Enhancing Public Awareness of Air Quality: Evaluating Communication Strategies and Design Prototypes using a Design-Based Implementation Research Approach

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Abstract. Despite the health risks associated with air pollution and the availability of data, public awareness of air quality remains limited. This paper examines communication strategies to enhance awareness in Germany and North Macedonia. Using the Design-Based Implementation Research approach, literature reviews, stakeholder interviews and surveys were conducted with 307 participants to identify knowledge gaps and effective methods.

Three citizen workshops led to the development and evaluation of five design prototypes, including an interactive installation ("Pollution Booth"), a VR application ("Visible Particulate Matter"), and a gamified learning experience ("End Game"). These prototypes addressed information accessibility, data representation, and environmentally conscious behavior. The results show that region-specific communication, interactive designs, and passive information methods in public spaces significantly improve the perception and understanding of air pollution data. Gamified approaches, such as the "End Game" prototype, were particularly effective in educating children about air pollution.

Thirty-two requirements for effective educational strategies were identified, including simplified data visualization, reduced content, and personalized information. The findings highlight the importance of local and personalized approaches, as well as methods for collective knowledge sharing, in promoting awareness and environmentally friendly behavior. Future work should further explore the long-term engagement and sustainable impact of such communication strategies.

Keywords: Air pollution · Public Awareness · Interaction Design · Science Communication · Environmental Data · Citizen Science

1 Introduction

Outdoor air pollution is estimated to cause 4.2 million premature deaths worldwide in 2019 [31] as a result of stroke, heart disease, respiratory disease such as chronic lung diseases, asthma, and lung cancer [30]. In the same year, 90 percent of the world's population lived in places where the recommended air quality limits of the WHO were not met [31] and were unaware of these dangers [7] [34]. However, the complex and non-transparent representation of air quality [11] is difficult to access for the general public [43], due to the scientific and technical language [36]. With the Ambient Air Quality Directives, the European Union (EU) commits to better information provision about air quality and its impacts on the public [42]. In a comparative Eurobarometer survey, Grossberndt et al. [16] found that more than half of the EU population, 59% in 2012 and 54% in 2019, were not informed about air quality problems in their country [8] [9].

More people might adopt climate protection measures if they had a clearer understanding of how air pollution personally affects their health and living environment, but the impacts of air pollution are often subtle and not immediately noticeable. In addition to natural environmental factors, most air pollutants are the result of human activities, particularly in industry, heat production, agriculture, waste, and transport [32]. Even small changes in citizen transportation habits can significantly reduce their exposure to pollutants [15]. Despite the public demand for information [43], little is known about the reach and effectiveness of current information sources [14] [37]. Visual representations of information can improve memory retention, facilitate decision-making, and streamline the analysis of large data sets [26]. It is also important to disseminate information across different population groups [36]. This study aims to explore design-oriented research approaches that promote interactive forms of communication to make air pollution visible, tangible, or otherwise experiential to the non-scientific public to increase awareness of the problem and encourage behavioral change or demands on decision-makers. To understand the effectiveness and user experience of the introduced communication artifacts, the following research questions are examined: (i) How well are citizens informed about the air quality in their residential areas and the impacts of airborne pollutants? (ii) Which information channels do citizens use, and what data and information are relevant to them? (iii) What impact does the use of educational technologies have on public awareness and perception of air pollution?

This paper is structured in a Related Work section, where the relevant literature and current state of research on education strategies for air pollution is introduced. Methodology describes the procedure of identifying, reviewing, developing, evaluating, and analyzing information requirements and awareness prototypes. The evaluation and results of the surveys on information needs and current information demand in the population follow. In addition, an exploratory study on the effectiveness of five different design prototypes for information dissemination is presented. The results of these investigations are then interpreted and discussed to gain insight for further developing effective communication strategies in the field of air pollution.

2 Related Work

Air quality indexes provided by the authorities are recognized as valid risk indicators, but their effectiveness in raising public awareness is limited, in part due to their technical complexity and expert-oriented presentation [36]. Residents are aware of air pollution but often lack understanding of its causes and ways to engage in solutions, often due to information overload and message fatigue. For example, in a Malaysian study, participants acknowledged air pollution but downplayed its risks unless they were personally affected [6, 7].

Effective communication requires presenting air quality data in simple language with actionable advice, emphasizing health impacts and practical solutions [4]. Beaumont et al. [4] found that residents prefer plain language, historical data, and the accountability of political decision makers. Local information and positive framing resonate more with citizens, while confronting them with negative consequences can trigger cognitive dissonance. Nevertheless, emotional communication strategies prove promising effects in activating social norms and creating a sense of collective responsibility [36]. To increase awareness, air quality data can be adjusted to personal interests tailored to specific individual needs [27]. Liao et al. [22] examined the willingness of citizens (n=347) to change behaviors using a smartphone app to avoid air pollution and found that behavioral changes are more strongly influenced by peer-to-peer interactions.

Ward et al. [19] have explored various engagement methods, including interviews, workshops, citizen science, and digital tools such as apps, sensors, AR & VR applications, and gamification [4, 28, 44, 18]. Research highlights a growing interest in using digital tools for environmental education, such as apps, web applications, warning systems, electronic street signs, sensors, IoT devices, AR&VR, video podcasts, gamification, and data visualizations [10, 41, 24, 44, 18]. Among participatory approaches, citizen involvement in air quality monitoring is most common, often using low-cost sensors or sampling kits to measure local conditions [43]. For instance, Haddad & Nazelle [17] surveyed London participants using an app and sensors for monitoring NO and VOC levels but found no significant effect on travel behavior. Nevertheless, smart city IoT infrastructures make real-time pollution visualization more accessible, underlining the need for simple and effective government-led visualizations [37].

Smartphones are the preferred medium for accessing environmental information, with the Internet (82%) and social media (especially Instagram) as key sources [1, 15]. However, information often lacks interpretation, creating barriers to understanding. Access to technology is another significant challenge [36]. Wong et al. [46] demonstrated that collaborative environments, where high school students teach older adults to use interactive pollution maps, enhance scientific understanding and foster discourse on environmental and health topics.

Artistic approaches, like Pollution Pods, use everyday experiences and concerns about air pollution to inspire political action by making the intangible tangible, the invisible visible, and by transforming the familiar into something unfamiliar. Although effective, evaluations show limited long-term behavioral effects, focusing more on evoking emotions than direct education [40, 20].

The immersive nature of VR and AR enhances engagement and provides a more impactful experience compared to non-VR settings. These tools allow students to use multiple senses to perceive physical properties, creating rich sensory and emotional experiences that promote learning in environmental education and raise sustainability awareness[18]. Using an augmented reality application, Mathews et al. [24] visualize pollutants in the air, which can be viewed with mobile smart devices. The AiR application accesses the nearest air monitoring station and uses current data for particulate matter (PM10 & PM2.5), nitrogen dioxide (NO2), sulfur dioxide (SO2), carbon monoxide (CO), and ammonia (NH3). The effectiveness has not yet been tested on participants.

Existing efforts often lack detailed participant insights and focus more on engagement than knowledge transfer or regular updates. This study addresses gaps in integrating air quality information into public spaces, engagement, knowledge transfer, and sustained awareness.

3 Methodology

To investigate the research questions, we adopted the Design-Based Implementation Research (DBIR) approach, focusing on effectively communicating air quality data and raising public awareness of its health hazards. This study was conducted in four cyclical phases: preliminary research, implementation, analysis, and design refinement. The **research** phase included a snowball-method literature review [45] and stakeholder interviews with eight experts in air pollution science. Promoting environmental health literacy requires involving the public as part of the solution [13], because community engagement fosters behavioral change more effectively than individual efforts [38], such as avoiding air travel. To address this, three citizen workshops were conducted to evaluate knowledge, prioritize relevant information, and gather insights into preferred communication channels, enriched by expert input [5, 23].

Air quality has improved in Germany and other EU countries due to measures such as pollutant filters and city speed limits [3]. However, Skopje, North Macedonia, remains a global hotspot for air pollution and particulate matter [2]. An interdisciplinary team of industrial designers from Germany and computer scientists from North Macedonia [38] used insights from previous activities to develop five exploratory design prototypes. During the **implementation** phase, participants evaluated the prototypes using qualitative questionnaires and the standardized User Experience Questionnaire. The **analysis** phase examined cultural and regional differences in information reception, the findings used to refine the **design characteristics** for transparent communication.

3.1 Pre-Questionnaire

The results of the online questionnaire regarding current state of knowledge about air pollution, interest, and information demand in the local population were quantitatively assessed and descriptively analyzed with SPSS software. The

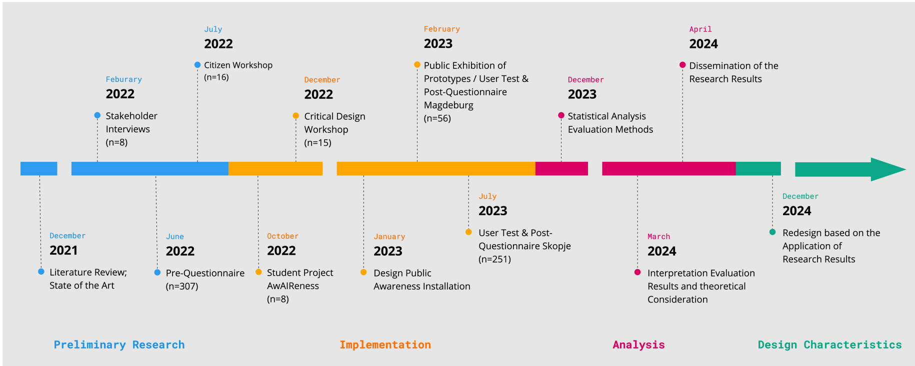

Fig. 1. Study Design according to Design-Based Implementation Research approach

survey included 56 participants (18.2%) from Magdeburg-Stendal University of Applied Sciences and 251 participants (81.8%) from the University of Skopje. Students and academics act as "early adopters," whose opinions and experiences contribute to the development of successful and innovative dissemination strategies for different social groups [35]. The current level of knowledge and the access to information were assessed using 6 statements about air pollution on a 5-point Likert scale: disagreement (Strongly Disagree = 1 / disagree = 2), neutral (neutral = 3), or agreement (approval = 4 / Strongly Agree = 5).

Table 1. Socio-demographic data Online Questionnaire

Sociodemographic Data	**N = 307**
University	
Magdeburg	56
Skopje	251
Age	
18-19 years	4 (1,3%)
20-29 years	278 (90,6%)
30-39 years	20 (6,5%)
40-60 years	5 (1,6%)
Gender	
Male	153
Female	143
Diverse	11
Occupation	
Student	282
Professor / Lecturer	8
Scientific Staff	12
Administration Staff / Laboratory Engineer	4
Guest	1

3.2 Citizen Workshops

Sixteen local citizens from Magdeburg, aged between 19 and 41 years, participated in the workshops. The sample included 10 male and 6 female participants, none of whom had children at the time of the workshop. One participant reported having a pre-existing condition (chronic bronchitis). The sample included 7 students and 9 employed individuals.

After a brief introduction, brainstorming sessions were conducted in small groups on key questions about air pollution. The responses were subsequently supplemented by a specialist lecture. The participants collected the results, opinions, wishes, and needs, clustering them into overarching thematic areas. Using dot voting [12], priorities for information provision were identified. A pre-test assessed demographics, societal interest, and prior knowledge of air quality sources. The post-test measured knowledge gains, increased interest, and the influence of new insights on future decisions. Qualitative questionnaires were descriptively analyzed using SPSS statistical software.

3.3 Prototypes Development and Evaluation

A team of eight industrial design students, two professors, and two researchers explored ways to communicate air quality data in public spaces through an iterative Design Science Research process [33]. This approach aimed to improve air quality awareness by presenting information interactively, creatively and artistically. The design process included the phases **Explore, Imagine, Inform, Create, and Test**.

Exploring involved an expert lecture on air quality measurement, pollutants, causes and countermeasures as well as a visit to a municipal measuring facility. Additionally, research was conducted on best practices in data visualization, speculative design, problem-solving, gamification, and interactive installations. Design methods such as brainstorming, opportunity maps, and interviews were used to generate ideas **(Imagine)**, as well as sketches, personas, and scenarios during concept development. In collaboration with the Laboratory for Eco-Informatics at Methodius University in Skopje, a seven-day design workshop **(Inform)** was held. The concepts prepared by the industrial designers were introduced to 7 computer science students from Skopje, who gave feedback. The interdisciplinary collaboration serves the exchange about the topic from different cultural as well as professional perspectives. In small groups of designers and computer scientists, the concepts are refined, and the first preliminary models are created as paper prototypes (representation of the public installation as a paper model) and video prototypes (simulation of the concept in a short film). The prototypes are used to gain feedback from citizens in Skopje. The results of the design sprint serve to **Create** high fidelity prototypes with physical computing (sensors and microcontrollers to perform interactions with users) in a second iteration loop. The user **Testing** determined which design approach provided the most comprehensible knowledge transfer, intuitive access, and increased attention. The prototypes were evaluated by Magdeburg and

Skopje participants (N = 307). In Magdeburg, exhibits were displayed at a public design fair for interactive testing. In Skopje, participants assessed video prototypes, images, abstracts, and functional descriptions. Participants in the user study were informed about the data protection regulations and ethical aspects of their participation and gave their consent. Effectiveness was measured using a post-questionnaire with 5 items and 2 open-ended questions. Participants rated 5 statements on a 5-point Likert scale and the items were descriptively analyzed using SPSS.

– `Item 1`: I easily understood the concept and handling of the installation.
– `Item 2`: The installation contributes to increased awareness (in public places) of air pollution.
– `Item 3`: The conveyed information is understandable and has expanded my knowledge of air quality.
– `Item 4`: The installation is easy and intuitive.
– `Item 5`: The installation should be visible/usable in public places for citizens.
– `Question 1`: What I particularly liked about the installation ...
– `Question 2`: What I did not like about the installation...

The two open-ended questions provided insight into the strengths and weaknesses of the concepts and identified areas for improvement in the installations. The free-text responses were analyzed using qualitative content analysis according to Mayring [25]. Usability was assessed using the standardized User Experience Questionnaire (UEQ), which measures UX on six scales: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty [21]. Testers rated 26 bipolar word pairs (e.g., Not understandable & Understandable) on a 7-point Likert scale, with responses ranging from -3 (fully agree with the negative term) to +3 (fully agree with the positive term). The mean values of the scale were compared with a benchmark dataset [39].

3.4 Awareness Prototypes

The interactive installation **Pollution Booth** is located in urban areas and measures the current levels of particulate matter in its location. The interaction mimics the operation of a public photo booth. Users receive a personal souvenir photo in two versions; a regular print and a second image that depicts the particulate matter particles at the measurement location of the current hour scaled over the faces. The confetti overlay is not just a visual effect, but also represents various pollutants and their sources with different colors. The key terms for air quality are explained in simple language in the back. The functional prototype consists of a camera, printer, tablet, and computer inside the photo box, all connected via an Arduino. User interaction occurs on the tablet screen. The photo countdown triggers the camera, which sends the photo to the computer. The current PM value is retrieved from the website of the Saxony-Anhalt air monitoring system and visualized as confetti on the photo template. The image file is then sent to the printer. The concept was selected because it can be easily installed

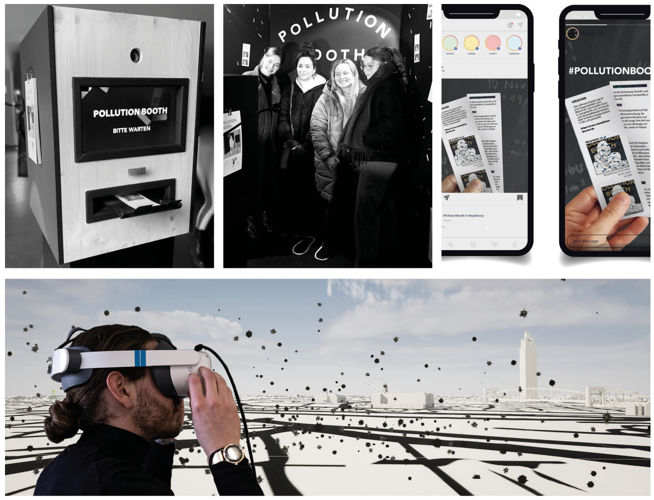

Fig. 2. Prototypes Pollution Booth (top) & Visible Particulate Matter (bottom)

in public spaces, buildings, or at events, and it appeals to a broad audience due to its entertaining nature.

For immersion in the Virtual Reality (VR) prototype **Visible Particulate Matter** users put on a VR headset (Oculus Quest 2) and enter virtual exhibition rooms. In the foyer, players receive information on the causes and effects of air pollutants on the human body. They can choose between the cities of Skopje (North Macedonia) and Magdeburg (Germany) and select a specific day to investigate its air quality. This selection brings players to a map of the chosen city, where they can navigate across different locations. The pollutant particles float in the air. The goal is to find the place with the lowest air pollution on that day. The real-time data is sourced from the open-source platform Pulse.Eco and transferred via an API (Java Spring Boot) to the Processing software, which maps pollutant measurements to their respective locations on the map. These measurements are then displayed as virtual particles in the Unreal Engine. The VR application is particularly effective in visualizing otherwise invisible air pollutants directly in urban locations where they are present at the time.

The computer game **End Game** is mainly aimed at elementary school children and is inspired by the well-known video game Super Mario by Nintendo. Children and people with pre-existing conditions are the most affected by the health hazards of air pollution [36]. The game conveys information on behaviors to reduce risk. Instead of removing mushrooms, the avatar transforms cars into bicycles and CO2 clouds into fresh air. By jumping on the causes of air pollution, they are combated, and the air is cleaned. Players receive compact facts about the causes of air pollution. The interactive click prototype and character design were created with Adobe XD. The gamification approach lowers the inhibition threshold for engaging in the complex topic, allowing users to learn about air pollution while playing.

Fig. 3. Prototypes End Game (top), Air Where (middle) & Breathe (bottom)

The exhibit **Air Where** is a speculative design intended as a warning. The future vision transports viewers to the year 2050, where fresh air is no longer taken for granted and masks become the norm in everyday life. The speculation considers trends based on currently available research results. Air Where is not a prophecy – the narrative aims to show what could happen if the current treatment of the environment continues. A personalized device guides users as a navigation tool to fresh air zones. Upon arrival, users can remove their masks and breathe natural air without negative health effects. The speculation is conveyed in a short movie. Part of this narrative is a tangible prototype made of silicone and Scoby to best simulate the experience of skin. It is equipped with vibration motors controlled by an Arduino that navigate the user in the right direction using different vibration patterns and provide discrete distance information. This vision of the future aims to leverage the users' sense of shock to motivate them to take potential countermeasures.

The concept **Breathe** is a participatory format intended to encourage rethinking in public spaces. Artists can submit works on the theme "Clean air as a privilege." The artwork is prominently displayed on an interactive panel in urban spaces. The screen responds in real-time to the amount of harmful air pollutants in the ambient air and depicts the particles as gray "bubbles" over the artwork. When air pollution is particularly high, the pollutant particles become denser and air pollution becomes visible to passersby. Citizens can receive more information on the topic using the interactive touchscreen using the particles as buttons. For the small-scale functional prototype, the screen was divided into four vertical segments. When the battery-operated car (computer mouse) drives past the screen, the amount and color of pollutants projected onto the screen changes according to the y-value of the mouse using Visual Studio Code.

4 Results

4.1 Pre-Questionnaire

The survey revealed a strong demand for accessible and comprehensible air pollution data (M=4.27); however, current information provision lacks transparency (M=4.44). Citizens report limited knowledge and rarely seek information due to inaccessible reporting (M=3.01), complex data and low self-motivation. Nevertheless, participants expressed a high willingness to adapt their behavior (M=4.26) if provided with clear evidence of its positive impact on air quality (see Table 2).

The t-test revealed significant differences between participants from Magdeburg (MD) and the University of Skopje (SKP) in their perception and self-reported knowledge of air pollution. The Skopje participants felt more informed (M=3.96) and found information more accessible (M=3.76) compared to those in Magdeburg (M=3.45; M=2.89). The statement "I regularly seek information about air quality in my residential area" was mostly disagreed with by Magdeburg participants (M=2.11), while those in Skopje partially agreed (M=3.21).

4.2 Citizen Workshops

Participants found online air quality information hard to access and understand due to technical language and data-heavy presentation. Abbreviations like AQI and PM further complicated comprehension. Although the survey indicated awareness, only 6 of 16 participants could name air quality sources or channels, and just 5 had prior engagement with the topic in Magdeburg.

The responses to four key questions about air pollution were grouped into four clusters: causes of pollution, areas of interest, information channels, and mitigation measures. The 16 participants received point stickers to prioritize information according to their interest and relevance. A descriptive cluster analysis revealed that the participants have a broad and detailed understanding of the causes of air pollution and show interest in various topics related to air quality, pollutants, and health risks. Preventive and combative measures against air pollution are of the highest priority. Current information is often prepared for the experts, making it difficult for the general public to understand ("expert

Table 2. Mean Values of Pre-Questionnaire Results

Items	N	Min	Max	M	SD
Item1 I am well-informed about air pollution (causes, effects, data collection).	307	1	5	3,87	0,958
Item 2 Information and data on air quality are easily accessible and understandable.	307	1	5	3,60	1,069
Item 3 I regularly seek information about the air quality in my residential area.	307	1	5	**3,01**	1,321
Item 4 I would like to know more about the current air quality and potential risks due to pollution.	307	1	5	4,27	0,947
Item 5 Air quality data need to be more accessible and easier to understand.	307	1	5	**4,44**	0,866
Item 6 I would adjust my behavior or habits if I knew it would contribute to improving air quality.	307	1	5	4,26	0,966

jungle"). However, participants mainly trust scientific and governmental sources that operate independently of political influence and desire traceable origins to validate its authenticity. There is increased interest in air quality information related to immediate surroundings, frequently visited locations, and the significance of threshold values for health risks.

Participants preferred passive information methods, such as air quality displays in public transport, low-cost sensors, or daily news updates, eliminating the need for active searching. The participants indicated their willingness to contribute to improving the situation. However, both urban planning and political regulations are demanded by the general public to facilitate and promote environmentally conscious actions. The expansion of measurement stations, combined with brief training on how to interpret air quality data to identify the causes and sources of locally and temporarily occurring air pollution, could increase interest and a sense of self-efficacy among the population [29].

4.3 Awareness Prototypes

Post-Questionnaire The concept and handling of the video game "End Game" were best understood (M=4.48), while the speculative installation "Air Where" was the least understood (M=4.01), indicating that participants found it challenging to grasp its concept and purpose. The installations "Pollution Booth" (M=4.10) and "Breathe" (M=4.10) have the most potential to increase awareness of air pollution and be placed in public (M=4.58; M=4,33); whereas "End Game" (M=3.72) contributed less to raising awareness. The "End Game" (M=3.89) was deemed unsuitable for installation in public spaces. The most effective knowledge transfer was also produced by the "Pollution Booth" (M=3.98), and the least informational content was found in the "Air Where" prototype (M=3.57), suggesting that it did not effectively convey educational messages about air pollution. The operation of the VR application "Visible Particulate Matter" (M=3.73) appeared the least intuitive to users. The usability (M=4.13) was rated highest for the "Pollution Booth."

Table 3. Evaluation Prototypes

Prototype	Item	N	Min	Max	M	SD
Pollution Booth	Comprehensibility	271	1	5	4,25	0,809
	Increased Awareness	271	1	5	**4,10**	0,903
	Knowledge Transfer	271	1	5	**3,96**	0,885
	Intuitive Operation	271	1	5	**4,13**	0,912
	Usable in Public Spaces	271	1	5	**4,58**	0,775
Particulate Matter	Comprehensibility	247	1	5	4,08	1,112
	Increased Awareness	247	1	5	4,06	1,040
	Knowledge Transfer	247	1	5	3,85	1,173
	Intuitive Operation	247	1	5	**3,73**	1,234
	Usable in Public Spaces	247	1	5	3,93	1,168
End Game	Comprehensibility	261	1	5	**4,48**	0,841
	Increased Awareness	261	1	5	**3,72**	1,145
	Knowledge Transfer	261	1	5	3,74	1,097
	Intuitive Operation	261	1	5	4,10	1,000
	Usable in Public Spaces	261	1	5	**3,89**	1,199
Air Where	Comprehensibility	249	1	5	**4,01**	1,177
	Increased Awareness	249	1	5	3,80	1,196
	Knowledge Transfer	249	1	5	**3,75**	1,229
	Intuitive Operation	249	1	5	3,84	1,164
	Usable in Public Spaces	249	1	5	4,03	1,130
Breathe	Comprehensibility	251	1	5	4,07	1,031
	Increased Awareness	251	1	5	**4,10**	0,991
	Knowledge Transfer	251	1	5	3,84	1,084
	Intuitive Operation	251	1	5	3,93	1,052
	Usable in Public Spaces	251	1	5	4,33	0,995

Free-text Responses Based on inductive category development [25], 694 free-text responses were allocated in seven main categories by two independent researchers. The categories were considered positive aspects for responses to Question 1 and negative for free-text responses to question 2. Specifically, statements with feedback on specific functionalities or suggestions for improvement were manually selected and highlighted.

- `Attractiveness`: How much did the participants like or dislike the concept, idea and technical implementation of the prototype?
- `Interaction`: How intuitive is the operation of the prototype and how well is the method of dissemination?
- `Awareness`: Does the concept increase awareness of air pollution?
- `Knowledge Transfer`: How do participants rate the density and comprehensibility of the information?
- `Public Space`: Is the concept usable in public spaces?
- `Target Group`: Which target groups can be reached with the concept and which cannot?

The installation **Pollution Booth** showed a balanced reception, with a strong presence in both positive and negative feedback categories and received the most positive comments for its presence in public spaces. This indicates that while the concept was appealing and practical for public participation, there were challenges in its user experience. Participants suggested reducing technical terms of pollutants and providing more actionable recommendations.

The VR Application **Visible Particulate Matter** application was praised for its attractiveness and effectiveness in making invisible pollutants visible and understandable. The participants found it innovative and engaging, helping them gain a deeper understanding of air pollution. Feedback included a notable amount of negative feedback in the interaction category, suggesting issues with user engagement or usability of the interface. Criticisms included the complexity of interaction, usability issues in public places, and limited accessibility due to the cost and availability of VR headsets. The participants also noted a lack of introductory content and clear objectives.

The prototype **End Game** received the most positive mentions overall, particularly in the categories of interaction and target group. This game was highly rated for its interactive approach, ease of understanding, and effectiveness in educating children through play. It received positive comments for its gamification and user interface design. Some participants felt that the educational impact was low due to a lack of direct connection to the topic and missing data. The game was considered primarily suitable for children, with suggestions to include more concrete actions such as tree planting and waste recycling to improve its educational value.

The speculative design **Air Where** received the fewest positive and the highest number of negative mentions, especially in terms of attractiveness and suitability of public spaces. Many participants misunderstood its aim to create a deterrent effect regarding air pollution. Participants felt that it lacked immediate solutions, actionable steps, and current data. The concept was considered to be uneffective in raising awareness or encouraging behavioral changes. Some users appreciated the emotional impact and its ability to capture users' attention through a futuristic and thought-provoking scenario, acknowledging its potential to evoke a strong response and highlight the urgency of air pollution issues.

The Interactive Artwork **Breathe** received the fewest negative responses. It was praised for its direct communication, easy access, and visibility in public spaces. It effectively reminded viewers of the ongoing issue of pollution, but may also have lacked in delivering detailed information or innovative design elements.

Table 4. Number of Positive and Negative Mentions (N) in Free-Text Responses

	P. B.	**P. M.**	**E. G.**	**A. W.**	**B.**	**Total**
Attractiveness	45 (Pos)/ 58 (Neg)	**102** (Pos)/ 16 (Neg)	66 (Pos)/ 14 (Neg)	53 (Pos)/ **33** (Neg)	63 (Pos)/ 7 (Neg)	329
Interaction	56 (Pos)/ 19 (Neg)	29 (Pos)/ **35** (Neg)	**59** (Pos)/ 26 (Neg)	32 (Pos)/ 29 (Neg)	30 (Pos)/ 25 (Neg)	206
Awareness	20 (Pos)/ 6 (Neg)	**27** (Pos)/ 7 (Neg)	24 (Pos)/ 5 (Neg)	23 (Pos)/ **11** (Neg)	18 (Pos)/ 9 (Neg)	112
Knowledge	24 (Pos)/ 12 (Neg)	15 (Pos)/ 9 (Neg)	**33** (Pos)/ **21** (Neg)	11 (Pos)/ 14 (Neg)	10 (Pos)/ 4 (Neg)	93
Public Space	**7** (Pos)/ 11 (Neg)	2 (Pos)/ **27** (Neg)	1 (Pos)/ 7 (Neg)	5 (Pos)/ 11 (Neg)	5 (Pos)/ 4 (Neg)	20
Target group	6 (Pos)/ 6 (Neg)	6 (Pos)/ **14** (Neg)	**51** (Pos)/ **14** (Neg)	1 (Pos)/ 4 (Neg)	6 (Pos)/ 2 (Neg)	70
Total Pos/Neg	121 (Pos)/ 58 (Neg)	145 (Pos)/ 88 (Neg)	**151** (Pos)/ 75 (Neg)	**111** (Pos)/ **96** (Neg)	113 (Pos)/ **51** (Neg)	641 (Pos)/ 368 (Neg)

User Experience Questionnaire The **Pollution Booth** prototype achieved the highest scores in the Perspicuity dimension (M=1.76), indicating that the operation of the photo booth was perceived as very intuitive and easy to learn. The lowest scores were given to the Dependability dimension (M=1.65), suggesting that the interaction was partially unexpected or hindering. Specific items such as "unpredictable - predictable" (M=0.7) and "conventional - inventive" (M=0.7) received below average scores, indicating areas for improvement. In benchmark comparison, the dimensions Attractiveness, Perspicuity, Stimulation, and Novelty were rated "Good", indicating that the prototype is visually appealing, engaging, and creatively interesting. Efficiency and Dependability were interpreted "Above Average".

The second Prototype **Visible Particulate Matter** performed best in the Novelty dimension (M=1.69). Particularly, the item "creative - dull" (M=2.1) stood out with an "Above Average" positive rating. The Dependability (M=1.06) and Efficiency (M=1.06) of the application were rated the lowest compared to the 5 prototypes, with especially low mean values for the items "unpredictable - predictable" (M=0.2) and "complicated - easy" (M=0.8). In the benchmark comparison, the Novelty dimension is rated "Excellent", Stimulation as "Good", Efficiency and Attractiveness "Above Average" and Perspicuity and Dependability "Below Average".

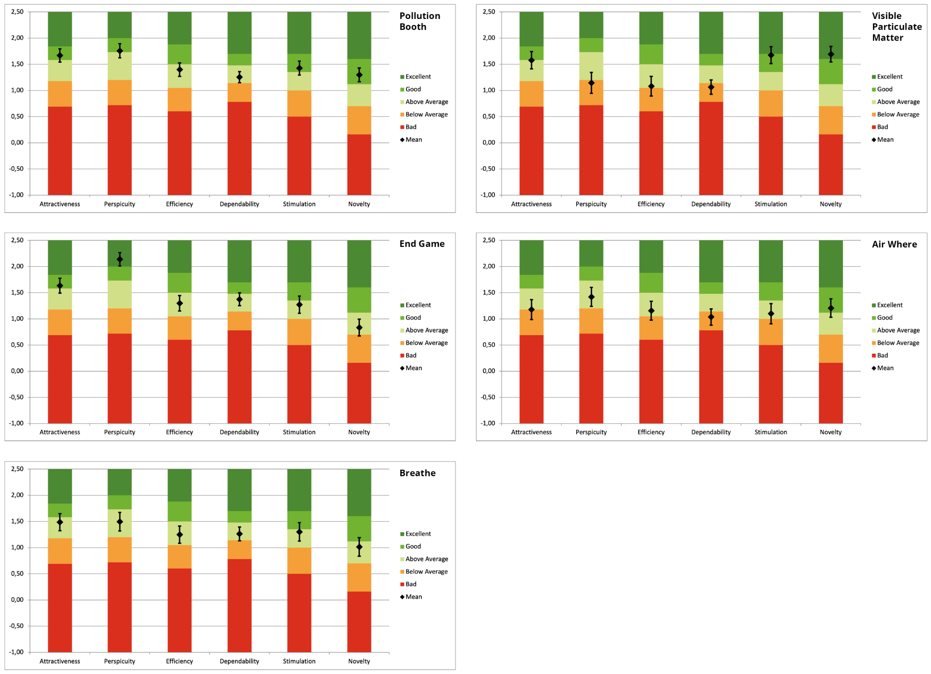

Fig. 4. Classification of the Prototypes in Benchmark Comparison

The **End Game´s** Perspicuity (M=2.14) received the highest mean value, suggesting that the game is very easy to understand and use, making it accessible to a wide audience. The Novelty (M=0.83) of the game was rated particularly low, indicating that the game may not be perceived as innovative or unique. In the benchmark comparison, Perspicuity is rated "Excellent," Attractiveness "Good," and the four other dimensions as "Above Average."

The Perspicuity of (M=1.42) of the speculative design **Air Where** was rated the highest of the 6 dimensions, indicating that the speculative design is relatively easy to understand. Dependability (M=1.04) was rated the lowest, suggesting that users experienced problems with the reliability and consistency of the interaction. However, in the benchmark comparison, the novelty dimension is rated "Good" above all others, indicating that participants found the concept creatively engaging. Perspicuity, Efficiency, and Stimulation are interpreted as "Above Average," and Attractiveness and Dependability as "Below Average."

The concept **Breathe** got the best ratings for Attractiveness (M=1.49) and Perspicuity (M=1.49), indicating that the installation is visually appealing and easy to understand. The low score on the dimension of novelty (M=1.01) and a particularly poor performance on the element 'conventional - inventive' (M=0.4) suggest the need for more innovative features. In the benchmark comparison, all seven dimensions fall in the "Above Average" range.

5 Discussion

5.1 Key Findings

Using a pre-questionnaire, we assessed (i) public knowledge and information demand regarding air quality and pollutant impacts in residential areas. Despite clear interest, current information provision is inadequate, resulting in moderate awareness and infrequent information seeking. Making air quality data more accessible and understandable has strong potential to improve public engagement. A comparison between Magdeburg and Skopje reveals local differences in perception and information behavior. Increased personal concern correlates with greater interest in local air quality and explains the increased commitment in Skopje to disseminate air quality data. Citizens feel compelled to act independently to counteract health risks in the future, whereas in Magdeburg responsibility is shifted from individuals to higher-level institutions. These findings suggest that tailored communication strategies are needed to improve air quality awareness and engagement.

(ii) Which information channels citizens use, and what data and information are relevant to them was explored conducting three citizen workshops. Indirect passive information methods, such as public displays and data at the measuring stations, are preferred. Relevant information includes causes, health impacts, and measures to combat air pollution, with a preference for local data from reliable and independent sources.

An exploratory design study investigated (iii) the impact communication strategies have in terms of raising awareness, knowledge transfer, and encouraging behavior change. Five digital prototypes were created for the interactive transfer of knowledge on air quality, which users evaluated using the standardized UEQ for usability and a questionnaire for their effectiveness. In the UEQ benchmark comparison, all five prototypes fall within a similar range in the "Good" category. The results for Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty generally show consistent performance, with only a few extremes at the highest (full agreement) and lowest (no agreement) ends of the scale. The evaluation of the five prototypes reveals distinct strengths and limitations in communicating air quality data to the public. While some excel in interactivity, others provide visually appealing yet passive experiences. The findings suggest that no single prototype fully meets all communication requirements; instead, their respective advantages and challenges can be compared in terms of engagement, accessibility, and long-term effectiveness.

By visualizing particulate matter levels through an interactive photo experience the **Pollution Booth** makes air pollution tangible and personally relevant. However, its ability to convey in-depth knowledge is limited, as participants noted that explanations lacked clarity and contained overly technical terminology. While the installation is engaging, its effectiveness in sustaining long-term interest could be enhanced by integrating additional educational components.

The **Visible Particulate Matter** prototype leverages Virtual Reality (VR) to provide an immersive visualization of air pollution. This novel approach allows users to explore invisible pollutants in an engaging and interactive way. However, usability issues were identified, as navigation within the VR environment was challenging for some participants. Furthermore, the requirement for VR headsets limits accessibility and scalability for broader public use. A clearer introduction and simplified navigation could improve its effectiveness in educational settings.

The **End Game** effectively engages younger audiences by making environmental topics approachable through gamification. However, its effectiveness was reduced by a lack of clear connections between in-game actions and real-world air pollution effects. Additionally, the absence of real-time air quality data limited its educational depth. Providing supplementary learning materials, such as teacher guides, could further enhance its impact as an educational tool.

The **Air Where** prototype adopted a speculative design approach, using provocative future scenarios to generate awareness and public debate. This method successfully elicited strong emotional responses and stimulated reflection on environmental responsibility. However, Some participants found its message unclear and lacking present-day relevance. Enhancing its educational value could involve integrating real-world data alongside speculative elements to provide a clearer contextual framework.

The **Breathe** installation excelled in its seamless integration into public spaces, offering an intuitive and visually compelling representation of air pollution. By providing passive exposure to real-time data, it ensures continuous engagement without requiring active user input. However, the lack of interactive elements reduced its effectiveness in conveying detailed information. Participants suggested incorporating additional features, such as soundscapes or explanatory text, to enhance understanding of the visual changes in air quality representation.

A comparison of these prototypes highlights the strengths of different communication strategies. While Pollution Booth and Breathe are highly usable and effectively reach a broad audience in public spaces, Visible Particulate Matter offers an immersive experience that makes air pollution visually tangible. End Game successfully engages younger demographics through gamification, whereas Air Where uses emotional engagement to provoke discourse. The findings suggest that a hybrid approach, combining different strategies, may be most effective. For instance, blending passive communication methods (e.g., public displays and real-time pollution indicators) with interactive tools (e.g., gamification, VR) could enhance both immediate engagement and deeper understanding.

Future developments should focus on improving accessibility, ensuring that emotional engagement is effectively linked to scientific information. The integration of real-time air quality data, simplified usability, and audience-specific adaptations could further enhance effectiveness. Regular content updates may also be necessary to maintain long-term public interest. Ultimately, the findings indicate that air pollution communication should not only be informative but also interactive, emotionally engaging, and widely accessible to ensure lasting impact.

5.2 Design Implications

Unlike previous studies, this participatory design process revealed that while users in surveys express a preference for personal smart devices, such as tablets or smartphone applications, these tools have not demonstrated a significant effect on increasing attention and knowledge acquisition. This lack of impact is attributed to the self-initiative required for individual information collection. Participants in citizen workshops highlighted a preference for collective knowledge about air pollution to collaboratively work towards a solution and ensure measures are not ignored. In addition, a shared data foundation facilitates more effective advocacy for air quality regulations with decision makers. The confrontation in urban spaces provides users with the opportunity to receive information without having to actively seek it out. The study defines 32 key design requirements across four categories, which should be taken into account by policy makers and urban planners when implementing public information systems.

Information Selection: To effectively communicate air pollution data, information must be relevant and easy to understand. Key aspects include location, ensuring that data are directly linked to the user's surroundings, and communication of health impacts, highlighting specific risks such as acute symptoms and long-term disease effects [38]. Providing practical steps that individuals can take for self-protection and clear links between actions and their impact on air quality can strengthen the educational effect. Other essential elements include historical data for trend analysis, clear identification of air pollutants and their sources, and transparent presentation of political decision-makers responsible for regulations [23].

Mediation: While the highest-rated prototype Pollution Booth does not necessarily achieve the greatest impact in terms of increasing awareness, in fact, the Air Where prototype, with its provocative speculation, demonstrates that unconventional and controversial approaches can effectively capture attention and stimulate curiosity and debate. However, for educational purposes, communication methods must go beyond artistic approaches and provide concrete and actionable information. Although emotional engagement strategies can activate social norms and collective responsibility, supplementing them with peer-to-peer interactions and clear evidence-based messaging ensures a stronger and more sustainable impact on environmental behavior [38, **?**]. By combining the attention-grabbing power of speculative approaches with practical, behavior-oriented communication, awareness campaigns can maximize both short-term engagement and long-term effectiveness. The attractiveness of an application is influenced by quick accessibility (e.g. structured intro tutorial), the fun factor in operation, the opportunity for active participation, the acquisition of knowledge helping to improve one's living conditions, and the curiosity to try new things. Additionally, tangible and embodied experiences, gamification elements, such as challenges and interactive storytelling, and familiar operation can improve usability and encourage users to engage with complex topics like air pollution. Citizen science initiatives can empower people with the knowledge to interpret air quality data and take action, particularly through brief training sessions that enhance self-efficacy and engagement. These educational formats should be tailored to specific target groups to maximize effectiveness. Regular updates sustain long-term engagement.

Media Channel: The study supports the use of passive communication methods, such as digital screens in public spaces, as they minimize the effort required by individuals to seek information. High-traffic areas such as transportation hubs, shopping centers, and parks are suitable locations. Educational partnerships with schools and libraries can facilitate immersive learning experiences using technologies like VR and AR. In addition, leveraging daily news channels, social networks, and mobile applications can increase reach, with the smartphone remaining the preferred device for accessing environmental information. To ensure transparency and credibility, information should come from reliable and independent sources, such as scientific or governmental institutions, free from political or economic influence.

Data Visualization: To make complex scientific data accessible to a broad audience, the installation must prioritize simple, non-technical language and avoid overwhelming users with pollutant level data. Using visual elements such as color-coded indicators, infographics, and dynamic soundscapes can make invisible pollutants tangible. Inclusive design principles, such as strong contrasts, legible fonts, audio instructions, and adjustable interfaces, ensure accessibility. The User Interface Design should have a clear, concise, and well-structured design and focus on core information. Additionally, positive framing—emphasizing solutions rather than solely highlighting negative consequences—has been shown to enhance public engagement and comprehension [38]. Finally, content reduction focusing on essential information and layering details based on user interest allows for a more effective communication approach.

5.3 Limitations

Several limitations had to be accepted in conducting the surveys in this study, which must be considered when interpreting the results. Firstly, there is an unequal distribution in sample size between Magdeburg and Skopje. Students in Skopje received extra credits as an incentive to participate in the study. Secondly, the testing in Magdeburg was conducted in person on a fixed date, while the survey in Skopje was conducted digitally and independently of time. The prototypes were available for direct use by participants in Magdeburg. Due to the large transportation effort and additional costs, only digital testing of the prototypes was possible for participants in Skopje. This may influence the subjective assessment of the communication concepts.

Furthermore, the sample does not represent a cross-section of the population. The average age is below that of the general population. Additionally, mainly university and college members were recruited for participation. These individuals tend to already have higher environmental awareness and media competence. However, studies examining the impact of demographic data on UX ratings found no significant influence on usability ratings [45]. In particular, there may already have been an interest in the topics covered for workshop participation. The workshops were conducted only in Magdeburg. Therefore, only local preferences in the prioritization of topics could be evaluated, and there was no cultural comparison.

6 Conclusion & Future Work

This study investigated the communication of air quality data to the public to raise awareness about the health hazards of air pollution. Using the Design-Based Implementation Research approach, we explored five design prototypes tested with participants from Germany and North Macedonia. Findings highlighted the population's interest in the issue but limited knowledge about air quality. Despite interest, information barriers and low motivation hinder regular engagement. The identified requirements for knowledge communication suggest that using familiar operating concepts, targeted selection and reduction of content, region-specific communication strategies with locally relevant and health-focused information, passive information methods in public spaces with minimal effort required to obtain the information, employ interactive and emotional engagement strategies and simple, illustrative presentation of information as effective tools for increasing problem awareness to promote environmentally conscious behavior. Citizen Workshops revealed a preference among participants for collective knowledge sharing, indicating a communal approach to tackling air pollution. This collective knowledge base could help in advocating for better air quality regulations.

The results demonstrated which design principles are effective in raising awareness of the issue. In addition to citizens and users, future work should also involve experts in the development process, e.g. to prioritize the identified requirements, to further develop the concepts and ideas and to evaluate the approaches from different professional perspectives. However, it remains to be determined what the optimal amount of input and the most effective communication methods are to maintain long-term attention and determine which data are of lasting interest. Enhancing the usability of the artifacts will require repeated user testing and iterative adjustments. Therefore, an implementation of designs as fully functional installations that can be used in real public environments is necessary so that they can be evaluated with different methods on site. Only after the integration of improved information channels, a subsequent survey can explore the frequency of prototype usage; whether and how often citizens inform themselves about this topic. Future research is also needed to determine the most effective locations for their placement and the specific target groups that frequently seek information versus those that do not. Since this survey focused on design of communication methods they were not targeted to measure changes in participants' actual behavior, which needs to be done in future work.

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