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Making Environmental Data Meaningful: Designing an AR-Based Participatory Sensing System

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ABSTRACT

Participatory sensing systems are increasingly used to support environmental awareness by enabling individuals to collect and access environmental data. However, in many projects, citizen-generated data are presented in static forms that are weakly connected to lived experience and data-collection contexts. This research introduces Augmented Reality (AR) into the context of participatory sensing to explore new ways of interacting with data and engaging with the environment. We present CEDAR, a sensor-based AR application that incorporates a character growth mechanism and three modes of data interaction: environmental data visualisation, particle-removal gameplay, and creative data making. The project progressed through four Research through Design (RtD) stages: the development of the CEDAR toolkit, a participatory sensing workshop, the design and iterative refinement of the CEDAR application, and an evaluation phase. The research results show that CEDAR supports meaningful data exchange by developing these mechanisms. Through this process, participants perceived previously invisible environmental conditions, developed deeper understandings, reinterpreted data as responsive living objects, and formed dynamic, personalized dialogues with their surrounding environment. Finally, we further discuss the role of AR in environmental engagement and offer insights for the design of future participatory environmental data sensing practices.

KEYWORDS

Participatory sensing; data visualisation; AR-based interactive system; research through design; environmental engagement

1. Introduction

More than half of the world's population lives in cities, and this proportion is projected to approach 70% by 2050 (United Nations, 2019). While urban living offers many conveniences, it also increases residents' exposure to harmful pollutants (European Commission, 2010, 2016). In response, governments and relevant regulatory agencies have strengthened air quality monitoring and placed growing emphasis on public environmental awareness and citizen participation in environmental initiatives. Participatory sensing has emerged as a key approach in this context, enabling the public to collect, share, and interpret environmental data using more accessible technologies (Berti Suman and van Geenhuizen, 2020; Burke et al., 2006). Against this backdrop, a wide range of low-cost urban sensing tools for the public have been developed, including specialized sensing devices, mobile applications, and connected Internet of Things (IoT) devices (Brown et al., 2016; Camprodon et al., 2019; Predić et al., 2013). The data collected by these tools are typically uploaded to open data platforms, where users can view, compare, and analyze data from different regions in real time, thereby improving public understanding and participation (Mahajan et al., 2021; Tangmunarunkit et al., 2015).

Yet once published on these open platforms, data is often stripped of its original context, and reduced to charts and figures, making it difficult to convey the living circumstances and experiences it represents (De Greve et al., 2022; Liu et al., 2020). To address this limitation, recent research has

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explored methods to reconnect data with its collection sites and participants' subjective experiences, supporting more interpretable and contextually grounded data. These approaches include collage, drawing, and interactive visualization tools, to guide participants in overlaying their personal experiences and feelings onto data interpretation (De Greve et al., 2022; Liu et al., 2020). Some studies have worked collaboratively with community members to install public data visualization devices that contextually reflect environmental conditions, thereby enhancing participants' collective understanding of and engagement with data (Perovich et al., 2021; Woods et al., 2018). Beyond this, various technologies have been integrated into participatory sensing practices to enhance the level of interactivity. Building on this trajectory, immersive technologies such as augmented reality (AR), virtual reality (VR), and wearable devices have been explored to present environmental data in more immersive and dynamic ways (Novak et al., 2023; Pochwatko et al., 2022; Renault et al., 2024). These technologies seek to address the limitations of traditional static data representations.

While these methods have broadened the technical and expressive scope of participatory sensing, they remain largely limited to community-level interventions that are led by experts, targeting policymaking or local issues. They lack accessible platforms or tools that enable individuals to collect and interpret data in everyday contexts and to effectively transform it into contextualized, embodied, and personalized experiences. Moreover, the dominant framework focused primarily on data accuracy and verifiability, often neglects the potential of data to stimulate perception, emotional engagement, and creative expression (Booker et al., 2023; Gabrys, 2016). This approach tends to frame participation as an objective observation of the environment rather than as an opportunity to cultivate a more intrinsic and affective connection with it (Dunkley, 2023; Moon et al., 2024). Addressing this challenge requires more than optimising interactive interfaces; it calls for rethinking how data is generated, experienced, and mobilized to shape new modes of perception and environmental engagement (Gabrys, 2022).

In response, this research adopts a four-stage Research through Design (RtD) approach to develop CEDAR, a sensor-based AR system for exploring embodied, situated, and personalized environmental data interaction in participatory sensing. Rather than privileging data accuracy or behavioral change as dominant metrics, our research aims to create meaningful environmental experiences and engagement through interaction with data. Specifically, this research explores three core research questions (RQs): (RQ1) How can an AR-based system be designed to support participatory sensing practices? (RQ2) How do different AR-based interaction modes support meaningful engagement with environmental data? (RQ3) In what ways does AR-based data interaction enhance experiences of the environment in participatory sensing contexts?

The contributions of this study are as follows:

- Develop a toolkit that offers practical sensing devices and an action framework for conducting participatory environmental sensing practice.
- Design and implement a sensor-based AR application to innovate interactive experience with environmental data.
- Explore how AR-based data interaction can foster new forms of environmental perception, understanding, and engagement, and distill insights for the design of future participatory sensing practices.

2. Related work

This chapter reviews related work in participatory sensing and AR-based interaction. It begins by introducing the participatory sensing context, then examines existing approaches to environmental data interaction and their limitations. It then reviews research on AR visualization and gamification to articulate the rationale for adopting AR and inform the development of CEDAR.

2.1. Participatory sensing systems

As intelligent technologies and the IoT become increasingly prevalent, low-cost sensors are expected to enable large-scale monitoring in dense supplementary networks (Burke et al., 2006; Kumar et al., 2015).

The growing popularity of small, low-cost gas and particle sensors, microcontrollers, and open-source programs increasingly enables citizens to collect air pollution data (Wesseling et al., 2019). One large-scale and successful participatory sensing system is the *Smart Citizen Kit* (SCK), which integrates multiple environmental sensors and can upload data to an open platform in real-time for visualization and sharing (Camprodon et al., 2019; Coulson & Woods, 2021). In applications in cities such as Amsterdam and Manchester, the *SCK* has demonstrated its potential to enhance community environmental awareness and data literacy. Meanwhile, the project also exposed challenges in citizen participation in sensing, including limitations in sensor accuracy and data stability, as well as the need for stronger mechanisms to support sustained community engagement and data interpretation (Balestrini et al., 2015). Another project, AirKit, addresses these challenges by prioritizing pluralistic, dynamic, and relational sensing practices over data accuracy (Gabrys, 2022). It adopts data storytelling as a central mechanism, combining logbooks, portable sensors, and data visualization platforms to enable citizens to actively engage in sensing, interpreting, expressing, and collaborating (Gabrys, 2022; Mahajan et al., 2021). More recent studies have further critiqued purely quantitative methodologies that treat data accuracy and objectivity as the primary criteria for environmental sensing (Dunkley, 2023; Moon et al., 2024). From this perspective, participation in data collection is not understood as objective measurement alone, but as an embodied and relational process through which participants develop closer and more intimate connections with their surrounding environment (Dunkley, 2023). Building on these perspectives, this study draws on existing participatory systems, including low-cost sensor development and associated data display platforms. Rather than focusing on technical precision, it examines how data is produced, perceived, and used to support new forms of environmental understanding and relationships.

2.2. Interaction techniques for environmental data

As environmental data gathered through participatory sensing is increasingly presented in various ways, researchers have proposed strategies and tools to enhance its interaction with participants, preventing it from remaining merely at the stage of collection. Nold (2017), in his noise detection practice around Heathrow Airport, transformed noise from technical indicators into a public and contestable perceptual experience, emphasizing the social and political nature of environmental sensing. The *Air Quality Lens project* (De Greve et al., 2022) employs “ambiguity” as a design strategy, developing a series of installable mobile phone lenses that superimpose visual forms representing air quality data onto the real environment through photography. The device also encourages teenagers to engrave their own patterns on acrylic sheets during workshops to foster personalized emotional expression. Furthermore, traditional static data presentation methods are being replaced by more immersive and interactive interfaces. For example, Woods et al. (2018) collaborated with community advocates and local residents to collectively install a lighting installation linked to noise data in *Plaça del Sol*, Barcelona, enabling environmental information to intervene in daily life in a perceptible manner. Pochwatko et al. (2022) use VR to combine low-cost sensing data with multi-sensory interaction, supporting the collaborative creation of scenes that render air pollution perceptible through visual, auditory, olfactory, and tactile feedback. *DEVA* (Renault et al., 2024) is an AR application that retrieves data from open platforms such as *Sensor.Community and* directly presents various forms of visualizations (from basic 3D shapes to particle-based clouds) within the user’s surrounding environment. Although augmented reality has been applied in participatory sensing for data visualization, existing applications largely remain focused on information overlay. Support for meaningful data interaction is limited, and it remains unclear in these studies how such interactions influence users’ environmental experience. Therefore, this study explores a range of AR interaction principles and techniques to support more experiential forms of data interaction applicable to participatory sensing.

2.3. Interaction with AR visualisation

AR can superimpose dynamic and contextualized information onto the user’s visual scene to create an “enhanced space,” where the information has location sensitivity and contextual affinity (Manovich, 2006). Building on this, AR visualization technologies can immersively integrate digital information into physical environments, making invisible phenomena visible through situated visualization (Assor et al., 2024; An et al., 2024; Büschel et al., 2021; Renault et al., 2024; Sungur et al., 2024). Beyond this representational function, AR also supports embodied engagement (Jackson, 2016; Li & Duh, 2013) and participatory practices (Hunter et al., 2022; Lovett et al., 2024; Postert et al., 2022) across different contexts. Specifically, as an "on-site" embodied and interactive experience, AR images have their spatial technology, geolocation, and bodily participation collectively influencing meaning construction (Jackson, 2016). This research direction emphasizes the role of the body, sensorimotor interaction, and situational context in shaping cognitive processes and knowledge construction (Fortman & Quintana, 2023; Mansour et al., 2025). Li and Duh (2013) pointed out that Mobile AR has a high degree of physical participation, and its cognitive process is closely fused with the physical environment. For example, in *rediscOvery*, users' movements in urban space (walking, turning, changing position) continuously refresh phantom AR content. Through this process, historical significance is personally perceived and generated at specific locations (Jackson, 2016). In addition, AR visualization has become a powerful tool for customization and participation, allowing users to annotate or transform physical spaces with virtual content without altering the real environment (Postert et al., 2022). This functionality makes AR particularly valuable in community engagement (Hunter et al., 2022), urban co-creation projects (Paraschivoiu, 2025), and participatory artistic practices (Lovett et al., 2024), as it encourages personalization and expression. Such practices not only expand the relationship between digital content and physical materials but also inspire more inclusive and creative forms of participation (Lovett et al., 2024). We can observe that AR visualization has been widely explored across different contexts to support situated visualization, embodied interaction, and customization. This research draws on these well-established AR interaction characteristics to inform the design and development of an AR-based participatory sensing system.

2.4. AR game and gamification

AR games use mobile devices and location-based services to extend gameplay into daily spaces, transforming how players navigate and perceive their surroundings (Laato et al., 2021). Unlike traditional electronic platforms, playful experiences (Sicart, 2014) in AR combines spatial exploration, embodied participation, and situational responsiveness, allowing players to dynamically engage with both digital content and the physical environment (Nijholt, 2020). In environmental education and sustainability projects, it is often used to situate gameplay in ecologically meaningful contexts, using immersive interaction and emotional resonance to encourage public reflection on environmental issues (Arcos et al., 2016; Sandbrook et al., 2025; Yang & Ryokai, 2025). For example, *Being the Creek* (Yang & Ryokai, 2025), uses AR embodiment (Genay et al., 2022) to let users first-person "become" a creek, experiencing its encounters across eras, thereby enhancing empathy and understanding of the environmental impacts of human activities. Gamification refers to the application of computer game design elements in non-game contexts to boost users' learning motivation, engagement, and initiative (Deterding et al., 2011). Ma et al. (2023) designed an AR-based mobile educational application that guides students to learn about carbon neutrality, energy choices, and daily environmental behaviors through various gamification mechanisms such as simulated Q & A, cartoon characters, point rewards, and social sharing. This attribute is widely used in the realm of environmental education to incentivize users to actively participate in environmental protection practices and cultivate long-running sustainable behavior habits (López-Faican & Jaen, 2023; Ma et al., 2023; Mensink et al., 2022). Previous studies have shown that emotional resonance in AR games, as well as the design of gamification mechanisms, can effectively motivate participation and engagement in environmental education and sustainability-related contexts. Building on these insights, this study further incorporates gamification mechanisms and playful interaction into the design of CEDAR.

3. Methodology

We adopted a "Research through Design (RtD)" approach (Zimmerman et al., 2007) to demonstrate the interconnections between the various phases of this article, from toolkit development to AR system evaluation. RtD emphasizes exploring the problem space through design (Zimmerman & Forlizzi, 2008), focusing on creating "what could be" rather than "what is" (Gaver, 2012). In this article, we combined design, making, reflection, and knowledge generation, with the entire design process serving both as an inquiry method and a means of knowledge generation. Specifically, this study responds to RQ1 through the presentation of the complete design and development process of CEDAR as a form of practice-based inquiry. Insights generated through the design practice further examine how AR-based interaction supports meaningful engagement with environmental data (RQ2) and analyses how such interaction enhances participants' environmental experience (RQ3).

The following outlines the four interrelated phases of our RtD work, each building on and shaping the next.

- ***Phase 1: Development of the CEDAR Toolkit.*** We develop the CEDAR Toolkit to integrate environmental sensing devices with a participatory sensing action framework. This toolkit establishes the technical and interactional foundation of the project and is specifically designed to support the subsequent workshop activities.
- ***Phase 2: Participatory Sensing Workshop.*** Building on the CEDAR Toolkit, we conduct participatory sensing workshops where participants collect and engage with environmental data. The insights gained inform key design considerations for the AR system.
- ***Phase 3: Development of the CEDAR Application.*** Guided by the workshop outcomes, we design multiple environmental data interaction mechanisms within the AR system. These functions are iteratively refined through initial user testing in preparation for subsequent evaluation.
- ***Phase 4: Evaluation.*** In the context of participatory sensing, we evaluated the effectiveness of the system functions and examined how, and in which aspects, they influenced participants' understanding, perception, and engagement with the environment.

4. Phase 1: Development of the CEDAR toolkit

4.1. CEDAR sensor design

In the context of participatory sensing, toolkits were initially introduced as a how-to collection for documenting and explaining the assembly of sensors and components to monitor issues such as air pollution (Gabrys, 2022). While it may appear in the form of a manual or instructional guide, it is better understood as an open and experimental practice for collectively generating, negotiating, and enacting more breathable worlds (Gabrys, 2022). Building on this understanding, the CEDAR Toolkit comprises a set of sensing devices, together with an action-oriented framework that guides how these tools are deployed and used within participatory sensing contexts. Beyond providing technical development and usage instructions, the toolkit emphasizes how sensing infrastructures can enable participants to perceive and interpret their surrounding environment in new ways. We designed CEDAR sensors to collect air quality and sound data, including particulate matter (PM2.5, PM10, PM1), humidity, temperature, and ambient noise levels. These parameters are commonly applied in urban environmental research to assess pollution levels and ecological health (Camprodon et al., 2019). Through 4G and Wi-Fi, the data can be transmitted to a cloud server in real time to support data sharing in subsequent development. Operating the sensors requires no professional technical knowledge; data can be accessed via the tiny screen interface simply by pressing a button. The enclosures of sensors (Figure 1) are designed into five anthropomorphic forms (tree, water, bird, moss, and rock) inspired by Donna Haraway's "Companion Species Theory" (2006) and the increasingly emphasized concept of multispecies perception in participatory sensing research (Dunkley, 2023; Westerlaken et al., 2023). This design strategy encourages participants, through the selection of different enclosures, to imagine themselves as the natural entities represented by the sensor forms and to attend to different aspects of the urban environment from that perspective.

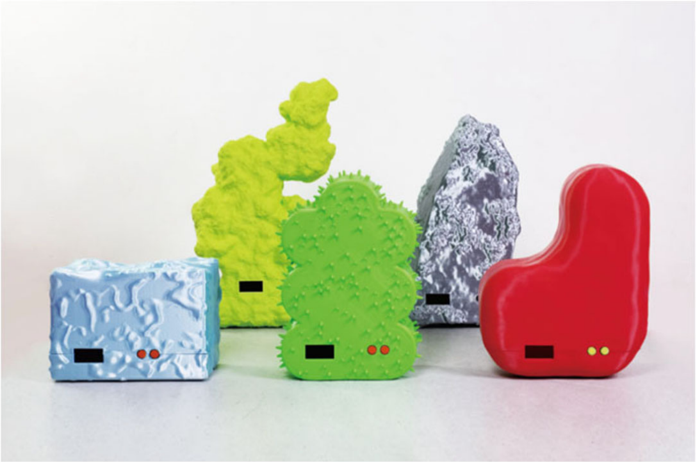
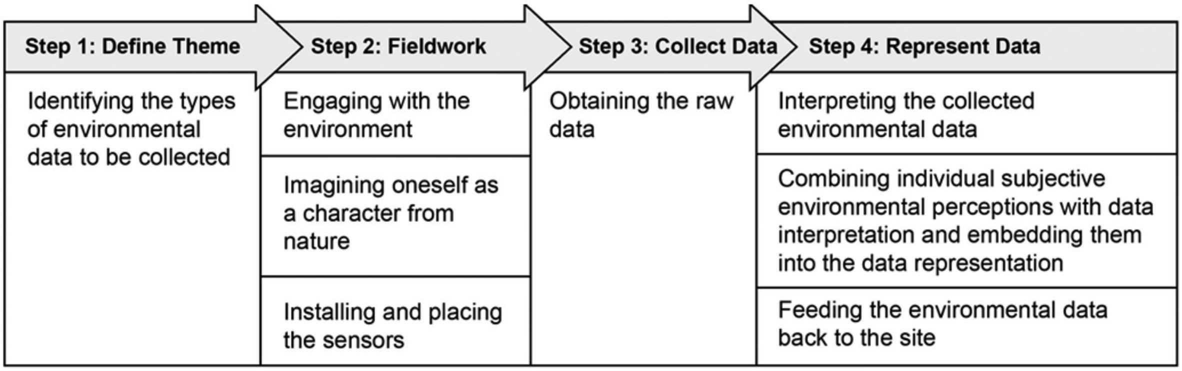


Figure 1. Five anthropomorphic sensor designs: tree, water, bird, moss, and rock.



Step 1: Define Theme	Step 2: Fieldwork	Step 3: Collect Data	Step 4: Represent Data
Identifying the types of environmental data to be collected	Engaging with the environment	Obtaining the raw data	Interpreting the collected environmental data
	Imagining oneself as a character from nature		Combining individual subjective environmental perceptions with data interpretation and embedding them into the data representation
	Installing and placing the sensors		Feeding the environmental data back to the site

Figure 2. Process of participatory sensing practice guided by CEDAR toolkit.

4.2. An action framework for participatory sensing

In Burke et al. (2006) and follow-up works (Coulson & Woods, 2021; Gabrys, 2022), participatory sensing is often broken down into core actions (framing the issue, mobilizing participants, collecting data, interpreting it, acting on it, etc.). These are understood as a cycle of actions that structure participatory sensing. In this study, we use the term Action Framework to describe a conceptual structure that builds on these phases to guide the design and practice of participatory sensing. Building on this foundation, we introduce participatory data visualization as a means to enhance situated engagement with environmental data and to foster deeper connections between participants, sensing technology, and their surroundings. To this end, we borrow the terms "data physicalisation" (Jansen et al., 2015) and "data sculpture" (Zhao & Vande Moere, 2008) to describe the process and the materialized result of transforming abstract data into a perceptible and manipulable form through specific physical forms. In this way, the action framework supports active sensing of the air through bodily action, situated observation, and personalized interpretation, encouraging embodied and contextualized data practices. It emphasizes participant engagement at every stage of interaction with data, including defining themes to identify relevant data, conducting fieldwork to engage with the environment, collecting data, and representing it. Through this process, participants are encouraged to gain new insights through embodied and situated interactions with data. Specifically, the process consists of the following steps (Figure 2). This phase provides tools and guidance for rethinking how participatory sensing can become an embodied and contextualized data practice and also lays the foundation for the subsequent development of both the workshops and the AR interaction system.

5. Phase 2: Participatory sensing workshop

5.1. Workshop procedure

Participants for the workshops were recruited through social media, Meetup and Eventbrite event platforms, as well as the UAL Student Union, with a total of 13 participants from diverse backgrounds including journalism, design, and data science invited. The workshops consisted of two phases: data collection and data visualization, with an interval of one week. A total of 13 participants took part in the data collection phase, of whom 8 continued with the data visualization phase. The overall process is shown in Figure 3. At the beginning, participants were introduced to the project objectives, the use of the sensors, and the different types of environmental data that the sensors could collect. Subsequently, we conducted fieldwork, guiding participants to explore different urban environments and assisting them in deciding where to place their sensors. The collected data was initially presented in the form of a dashboard, and after collective discussion and interpretation, participants created their own data sculptures using the provided materials. Figure 4 presents some examples of participants' works.

Figure 3. Overview of the workshop process: (a) participants being introduced to the workshop objectives and agenda; (b) the researcher explaining how to operate the sensor; (c) participants and researchers conducting fieldwork together; (d) a sensor installed by a participant; (e) an informational leaflet illustrating the types of data the sensor can collect; (f) participants engaging in data creation based on the data overview and dashboard; (g) materials provided for the workshop; (h) a participant in the process of creating their data sculpture.

Figure 4. Participants' creative outcomes: (a) using clay, sound-related data collected during the sensing activity were represented; (b) humidity-related data were expressed using beads placed inside a blue fabric pouch; (c) changes in particulate matter were conveyed with balloons of varying heights; (d) a small physical scene was constructed to contextualize the collected data, with data representations positioned above it; (e) data represented as a matrix of beads, encapsulated between two transparent acrylic panels; (f) air quality data metaphorically expressed through layered, semi-transparent black textiles using cutting and overlaying techniques. (g–h) participants presenting and explaining their own data sculptures to others.

Throughout the process, we employed questionnaires and contextual inquiry to gain a deeper understanding of participants' experiences in data collection and creative interpretation. The results demonstrate the practical application of the CEDAR toolkit and provide valuable insights that informed the development of the subsequent AR application.

5.2. Defining the design considerations for the AR system

From participants' interactions and feedback in the workshops, we derived a set of insights that informed the following design considerations (DCs) for the AR application.

DC1: Connecting CEDAR sensor design and data experience

Participants appreciated the CEDAR sensors for their unique appearances and incorporation of natural elements, but they also expressed a desire for the design to be more directly connected to their data experience. This idea was verbally emphasized during the workshop, for example by encouraging participants to imagine themselves as the natural entities represented by their chosen sensors. The AR system requires a more comprehensive game mechanism to reinforce the idea of the sensor as one's own character and to integrate it into the data interaction experience to encourage participation.

DC2: Designing templates to lower the threshold for data creation

We observed that when participants encountered raw data such as line graphs or scatter plots, they intuitively transformed them into tangible shapes. For example, using wires to reconstruct data trends, or building spatial layouts with point-like distributions using clay and strings. In doing so, they incorporated personal feelings and interpretations, giving the data new meanings. This observation prompted us to develop easy-to-understand and easy-to-use creation templates in AR systems to support users in combining the visual form of raw data with individual creative expression.

DC3: Enhancing the intuitiveness of knowledge introduction

Many participants lack basic knowledge about air quality data such as particulate matter, even though paper-based information introductions were provided in this workshop. However, in most cases, they still relied on the researchers' on-site explanations. This highlights the necessity of introducing real-time interactive elements during the creation process to guide understanding.

DC4: Designing playable interaction

Participants highlighted the exploratory and creative enjoyment of engaging with different materials. For instance, one participant created a data sculpture symbolizing PM values using balloons. After the final presentation, we popped the balloons together, remarking that the act felt like eliminating the pollution data. This playable interaction can be embedded in AR system design to enhance metaphorical meaning.

Centering around these design considerations, we have combined the characteristics of AR technology to determine specific design strategies to further guide the development of AR applications. As detailed in Chapters 2.3 and 2.4, these characteristics involve situated visualization, embodied interaction, and customization. These are combined with game mechanics to create playful experiences.

6. Phase 3: Development of the CEDAR application

6.1. Designing the CEDAR application

The whole CEDAR interactive system consists of the CEDAR sensor and an AR application. The data captured by the sensors are transmitted in real time to a backend server using Wi-Fi when available, while a 4G communication module provides connectivity in the absence of Wi-Fi. The Unity-based AR application subsequently retrieves the latest data from the server and visualizes them as live environmental feedback. To address the four DCs outlined above, we designed four core mechanisms. These include three modes of data interaction, namely creation mode, observation mode, and battle mode, which are integrated within a progression mechanism (Figure 5). After entering basic information to connect with

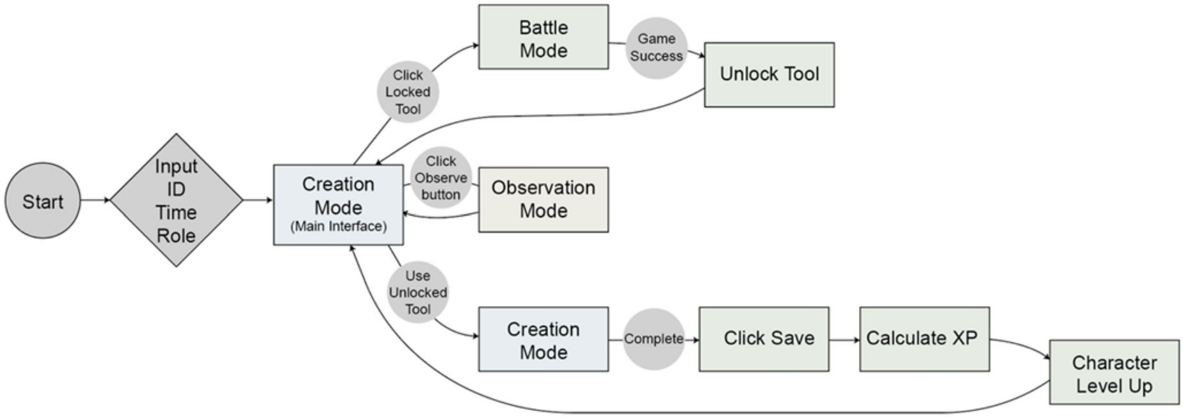
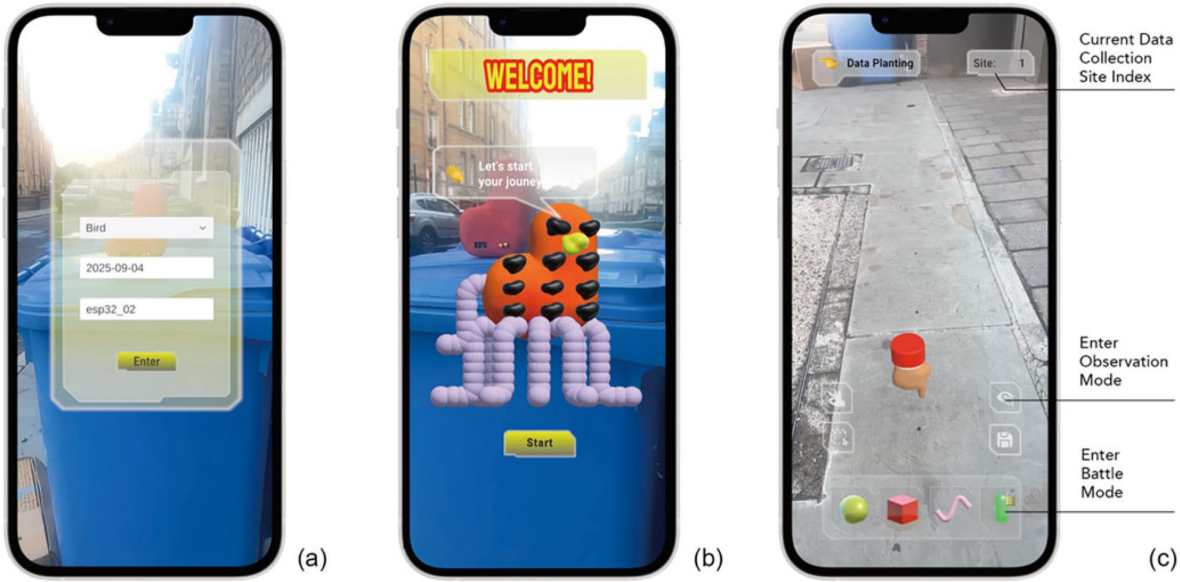


Figure 5. Flowchart of the CEDAR application (initial version).


Bird
2025-09-04
esp32_02
Enter

WELCOME!
Let's start your jouney
Start

Data Planting
Site: 1

Figure 6. Interface of the CEDAR application during startup: (a) entering the sensor's associated character, time, and sensor ID; (b) welcome screen displaying the chosen character, with a start option; (c) transition to the main interface, which presents the system layout, ground detection, data point generation, location information, and mode-switching controls.

the sensor (Figure 6a), users see their chosen character (Figure 6b) and click "Start" to enter the main interface (Figure 6c). This main interface corresponds to the creation mode, in which the system generates raw data points and supports users in visually manipulating and recombining them to construct personalized forms of data representation. Users can access two additional modes via buttons on the main screen to sense and understand current environmental conditions (Figure 6c). The observation mode presents real-time environmental data in a tangible form, while the battle mode enables an interactive particle-removal gameplay based on actual air quality levels. Completing battle mode tasks can unlock new tools for creation mode. These modes are embedded within a progression-based game mechanism to encourage users to upgrade the characters they chose by completing tasks that involve interacting with the data. The following sections provide a detailed introduction to the four core functions of the CEDAR application: game mechanism, creation mode, observation mode, battle mode.

6.1.1. Character-growth mechanism

In response to DC1, we develop a character growth system in which the sensor's appearance is translated into an in-game avatar. Once activated, users are guided to select a sensor role, which becomes their avatar in the system. These avatars are stylized based on the project's physical sensors, translating

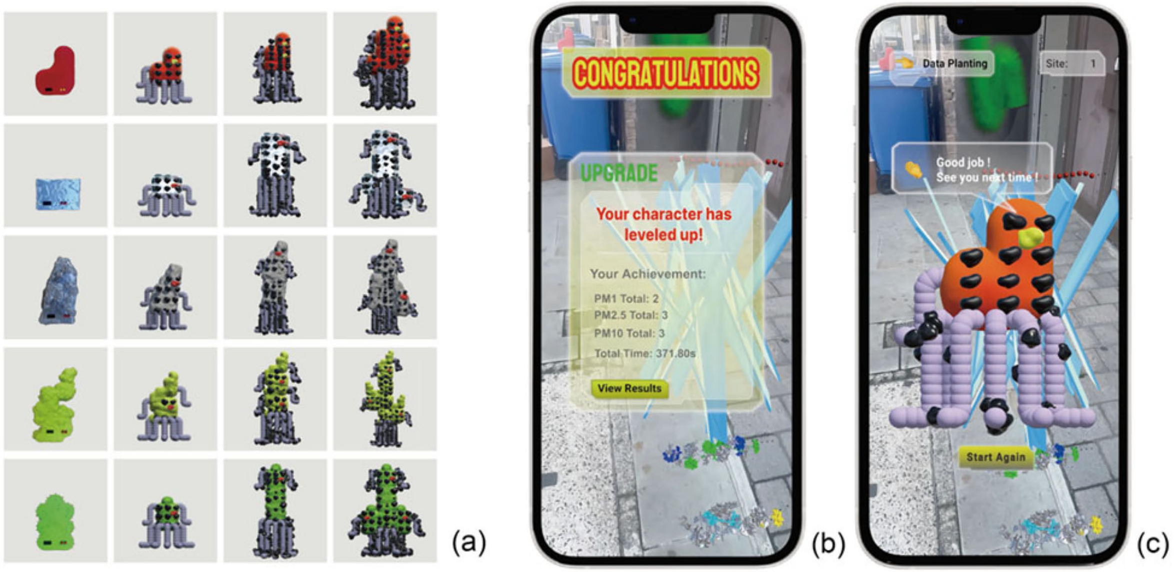


Figure 7. Design elements of the CEDAR game mechanism: (a) avatar design inspired by the five different enclosures of CEDAR sensors; (b) result screen showing the character's level-up and performance summary; (c) screenshot of the avatar's growth during interaction.

each device's form and material characteristics into a corresponding monster-like character (Figure 7a). This idea draws on the "avatar" theory in game studies, which conceptualizes the avatar not merely as a visual representation of the player in a digital environment but as an extension of the player's identity, intentions, and actions within virtual space (Taylor, 2002; Boellstorff, 2016). The purpose of this design is to connect the enclosure design of the CEDAR sensors with the AR system, encouraging users to perceive the interconnections among different elements of the natural world. In addition, drawing on the gamification design principles (Deterding et al., 2011), the system incorporates point-based rewards and progression mechanisms to structure tasks and support user engagement. Users level up their avatar by completing data collection and interaction tasks (Figure 7b,7c). As they unlock new locations, the avatar gradually evolves, eventually becoming a large "monster" (Figure 7a). The character growth mechanism is implemented through a parametric design, generating a unique growth trajectory for each user. The transformation from a small initial form to a large monster symbolically and conceptually represents the increasing strength and capability of the character. In character-driven and gamified systems, progression from a weaker to a stronger form is a well-established design strategy that materializes players' time and actions into visible change (Lankoski, 2011). Such progression makes the outcomes of user actions immediately legible, thereby reinforcing sustained participation and long-term engagement (Rapp, 2022). Although its long-term effects have not yet been systematically evaluated, it enhances playfulness to some extent and provides a clear way to visualize task outcomes, thereby strengthening users' sense of participation and accomplishment.

6.1.2. Creation mode

The creation mode provides interactive templates that enable users to participate in data making, responding to DC2. It translates users' ways of engaging with physical materials and their personal preferences into the AR interface. This interaction mode leverages key affordances of AR within participatory design contexts (Hunter et al., 2022; Lovett et al., 2024; Paraschivoiu, 2025), enabling users to customize how environmental data are expressed within real-world environments. To achieve this, we first map five types of environmental data collected by the system in real-time into the AR scene as spatial trajectories, forming a continuously "growing" data path (resembling a scatter plot). The system receives new data every 20 s and converts it into a data point positioned within three-dimensional space. The position of each point and its corresponding value vary proportionally with height. Each data point is interactive: when clicked, players can view its specific corresponding value and then use toolbar buttons to materialize the original data point, creating their own data sculpture (Figure 8a, 8b). When users click on an

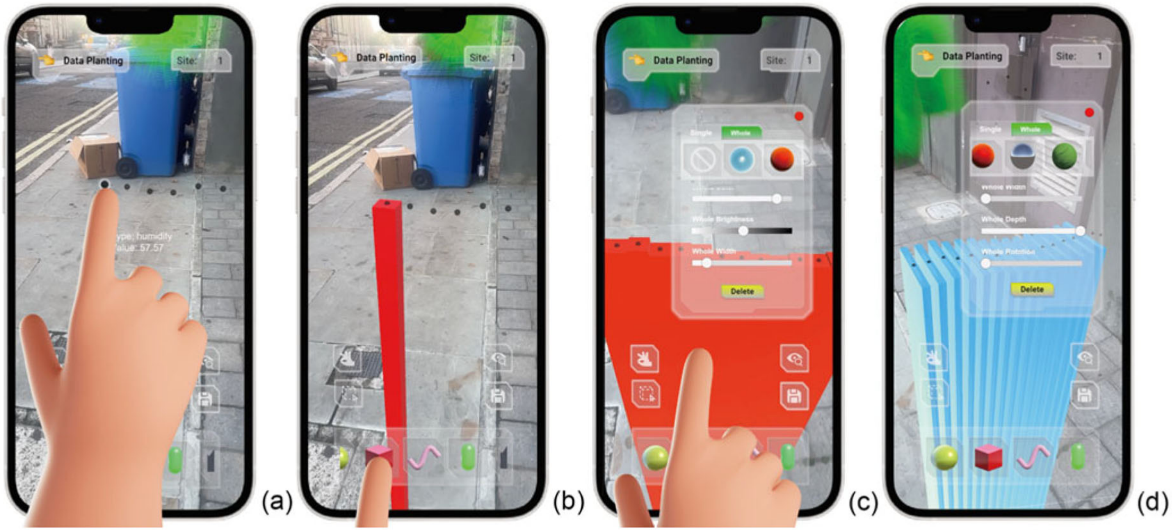


Figure 8. Screenshots of creation mode: (a) by clicking on a single data point, users can view its specific value and type; (b) the toolbar button can be used to materialize the selected point; (c) tapping on a 3D object in the scene brings up a parameter adjustment window; (d) the material sphere above the sliders allows users to change the material.

Figure 9. Examples of data sculptures produced using the CEDAR creation mode, illustrating how different materials, textures, and forms can be used to represent environmental data in diverse and expressive ways.

existing data sculpture in the scene, they can access further parametric settings to adjust attributes such as color, transparency, size, and surface texture (Figure 8c, 8d). Its appearance can vary in multiple ways based on these adjustment mechanisms, until it aligns with the users' own expression (Figure 9). This interactive mode was inspired by the participatory sensing workshop (see Chapter 5), where participants reshaped scatter plots and line graphs with physical materials, translating objective data while adding personal insights (Figure 10). We also recognize that data visualization skills may pose barriers to participation. Therefore, it is important to note that our system provides a basic interface where simple visualizations can be created with a single click, enabling users without prior expertise to participate. At the same time, parameter adjustment functions support more advanced exploration, accommodating different levels of expertise. This feature allows users to think, express, and create through AR directly at the site of data collection. By placing the data sculpture virtually within the AR interface, users can directly convey their feelings about the environment and data at the very site of data collection. In addition, this spatial-scale data visualization template uses AR as an embodied interaction medium (Jackson, 2016; Li &

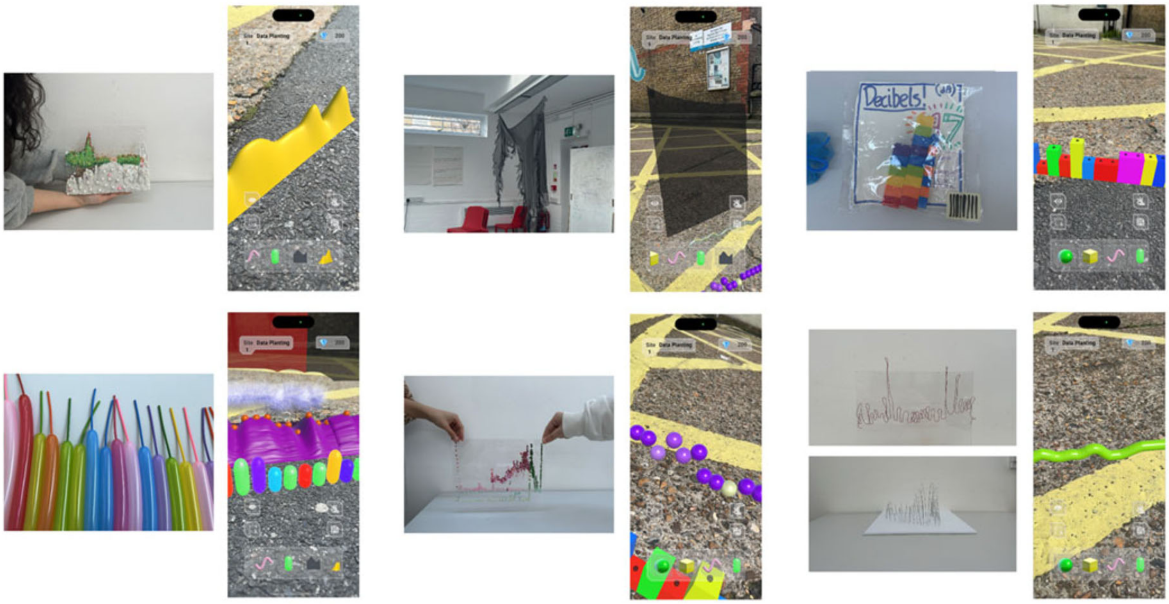


Figure 10. The figure illustrates the progression from the participatory sensing workshop to the AR system.

Figure 11. Screenshots of observation mode: (a) visualisation principles of different data types; (b) a screenshot showing collected data being physicalised in the AR interface; (c) users interacting with the physicalised data through gesture recognition; (d) overview of the in-app hand-based materials, their corresponding sensing devices, and the natural elements that inspired their form and material qualities.

Duh, 2013), allowing users to construct their own understanding of the data through bodily movement within real-world environments (Fortman & Quintana, 2023; Mansour et al., 2025).

6.1.3. Observation mode

To enhance the intuitiveness of knowledge introduction in response to DC3, we design an observation mode that transforms sensed data into tangible visual forms. This design leverages AR-based situated visualization (Assor et al., 2024; An et al., 2024; Renault et al., 2024; Sungur et al., 2024) to enable users to immerse themselves in and experience surrounding environmental conditions. Three key environmental variables arephysicalised: particulate matter, humidity, and sound. Particulate matter (PM1, PM2.5, PM10) is shown as grey floating particles, humidity as varying densities of water droplets, and sound as pulsating blue particles that change with noise levels (Figure 11a, 11b). These visualizations make invisible environmental variables perceptible and relatable. We have also integrated gesture recognition functionality to further enhance users' embodied participation experience. In the AR interface, when users extend their palms, the system maps the texture corresponding to their avatar onto their

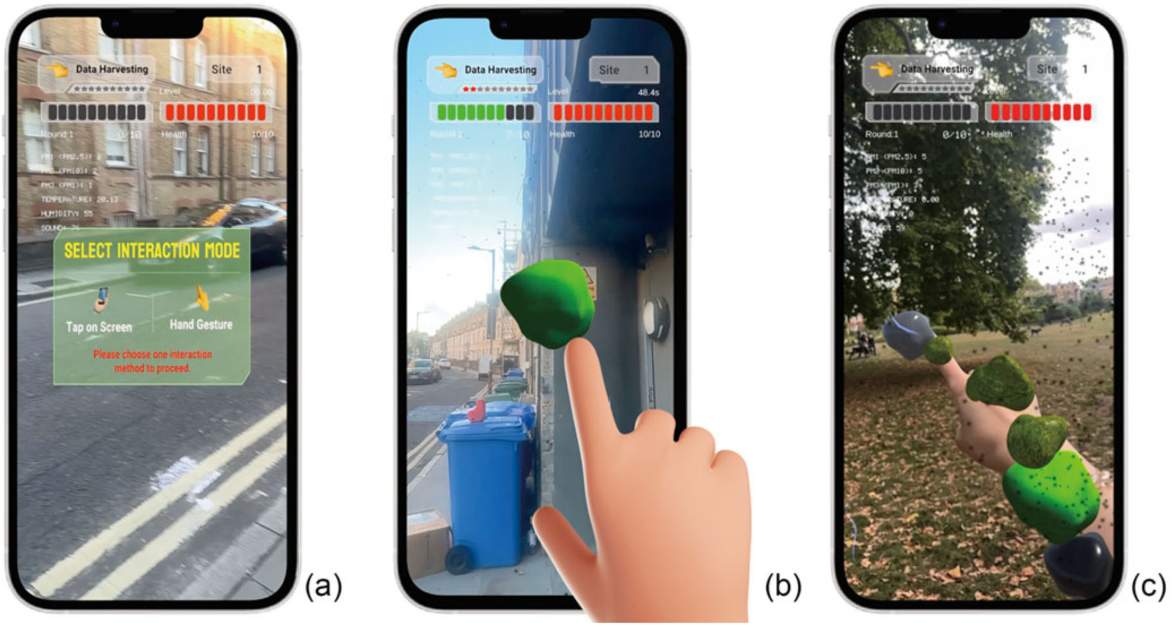


Figure 12. Screenshots of battle mode: (a) users can choose either to tap on the screen or to use gesture recognition to eliminate pollutants; (b) a screenshot showing pollutants being eliminated through screen tapping; (c) a screenshot showing pollutants being eliminated through gesture recognition.

hands, and real-time data is transformed into particles or water droplets that adhere to the hand surface (Figure 11c, 11d). In this way, users not only "become" a certain natural symbolic character but can also directly perceive and carry environmental changes with their bodies. This design highlights embodiment in AR (Genay et al., 2022), enhances emotional resonance through a first-person perspective (Yang & Ryokai, 2025), and strengthens the connection between the AR interface and the nature-inspired CEDAR sensors.

6.1.4. Battle mode

Inspired by the workshop activity in which participants burst balloons representing pollutants, and in response to DC4, we design a game-based interaction mode. In this mode, particulate matter is visualized as virtual pollution particles floating in the AR space, and players are required to eliminate all pollutants in order to achieve task success. The interface offers two modes (Figure 12a), allowing players to either tap the screen (Figure 12b) or use gesture-based interactions to clear the particles (Figure 12c). Gesture recognition also visually merges the player's hand with their chosen avatar (Figure 12c). Since these natural characters symbolize different purification functions, the interaction symbolizes engaging in environmental governance as a natural entity. We adopted a gamification-based design approach (Deterding et al., 2011), designing a progress bar and a health indicator. The progress bar provides participants with immediate feedback on task progression, thereby enhancing a sense of task completion, while the health indicator symbolically represents the potential bodily impact of environmental exposure. Unlike preset difficulty levels, the challenge is determined by the actual environment: fewer particles appear in cleaner air, while higher pollution levels generate more particles and require more effort to complete. If players are "hit" by particles, their health points decrease, reinforcing the health risks of pollutants. This mechanism enhances environmental responsiveness, making players experience clear differences under varying pollution conditions. The design draws on object-oriented design (Bogost, 2012), treating pollutants as active agents and acknowledging the uncertainty and complexity of non-human entities. Meanwhile, studies show that behaviors in virtual environments, especially games, can influence real-world attitudes and actions (Gentile, 2009; Greitemeyer & Osswald, 2010). While our design does not directly target behavioral change, it offers an immersive experience that subtly prompts players to notice and reflect on environmental conditions.

6.2. User testing

The initial user study aimed to evaluate the coherence of the interaction functions and the overall usability of the CEDAR prototype to inform subsequent iterations. For this reason, the study was deliberately conducted in a controlled indoor environment, enabling a focused examination of the system's usability and interaction logic. Despite the indoor setting, we ensured that the sensors continued to measure real-time environmental conditions at the study location. This allowed us to capture and observe participants' experiences as they interacted with live environmental data.

6.2.1. Participants and procedure

User testing of the AR system involved 30 participants (14 male, 16 female) recruited across two UAL campuses through on-campus posters and open calls, with participation based on voluntary self-selection. Participants were aged between 21 and 30 years ($M = 23.6$, $SD = 2.3$). The sample consisted primarily of individuals with technical or design-related backgrounds, but with limited prior experience with AR applications; only three reported familiarity with AR. All participants indicated an interest in environmental-related topics, consistent with the voluntary nature of participation. Before the testing session, they signed informed consent forms, received a brief introduction to the research objectives of CEDAR, and were given instructions on how to use the application (Figure 13a). They were then asked to select a specific natural-form sensor and use it to log into the application (Figure 13b). The collected data were directly visualized in the AR application, allowing users to interact with them in situ. Participants subsequently engaged with the CEDAR application to complete the full process of data collection and interaction (Figure 13c-h), which took approximately 10–15 min. One researcher was present throughout to provide technical support when necessary and respond to participants' questions, while another researcher video-recorded the session.

6.2.2. Data collection and analysis

To evaluate the system in terms of usability and user experience, we adopted a mixed-methods approach combining the System Usability Scale (SUS) questionnaire with video-based qualitative analysis. First, the SUS (Brooke, 1996) was used to quantitatively assess user satisfaction and perceived usability. Second, qualitative video analysis captured participants' behaviors, engagement, and meaning-making processes, allowing us to observe non-verbal reactions and spontaneous reflections often missed by questionnaires (Heath et al., 2010; Derry et al., 2010). Our video recordings followed participants' interactions, and the recorded videos had an average length of about 12 min. Participants were coded from 1 to 30 based on their video IDs. Initial codes were then generated to capture common interests, interaction behaviors, and verbal expressions related to their reflection and insights, helping us understand users' performance and responses during data interactions. Together, these methods provide a comprehensive understanding of both functional usability and experiential interaction.

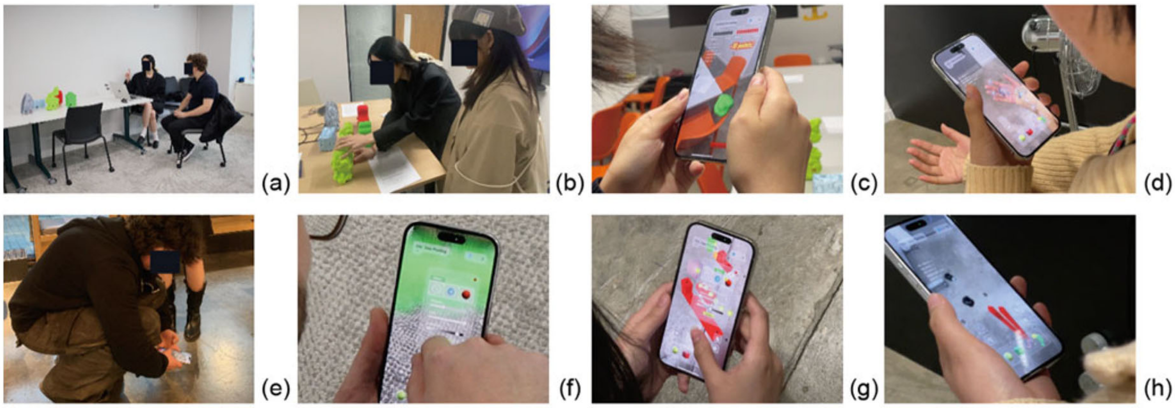


Figure 13. Overview of the testing session: (a) a researcher providing a one-to-one introduction to the participant; (b) the participant selecting a sensor; (c–h) the participant interacting with the CEDAR prototype.

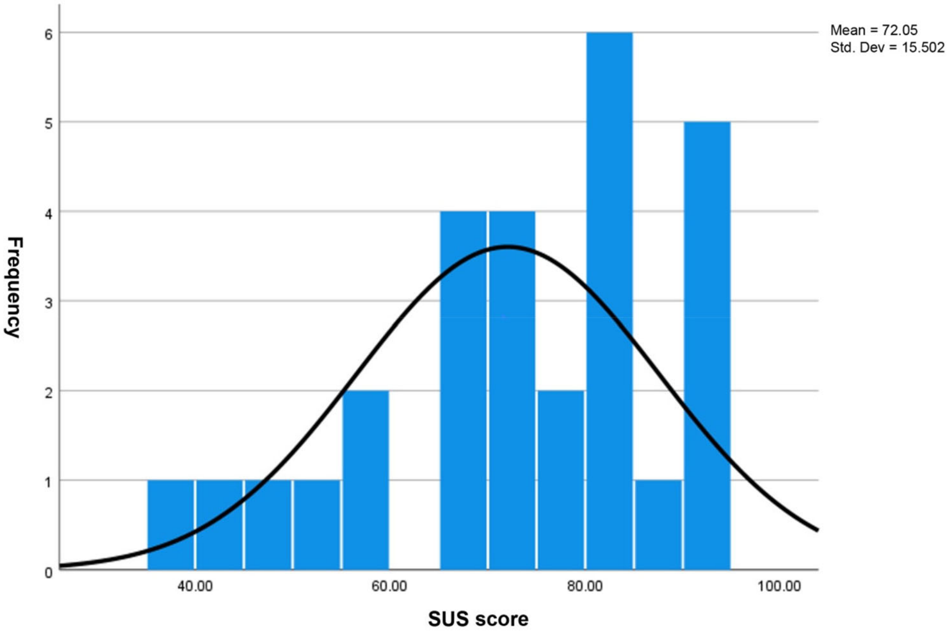


Figure 14. Distribution of SUS scores for the CEDAR application.

6.2.3. Result: SUS score

The SUS questionnaire results indicate a high level of user satisfaction. The average SUS score of the sample was 72.05 (SD = 15.50) (Figure 14). This suggests that most participants perceive the AR system as highly usable and well-integrated. The histogram of SUS score distribution shows that scores are concentrated between 60 and 80, indicating that most participants rated the system's usability in the "good" to "excellent" range. The score distribution is slightly skewed toward higher ratings, which further demonstrates the effectiveness of the system in supporting user engagement and interaction.

6.2.4. Result: Video analysis

Overall, the results reveal that users' engagement with CEDAR was multi-layered, spanning emotional, bodily, and discursive dimensions.

6.2.4.1. Common interests. Common points of interest were identified as moments marked by recurring, observable affective and behavioral cues among participants, including excited vocal tones, laughter, and communicative gestures (e.g., thumbs-up) during interaction. The most common occurred when a tool button was successfully activated and triggered the corresponding visual effect (P1–P4, P6–P11, P13, P15–P20, P22–P30). Excitement also increased in cases such as P8, P15, P20, and P30 when the visual effects changed more dramatically in response to their actions. This highlights the role of customization in fostering emotional engagement. Participants showed clear excitement when airborne particles appeared in real time (P3–P4, P7, P10, P12–P16, P20–P21, P23, P25–P27) and when particles were eliminated (P3–P4, P7, P15, P17, P23, P29–P30). When gesture recognition was used to interact with the data (P3, P8, P10, P11, P13, P16, P20, P25–P29), participants exhibited strong excitement, which shows that bodily engagement plays a key role in strengthening interactivity and immersion. Finally, when participants observed their chosen role grow in response to data changes (P1–P2, P8, P17, P18, P21, P23–P25), they responded positively. This underscores the importance of narrative and game mechanism in supporting emotional engagement. Taken together, these observations suggest that in AR-based data interaction, the mix of real-time feedback, salient responses, and embodied interaction can significantly enhance users' emotional engagement and active participation.

6.2.4.2. Interaction behaviors. All participants continuously engaged with the CEDAR application through bodily interaction, including actions such as crouching to view, leaning in, stepping back, and shifting positions. Several participants rotated their mobile phones around the sculpture from multiple angles to examine the data sculpture they had created (P5, P7, P8, P9, P20). These observed actions suggest that bodily movement formed part of the process of exploring and making sense of the environmental data, contributing to a more situated engagement with the spatial environment. We also observed that participants did not plan a clear structure in advance during the creation process but instead relied on interface prompts, material feedback, and operability to construct and adjust intuitively. As their works gradually took shape, they showed a clear shift in awareness, beginning to recognize how the generated data was visually and meaningfully represented. However, interaction behaviors also revealed moments of difficulty. Participants paused or slowed when data points were difficult to locate or when multiple virtual elements complicated object selection (P3–P6, P9–P16, P18–P23, P25–P30). Gesture recognition instability occasionally led to interrupted interactions (P3, P7, P10, P24), and some participants remained on the main interface without exploring other functions (P6, P12, P14, P26, P29). Overall, AR-based data interaction supports embodied engagement, where understanding develops through bodily movement, system feedback, and dynamic interaction, while also revealing several interaction challenges.

6.2.4.3. Verbal expressions. Participants voiced curiosity and surprise toward the underlying mechanisms, asking questions about whether the particles were changing in real time and how they were generated (P1, P10–P12, P19, P24–P26, P30). Some participants related these visualizations to their own thoughts of air quality. After viewing an AR scene with good air quality, P30 remarked, “If this were in my hometown, the entire room would be filled with pollutants.” When noticing floating pollutants, P3 asked, “Did someone smoke here just now?” Others focused on their own creative process and the meanings embedded in their designs. P10, for instance, customized visual particles with a smoke-like texture, explaining, “I want to use this texture and colour to represent air quality […] it’s disgusting.” They later added, “This smiling face is so cute, but the air quality is so bad that it shouldn’t be portrayed like this.” This shows how participants incorporated personal feelings into the creative process, linking aesthetic choices with perceptions of environmental conditions. There were also participants who raised critical observations about the coherence of the system. As P6 commented, “I enjoy creating the data sculpture, but I’m a bit confused about the need to unlock […] playing a game doesn’t necessarily require a goal […] sometimes it’s just for exploration.” Such comments prompt reflection on the coherence between different functions and highlight the need for iterative refinements to make interactions more cohesive. Participants’ verbal expressions reflected their experiences of the system, highlighting curiosity and personal reflection on environmental data, as well as moments of questioning and critique of certain system functions.

6.3. Define key challenges

During user testing, we identified two main categories of challenges affecting the system. On the performance side, our user testing identified several key factors affecting the overall user experience. First, navigation issues were observed as participants sometimes struggled to locate newly generated data points in the 3D environment. Second, object selection proved challenging, as participants occasionally found it difficult to click on certain objects, and overlapping UI elements sometimes disrupted the flow of interaction. Finally, gesture recognition was unstable in certain cases, occasionally causing the application to crash and interrupting the immersive experience. On the functional side, several participants remained on the “data sculpture” main interface for extended periods, rarely exploring other system features and expressing uncertainty about their task completion progress. Combined with P6’s feedback during use (see Chapter 6.2.4), this seems to stem from insufficient clarity in how the interface presents the relationships between core functions, which limited participants’ understanding of task motivation and progress. Taken together, these findings highlight issues of technical stability and interaction logic, providing clear directions for subsequent iterations.

6.4. Iteration

Based on user testing results, we first iterated on performance by adding directional guidance, expanding object click ranges, clearly separating UI elements from 3D interactive objects, and reducing gesture recognition frequency to improve stability. For the functional aspects, we adopted a modular design approach to reconstruct the interface architecture. Research has shown that modular design helps to improve user autonomy and system usability, and in particular, can reduce cognitive load and enhance a sense of exploration and engagement in interactive experiences (Curtis, 2010). Specifically, while retaining the four core functions, we decomposed the originally serially connected features into three relatively independent and freely switchable interaction modules: Observation Mode, Battle Mode, and Data Creation Mode. In this version, a main interface was added to the startup sequence, allowing users to freely access any module through it without the need to complete tasks to unlock other functions (Figure 15). This approach avoids framing the unlocking of creative tools as the main incentive for completing data visualization, but rather highlights exploration and experiential engagement as central to the process.

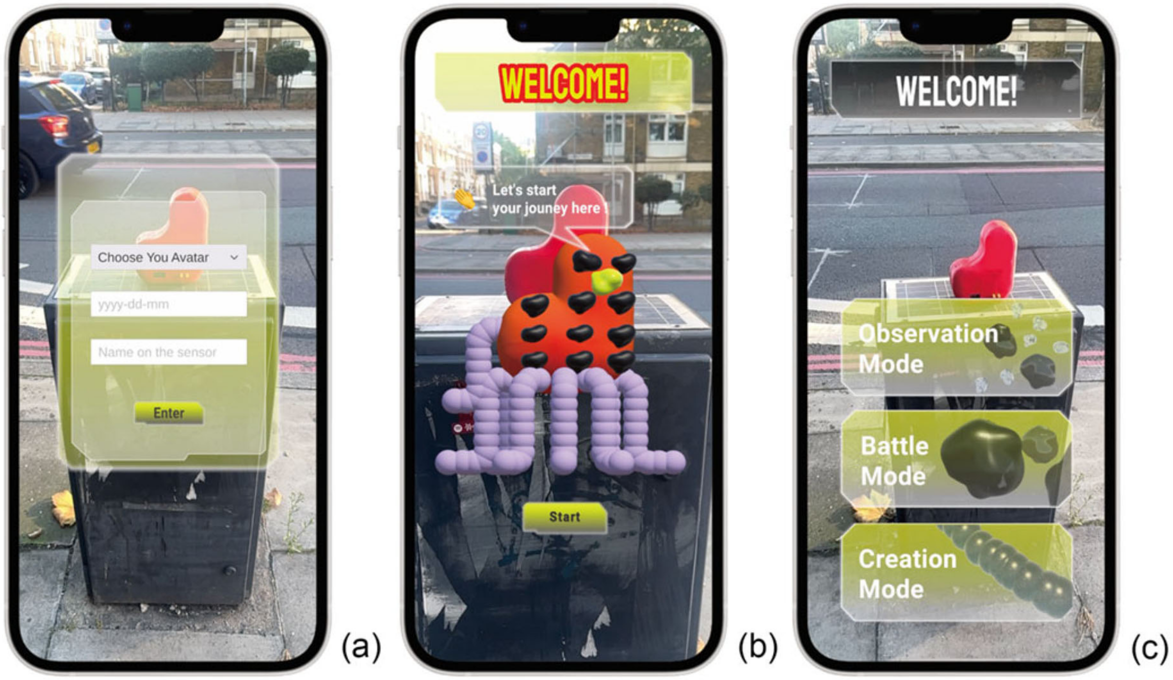


Figure 15. Iterated interface: (a) the same information input screen as in the previous version; (b) the same welcome screen with the avatar; (c) the newly added main interface for navigating to different modes.

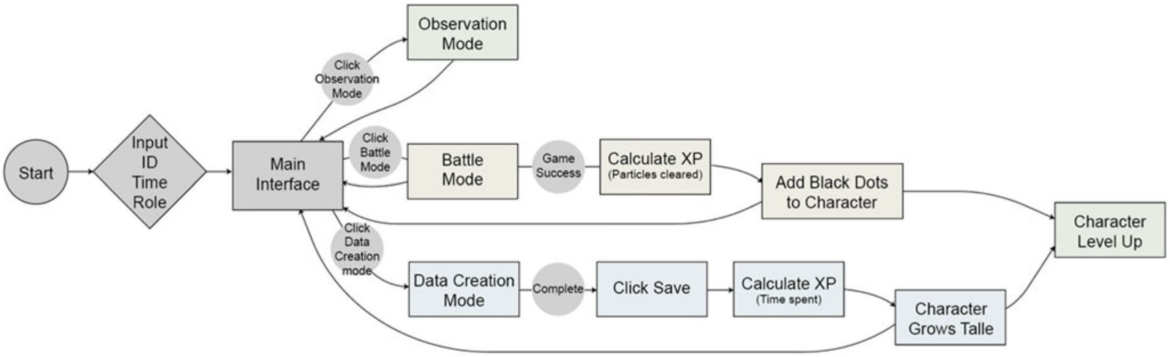


Figure 16. Flowchart of the CEDAR application (iterated version).

In addition, we retained the character growth mechanism but adjusted it to accumulate experience points separately based on different interaction methods. For example, in "Battle Mode," users can add black patterns to the character's body by clearing pollutants; while in "Data Creation Mode," their avatar will gradually grow taller and bigger according to the duration of the data creation. Such growth mechanism allows users to more intuitively perceive their personalized trajectories of interaction with data through changes in the avatar. The detailed interaction flow is shown in Figure 16. Overall, this iteration clarifies data interaction mechanisms and simplifies the process structure. This helps users better understand their tasks and increases their attention to and engagement with the environment.

7. Phase 4: Evaluation

Our goal of the evaluation stage is to examine how each AR-based interaction mode in CEDAR supports meaningful engagement with environmental data. It analyses in what ways such interaction can shape participants' experiences of the environment, addressing RQ2 and RQ3.

7. 1. Participants and procedure

A total of 11 participants were recruited for this study from UAL, as detailed in Table 1. Each participant was accompanied by a researcher who provided procedural and technical support with minimal interference. Prior to the session, participants were briefed on the study and system operation and gave written informed consent. Following this briefing, participants selected one of five sensor designs, each linked to an in-app avatar. All sessions then began from a UAL campus as a common starting point, from which participants independently explored the surrounding area to identify a suitable sensor placement location. At the start of this exploration, sensors were activated (Figure 17a), allowing participants to observe environmental data changes across different urban contexts and make placement decisions based on this situated experience (Figure 17b). After placing

Table 1. Demographic information of the participants.

Participants	Age	Gender	Background
P1	32	Female	VR and data visualization
P2	26	Male	AI reading
P3	27	Female	AI music
P4	30	Male	Computer science
P5	24	Female	AI music
P6	26	Male	AI and VR
P7	25	Female	Psychology
P8	23	Female	Creative computing
P9	26	Female	AI music and psychology
P10	20	Male	Graphic design
P11	26	Male	Film

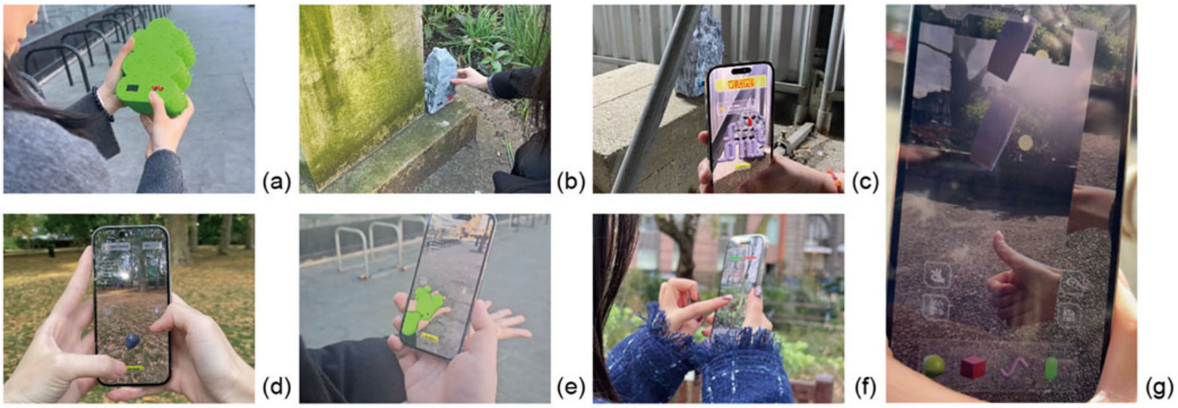


Figure 17. Overview of the testing session: (a) participant holding the sensor to collect data and selecting a suitable location; (b) participant placing the sensor; (c) participant entering the interface and viewing their avatar; (d) participant observing data in CEDAR; (e) participant extending their hand to observe the interaction between data and their body; (f) participant eliminating airborne particles; (g) participant showcasing her virtual data sculpture.

the sensor, participants were asked to open the CEDAR application (Figure 17c) and engage sequentially with the system's three data interaction modes (Figure 17d–f). Finally, the session concluded with participants saving their self-created data sculpture and completing a single character upgrade within the system (Figure 17g). The in-app testing session lasted approximately 15–20 min, varying slightly across participants, with around 15 min allocated to completing the questionnaire and answering interview questions.

7.2. Data collection and analysis

As part of the Research through Design (RtD) process, we adopt an experience-focused qualitative evaluation strategy, focusing on how participants interact with the system in real-world use and how meaning is constructed through these interactions (Crabtree, 2025; Denzin & Lincoln, 1994; Dourish, 2014). Data were collected through interviews and questionnaires with 11 participants. Participants responded to questions regarding their experiences with, and environmental insights gained from, the four core system functions (see Appendix A). Given that the sense of connection to the environment is a key experiential dimension in participatory sensing (Dunkley, 2023; Moon et al., 2024), we intentionally included this aspect in the interview questions. To complement these qualitative insights, we employed the Connectedness to Nature Scale (see Appendix B) before and after the study, a measure commonly used in HCI research to capture experiential changes in users' psychological connectedness to the natural environment following interaction (Chen et al., 2025; Maggipinto et al., 2025; van Houwelingen-Snippe et al., 2020). We used the 8-item Connectedness to Nature Scale (CN8) developed by Musitu-Ferrer et al. (2019), based on Mayer and Frantz (2004), as it places greater emphasis on relational understanding of human–nature relationships rather than stable environmental attitudes, aligning with the study's focus on reflective awareness fostered by situated experiences.

The data were analyzed in two complementary steps:

- First, we analyzed participants' feedback on individual system features to examine how different AR-based interaction modes support meaningful engagement with environmental data (RQ2).
- Second, we conducted a thematic analysis, supplemented by questionnaire data, to identify the ways in which AR-based data interaction enhances experiences of the environment (RQ3).

Based on this, the interview data were coded and analyzed according to two dimensions, the four functional categories and the recurring themes identified across participants' responses. Questionnaire responses were rated on a 5-point Likert scale ranging from 1 (never) to 5 (always), with higher scores indicating a stronger sense of connectedness to nature. Given the small sample size, the quantitative findings are treated as trend-based evidence and serve to provide supplementary insight into participants' sense of connection to the environment. In the following sections, we separately report the quantitative findings and the qualitative findings.

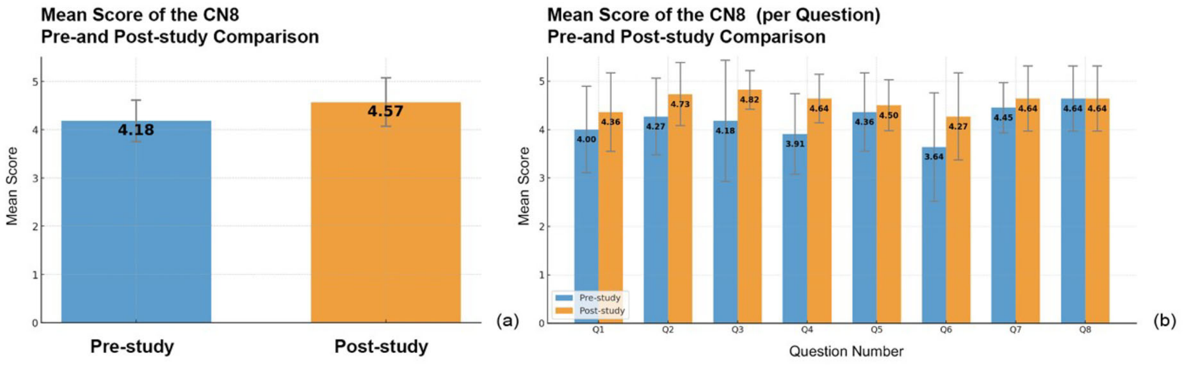


Figure 18. Results of the Connectedness to Nature Scale (CN8) before and after using the CEDAR prototype: (a) mean overall CN8 score before and after the intervention; (b) mean scores for each CN8 item (Q1–Q8) before and after the intervention.

7.3. Findings: Quantitative measurement

We conducted a paired-samples t-test on the total score and each individual item of the CN8 (Figure 18). The mean total score increased from 4.18 (SD = 0.43) before the study to 4.57 (SD = 0.50) after the study; however, this increase did not reach statistical significance (t (10) = 1.43, $p = 0.18$). Across all eight items, the average scores of most questions showed an upward trend after the study, with the item "I have a very close and respectful relationship with the natural environment" exhibiting a relatively higher increase compared to others. Although none of the changes were statistically significant, these results suggest a positive tendency, and the significance of this trend may be further verified with a larger sample size and longer-term testing in future research.

7.4. Findings: User feedback on CEDAR

The following sections are divided into two parts. First, we present the qualitative findings organized around CEDAR's four core functions. Then, we highlight the recurring themes that emerged from participants' experiences and reflections.

7.4.1. Feedback to individual features

7.4.1.1. Observation mode. All participants reported that seeing environmental data in real-time through AR significantly enhanced their awareness of pollution levels and made invisible conditions more tangible. For example, several participants (P1, P2, P3) described how the visualization of "pollution particles" blended with their physical surroundings transformed abstract environmental information into a vivid and interactive experience: "Seeing the data update in real-time is pretty cool… it translated invisible conditions into tangible visual feedback that was easy to interpret." Some participants emphasized the emotional impact created by such visualization. P4 and P5 explained that observing pollutants as visual particles made the issue feel personal and pressing, in contrast to viewing "cold, static charts." P6 noted that "CEDAR makes invisible threats like air pollution particles more tangible. I can see how close these threats are to me and how they fluctuate over time, giving me a strong personal emotional impact."

7.4.1.2. Battle mode. Nine participants acknowledged that actively engaging in pollution reduction through AR reshaped their views on real-world environmental issues. For instance, P1 explained that the progress bar showing "one pollutant left" strongly motivated them to complete the task, leading to the realization that "individual actions can genuinely contribute to reducing pollution." Similarly, P3 described the experience as turning passive awareness into proactive involvement, increasing mindfulness of daily environmental impact and reinforcing commitment to sustainability. Others (P4, P5, P6, P7, P8) highlighted how the embodied and interactive nature of the task deepened their understanding. P4 reflected that earning points while reducing pollutants, alongside losing health points when hit, symbolized both the collective impact of small positive actions and the risks of inaction. P5 noted that scanning every direction to locate pollutants showed how pollution pervades daily spaces, enhancing awareness of protection and prevention. P6 emphasized that small actions, when accumulated, lead to significant change, while P7 and P8 remarked that visualizing pollutant reduction revealed how the environment could become "better and brighter," exposing previously ignored contaminants. Two participants questioned its practical effectiveness in addressing environmental issues (P9), with P2 suggesting it would be stronger if linked to local pollution sources. Overall, while an application alone cannot bring about real change, such designs hold strong potential to enhance personal agency and environmental responsibility by making invisible issues tangible.

7.4.1.3. Creation mode. Most participants noted that designing or sculpting data in AR helped them establish a more personalized way of expressing environmental information (P1, P3, P6, P4, P8, P9, P11). P1 found the DIY data sculpture "particularly interesting," highlighting that customizing the form, texture, and size of the sculpture enhanced engagement and made data exploration feel more personalized. Some participants also regarded this creative process as a way of building a connection with the environment (P4, P9, P11). P4 remarked, "The environmental data is not just numbers but more like a story of my interaction with the environment." Similarly, P11 explained, "I felt as if I created this work together with the environment, as it guided me to certain places, and I added the elements I liked on top of it." Not all responses are positive, P5 suggested that the representations were "not very intuitive," and proposed that using the volume or outline of sculptures to generate more concrete, narrative-driven figures might make the dangers of pollution more vivid. At the same time, some participants, such as P1 and P8, regarded this feature as the most effective in fostering a personal connection to environmental issues, which reflects individual differences in how participants perceived the value of the function.

7.4.1.4. Character-growth mechanism. Participants noted that the growth of their in-game character provided a symbolic and engaging way to reflect on environmental actions. P3 and P6 explained that this progression reinforced the idea that individual efforts matter, with P3 describing the bird avatar's changes as "a vivid symbol of my deepening understanding of environmental issues," while P6 noted that their character's development mirrored their own understanding of environmental change, linking personal actions with broader responsibility. From another perspective, P4 and P8 emphasized the sense of achievement gained through character development. However, P2 felt that while the concept made sense, it would be more meaningful in a longer-term and continuous context, where environmental changes could be tracked over time and across different locations. This also suggests that the growth mechanism requires long-term testing to evaluate its effectiveness and relevance.

7.4.2. Recurring themes

7.4.2.1. See the unseen. AR-supported participatory sensing enabled participants to perceive environmental elements that are otherwise invisible. By transforming abstract data into tangible, interactive, and spatialized forms, many participants reported a shift from vague awareness to concrete perception, recognizing these elements as ever-present and coexisting with them in daily life. In their feedback, participants highlighted that interacting with "invisible particles" not only strengthened their environmental perception but also evoked strong emotional responses, making environmental issues feel more immediate, urgent, and impossible to ignore.

7.4.2.2. Enhance environmental understanding. Through embodied, interactive, and tangible engagement with AR data, participants developed new and deeper understandings of environmental issues. The physicalised forms of data allowed them to intuitively grasp environmental information. In battling pollutants, participants further realized the connection between individual actions and environmental improvement. By customizing materials, shapes, and sizes, they developed personalized modes of data expression, transforming environmental data into meaningful narratives. At the same time, the growth of avatars served as a metaphor, helping participants more clearly understand the relationship between environmental change and personal responsibility. Collectively, these experiences reveal how the CEDAR system, through its diverse design strategies, can foster new understandings of the environment.

7.4.2.3. Living data. In participants' feedback, we found that data is endowed with intentional and emotional characteristics and was regarded as a kind of "living object" (Lupton, 2017, 2020). Participants noted that CEDAR helped them recognize data as responsive rather than fixed or restrictive, capable of changing in relation to their actions and even allowing them to experience being "hit by pollution." Participants also described the data as "dynamic," "vivid," "cute," and "constantly growing." Such descriptions suggest that users were not engaging with a static environment but rather perceiving it as a "living entity" capable of actively responding to and providing feedback on their actions.

7.4.2.4. Connect with the environment. Participants noted that through interaction they developed a deeper, more personal, and emotional connection with the environment. First, AR visualization made environmental data inseparable from everyday living spaces. As P2 described, interacting with the physicalised data "allowed me to understand the surrounding space more directly and feel a deeper connection to it, particularly through my hands, which made me see that I am part of the environment." For some participants, reducing pollutants in AR was not merely a game-like experience but also revealed how individual actions are connected to broader environmental outcomes. Additionally, by customizing the material, form, and scale of their data sculptures, participants developed personalized environmental narratives. Participants described this process as “story of my interaction with the environment,” “actively constructing my own knowledge,” “sculpting data into part of the environment,” and “co-creating with the environment,” highlighting that such connection constitutes an intrinsic relationship with the environment.

8. Discussion

8.1. Summary of key findings

This section synthesizes the key findings of the study in relation to the three research questions, addressing how the CEDAR system was designed, how its AR-based interaction modes supported engagement with environmental data, and how these interactions shaped participants’ experiences of the environment within participatory sensing contexts.

8.1.1. How can an AR-based system be designed to support participatory sensing practices?

This research question was addressed through the design and implementation of the CEDAR system, documented across the full development process, including toolkit construction, a workshop-based pre-study, and the iterative design of the AR application. Design considerations emerging from the workshop directly shaped the interaction logic and functional architecture of the CEDAR application, with findings from subsequent user testing contributing to their further refinement. As a result, CEDAR supports participatory sensing practices through the integration of three distinct AR-based data interaction modes, observation, battle, and creation, alongside a character growth mechanism. Together, these design elements scaffold participants’ engagement with environmental data across perception, action, and reflection, enabling sensing activities to be situated, embodied, and meaningfully contextualized within participants’ lived environments.

8.1.2. How do different AR-based interaction modes support meaningful engagement with environmental data?

The findings demonstrate that CEDAR’s interaction modes support meaningful engagement with environmental data by repositioning participatory sensing as a situated, playful, and embodied practice. Each interaction mode contributes differently to this engagement. The *observation mode* enables participants to intuitively perceive environmental conditions through situated and tangible visualization, supporting immediate and sensory forms of understanding. The *battle mode* foregrounds the relationship between individual actions and environmental impact, encouraging participants to reflect on agency, consequence, and responsibility. The *creation mode* encourages participants to transform their interaction with data into personal experience. In addition, the character growth mechanism enhanced participants’ sense of progression, task completion and satisfaction, by making the cumulative effects of their individual actions visible over time. However, while these mechanisms were effective in supporting short-term engagement and motivation, the extent to which game-based AR interactions influence sustained real-world behavior remains contested. Similarly, the long-term impact of the character growth mechanisms requires longitudinal investigation.

8.1.3. In what ways does AR-based data interaction enhance experiences of the environment in participatory sensing contexts?

Across the study, AR-based data interaction was found to enhance participants’ experiences of the environment by fostering new forms of perception, understanding, and connection with the environment. By making otherwise invisible environmental conditions perceptible, AR-supported participatory sensing shifted participants’ environmental awareness from abstract information to lived and emotionally engaging experience. Furthermore, AR enhanced environmental understanding by transforming data into embodied, personalized, and action-oriented experiences. Participants increasingly perceived environmental data as a responsive and “living” presence that reacted to their movements, decisions, and creative input, rather than as static or passive information. Through personalized and creative interactions with location-based environmental data, participants engaged in dynamic dialogues with their surroundings, strengthening their sense of connection to place and environment. This shift is reflected in the positive trends observed in the Connectedness to Nature Scale scores.

8.2. AR for fostering new forms of environmental engagement

AR technology mediates our engagement with the world, overlaying additional layers of perception that can reveal hidden aspects of our surroundings and transform how we interpret and interact with them (Feyles, 2020). In our study, the integration of AR with participatory sensing practices actively draws participants into outdoor and urban spaces, prompting them to reexamine familiar environments by interpreting environmental information in situated ways. In addition to this, AR extends the boundaries of human perception, enabling participants to perceive and understand environmental conditions from entirely new perspectives (Nijholt, 2022; Wellner, 2020). For pollution that is difficult to perceive with the naked eye, AR makes it perceptible through direct bodily perception, enhancing sensory acuity and enabling users to perceive and respond to environmental changes. Such mode of perception not only strengthens the connection between information and bodily experience but also facilitates the integration of body and technology (Ihde, 1990; Nijholt, 2022; Verbeek, 2005). Furthermore, AR's place-based and situated presentation of information serves as a medium for "giving voice" to places (Yang & Ryokai, 2025). By interacting with data from a specific environment via AR, participants engage in a dialogue with that environment. Through this process, an internalized connection is fostered, in which geographical location and bodily engagement jointly shape meaning-making (Jackson, 2016). As a result, users can gain new insights and establish an internal relationship with the environment, fostering an environmental engagement model grounded in diverse modes of knowledge acquisition.

8.3. Design implications for environmental data interaction in participatory sensing

Based on participants' experiences with different functions of the CEDAR system and their feedback on effectiveness, we identify several design implications that can inform environmental data interaction in participatory sensing contexts. As is well known, games and gamification are common strategies for maintaining engagement and raising environmental awareness in participatory sensing (Han, 2015; Matsuda et al., 2022; Resek et al., 2024). In this context, avatar design can be introduced to enable participants to "become" non-human organisms such as animals and plants to experience the environment from diverse perspectives. This approach has the potential to enhance enjoyment and respond to the concept of multispecies sensing that has been proposed in the field in recent years (Dunkley, 2023; Westerlaken et al., 2023). Furthermore, designers can develop interactions or game mechanics driven by real-time environmental data. Real-time data such as air quality, temperature, humidity, and pollution concentration can be treated as key variables used to generate dynamic game mechanics, including challenges, feedback, and rewards. This approach transforms the environment from a static background into a responsive and proactive interactive element. Simultaneously, this mechanism has the potential to weaken anthropocentric control methods, enabling participants to further perceive and cognize the complexity and contingency of climate change and the environment (Biggs & Desjardins, 2020). Finally, participatory data visualization can be introduced into participatory sensing as a new means of engaging with the environment. In practice, organizers can encourage participants to create tangible or site-specific representations of environmental data (whether in physical or mixed reality formats). By emphasizing interaction through material and bodily engagement (Lupton, 2017), this approach embeds individuals' sensory experiences within dynamic interactions among data, the environment, and technology, fostering new relationships and environmental entities (Uğur Yavuz et al., 2025; Nold, 2017). Overall, these implications show that participatory sensing extends beyond data collection toward situated, embodied, and multispecies engagement. They further encourage practitioners to use emerging technologies to explore diverse data interaction practices. Finally, the platform itself is highly extensible and can be expanded to incorporate new modes of environmental interaction, supporting diverse forms of experiential and participatory engagement.

8.4. Limitation and future work

This study is exploratory research aiming to verify the feasibility and potential value of the proposed AR interaction system and its design strategies in real-world environments, rather than obtaining statistically significant empirical results. Therefore, the deployment time of the research is relatively short, and the testing scale is limited, which to some extent restricts the generalizability of the results to a larger population and diverse scenarios. Future work will extend this research through larger-scale and longer-term deployments with more diverse participant populations. It will also explore applications in contexts such as museums, schools, and public educational activities to further assess the potential of AR for data interaction and environmental engagement. In addition, the system's personalized data visualization mechanism may, after repeated use, lead to a certain convergence in visual effects, potentially reducing the novelty of the interaction over time. Future design iterations could address this by incorporating AI-generated visualizations that allow users to introduce new design elements via text input, thereby maintaining variety and sustaining long-term engagement.

9. Conclusion

This article introduces CEDAR, a sensor-based AR participatory sensing system developed through a Research through Design process. CEDAR integrates real-time environmental data collection with AR-based interaction to reconnect environmental data with place, bodily experience, and personal meaning. The study contributes (1) a participatory sensing toolkit and action framework, (2) the design and implementation of an AR-based system with multiple data interaction modes, and (3) empirical insights into how AR-based data interaction fosters meaningful engagement with environmental data and enhance environmental experiences, informing the design of future participatory sensing practices. Through situated observation, playful interaction, and creative data making, participants experienced environmental data as responsive rather than static, supporting new forms of perception, understanding, and connection to the environment. These findings highlight the potential of AR to reframe participatory sensing beyond data collection toward situated and experiential engagement. The design implications outlined in this article suggest directions for future participatory sensing systems that incorporate multispecies perspectives, data-driven environmental responsiveness, and participatory data visualization. Overall, this research demonstrates how situating data within lived experience through AR can support more meaningful environmental engagement and inform the design of future participatory sensing and immersive interactive systems.

Authors' contributions

CRediT: **Mengci Liu**: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft; **Anna Troisi**: Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing; **Peter A. Hall**: Conceptualization, Methodology, Supervision, Writing – review & editing; **Stella Doukianou**: Conceptualization, Methodology, Supervision, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethics statement

This study received ethical approval from the University of the Arts London (UAL) Research Ethics Sub-Committee (RESC). The committee does not issue reference numbers for approvals of this type. All participants were informed about the purpose of the study and provided written consent prior to participation.

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Appendix A. Interview questions

Q1. When using CEDAR's observation mode to view environmental data in AR, what kinds of experiences did you have, and what insights about the environment did you gain?
Q2. When using CEDAR's battle mode to interact with particulate matter, what kinds of experiences did you have, and what insights about the environment did you gain? (For example, did actively engaging in reducing pollution in AR change how you think about real- world environmental issues? If yes, please explain how it affected you. If no, please share your reason.)
Q3. When using CEDAR's creation mode to interact with the environmental data you collected, what kinds of experiences did you have, and what insights about the environment did you gain?
Q4. When you saw your in-game character grow, what kinds of experiences did you have, and what insights about the environment did you gain?
Q5. Did the AR-supported data visualization help you feel more connected to environmental issues? (Yes/No. If yes, why?/If no, what aspects of the AR experience could be improved?)

Appendix B. Connectedness to nature scale items

Q1. I am aware that some of my behaviors have a negative effect on the natural environment.
Q2. I am convinced that I am a direct part of the natural environment.
Q3. I cannot imagine my life and the life of human beings without the natural environment.
Q4. I have a very close and respectful relationship with the natural environment.
Q5. I think that everything on Earth (alive and not alive), including me, is interconnected.
Q6. I identify with everything that happens in the natural environment.
Q7. I feel that animals and plants are part of my life.
Q8. My health and the health of the natural environment are closely related.