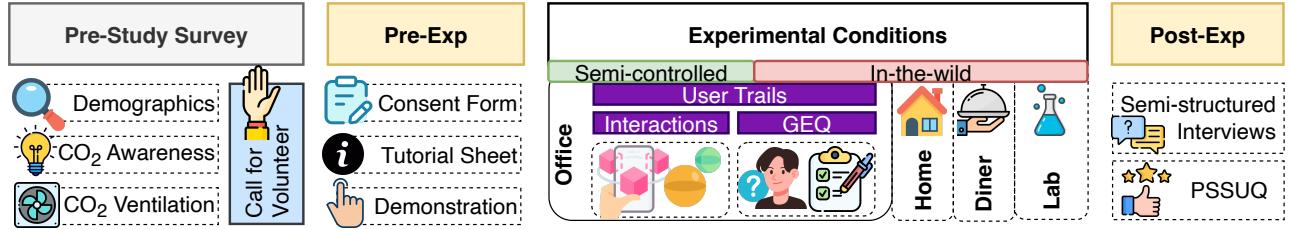
In the semi-controlled user experiments, among 35 participants, 31 participated in session S1, and 34 participated in session S2 (i.e., 30 participated in both S1 and S2, achieving 80% statistical power for medium-to-large effects). Moreover, the in-the-wild user experiments were conducted opportunistically in real-world indoor setups (i.e., dinner, research lab, office, and households). Due to the sporadic availability of these spaces and overlap with participants' availability, 20 participants who participated in both S1 and S2 (i.e., among 30) took part in these sessions. Finally, these participants who took part in all the AR sessions, baseline our approach with a generic 2D pollution heatmap visualization, ensuring sufficient power to detect medium-to-large effects for analyzing user experience and perception.

#### 4.5 Study Procedure

The study contained three phases after recruiting the volunteers: (1) Pre-experiment activities (i.e., informed consents, explanation of the experiments, demonstration of the AR app, etc.), (2) User experiments (i.e., live interaction and game experience survey), and (3) Post-experiment activities (i.e., semi-structured interviews and system usability survey). Figure 8 depicts the overall study procedure. All survey questionnaires are included in the Appendix A.

**4.5.1 Pre-experiment Activities.** First, an information sheet is handed out to the participants that describes the study overview, the objective of the participant during the study, how to use the smartphone AR gaming app, and the *CoWear* wrist-wearable to measure CO<sub>2</sub> concentration at any location of an indoor space. The information sheet also mentions the deployed sensors and the modalities being collected from the participants. Thereafter, participants signed a consent form to collect personal and experimental data during this study. Next, a research associate provided a brief tutorial to the new participants in a session by demonstrating the AR app (i.e., how to place the AR bubbles, how participants must align their hand to co-locate the *CoWear* wrist-wearable and the AR bubble to observe the changes in bubble color and size with the accumulation of pollutants over time).

**4.5.2 User Experiments.** A research associate helped the participants to put on *CoWear* wrist-wearable, an Empatica E4 watch, and a body camera to capture the participant's personalized CO<sub>2</sub> exposure, physiological data, and a first-person view of their actions. In a semi-controlled session, the research associate ensures that



**Figure 8: Overall study procedure - We estimated user awareness and recruited participants with a pre-study survey. We took consent from the participants, and after each user trial, we took an experience survey. Lastly, the participants took part in semi-structured interviews and usability surveys.**

the CO<sub>2</sub> sources are active in their designated locations. Whereas, CO<sub>2</sub> sources are dynamic for in-the-wild sessions and depend on occupants' indoor activities as discussed in section 4.3. We designed these sessions as gaming experiences for the participants, where they explore the indoor space and identify areas with higher CO<sub>2</sub> concentration by placing representative AR bubbles using the app. Further, the participants utilized the available tools (i.e., hand fans, battery-operated fans, etc.) and ventilation equipment (i.e., ceiling fan, pedestal fan, window ventilator, etc.) to direct airflow towards the AR bubbles, reducing CO<sub>2</sub> concentration in the space as discussed in section 4.2.3. We kept 800 ppm indoor CO<sub>2</sub> concentration as the sessions' stopping criterion (softbound). However, the participants can continue and further reduce the pollutants. A particular session can last between 20 and 40 minutes, including the pre-experiment activities. After each session, the participant completed the *Game Experience Questionnaire* (GEQ) [32], included in Appendix A.2, to assess their experiences and interactions with ventilating CO<sub>2</sub> using AR bubbles. We have used the (i) in-game GEQ and (ii) the post-game GEQ Questionnaires. Note that different user sessions are conducted on separate days.

**4.5.3 Post-experiment Activities.** After the user experiments, the participants were subjected to *Post Study System Usability Questionnaire* (PSSUQ) [64] on the AR app. PSSUQ determines user-perceived system satisfaction with 16 questions on a 7-point Likert scale (included in Appendix A.3), where a lower score indicates better usability. The participants also provided feedback on: (i) whether their view on air pollutants improved compared to the prestudy survey, and (ii) features they would like to see in future versions of the AR app. Next, we organized *Semi-structured Interviews* as focus group discussions among three participant groups and one research associate to understand their experience with different aspects of the system. The research associate moderated a discussion on how in-game interactions affected participants' perceptions of air pollutants and their gaming experience, along with suggestions to improve the current platform (discussion topics are included in Appendix A.4). Participants can speak up in any order about the currently discussed topic and share their views without a time limit. We recorded the transcripts of the participants' opinions on their overall experience with the AR app and suggestions for improving the system. We next discuss our observations from these user experiments, surveys, and interviews.

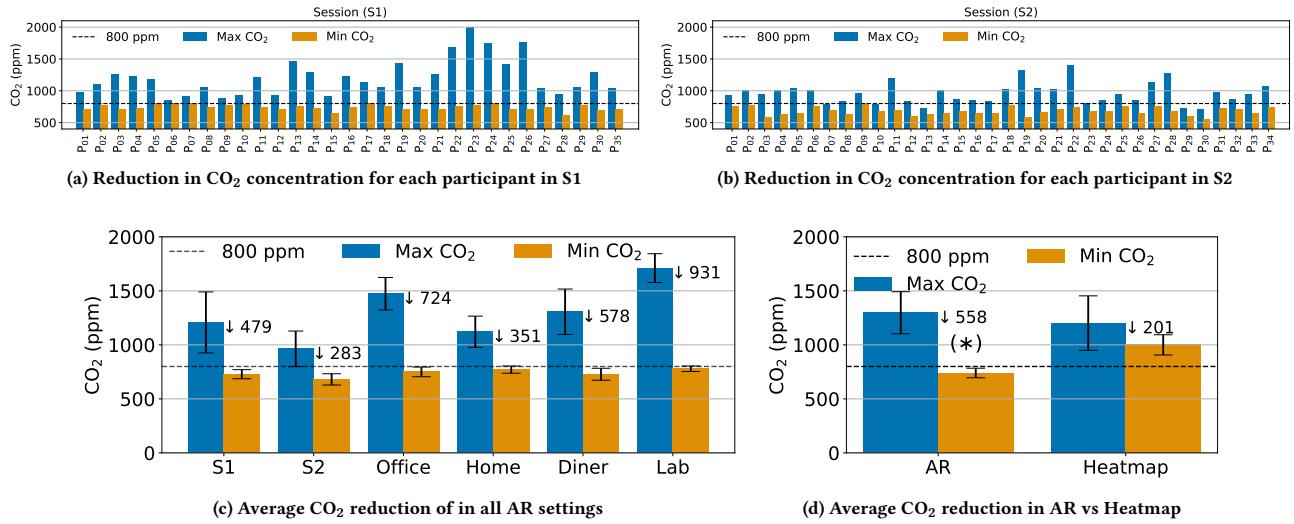
## 5 Study Results

This section analyzes how the participants perceived the visualization, gameplay, and overall experience during the semi-controlled and in-the-wild user experiment sessions.

### 5.1 Effective CO<sub>2</sub> Reduction

**5.1.1 Effectiveness of the Augmented Reality Application.** In session S1, the average starting CO<sub>2</sub> concentration was 1207 ppm, and the ending concentration was 728 ppm. We observe an average reduction of 479 ( $\pm 281$ ) ppm. Individual reduction for each participant is shown in Figure 9a. In S1, most of the participants were newly introduced to the AR app. They took around 2.14 ( $\pm 1.6$ ) minutes per 100 ppm of CO<sub>2</sub> reduction. The maximum and minimum time participants took to ventilate 100 ppm CO<sub>2</sub> in S1 were 6 minutes and 0.34 minutes, respectively. In session S2, the average starting CO<sub>2</sub> concentration was 963 ppm, and the ending concentration was 680 ppm. We observe, on average, 283 ( $\pm 155$ ) ppm reduction during the session as shown in Figure 9b. In S2, 30 participants were familiar with the AR app from S1, so we observed faster CO<sub>2</sub> ventilation. Four newly introduced participants were also able to reduce CO<sub>2</sub> levels below the 800 ppm target. Participants took around 1.48 ( $\pm 1.11$ ) minutes (i.e., approx. 40 seconds less than S1) to ventilate 100 ppm of CO<sub>2</sub>. The participants took a maximum of 5.7 minutes and a minimum of 0.3 minutes to ventilate 100 ppm CO<sub>2</sub> in S2. Similarly, during the in-the-wild experiments, we observe an average CO<sub>2</sub> reduction of 724 ppm, 351 ppm, 578 ppm, and 931 ppm in Office, Home, Diner, and Lab environments, respectively. Figure 9c shows the average starting and ending CO<sub>2</sub> concentration from the user experiments in different indoor setups. We observe a significant reduction (i.e., using Welch's t-test, t-statistic 6.54,  $p < .01$ , medium-to-large effect with Cohen's  $d = -1.36$ ) of 558 ppm CO<sub>2</sub> on average with the AR app in indoor environments as shown in Figure 9d. Thus, the AR app and *CoWear* wrist-wearable have effectively represented CO<sub>2</sub> bubbles for participants to act upon and ventilate the pollutant from the indoor space.

**5.1.2 Effectiveness of 2D Spatial Heatmap.** To compare the effectiveness of the AR app, we tested with a 2D spatial heatmap visualization of CO<sub>2</sub> like Figure 4 in Section 3.3. We deployed six static CO<sub>2</sub> sensors to generate a real-time pollution map of the office room (R1). Further, we conducted user experiments to understand how participants perceive the 2D pollution map and interact with the ventilation tools and equipment available near them. The 2D



**Figure 9: Effectiveness of the CoWear wearable and the AR app - (a,b) maximum CO<sub>2</sub> readings during the session S1, S2 and CO<sub>2</sub> reading at the end of the session after using the AR app to visualize and ventilate the pollutants, (c) average CO<sub>2</sub> reduction in each augmented reality setting, (d) average CO<sub>2</sub> reduction in augmented reality vs baseline 2D heatmap visualization. (\*) indicates statistically significant CO<sub>2</sub> reduction with AR app.**

heatmap user experiments were conducted similarly to the semi-controlled AR sessions, and a research associate demonstrated the user interface to the participants before the experiments. We observed that participants faced difficulties planning targeted ventilation strategies with the heatmap visualization, resulting in longer session durations and inadequate ventilation. With the CoWear wearable and the AR app, we observe a significant CO<sub>2</sub> ventilation (i.e., 558 ppm CO<sub>2</sub> on average); however, with the heatmap, participants can only ventilate up to 201 ppm CO<sub>2</sub> on average with no statistical difference between the starting and ending CO<sub>2</sub> concentration, as shown in Figure 9d. Most participants could not achieve the 800 ppm target CO<sub>2</sub> level with the heatmap, even with longer session duration.

## 5.2 Impact on User's Awareness

As shown in Figure 10a, most participants reported that the smartphone AR app improved their overall understanding and awareness about indoor pollutants over the semi-controlled sessions. In S1, 8 (25.8%) *extremely agree*, 17 (54.8%) *fairly agree*, and in S2, 15 (44.1%) *extremely agree*, 13 (38.2%) *fairly agree* on the same. We observe a large association in the understanding of indoor pollutants ( $\chi^2 = 41.64$ ,  $p < .01$ , Cramer's  $V = 0.68$ ) from session S1 to S2 among the 30 participants who attended both the sessions. An interesting participant comment related to awareness (AC) on how the app improves their understanding of indoor pollutants is as follows.

AC#1: “This fact, I didn't know at all, indoor pollution is a thing that we should be discussing. We always talk about outdoor pollution, but we never talk about indoor pollution. We might think, okay, candles and cooking, how much pollution can that be, but this made us realize

that, just with two or three candles burning, this is the amount of ppm that you can get.”

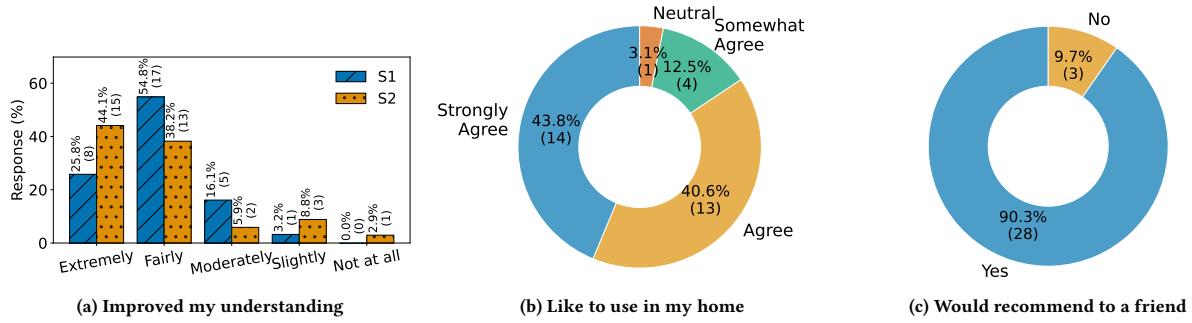
Moreover, 54.5% *strongly agree*, 30.3% *agree*, and 9% *somewhat agree* that this game makes the participants more aware of the pollution sources (like indoor gatherings, candles, etc) indoors. Among the participants, 14 (43.8%) *strongly agree*, 13 (40.6%) *agree* and 4 (12.5%) *somewhat agree* to use this AR app in their home to reduce pollutants in places such as kitchen during cooking, and living room during a family get-together as shown in Figure 10b. Notably, 28 (90.3%) participants wanted to recommend the app to their family members and friends (see Figure 10c) to make them more aware of pollution in their homes. Some participant comments related to indoor pollution sources are as follows:

AC#2: “We usually don't think about this. The small things, such as indoor group meetings, generate that high concentration of CO<sub>2</sub>. I guess the application has placed a sense and the fact that we usually feel tired and sleepy because of pollutants.”

AC#3: “It increased really quickly, I had not heard that indoor pollution has a higher carbon dioxide level than outdoor pollution. It helps in reducing the carbon dioxide level, and also it makes me aware of how to deal with trapped pollutants.”

## 5.3 Quantitative User Feedback

Here, we analyze the game enjoyment of the participants in terms of immersiveness and how competent and skillful they feel during the sessions, their interest and success in ventilating CO<sub>2</sub>, and the degree of positive experiences and associated physical (i.e., tiredness) and physiological overhead (i.e., tension, challenge, negative experiences, etc.).



**Figure 10: Understanding and awareness responses - (a) the AR app and the CoWear improved the understanding of the participants about indoor pollution, (b) the participants would like to use this app in their house to reduce pollution in kitchen and living room, (c) he participants would recommend this app to their friends and family to make them more aware about indoor pollution.**

**5.3.1 Competence.** Competence represents how capable and skilled the player feels after completing the game. We found that in S1, most participants (18, 58%) showed a fair to an extreme level of competence. Whereas 10 (32.2%) showed moderate to fair and only three (9.6%) showed slight to moderate competence levels during the gameplay. Similarly, in S2, 23 (67.6%) show fair to extreme, 9 (26.4%) show moderate to fair, and only two (5.8%) participants show slight to moderate competence. Among the 30 participants ( $P_{01}$  to  $P_{30}$ ) who participated in both the semi-controlled sessions, 10 (33.3%) have improved competence from S1 to S2. While 18 (60%) participants show no significant change in their competence across the sessions, and only two (6.6%) experience a slight reduction in their competence score. Therefore, with more practice sessions, one can improve their competence with the AR app to effectively reduce CO<sub>2</sub>. The participants show fair competence across the semi-controlled and in-the-wild experiments, as shown in Figure 11c and Figure 12. In comparison, participants show moderate competence with the baseline spatial 2D heatmap visualization. Figure 11c indicates a statistically significant (using Welch's t-test, t-statistic 2.64,  $p < .05$ , medium-to-large effect with Cohen's  $d = 1.27$ ) difference in competence due to visualization technique among the 20 participants who attended all AR and baseline 2D heatmap sessions.

**5.3.2 Sensory and Imaginative Immersion.** Immersion represents the degree of absorption in the game world. 26 (83.8%) participants in S1 and 28 (82.3%) participants in S2 experiences *fair* to *extreme* immersion. While immersion remains consistent across sessions for most of the participants, eight (26.6%) participants experienced improved immersion levels from *slight* to *fair* or *fair* to *extreme*. Thus, for some participants, the game becomes more enjoyable with subsequent sessions. Overall, the participants show fair to extreme median immersion across the semi-controlled and in-the-wild experiments, as shown in Figure 11c. In comparison, participants show fair median immersion with the baseline 2D heatmap, with no statistically significant difference due to the visualization technique.

**5.3.3 Participant Interest and Immediate Rewards.** During the sessions, participants must locate the CO<sub>2</sub> bubbles in an indoor space and ventilate them, thereby reducing the CO<sub>2</sub> concentration. As

shown in Figure 11a, 27 (87.1%) and 29 (85.3%) participants show *extreme* and *fair* interest for the two sessions, respectively. While four (12.9%) participants show *moderate* interest during S1. The participants who had already participated in S1 were more interested in S2. 20 (58.8%) were extremely, and 9 (26.5%) were *fairly* interested in the game's story. Among the participants ( $P_{31}$  to  $P_{34}$ ) who only participated in S2, two (5.9%) show slight interest.

Almost all the participants in S2 felt successful in reducing the pollutants. As shown in Figure 11b, 16 (47%) felt *extremely*, 17 (50%) felt *fairly*, and only one (2.9%) felt *moderately* successful. However, in S1, 11 (35.5%) and 13 (41.9%) felt *extreme* and *fair* success, respectively, and 6 (19.4%) felt *moderate* success. As mentioned earlier, a research associate demonstrated the user interface and functionality of the AR app to the participants in S1, as they were newly introduced to the AR app and the wearable device. In subsequent sessions, participants could use the AR app and reduce CO<sub>2</sub> bubbles without any tutorial, thereby improving their sense of achievement and success. Whereas, with the baseline 2D heatmap, only two (10%) participants *extremely*, 12 (60%) *fairly*, and 6 (30%) *slightly* reduce the CO<sub>2</sub> concentration within the session. The primary reason is a missing sense of urgency and actionable local pollution context. Thus, participants faced difficulties in planning and acting on one strategy, resulting in longer session durations and inadequate ventilation.

**5.3.4 Positive and Negative Experience.** We observe that across the sessions S1, S2, and in-the-wild, the average competence with the game and positive experience of the participants remain fairly high with the AR app, as shown in Figure 12. Whereas undesired experiences, such as in-game tension, tiredness, and negative experience after the gameplay session, were negligible. Moreover, the gameplay challenge reduces from S1 to S2, indicating an easy learning curve to use the AR app and the CoWear wearable for the participants. Thus, in S2, participants faced fewer challenges in finding the CO<sub>2</sub> bubbles. During the in-the-wild experiments, the gameplay challenge increases marginally due to dynamic pollution sources. However, the participants could find, ventilate, and reduce the CO<sub>2</sub> bubbles on their own (i.e., 45.4% strongly agree, 33.3% agree, and

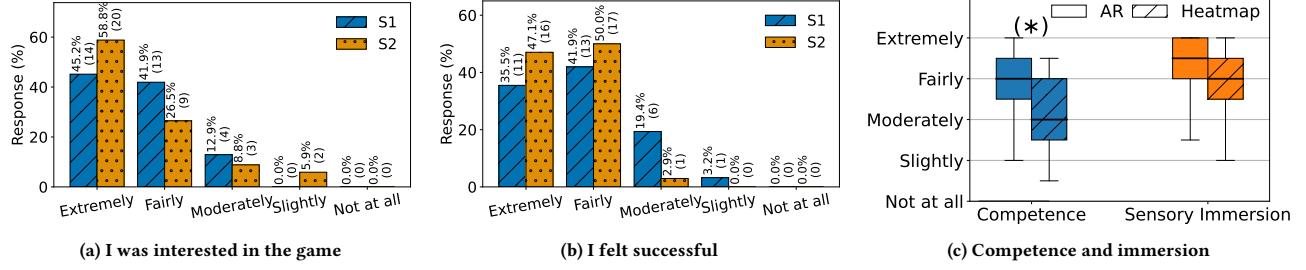


Figure 11: Participant's perception - (a) interest in the game story, (b) feeling of achievement and success after playing the game. In (c), competence and immersion in the AR app vs the baseline 2D spatial heatmap visualization. (\*) indicates a statistically significant difference in competence among 20 participants who attend all sessions.

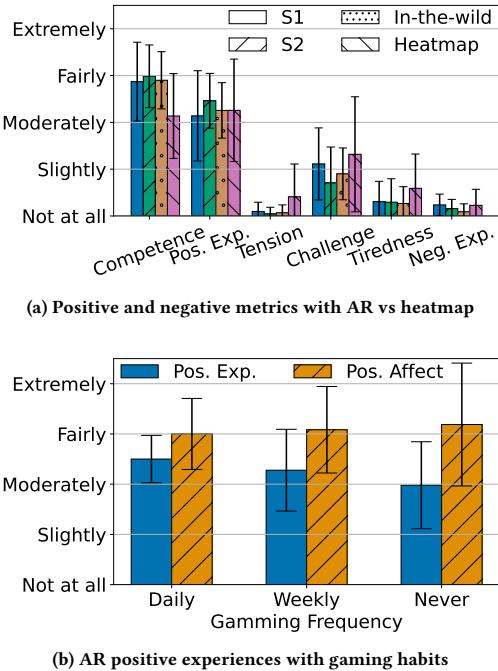


Figure 12: Game experience - (a) positive and negative metrics with the AR app vs the baseline heatmap, (b) AR positive experience with gaming habits of the participants.

6% somewhat agree). Whereas, with the baseline 2D heatmap visualization, the gameplay challenges and tiredness increase, resulting in lower in-game competence and post-game tiredness.

Moreover, we also observe that participants gain consistent in-game short-term positive affect and long-term positive experience, irrespective of their gaming frequency. This indicates an easy-to-learn AR gaming experience for new users with little to no prior gaming expertise. Figure 12b shows that the participants who do not play mobile games gain a statistically similar long-term positive affect and long-term positive experience during the AR gameplay session as those who play games on a daily basis.

## 5.4 Gameplay Experience and User Perceptions

Table 2 compares the associations between different game experience metrics and the participants' awareness, interest, and success, using chi-square tests for both the AR app and the 2D heatmap visualization. In the AR app, competence and immersion are significantly related to *awareness*, where immersion ( $\chi^2 = 21.70$ ,  $p < .01$ ) shows medium-to-large and competence ( $\chi^2 = 21.42$ ,  $p < .05$ ) shows medium association. Moreover, tiredness ( $\chi^2 = 17.26$ ,  $p < .05$ ) also shows medium-to-large association to awareness. Therefore, as the participants explore indoor space, they become more aware of the pollution dynamics. *Interest* in the AR app shows large association with immersion ( $\chi^2 = 63.17$ ,  $p < .01$ ) along with medium association with competence ( $\chi^2 = 20.88$ ,  $p < .05$ ) and positive affect ( $\chi^2 = 21.39$ ,  $p < .05$ ) while proactively ventilating CO<sub>2</sub> bubbles. *Success* shows the large association with competence ( $\chi^2 = 85.13$ ,  $p < .01$ ) and positive affect ( $\chi^2 = 82.33$ ,  $p < .01$ ), which leads to medium-to-large effect on long-term positive experiences ( $\chi^2 = 32.26$ ,  $p < .01$ ), highlighting the effectiveness of the AR app in reducing indoor CO<sub>2</sub>.

In contrast, the 2D heatmap exhibits weaker associations. *Interest* is largely connected to both competence ( $\chi^2 = 23.76$ ,  $p < .05$ ) and immersion ( $\chi^2 = 24.20$ ,  $p < .01$ ). However, success displays insignificant associations across all game experience metrics, indicating that the 2D heatmap is less effective in enhancing users' feelings of achievement. These findings suggest that the AR app enhances game experience metrics like *immersion* and *competence*, nudging users' *awareness* and *interest* towards concrete actions, such as engaging with ventilation systems, windows, or directing airflow (validating H2, from awareness to actionability), to *successfully* reduce indoor CO<sub>2</sub>.

## 5.5 Post-Study System Usability of CoWear

Here, we analyze the perceived satisfaction level of the participants and whether they were confident in ventilating accumulated CO<sub>2</sub> bubbles using the *CoWear* wrist-wearable and the AR app. As shown in Figure 13a, among all the participants across the sessions, 22 (62.9%) participants strongly agreed, 11 (31.4%) participants agreed, and the remaining (5.7%) somewhat agreed that it was easy to find the CO<sub>2</sub> bubbles. They can clearly observe the gradual changes in CO<sub>2</sub> concentration. 23 (65.7%) strongly agree, 9 (25.7%) agree,

**Table 2: Chi-square ( $\chi^2$ ) statistic indicates strong association among GEQ metrics and participants' awareness, interest, and success in the AR app compared to baseline 2D heatmap visualization. Here, \* means  $p < .05$ , \*\* means  $p < .01$ , and reports Cramer's  $V$  with small (0.17), medium (0.33), and large (0.54) effect size thresholds for within-group AR studies [53].**

AR App	In-Game GEQ				Post-Game GEQ	
	Competence	Immersion	Challenge	Pos. Affect	Pos. Exp	Tiredness
Awareness	21.42* (0.33)	21.70** (0.41)	7.30	17.19	19.66	17.26* (0.36)
Interest	20.88* (0.33)	63.17** (0.7)	15.39	21.39* (0.33)	16.48	11.84
Success	85.13** (0.66)	17.01** (0.36)	18.11* (0.3)	82.33** (0.65)	32.26** (0.41)	3.05
2D Heatmap	Competence	Immersion	Challenge	Pos. Affect	Pos. Exp	Tiredness
Awareness	12.83	10.77	20.62	9.17	16.50	4.81
Interest	23.76* (0.85)	24.20** (0.86)	16.78	13.57	20.49	12.10
Success	8.38	7.25	12.22	4.19	11.17	6.81

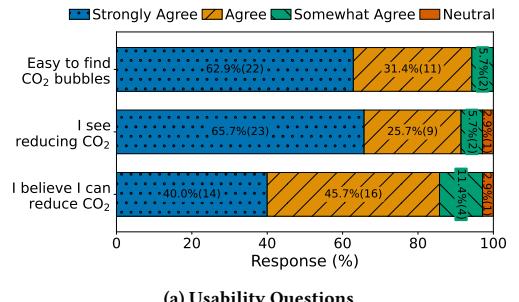
and two (5.7%) somewhat agree that they can see the reduction in CO<sub>2</sub> readings after they start the window ventilator, or open the window, etc. The participants were confident, 14 (40%) strongly believed, 16 (45.7%) believed, and 4 (11.4%) somewhat believed that they could reduce CO<sub>2</sub> on their own.

In Table 3, we present the relationships between PSSUQ questions and user perception, like competence, immersion, awareness, and effective CO<sub>2</sub> reduction when using the AR app. For *competence*, the most substantial associations are observed with comfort using the AR app (Q4,  $\chi^2 = 22.50$ ,  $p < .05$ ) and belief in reducing pollutants (Q6,  $\chi^2 = 29.42$ ,  $p < .05$ ). Notably, the satisfaction with the app's overall experience (Q16) also shows a large association ( $\chi^2 = 27.66$ ,  $p < .01$ ). These results imply that competence is significantly linked to ease of use and perceived effectiveness in CO<sub>2</sub> ventilation. *Immersion* shows a significant association specifically with the simplicity of using the AR app (Q2,  $\chi^2 = 18.42$ ,  $p < .05$ ), highlighting that an easy-to-use interface enhances user immersion in the experience. *Awareness* exhibits a strong link with the ease of finding CO<sub>2</sub> bubbles (Q10,  $\chi^2 = 19.45$ ,  $p < .01$ ). For CO<sub>2</sub> *reduction*, significant associations are found with ease of learning (Q5,  $\chi^2 = 6.34$ ,  $p < .05$ ) and users' confidence with the AR app (Q6,  $\chi^2 = 11.61$ ,  $p < .01$ ). Additionally, error handling (Q7,  $\chi^2 = 12.94$ ,  $p < .05$ ) largely contributes to the perceived effectiveness in reducing CO<sub>2</sub>.

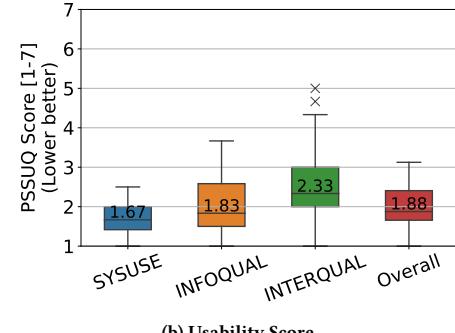
Finally, Figure 13b shows box plots of the PSSUQ (Post-Study System Usability Questionnaire) scores reported by the participants; note that a lower PSSUQ score means better. Median system usability (SYSUSE) is 1.67, indicating the practicality of the AR visualization. Further, the information, such as the information sheet (i.e., shared during first-time participation) and AR app demonstration, benefited the participants. The information quality (INFOQUAL) is 1.83. The interface quality (INTERQUAL) is 2.33, indicating a reasonably good and responsive application interface. Overall, the wearable and the AR app achieve a median PSSUQ score of 1.88, which is perceived as usable and compelling to the participants. In a nutshell, the AR app's design elements, such as ease of use, clear visual representation, and effective error handling, strongly influence user engagement, perceived competence, environmental awareness, and impact. However, there is room for further improvement as discussed in the following section.

## 5.6 Qualitative User Feedback

As mentioned earlier in section 4.5, we moderated three-member focus group discussions over the following topics: (i) their overall



(a) Usability Questions



**Figure 13: Post study system usability:** (a) response to usability questions (b) Computed usability scores for semi-controlled and in-the-wild user experiments.

experience with the AR game, (ii) how the in-game experience impacted their perception of air pollution, and (iii) the suggestions to improve the platform. See Appendix A.4 for topic details. Table 4 presents the summary of sentiments over different aspects of the study. We next discuss the core observations from the discussions.

**5.6.1 Experience with the AR Application.** The participants were overall satisfied with the AR app. Notably, using an AR app and playing an AR game was a first-time experience for many of our participants, and the quantitative feedback says that they enjoyed the application. During the focus group discussions, almost 75% of participant comments were positive (i.e., keywords such as good, smooth, interesting, and great) as shown in Table 4.

*EX#1: "The best part was that it was very interactive and creative. It's like a camera we have for the surrounding CO<sub>2</sub> level."*

**Table 3: Chi-square ( $\chi^2$ ) statistic indicates strong association among system usability metrics and participant engagement factors. Here, \* means  $p < .05$ , \*\* means  $p < .01$ , and reports Cramer's V with small (0.17), medium (0.33), and large (0.54) effect size thresholds for within-group AR studies [53]. PSSUQ questionnaire is included in Appendix A.3.**

Factors	SYSUSE						INFOQUAL						INTERQUAL					
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16		
Competence	10.45	10.85	18.32	22.50*	16.60	29.42*	20.07	34.32	17.98	16.06	23.05	31.00	42.50*	43.44	21.90	27.66**		
Immersion	8.63	18.42*	(0.55)	12.42	14.39	3.99	8.80	28.10	28.16	28.80	9.12	22.65	21.87	20.59	18.08	19.75	11.91	
Awareness	2.24	5.24	4.93	5.52	5.62	9.80	11.61	17.40	8.51	19.45**	(0.56)	8.61	11.74	9.50	7.08	4.15	2.97	
CO <sub>2</sub> ↓(>100ppm/m)	0.89	0.12	2.22	0.67	6.34*	11.61**	(0.45)	12.94*	(0.65)	10.39	2.47	0.96	6.52	6.91	3.00	4.17	1.37	0.42

Notably, the participants were excited about observing a visual representation of their personal pollution exposure through the AR bubbles, and they were enthusiastic about exploring the CO<sub>2</sub> concentration at various corners of the rooms. In section 5.2, more than 80% of participants agreed on improved overall understanding of indoor pollutants. During the focus group discussions, almost 85% of participants shared strong positive remarks about increased awareness. Participants were surprised by how quickly indoor CO<sub>2</sub> can reach unhealthy levels. Moreover, participants found the AR app engaging, and almost 40% of them wanted a longer gameplay session.

*EX#2: “Of course, because I haven’t seen any numerical or quantitative value of pollution before that. So, I can see those pollutants, not with my naked eyes, but with the AR app. That was very cool.”*

**5.6.2 Bubble Visualization and User Interface of the Application.** Participants have focused on the dynamic size and color of the AR bubbles for real-time monitoring of CO<sub>2</sub>, which has turned out to be an exciting feature for them. They felt that the AR bubbles helped them interact more effectively with the CO<sub>2</sub> bubbles around them, and they were motivated to trigger directed airflow to reduce the CO<sub>2</sub> bubbles in the AR app. Almost 70% of participant comments about the AR visualization were positive during the focus group discussions, as shown in Table 4. We observed a mixed response (i.e., 45% positive) for the user interface. While participants were positive about the interface clarity, they also raised concerns about the app’s non-intuitive nature at the beginning and suggested the inclusion of startup tutorials.

*BV#1: “In responsiveness and clarity, it is very good. In addition to the clarity, whenever I place a bubble, the size of the bubble increases, and then it shows how much PPM. It was also increasing. So, it’s clear that you’re searching for CO<sub>2</sub>. ”*

*BV#2: “The bubbles were decreasing when we were opening the window or AC or switching on the fan. Well made.”*

Moreover, 60% of participants also felt that a higher responsiveness of the AR bubbles would have been better for triggering quicker actions. Notably, when the participant moves away from an AR bubble and comes back later on to check, the CoWear wrist-wearable takes around 30 seconds to adjust to the CO<sub>2</sub> concentration at that location and update the bubble size and color in the app.

**5.6.3 Suggestions and Feedback from the Participants.** We received constructive feedback from the participants during the focus group discussions. First, a few participants felt that the first-time tutorial instructions could be directly embedded in the app, covering some basic ideas about pollutants and their equivalent representations in

AR bubbles. Second, rather than creating multiple AR bubbles at the same location with multiple taps and subsequently cluttering the app interface, the participants suggested merging such repeated bubbles to represent the CO<sub>2</sub> concentration around that location. Finally, a few participants indicated having a lifetime of AR bubbles and representing it using opaqueness, which adds another dimension to the bubbles’ trustfulness. For instance, a bubble placed long back might not represent the actual CO<sub>2</sub> concentration at that location, so over time, it may get opaque to indicate the trustfulness of the data.

## 6 Discussion

In this section, we discuss some important takeaways based on our experience on the overall development of *CoWear*.

### 6.1 Advantages over the Baseline 2D Heatmap Visualization

Traditional 2D heatmaps visualize CO<sub>2</sub> concentration within the spatial dimension of the indoor space, which limits user engagement and poses a critical problem of sensor placement. CO<sub>2</sub> bubbles are formed at source heights and get trapped in different parts of the indoor space (see pilot experiment in section 3.3). Hence, the optimal placement of static sensors is very challenging, and we must follow a dense deployment strategy, incurring high financial costs for accurate ambient monitoring. In contrast, the proposed AR-based approach uses low-cost *CoWear* wrist-wearable and provides clearer 3D awareness by visualizing CO<sub>2</sub> concentrations at varying heights, including bubbles that form near occupants’ breathing zones. As users can physically move around to inspect real-time changes, they gain more dynamic insight than static heatmaps allow. Moreover, we observe that AR bubbles heightened the sense of presence and urgency (see section 5.2), which leads to quicker responses, such as opening windows or turning on fans.

However, such wearable-based ambient sensing relies on the user to continuously move around the indoor space for the trustworthiness of the data. Thus, both low-cost wearable and static pollution sensors must function jointly as a trustworthy data source for long-term human-centered applications, covering larger indoor spaces than the sum of their components to enable continuous ambient sensing and immersive AR visualization [74]. We left this for future work.

**Table 4: Summary of sentiments in the semi-structured interviews for different aspects of the study.**

Aspect	Sentiment (+%)	Feedback Summary
Overall Experience	Positive (75%)	Majority of comments were positive about the experience ("good," "smooth," "interesting," "great"), with some negatives about sensing delay or learning curve.
Awareness/Learning	Positive (85%)	Strong positive remarks about increased awareness, surprise at indoor CO <sub>2</sub> levels.
AR Visualization	Positive (70%)	AR bubbles are intuitive and color/size changes are helpful, but some concerns about clutter and bubble size filling the smartphone screen.
Responsiveness	Mixed/Negative (40%)	Mixed sentiment with negative feedback about sensing delay of approx. 30 sec to adjust to CO <sub>2</sub> concentration at a new location, desire for real-time change.
Interface Usability	Mixed/Negative (45%)	Positive about interface clarity, Non-intuitive for new participants, requests for tutorials and start-up instructions to reduce the learning curve.
Game Duration	Mixed (60%)	Some participants wanted longer gameplay sessions, but overall found it engaging.

## 6.2 Trade-off Between Ventilation, Thermal Comfort, and Energy

While *CoWear*'s AR visualization encourages users to ventilate when CO<sub>2</sub> levels rise, in practice, such decisions are in direct conflict with thermal comfort and energy consumption. Studies [36, 78] have consistently found that occupants avoid opening windows in cold climates because doing so introduces thermal discomfort, even when air quality is poor. This is a recurring theme in real-world settings, where occupants explicitly prioritize warmth over ventilation in winter. In shared environments like classrooms [25] and offices [68, 79], these tensions are amplified as one person's decision to ventilate can negatively impact others' comfort, leading to disagreements and complaints about cold air or drafts. Reluctance to ventilation is further linked to increased heating demand to maintain comfortable indoor temperatures, significantly raising energy costs [31]. Acknowledging this difficult trade-off between ventilation, thermal comfort, and energy costs clarifies why visualizing pollutants alone may not always lead to ventilation actions by occupants in real-world environments. In future versions of *CoWear*, we plan to integrate temperature data to offer more context-aware recommendations, helping users navigate these competing priorities rather than treating ventilation as the only response to indoor pollutants.

## 6.3 Practical Limitations of the Current Setup

We observed that participants appreciated the concept of using AR visualization to provide real-time insights into air pollutants and using game-based prevention to reduce pollution exposure. At the same time, they have also complained about the system's responsiveness (approx. 30 sec waiting time for getting the updated CO<sub>2</sub> values), the excessive density of the spheres (ability to place multiple spheres at a close location), and supporting on-app tutorials for new users. While some of them can be fixed easily from the software side, improving the system's responsiveness is more of a hardware issue that needs careful consideration of sensor price and accuracy trade-offs, which is left for future work.

## 6.4 Extending the *CoWear* Platform

The *CoWear* platform can be extended beyond CO<sub>2</sub> to support other indoor pollutants, such as VOCs and PM<sub>2.5</sub>. Doing so would require integrating additional sensors into the wearable, developing visualization strategies that capture each pollutant's unique dispersion patterns (e.g., the wave-like spread of VOCs [28]), and designing pollutant-specific interaction models (e.g., ceiling fans can disperse

gases but may pull PM<sub>2.5</sub> [36, 44]). The platform can also be expanded into a multiplayer system, where readings from multiple wearables are combined to create richer, shared views of exposure. Such collaborative interactions, like one participant directing airflow with a pedestal fan while another operates window ventilation, can improve indoor air quality while fostering cooperation, social engagement, and environmental awareness [50].

## 7 Conclusion

Illustrating indoor CO<sub>2</sub> levels within physical spaces is instrumental in raising awareness of associated health risks. We introduced an augmented reality (AR) experience that combines real-time CO<sub>2</sub> monitoring through a wrist-worn *CoWear* sensor with immersive, game-like interactions, with the goal of encouraging healthier indoor habits. From a study involving 35 participants, our findings revealed an increased engagement and a better understanding of indoor pollutants. Moreover, with a median usability score of 1.88, the system underscores both its user-friendliness and its potential to be applied in real-world settings for promoting improved indoor air quality.

## Ethical Considerations

The institute's ethical review committee has approved this study (Order No: IIT/SRIC/DEAN/2023, dated July 31, 2023). Moreover, we have made significant efforts to anonymize the participants to preserve privacy while providing the necessary details on the study methodology. All participants signed forms consenting to the use of collected pollutant measurements and video, audio, and physiological measurements for non-commercial research purposes.

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<sup>3</sup><https://chatgpt.com/>

## References

- [1] Junho Ahn, James Williamson, Mike Gartrell, Richard Han, Qin Lv, and Shivakant Mishra. 2015. Supporting healthy grocery shopping via mobile augmented reality. *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)* 12, 1s (2015), 1–24.
- [2] Raghad Albar, Andreia Gauthier, and Asimina Vasalou. 2024. A Playful Path to Sustainability: Synthesizing design strategies for children's environmental sustainability learning through gameful interventions. In *Proceedings of the 23rd Annual ACM Interaction Design and Children Conference*. 201–217.
- [3] Joseph G Allen, Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino, and John D Spengler. 2016. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments. *Environmental health perspectives* 124, 6 (2016), 805–812.
- [4] Joseph G Allen, Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino, and John D Spengler. 2016. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments. *Environmental health perspectives* 124, 6 (2016), 805–812.
- [5] Jesús Omar Álvarez Márquez and Jürgen Ziegler. 2020. In-store augmented reality-enabled product comparison and recommendation. In *Proceedings of the 14th ACM Conference on Recommender Systems*. 180–189.
- [6] Shan An, Guangfu Che, Jinghao Guo, Haogang Zhu, Junjie Ye, Fangru Zhou, Zhaoqi Zhu, Dong Wei, Aishan Liu, and Wei Zhang. 2021. ARShoe: Real-time augmented reality shoe try-on system on smartphones. In *Proceedings of the 29th ACM International Conference on Multimedia*. 1111–1119.
- [7] Ambre Assor, Arnaud Prouzeau, Pierre Dragicevic, and Martin Hachet. 2024. Augmented reality waste accumulation visualizations. *ACM Journal on Computing and Sustainable Societies* 2, 2 (2024), 1–29.
- [8] Kenichi Azuma, Naoki Kagi, U Yanagi, and Haruki Osawa. 2018. Effects of low-level inhalation exposure to carbon dioxide in indoor environments: A short review on human health and psychomotor performance. *Environment international* 121 (2018), 51–56.
- [9] Mathias Bauer and Malte Weiß. 2023. Improving Environmental Knowledge with a Serious Game: An experimental study. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–10.
- [10] Jacky Cao, Kit-Yung Lam, Lik-Hang Lee, Xiaoli Liu, Pan Hui, and Xiang Su. 2023. Mobile augmented reality: User interfaces, frameworks, and intelligence. *Comput. Surveys* 55, 9 (2023), 1–36.
- [11] Chiara Ceccarini and Catia Prandi. 2022. EscapeCampus: exploiting a Game-based Learning tool to increase the sustainability knowledge of students. In *Proceedings of the 2022 ACM Conference on Information Technology for Social Good*. 390–396.
- [12] Joohwan Chae, Donghan Kim, Wooseok Jeong, Eunchan Jo, Won-Ki Jeong, Jun-Young Choi, Seung-wook Kim, Myoung Gon Kim, Jae-Won Lee, Hyechan Lee, et al. 2022. Virtual air conditioner's airflow simulation and visualization in ar. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology*. 1–11.
- [13] Pengyu Chen. 2019. Visualization of real-time monitoring datagraphic of urban environmental quality. *Eurasip Journal on Image and Video Processing* 2019, 1 (2019), 42.
- [14] Meghan Clark, Mark W Newman, and Prabal Dutta. 2022. ARticulate: one-shot interactions with intelligent assistants in unfamiliar smart spaces using augmented reality. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 6, 1 (2022), 1–24.
- [15] Laura D Cosio, Oğuz’Oz’ Buruk, Daniel Fernández Galeote, Isak De Villiers Bosman, and Juho Hamari. 2023. Virtual and augmented reality for environmental sustainability: A systematic review. In *Proceedings of the 2023 CHI conference on human factors in computing systems*. 1–23.
- [16] Balázs Csoma, Maria Rosaria Vulpi, Silvano Dragonieri, Andrew Bentley, Timothy Felton, Zsófia Lázár, and Andras Bikov. 2022. Hypercapnia in COPD: causes, consequences, and therapy. *Journal of Clinical Medicine* 11, 11 (2022), 3180.
- [17] Bowen Du, Marlie C Tandoc, Michael L Mack, and Jeffrey A Siegel. 2020. Indoor CO<sub>2</sub> concentrations and cognitive function: A critical review. *Indoor air* 30, 6 (2020), 1067–1082.
- [18] Ruofei Du, Eric Turner, Maksym Dzitsiuk, Luca Prasso, Ivo Duarte, Jason Dourgarian, Joao Afonso, Jose Pascoal, Josh Gladstone, Nuno Cruces, et al. 2020. DepthLab: Real-time 3D interaction with depth maps for mobile augmented reality. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. 829–843.
- [19] Oscar R Enríquez, Chao Sun, Detlef Lohse, Andrea Prosperetti, and Devaraj Van Der Meer. 2014. The quasi-static growth of CO<sub>2</sub> bubbles. *Journal of fluid mechanics* 741 (2014), R1.
- [20] EPA. 2024. The Inside Story: A Guide to Indoor Air Quality. <https://www.epa.gov/indoor-air-quality-iaq/inside-story-guide-indoor-air-quality>.
- [21] Yuejie Fan, Xiaodong Cao, Jie Zhang, Dayi Lai, and Liping Pang. 2023. Short-term exposure to indoor carbon dioxide and cognitive task performance: A systematic review and meta-analysis. *Building and Environment* 237 (2023), 110331.
- [22] Biyi Fang, Qiumin Xu, Taiwoo Park, and Mi Zhang. 2016. AirSense: an intelligent home-based sensing system for indoor air quality analytics. In *Proceedings of the 2016 ACM International joint conference on pervasive and ubiquitous computing*. 109–119.
- [23] Andrea M Feldpausch-Parker, Megan O'Byrne, Danielle Endres, and Tarla R Peterson. 2013. The Adventures of Carbon Bond: Using a melodramatic game to explain CCS as a mitigation strategy for climate change. *Greenhouse Gases: Science and Technology* 3, 1 (2013), 21–29.
- [24] Elliott T Gall, Toby Cheung, Irvan Luhung, Stefano Schiavon, and William W Nazaroff. 2016. Real-time monitoring of personal exposures to carbon dioxide. *Building and Environment* 104 (2016), 59–67.
- [25] Nan Gao, Wei Shao, Mohammad Saiedur Rahaman, and Flora D Salim. 2020. n-gage: Predicting in-class emotional, behavioural and cognitive engagement in the wild. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 4, 3 (2020), 1–26.
- [26] Ali Ghahramani, Jovan Pantelic, Matthew Vannucci, Lorenza Pistore, Shichao Liu, Brian Gilligan, Soheila Alyasin, Edward Arens, Kevin Kampshire, and Esther Sternberg. 2019. Personal CO<sub>2</sub> bubble: Context-dependent variations and wearable sensors usability. *Journal of Building Engineering* 22 (2019), 295–304.
- [27] Meghna Gupta and Grace Eden. 2022. The Human-Air Interface: Responding To Poor Air Quality Through Lived Experience and Digital Information. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference*. 1085–1098.
- [28] Nurul Liyana Lukman Hekiem, Aliza Aini Md Ralib, Farah B Ahmad, Anis Nurashikin Nordin, Rosminazuin Ab Rahim, Nor Farahidah Za'bah, et al. 2021. Advanced vapour sensing materials: Existing and latent to acoustic wave sensors for VOCs detection as the potential exhaled breath biomarkers for lung cancer. *Sensors and Actuators A: Physical* 329 (2021), 112792.
- [29] Yen-Chia Hsu, Jennifer Cross, Paul Dille, Michael Tasota, Beatrice Dias, Randy Sargent, Ting-Hao Huang, and Illah Nourbakhsh. 2020. Smell Pittsburgh: engaging community citizen science for air quality. *ACM Transactions on Interactive Intelligent Systems (TiIS)* 10, 4 (2020), 1–49.
- [30] Yen-Chia Hsu, Paul Dille, Jennifer Cross, Beatrice Dias, Randy Sargent, and Illah Nourbakhsh. 2017. Community-empowered air quality monitoring system. In *Proceedings of the 2017 CHI Conference on human factors in computing systems*. 1607–1619.
- [31] Iman Hussain, Adrian Friday, and Douglas Booker. 2023. The indoor Air quality trilemma: Improving Air quality, using less energy, and meeting stakeholder requirements. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–6.
- [32] Wijnand A IJsselstein, Yvonne AW De Kort, and Karolien Poels. 2013. The game experience questionnaire. (2013).
- [33] Yohanna Ishoij-Paris, Ariane Gravel-Villeneuve, Francis Vermette-David, Lissa Dixon-Sequeira, Maxime Dicaire, Maxime Morin-Grandmont, Naomi Jomphe, Nathaelle Fournier, Ophelie Champeau-Fournier, Cassandra Paré, et al. 2021. AXO: a video game that encourages recycling to preteens. In *Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play*. 350–355.
- [34] Yifei Jiang, Kun Li, Lei Tian, Ricardo Piedrahita, Xiang Yun, Omkar Mansata, Qin Lv, Robert P Dick, Michael Hannigan, and Li Shang. 2011. MAQS: a personalized mobile sensing system for indoor air quality monitoring. In *Proceedings of the 13th international conference on Ubiquitous computing*. 271–280.
- [35] Xiaofu Jin, Wai Tong, Xiaoying Wei, Xian Wang, Emily Kuang, Xiaoyu Mo, Huamin Qu, and Mingming Fan. 2024. Exploring the Opportunity of Augmented Reality (AR) in Supporting Older Adults to Explore and Learn Smartphone Applications. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–18.
- [36] Prasenjit Karmakar, Swadhin Pradhan, and Sandip Chakraborty. 2024. Exploring Indoor Air Quality Dynamics in Developing Nations: A Perspective from India. *ACM Journal on Computing and Sustainable Societies* (2024).
- [37] Minas Katsikalis, Elisavet Tseleri, Aikaterini Lilli, Konstantinos Gobakis, Dionysia Kolokotsa, and Katerina Mania. 2023. GoNature AR: Air Quality & Noise Visualization Through a Multimodal and Interactive Augmented Reality Experience. In *Proceedings of the 2023 ACM International Conference on Interactive Media Experiences*. 366–369.
- [38] Sunyoung Kim and Muyang Li. 2020. Awareness, understanding, and action: a conceptual framework of user experiences and expectations about indoor air quality visualizations. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.
- [39] Sarah Krings, Enes Yigitbas, Ivan Jovanovikj, Stefan Sauer, and Gregor Engels. 2020. Development framework for context-aware augmented reality applications. In *Companion Proceedings of the 12th ACM SIGCHI Symposium on Engineering Interactive Computing Systems*. 1–6.
- [40] Won Du Lee, Kayla Schultheis, and Tim Schwanen. 2022. An online interactive dashboard to explore personal exposure to air pollution. *Findings 2022* (2022).
- [41] Jiayang Li and Chongke Bi. 2023. Visual analysis of air pollution spatio-temporal patterns. *The Visual Computer* 39, 8 (2023), 3715–3726.
- [42] Martin Valdemar Anker Lindrup, Arjun Rajendran Menon, and Aksel Biørn-Hansen. 2023. Carbon Scales: Collective sense-making of carbon emissions from

- food production through physical data representation. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. 1515–1530.
- [43] Liang Liu, Wu Liu, Yu Zheng, Huadong Ma, and Cheng Zhang. 2018. Third-eye: A mobilephone-enabled crowdsensing system for air quality monitoring. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 1 (2018), 1–26.
- [44] Sumei Liu, Rui Song, and Tengfei Tim Zhang. 2021. Residential building ventilation in situations with outdoor PM<sub>2.5</sub> pollution. *Building and Environment* 202 (2021), 108040.
- [45] Szu-Yu Liu, Justin Cranshaw, and Asta Roseway. 2020. Making air quality data meaningful: Coupling objective measurement with subjective experience through narration. In *Proceedings of the 2020 ACM designing interactive systems conference*. 1313–1326.
- [46] Balz Maag, Zimu Zhou, and Lothar Thiele. 2018. W-air: Enabling personal air pollution monitoring on wearables. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 1 (2018), 1–25.
- [47] Eleni Margariti, Vasilis VLachokyriakos, Abigail C Durrant, and David Kirk. 2024. Evaluating ActuAir: Building Occupants' Experiences of a Shape-Changing Air Quality Display. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–21.
- [48] Adnan Masic, Dzevad Bibic, Boran Pikula, Almir Blazevic, Jasna Huremovic, and Sabina Zero. 2020. Evaluation of optical particulate matter sensors under realistic conditions of strong and mild urban pollution. *Atmospheric measurement techniques* 13, 12 (2020), 6427–6443.
- [49] Noble Saji Mathews, Sridhar Chimalakonda, and Suresh Jain. 2021. Air: An augmented reality application for visualizing air pollution. In *2021 IEEE Visualization Conference (VIS)*. IEEE, 146–150.
- [50] Gloria Mittmann, Adam Barnard, Ina Krammer, Diogo Martins, and João Dias. 2022. LINA-a social augmented reality game around mental health, supporting real-world connection and sense of belonging for early adolescents. *Proceedings of the ACM on Human-Computer Interaction* 6, CHI PLAY (2022), 1–21.
- [51] Jimmy Moore, Pascal Goffin, Miriah Meyer, Philip Lundrigan, Neal Patwari, Katherine Sward, and Jason Wiese. 2018. Managing in-home environments through sensing, annotating, and visualizing air quality data. *Proceedings of the ACM on interactive, mobile, wearable and ubiquitous technologies* 2, 3 (2018), 1–28.
- [52] Maya E Morales-McDevitt, Jitka Becanova, Arlene Blum, Thomas A Bruton, Simon Vojta, Melissa Woodward, and Rainer Lohmann. 2021. The air that we breathe: neutral and volatile PFAS in indoor air. *Environmental science & technology letters* 8, 10 (2021), 897–902.
- [53] Anna-Maria Ortloff, Florin Martius, Mischa Meier, Theo Raimbault, Lisa Geierhaas, and Matthew Smith. 2025. Small, Medium, Large? A Meta-Study of Effect Sizes at CHI to Aid Interpretation of Effect Sizes and Power Calculation. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. 1–28.
- [54] Jovan Pantelic, Shichao Liu, Lorenza Pistore, Dusan Licina, Matthew Vannucci, Sasan Sadrizadeh, Ali Ghahramani, Brian Gilligan, Esther Sternberg, Kevin Kamp-schroer, et al. 2020. Personal CO<sub>2</sub> cloud: laboratory measurements of metabolic CO<sub>2</sub> inhalation zone concentration and dispersion in a typical office desk setting. *Journal of exposure science & environmental epidemiology* 30, 2 (2020), 328–337.
- [55] Shivani Patel, Julia H Miao, Ekrem Yetiskul, Anya Anokhin, and Sapan H Majmundar. 2018. Physiology, carbon dioxide retention. (2018).
- [56] Kris Permentier, Steven Vercammen, Sylvia Soetaert, and Christian Schellemans. 2017. Carbon dioxide poisoning: a literature review of an often forgotten cause of intoxication in the emergency department. *International journal of emergency medicine* 10, 1 (2017), 14.
- [57] Catia Prandi, Chiara Ceccarini, and Paola Salomoni. 2019. Augmenting good behaviour: Mixing digital and reality to promote sustainability in a campus community. In *Proceedings of the 5th EAI International Conference on Smart Objects and Technologies for Social Good*. 189–194.
- [58] Jane Prophet, Yong Ming Kow, and Mark Hurry. 2018. Cultivating environmental awareness: Modeling air quality data via augmented reality miniature trees. In *Augmented Cognition: Intelligent Technologies: 12th International Conference, AC 2018, Held as Part of HCI International 2018, Las Vegas, NV, USA, July 15–20, 2018, Proceedings, Part I*. Springer, 406–424.
- [59] Olivier Ramalho, Guillaume Wyart, Corinne Mandin, Patrice Blondeau, Pierre-André Cabanes, Nathalie Leclerc, Jean-Ulrich Mullot, Guillaume Boulanger, and Matteo Redaelli. 2015. Association of carbon dioxide with indoor air pollutants and exceedance of health guideline values. *Building and Environment* 93 (2015), 115–124.
- [60] Tiago Relvas, Pedro Mariano, Susana Marta Almeida, and Pedro Santana. 2024. A serious game for raising air pollution perception in children. *Journal of Computers in Education* (2024), 1–31.
- [61] Tobias Röddiger, Dominik Doerner, and Michael Beigl. 2018. ARMart: AR-based shopping assistant to choose and find store items. In *Proceedings of the 2018 ACM international joint conference and 2018 international symposium on pervasive and ubiquitous computing and wearable computers*. 440–443.
- [62] Sheree May Saßmannshausen, Jörg Radtke, Nino Bohn, Hassan Hussein, Dave Randall, and Volkmar Pipek. 2021. Citizen-centered design in urban planning: How augmented reality can be used in citizen participation processes. In *Proceedings of the 2021 ACM Designing Interactive Systems Conference*. 250–265.
- [63] Usha Satish, Mark J Mendell, Krishnamurthy Shekhar, Toshifumi Hotchi, Douglas Sullivan, Siegfried Strefert, and William J Fisk. 2012. Is CO<sub>2</sub> an indoor pollutant? Direct effects of low-to-moderate CO<sub>2</sub> concentrations on human decision-making performance. *Environmental health perspectives* 120, 12 (2012), 1671–1677.
- [64] Jeff Sauro and James R Lewis. 2016. *Quantifying the user experience: Practical statistics for user research*. Morgan Kaufmann.
- [65] Philipp Schaper, Anna Riedmann, Sebastian Oberdörfer, Maileen Krähe, and Birgit Lugrin. 2022. Addressing waste separation with a persuasive augmented reality app. *Proceedings of the ACM on Human-Computer Interaction* 6, MHCI (2022), 1–16.
- [66] Daniel Schürholz, Meruyert Nurgazy, Arkady Zaslavsky, Prem Prakash Jayaraman, Sylvain Kubler, Karan Mitra, and Saguna Saguna. 2019. Myaqi: Context-aware outdoor air pollution monitoring system. In *Proceedings of the 9th International Conference on the Internet of Things*. 1–8.
- [67] SENSIORION. 2022. SCD41, Improved CO<sub>2</sub> accuracy with extended measurement range and single-shot mode. <https://sensirion.com/products/catalog/SCD41>.
- [68] Donya Sheikh Khan, Jakub Kolarik, and Peter Weitzmann. 2021. Application of an occupant voting system for continuous occupant feedback on thermal and indoor air quality – Case studies in office spaces. *Energy and Buildings* 251 (2021), 111363. <https://doi.org/10.1016/j.enbuild.2021.111363>
- [69] Rafael ML Silva, Erica Principe Cruz, Daniela K Rosner, Dayton Kelly, Andrés Monroy-Hernández, and Fannie Liu. 2022. Understanding AR activism: An interview study with creators of augmented reality experiences for social change. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. 1–15.
- [70] Stephen Snow, Michael Oakley, and MC Schraefel. 2019. Performance by design: supporting decisions around indoor air quality in offices. In *Proceedings of the 2019 on Designing Interactive Systems Conference*. 99–111.
- [71] Peter Strøm-Tøjsen, D Zukowska, Paweł Wargoński, and David Peter Wyon. 2016. The effects of bedroom air quality on sleep and next-day performance. *Indoor air* 26, 5 (2016), 679–686.
- [72] Bruno Teles, Pedro Mariano, and Pedro Santana. 2020. Game-like 3d visualisation of air quality data. *Multimodal Technologies and Interaction* 4, 3 (2020), 54.
- [73] Dai-Hua Tsai, Jia-Shiang Lin, and Chang-Chuan Chan. 2012. Office workers' sick building syndrome and indoor carbon dioxide concentrations. *Journal of occupational and environmental hygiene* 9, 5 (2012), 345–351.
- [74] Radu-Daniel Vatavu. 2022. Are ambient intelligence and augmented reality two sides of the same coin? Implications for human-computer interaction. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. 1–8.
- [75] Xia Wei, Nan Yu, Qi Ding, Jingting Ren, Jiuyun Mi, Lu Bai, Jianying Li, Min Qi, and Youmin Guo. 2018. The features of AECOPD with carbon dioxide retention. *BMC Pulmonary Medicine* 18, 1 (2018), 124.
- [76] WHO. 2022. Household air pollution. <https://www.who.int/news-room/factsheets/detail/household-air-pollution-and-health>.
- [77] Tongshu Zheng, Michael H Bergin, Karoline K Johnson, Sachchida N Tripathi, Shilpa Shirodkar, Matthew S Landis, Ronak Sutaria, and David E Carlson. 2018. Field evaluation of low-cost particulate matter sensors in high-and low-concentration environments. *Atmospheric Measurement Techniques* 11, 8 (2018), 4823–4846.
- [78] Sailin Zhong, Hamed S Alavi, and Denis Lalanne. 2020. Hilo-wear: exploring wearable interaction with indoor air quality forecast. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–8.
- [79] Sailin Zhong, Denis Lalanne, and Hamed Alavi. 2021. The Complexity of Indoor Air Quality Forecasting and the Simplicity of Interacting with It – A Case Study of 1007 Office Meetings. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–19.

## A Appendix

### A.1 Pre Study Survey Questionnaire

#### A.1.1 Demographics.

- (1) What is your age?
- (2) What is your gender?
  - Male
  - Female
  - Non-binary
  - Prefer not to answer
- (3) How would you describe your hometown?
  - Rural
  - Suburban
  - Urban
- (4) Do you live outside of your hometown for work?
  - Yes
  - No
- (5) In which city are you currently residing?
- (6) What is the highest educational level you have completed?
  - Primary
  - Secondary
  - Tertiary (College / University)
  - Postgraduate (Master / PHD)
- (7) Do you have any children?
  - Yes
  - No
- (8) How many members are there in your family?
- (9) Do you live with your family?
  - Yes
  - No
- (10) What is your employment status?
  - Employed
  - Retired
  - Housewife
  - Student
- (11) What is your household's monthly income (people living together as a family and sharing finances)?
  - <250 USD
  - 250 - 475 USD
  - 475 - 750 USD
  - 750-950 USD
  - >950 USD
  - Prefer not to answer
- (12) How would you describe your living place?
  - One storey House
  - Two storey House
  - Flat
  - 1BHK Apartment
  - Hostel Room
- (13) Do you / your family members have any respiratory disease/health condition that is caused by poor air quality?
  - Yes
  - No
  - If yes, please specify the health condition.

#### A.1.2 Awareness on Indoor Pollution.

Responses are selected from options:

- TRUE
- FALSE
- N/A

- Q1 One third of the global population is affected by harmful household air pollutants
- Q2 Approximately 11% of lung cancer deaths in adults are attributable to exposure to carcinogens from household air pollution
- Q3 Permissible carbon dioxide concentration in indoor spaces is 400 ppm for long-term
- Q4 The UK government has pledged to implement new standards, guidelines, and regulations that will require all newly constructed homes from 2025 onward to generate 75-80% fewer carbon emissions
- Q5 Road accidents cause more deaths than respiratory diseases in your country
- Q6 National Green Tribunal (NGT) recommended the government to mandate monitoring and reporting of Indoor Air Quality in all public buildings
- Q7 Indoor Air Quality regulations are strictly followed in some states of your country

#### A.1.3 Understanding of Indoor Pollutants.

- (1) Have you ever heard of sick building syndrome?
  - Yes
  - No

- (2) Have you ever taken any measurements of air pollutants in your home or office?
  - Yes
  - No
  - If yes, please specify the health condition.
- (3) What do you think are the possible pollution sources in your household? (e.g., Gas stove, Fridge, Incense sticks, etc.)
- (4) When do you think your house is more polluted?
  - Morning (06:00-12:00)
  - Afternoon (12:00-18:00)
  - Evening (18:00-00:00)
  - Night (00:00-06:00)
- (5) What do you think are the possible health impacts of air pollutants (e.g., Dizziness, irritation of eyes, etc)
- (6) According to you, order the following pollutants with respect to harmfulness (i.e., 1 - least harmful, 5 - most harmful)
  - Small dust particles (PM2.5)
  - Carbon dioxides (CO<sub>2</sub>)
  - Ethanol (C<sub>2</sub>H<sub>5</sub>OH)
  - Volatile Organic Compounds (VOC)
  - Nitrogen dioxide (NO<sub>2</sub>)
- (7) What would you do in the following scenarios? Select from the options:
  - Exhaust fan on
  - Ceiling fan on
  - Window ventilator on
  - Split AC on
  - Open window
  - Clean the area.
  - Kitchen is full of smoke
  - Food leftover in dining from yesterday
  - Sweeping dusts in bedroom
  - Family gathering
  - Smoking in room

#### A.1.4 Perception on Pollution and Countermeasures.

Responses are selected from options:

- Strongly Disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

- Q1 Exhaust fan helps ventilating the pollutants in kitchen
- Q2 Pollutants are not affected by ceiling fans
- Q3 Sometimes carbon dioxide concentration in the Bedroom is more compared to the Kitchen
- Q4 Split AC ventilates carbon dioxide and other pollutants from the room
- Q5 Indoor gathering increases the carbon dioxide concentration of the room
- Q6 Anyone can feel when pollutants are accumulating in their home
- Q7 Carbon dioxide lowers our ability to concentrate on a task
- Q8 There is less awareness about indoor air pollution among the general public
- Q9 Indoor is more polluted than outdoor
- Q10 You can reduce air pollutants if you can see where they are concentrated in your room

### A.2 Post Session Survey Questionnaire

GEQ scores are computed as the average value of their items. For in-game module – Competence: Q2 and Q9, Sensory and Imaginative Immersion: Q1 and Q4, Flow: Q5 and Q10, Tension: Q6 and Q8, Challenge: Q12 and Q13, Negative affect: Q3 and Q7, Positive affect: Q11 and Q14. For post-game module – Positive Experience: Q1, Q5, Q7, Q8, Q12, Q16, Negative Experience: Q2, Q4, Q6, Q11, Q14, Q15, Tiredness: Q10, Q13, Returning to Reality: Q3, Q9, Q17. Responses are selected from options:

- Not at all
- Slightly
- Moderately
- Fairly
- Extremely

#### A.2.1 In-game Experience Questionnaire.

- Q1 I was interested in the game's story
- Q2 I felt successful
- Q3 I felt bored
- Q4 I found it impressive
- Q5 I forgot everything around me
- Q6 I felt frustrated
- Q7 I found it tiresome
- Q8 I felt irritable
- Q9 I felt skilful
- Q10 I felt completely absorbed
- Q11 I felt content
- Q12 I felt challenged
- Q13 I had to put a lot of effort into it
- Q14 I felt good

#### A.2.2 Post-game Experience Questionnaire.

- Q1 I felt revived
- Q2 I felt bad
- Q3 I found it hard to get back to reality
- Q4 I felt guilty
- Q5 It felt like a victory
- Q6 I found it a waste of time
- Q7 I felt energised
- Q8 I felt satisfied
- Q9 I felt disoriented
- Q10 I felt exhausted
- Q11 I felt that I could have done more useful things
- Q12 I felt powerful
- Q13 I felt weary
- Q14 I felt regret
- Q15 I felt ashamed
- Q16 I felt proud
- Q17 I had a sense that I had returned from a journey

#### A.2.3 Post-experiment Feedback.

- (1) Did your understanding of indoor air pollution improve after playing this game?
  - Not at all ◦ Slightly ◦ Moderately ◦ Fairly ◦ Extremely
- (2) How often do you play mobile or AR/VR games?
  - Never ◦ Daily ◦ Weekly ◦ Monthly ◦ Rarely
- (3) I feel more familiar with the AR application in this session.
  - Strongly Disagree ◦ Disagree ◦ Somewhat Disagree ◦ Neutral ◦ Somewhat Agree ◦ Agree ◦ Strongly Agree
- (4) I want to use this app in my home to understand where the CO<sub>2</sub> bubbles are.
  - Strongly Disagree ◦ Disagree ◦ Somewhat Disagree ◦ Neutral ◦ Somewhat Agree ◦ Agree ◦ Strongly Agree
- (5) Would you recommend this game to others in your friend circle? ◦ Yes ◦ No
- (6) I want other pollutants (i.e., small dust particles, ethanol, etc.) to be integrated with this app.
  - Strongly Disagree ◦ Disagree ◦ Somewhat Disagree ◦ Neutral ◦ Somewhat Agree ◦ Agree ◦ Strongly Agree
- (7) Which game features would you like to see in the future
  - More players in multiplayer mode ◦ AR headset integration ◦ AI recommendations to help reduce pollutants

- (8) Any other suggestions to improve this Game

#### A.3 Post-Study System Usability Survey

PSSUQ consists of four usability scores. The scores are computed as the average value of their items – Overall: Q1 to Q16, System Usefulness (SYSUSE): Q1 to Q6, Information Quality (INFOQUAL): Q7 to Q12, Interface Quality (INTERQUAL): Q13 to Q16. Responses are selected from a 7-point Likert scale options: ◦ Strongly Disagree ◦ Disagree ◦ Somewhat Disagree ◦ Neutral ◦ Somewhat Agree ◦ Agree ◦ Strongly Agree.

- Q1 Overall, I am satisfied with how easy it is to play this game
- Q2 It was simple to use AR app
- Q3 I was able to see the reducing CO<sub>2</sub> concentration using the AR app
- Q4 I felt comfortable using this AR app
- Q5 It was easy to learn to use this AR app
- Q6 I believe I could reduce pollutants surrounding me using this AR app
- Q7 If there is any technical error during my session, the app gave error messages that clearly told me how to fix problems
- Q8 Whenever I made a mistake using the AR app, I could recover easily and quickly. (Wrong tagging the equipment, multiple bubbles)
- Q9 The information (such as information sheet, instructions by RA) provided with this AR app was clear
- Q10 It was easy to find the CO<sub>2</sub> concentration
- Q11 The information sheet was effective in helping me complete the tasks and scenarios
- Q12 The organisation of information on the app screen was clear
- Q13 The interface of this app was pleasant
- Q14 I liked using the interface of this app
- Q15 This app has all the functions and capabilities I expect it to have
- Q16 Overall, I am satisfied with this app

#### A.4 Semi-structured Interview Topics

##### A.4.1 Gameplay Experience.

- How did you find the overall experience of interacting with the game?
- Which parts did you enjoy the most and least?
- How did you feel about the design of the interface in terms of clarity, responsiveness, or understanding?
- What improvements would you suggest for the interface?

##### A.4.2 Impact of In-game Interactions on Perception of Air Pollutants.

- Before playing the game, how aware were you of air pollutants in your environment?
- Did the game change your awareness or understanding? If yes, how?
- Did the visualizations make the pollutants more relatable or noticeable to you?

##### A.4.3 Suggestions to Improve the Platform.

- What features or changes would you suggest to enhance the game's impact on your understanding of air quality?
- Are there any tools, information that you felt were missing?