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Seeing Clearly: A Situated Air Quality Visualization with AR Egocentric Viewpoint Extension

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Abstract

Raising public awareness about air quality is crucial for promoting individual and collective actions to mitigate the harmful effects of air pollution and achieve a healthier and more sustainable environment. This article presents an application that uses Augmented Reality (AR) and Situated Visualization (SV) to increase public awareness of air quality-related issues. The application, created according to the Human-Centered Design (HCD) methodology, overlays a visual representation of real-time air quality data onto the user's immediate environment, taking advantage of SV's contextualization capabilities. However, this kind of AR application faces some challenges, namely the AR egocentric viewpoint limitation of users when using SV. The application incorporates two solutions to mitigate this problem: multi-dynamic camera feeds (using the front and rear cameras of the mobile phone to extend the user's field of view) and side-by-side dynamic AR and Virtual Reality (VR) camera feeds (a transitional interface with an AR camera and a 3D virtual/digital representation of the area where the user is). Finally, the article evaluates the usability of the application and proposes solutions to mitigate egocentric viewpoint limitations. A study was conducted with seven participants with no prior experience in air quality visualization or AR to complete a task that involved pollution information retrieval using only the AR camera, as well as the side-by-side dynamic AR and VR camera feeds. The results showed that by using the solutions, the task completion time decreased by 42%. Additionally, the application received positive feedback regarding ease of understanding, complexity, and involvement, suggesting that it can be truly helpful.

CCS Concepts

• ***Interaction paradigms*** → *Mixed / augmented reality;* • ***HCI design and evaluation methods*** → *Usability testing;*

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1. Introduction

The growth of available information has contributed to the recognition of several fundamental problems in society. One important problem is the need to change routines due to the increase in air pollution, which is affecting people's health, sometimes without their knowledge. According to the World Health Organization (WHO), "*almost all of the global population (99%) breathe air that exceeds WHO guideline limits and contains high levels of pollutants, with low- and middle-income countries suffering from the highest exposures*" [Org23]. In Europe, air pollution is the largest environmental health risk and significantly impacts the health of the European population, particularly in urban areas. While emissions of key air pollutants and their concentrations (particulate matter - PM10 and PM2.5, nitrogen dioxide - NO2 and ozone - O3) in ambient air have fallen significantly over the past two decades in Europe, air quality remains poor in many areas (EEA, 2022). Making the general public aware of the air quality in their living area is the initial step towards reducing air pollution. However, this task is very challenging and complex. Despite the amount of information on air quality available from several environmental agencies (public and private), public awareness is still low.

The advancement of technological means can aid in the aforementioned effort. The global market for Augmented Reality (AR) technology is showing that it is gaining relevance, following in the footsteps of mobile phones and the internet. In this kind of reality, humans can access and interact with both digital and real content, augmenting the information captured by their senses in a normal situation [KBB*18]. In AR, virtual information is aligned with the user's perspective to create a seamless and augmented experience. Just like with air quality, context is a critical element for AR. This context refers to the set of conditions in which AR users build knowledge. It includes any information that characterizes the user, activity, content, purpose, and environment. To take advantage of the user's environment and deal with all of its contextual information, some AR applications use Situated Visualization (SV), which encompasses all the visualized content that changes its appearance based on context [Whi09]. SV considers visualizations that are rel-

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evant in the physical context in which they are displayed, enriching the AR experience through user interaction [KSWS11]. A full characterization of the SV model, within the scope of AR, can be seen in [MMDS22]. In AR, the egocentric viewpoint refers to the perspective of the user, and is determined by the position and orientation of the user's device concerning the AR environment. It's important to note that the egocentric viewpoint in AR is limited to the perspective of the users, preventing them to see information outside of their perspective [Tat15]. This situation creates some challenges and research opportunities regarding the use of SV [MDS20].

This article presents the development and usability evaluation of an AR-based SV application designed to increase public awareness of air quality. The development process involved a literature review and a participatory process with domain experts. With this application it is possible to visualize air quality data in real-time and in context, making it easier for the public to understand the impact of air pollution on their environment. The article by Merino et al. [MSK*20] served as the basis for the evaluation process.

2. Related work

For a better understanding of the work presented in this article, it is necessary to present the main challenge when combining SV with AR - the user's egocentric viewpoint limitation - as well as some relevant research in the area of air quality.

2.1. Augmented Reality user's egocentric viewpoint limitation

Situated Visualization faces several challenges that affect their applicability and usefulness. According to [Tat15] and [Mar21], the biggest challenge when using SV combined with AR is the egocentric viewpoint limitation of the user. The challenge is to see or collect information outside the screen or current viewpoint while avoiding or mitigating any alterations to the user's position. Figure 1(a) illustrates the meaning of an egocentric viewpoint, and Figure 1(b) shows the necessity of changing the user's field of view (FOV) or position to see, access, or collect information outside the current viewpoint.

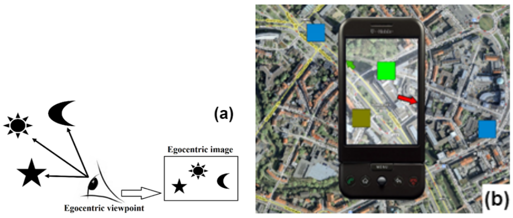


Figure 1: *Illustration of (a) egocentric viewpoint and (b) its limitation, from [HB10], the impossibility of seeing more information (real or digital) outside the user's perspective.*

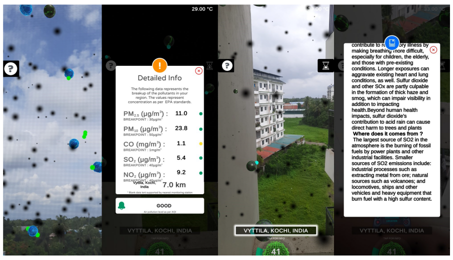
The two main techniques to mitigate the user's egocentric viewpoint limitation are multi-perspective rendering and transitional interfaces [Tat15] [MDS20] [ZJSH21] [JSG*21]. The multi-perspective rendering technique is used to add extra views of the real-world into the current AR user's egocentric view, thus extending their FOV. The transitional interface technique offers users a seamless way to switch from the AR user's egocentric viewpoint to other relevant virtual reality (VR) viewpoints of the same elements without altering their position.

2.2. Air quality visualization

To foster general public awareness, specialists first need to collect and analyze air quality data, which is typically organized by the hour, to understand the dynamic evolution of air pollution and identify the sources of pollution in a specific area. In [QLL*22], Qu et al. propose an interactive visual analytics system called AirLens to help domain specialists comprehend air quality evolution in urban areas from multiple aspects and levels (overall, stage, and detail levels). This tool uses information collected by the China National Environmental Monitoring Centre and integrates common pattern mining, city community extraction, and suitable filters to identify noteworthy data. Despite its effectiveness and usability, according to expert feedback, this visualization tool cannot be used by individuals with low knowledge of air quality. This limitation is reinforced by the amount of data and processing time required to visualize and analyze the results. The Qu et al. study presents some important related works on air quality analysis and visualization, being none of them based on AR technology.

For universal usage, the most common applications regarding air pollution are web-based. One of these applications that has significantly contributed to advancing the understanding of the impact of human activities on air quality and climate change is the Copernicus Atmosphere Monitoring Service (CAMS) [Com23]. CAMS is a comprehensive monitoring and forecasting system for atmospheric composition, air quality, and climate change. It utilizes various types of data, including satellite observations, ground-based measurements, and modeling approaches to generate accurate and reliable information on a global scale. This application provides open access to its data, enabling researchers, policymakers, and the general public to monitor and understand changes in the Earth's atmosphere. CAMS has been widely used in numerous studies to assess air pollution levels, to evaluate the impact of climate change on atmospheric composition, and to develop strategies for reducing greenhouse gas emissions. Another interesting example is the Lotos-Euros application [TNO23], which is based on a chemical transport model designed to simulate the behavior of air pollutants. It allows users to run simulations and visualize air quality levels all over the world. The model combines observations from ground-based monitoring stations with theoretical simulations to forecast air quality levels and evaluate the effectiveness of various air pollution control measures. Lotos-Euros has also been widely used by environmental agencies and policymakers to develop air quality management strategies, and it has been used in international studies to evaluate the long-range transport of air pollutants.

On the other hand, based on the premise that visualizing air quality in a person's living area could help bring awareness, [MCJ21] presents AiR, a mobile application based on Android and AR technology. This application allows the general public to visualize quantitative information about various air pollutants in their location (based on GPS devices) or in a selected area. The application also presents other related information, such as colour-coded air quality levels, pollutant concentrations, individual pollutant concern levels, breakpoints for good levels, pollutant molecular structure, pollutant information, ill effects due to pollutants, and sources of pollution controllable by the user. The used data is retrieved from the Central Pollution Control Board of India and can be from the past or present. The application only graphically represents the air quality on the user's display after the data for the defined location has been collected and processed. The pollutant elements are randomly drawn at unique positions, taking into account their molecular structure, and are given a slight rotation and velocity to create a dynamic visualization, as they are fluids. Apart from the variable size of the particulate matter, the sizes of the other pollutants are fixed. Whenever the application user leaves the processed area, the entire pollutant rendering process is updated. With this application, users can become aware of different pollutants, sources of pollution, and their impacts on health in an interactive way. An example of the AiR application can be seen in Figure 2.



Detailed Info

The following data represents the breakup of the pollutants in your region. The values represent concentration as per EPA standards.

PM$_{2.5}$ (µg/m^3) : 11.0
BREAKPOINT : 30µg/m^3

PM$_{10}$ (µg/m^3) : 23.8
BREAKPOINT : 50µg/m^3

CO (mg/m^3) : 1.1
BREAKPOINT : 1mg/m^3

SO$_2$ (µg/m^3) : 5.4
BREAKPOINT : 40µg/m^3

NO$_2$ (µg/m^3) : 9.2
BREAKPOINT : 40µg/m^3

Vytilla, Kochi, India 7.0 km

* Blank data isnt supported by nearest monitoring station

GOOD
Air pollution level as per AQI

contribute to re ory illness by making breathing more difficult, especially for children, the elderly, and those with pre-existing conditions. Longer exposures can aggravate existing heart and lung conditions, as well. Sulfur dioxide and other SOx are partly culpable in the formation of thick haze and smog, which can impair visibility in addition to impacting health.Beyond human health impacts, sulfur dioxide's contribution to acid rain can cause direct harm to trees and plants
Where does it comes from ?
The largest source of SO2 in the atmosphere is the burning of fossil fuels by power plants and other industrial facilities. Smaller sources of SO2 emissions include: industrial processes such as extracting metal from ore; natural sources such as volcanoes; and locomotives, ships and other vehicles and heavy equipment that burn fuel with a high sulfur content.

Figure 2: *A snapshot of the AiR, where several pollutants (the spheres) can be seen in real-time, from [MCJ21]. On the left side of the figure, there is a set of information linked to the concentration levels of pollutants, while on the right side, the user can understand, for example, where the pollution they see is coming from.*

The Air Transformed project, by the Environmental Defense Fund, is an AR air pollution application launched in 2018. It aims to raise awareness about the effects of air pollution on human health and the environment by overlaying digital images and information on top of real-world environments, such as city streets or parks. For example, users can see virtual "smog clouds" representing the amount of pollution in the air at the location they point their smartphone or tablet camera at and get real-time air quality data. The application also provides tips for reducing exposure to air pollution and suggestions for taking action to improve air quality [Edf18].

The BreezoMeter project, established in 2014, is a real-time air quality data platform that employs AR to visualize air pollution data in a user's local environment. The platform provides personalized air quality information, real-time air quality data in the user's surroundings, and predictions of air quality changes throughout the day. BreezoMeter is used in various applications, for example, to provide air quality information to people with asthma, to guide outdoor exercise activities, and to assist urban planners in making informed decisions about air pollution. The platform is regularly updated with new features and data sources [Gen14].

For reviewing the use of AR, VR, and Mixed Reality (MR) applications in environmental contexts, aimed at raising awareness and promoting sustainability, it is recommended the [RLS*21] survey.

None of the related works discussed above addresses the issue of the limited egocentric viewpoint of the AR camera. Hence, the following section describes the development of an application that proposes solutions to mitigate this problem.

3. AR application for air quality Situated Visualization

The development of an AR application to visualize air quality and increase public awareness in the area involved several phases. First, a discussion of the application in a focus group comprising four environmental experts and three AR specialists took place. The meeting with domain experts as part of the participatory process lasted around 1 hour and 40 minutes. Based on the outcomes of the meeting and the related works mentioned earlier, the following requirements were defined: use air quality data collected from reference agencies, allow the visualization of the air pollutants and use its molecular structure to represent them graphically, use simple animations in the augmentations to increase the impact on the users, perform simulations based on the air quality data obtained, present explanations regarding the information to be visualized, present related information, mainly the one that alerts the user (like ill effects due to pollutants and source of pollution controllable by user), allow the use of GPS to choose the area where the air quality data is to be displayed, and , use visual representations according to the recommendations of European institutions. The application used only the concentration levels of nitrogen dioxide, measured from a specific day. The European Environment Agency (EEA) provides several recommendations for visual representations of air quality. Key recommendations include using interactive and user-friendly visualizations, allowing users to explore the data and easily switch between different variables, locations, and time periods. Clear and concise labels and legends for all visual elements should be provided, ensuring that users can easily understand the data being presented. Intuitive and meaningful color scales should be used, avoiding overly complex or confusing color schemes.

To mitigate the user's egocentric viewpoint limitation, the following features are proposed:

- Side-by-side dynamic AR and VR camera feeds, as can be seen in Figure 3, as a transitional interface with an AR camera and a 3D virtual/digital representation of the area where the user is located (a 3D virtual map). It should also be possible to show each of these feeds separately to the user. Figure 3's right side offers an elevated viewpoint of the entire area for which data on pollution levels is available. On the left side of Figure 3, one of the views within that area, captured by the camera, is presented.
- Multi-dynamic camera feeds (the front and rear cameras of a smartphone), as can be seen in Figure 4. The left side of Figure 4 shows the image acquired by the front camera, while the right side shows the image taken by the rear camera. In this example, the user can see parts of two perpendicular roads. This solution avoids the main weakness of the multi-perspective renderings techniques, the difficulty users have in changing the viewpoint of the added images because they are usually static (specifically calculated for the situation) [Tat15] [MDS20] [Mar21];

The created application, developed in Unity® and C# scripts, uses the information gathered by the Department of Environment

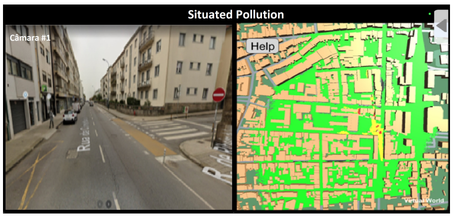


Figure 3: *Example of an extension of the user's egocentric viewpoint, by joining AR and VR related camera feeds. On the right side an elevated viewpoint of the entire area for which data on pollution levels is available. On the left side, one view within that area.*

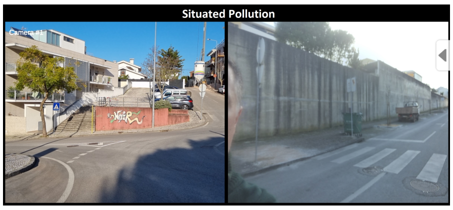
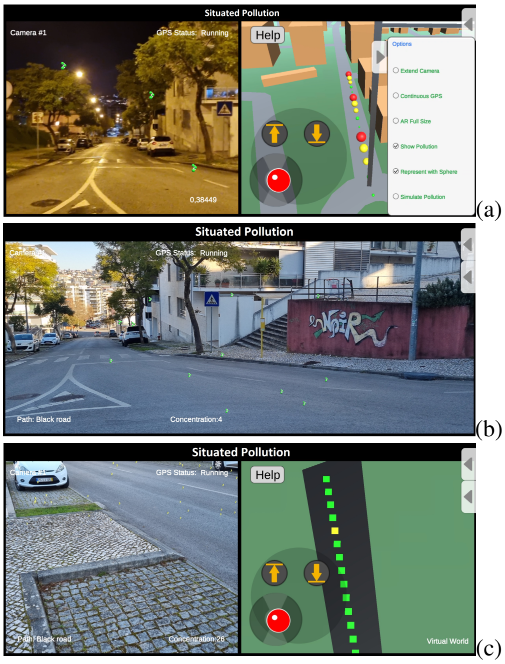


Figure 4: *Example of a dynamic user's egocentric viewpoint extension. The left side shows what the user sees through the front camera, while the right side shows the image captured by the rear camera.*

and Planning of University of Aveiro. The VR camera feeds (the 3D virtual map) were based on Google Maps SDK for Unity® package, which provides access to high-quality geo data from the Google Maps database to retrieve the virtual information according to the GPS coordinates. It is important to note that the AR application uses a simpler colour-code and numerical scale to report how clean or polluted the air is and what associated health effects might be of concern. In more detail, it uses green to represent good pollution levels (under 25 units) – Figure 5(a) and Figure 5(b), yellow to represent moderate and unhealthy pollution levels (more than 25 units and less than 200) – Figure 5(c) and red to represent very unhealthy and hazardous levels (more than 200 units). The mentioned units could be parts per million (ppm) or micrograms per cubic meter (µg/m^3), depending on the pollutant being measured. For example, carbon monoxide (CO) and nitrogen dioxide (NO_2) are often measured in ppm, while particulate matter (PM) is measured in µg/m³. The representation of pollution is done with spheres – Figure 5(a), planes – Figure 5(c) – or models of the molecule of the pollutant (only for the AR component) – all images of Figure 5. Each plane identifies the area where the pollutant concentration level was measured. In the representation using spheres, which are positioned at the centre of the area where the measurement was taken, the radius of the sphere increases as the concentration level increases. At the moment, following the environmental experts' advice, there are five different sizes to represent pollution levels (below 10 units, between 10 and 25 units, between 25 and 100 units, between 100 and 200 units and more than 200 units). The application can present the air pollution information in both AR and VR camera feeds simultaneously – Figure 5(a) and Figure 5(c), or in only one of the feeds – Figure 5(b), and can also perform simulations based on the air quality data obtained (for example, what would be the scenario if the pollution's concentrations were to rise or fall by a percentage value). The created AR mobile application allows the presentation of the names of the roads and the names of some buildings, that appear only in the 3D map, because the Google Maps SDK for Unity® package comes with that functionality.



Options
○ Extend Camera
○ Continuous GPS
○ AR Full Size
☑ Show Pollution
☑ Represent with Sphere
○ Simulate Pollution

Figure 5: *Screenshots of the created application running in real-time and in the exact user's location. On the right-hand side of (a) and (c), a virtual model of the user's surroundings is displayed, showing the pollution levels associated with it (as spheres and planes, respectively). In (b) and on the left side of (a) and (c), the image that the user sees is augmented with information on the concentration level of the pollutant in that location. (a) and (b) present good pollution levels and (c) shows moderate pollution levels.*

Figure 5(a) shows the configuration menu on the right side where users can select their running options. The graphical elements on the bottom of the right side of Figure 5(a) and Figure 5(c) serve to allow users to navigate on the virtual 3D map. When the *Continuous GPS* option is selected, the application shows always an image of the user's location, acquired by the front camera of the device, and overlaid with the augmented information (the molecules of the pollutant) based on the collected air pollution data. When the *AR Full Size* option is not selected, the right side of Figure 5(a) and Figure 5(c) presents a graphical representation of the user's location (wider than what the camera sees) and the related air pollution data. Accordingly, when the *AR Full Size* option is selected, only the AR camera is displayed.

4. User study

A user study was conducted to assess the potential of the application to effectively mitigate the limitations of the egocentric viewpoint and to collect feedback for further improvement. Additionally, the study evaluated the usability of the previously described application in terms of visualizing air quality.

4.1. Study description

The study was conducted in a public space, between two streets in a city, to evaluate the performance of proposed solutions in a realistic environment. To determine the effectiveness of the proposed solutions in mitigating the egocentric viewpoint limitation, each participant used both the mobile application with the proposed solutions (the side-by-side dynamic AR and VR camera feeds), which will be known as method AR+3D virtual map, and the mobile application without the proposed solutions, which will be referred as method AR. Each participant performed the task alone with only the observer present.

4.2. Study setup

Two distinct methods were used: method AR and method AR+3D virtual map. It should be noted that the hardware used was the same for both methods (a Samsung S21 5G), and only the characteristics of the application differed. The method AR+3D virtual map utilises transitional interfaces with both the AR camera and the virtual 3D representation of the area (i.e., a map), while the method AR uses only the interface of the AR camera. The Vuforia library (version 10.6) was used to place the augmented content in the real-world environment [Vuf23]. The use of method AR+3D virtual map can be seen in Figure 5(a) and Figure 5(c), whilst method AR is shown in Figure 5(b).

4.3. Task

The study took place in a delimited area, with two paths with information on air quality. The participants were asked to walk on both paths to retrieve specific pollution information. They were instructed to indicate the path with the lower level of pollution between the two presented and annotate the GPS coordinates of the location with the highest concentration level of pollutant on the chosen path, along with the value of that concentration. The task was performed twice, as explained in the previous subsections, with method AR and method AR+3D virtual map (in this order).

During the performance of the task, and as the participants had to walk on busy roads, they were provided with the possibility of resorting to the other proposed solution to mitigate the user's egocentric viewpoint limitation, the multi-dynamic camera feeds, so that they could make this crossing safely. With this solution, they had the chance to extend the original field of view of the AR camera (the front one), by using also the rear one. An illustration of this usage can be seen in Figure 4.

The rationale for choosing the mentioned task is that it simulates a real-life scenario where participants would use the application to make an informed decision about the least polluted route to follow. Additionally, the task highlights the limitations of the AR technology and its potential impact on decision-making.

4.4. Measurements

The data collected includes both objective measurements, such as the time taken to complete a task and the accuracy of the response (path and GPS coordinates), as well as subjective measurements, such as self-reported user experience with air quality visualization, AR technology and mobile applications, and effort needed to complete the task.

4.5. Procedure

The procedure involved explaining the scientific study that would be conducted to each of the participants and obtaining their informed consent for the processing of the data collected during the study. In addition to obtaining informed consent from the participants, measures taken to ensure the ethical conduct of the study included maintaining the confidentiality and anonymity of each participant in the data collected.The participants were given instructions on the study's setup and the tasks to be completed. They were given some time to adapt to the application under evaluation before the task was presented. Each participant was subsequently assigned the task to complete. The observer accompanying the participants may jot down pertinent information while they are performing the task. After accomplishing the tasks, the participants were requested to fill out a questionnaire and participate in a brief interview to share their opinions on the proposed prototype.

4.6. Participants

The recruitment process aimed to obtain a sample composed of individuals with different characteristics in terms of age, gender, level of education, and professional occupation. The recruitment was conducted among known individuals. Therefore, the sample included seven (7) participants with five (5) females - 71.4% and two (2) males - 28.6%. The age range of the participants was 17 to 77 years old (M = 49.4, SD = 16.6). Among them, two (2) had a secondary education level, while six (6) held a higher education degree. The participants consisted of one (1) student, one (1) retired individual, and five (5) active workers, four (4) of who were teachers in higher education. With respect to individual profiles, all participants had no prior experience with visualization of air quality information and only one had prior experience with AR. Regarding the degree of experience in using mobile applications, using a Likert-type scale (1 - no experience and 5 - a lot of experience), the median value of the participants' answers was 4, with one (1) participant without any experience at all and two (2) with a lot of experience.

5. Results and discussion

All participants completed the task at hand correctly, without making any errors. Using a Likert-type scale where 1 indicates that a task was very difficult and 5 indicates that the task was very easy, participants indicated that performing the task using only the AR camera (method AR) was slightly less challenging (median = 5) than performing the method AR+3D virtual map (median = 4), the task using both the AR camera and 3D map, but both conditions were still considered easy. These findings were confirmed by the observer, who perceived that the participants overall found the task to be easy (median = 4). Regarding the ease and difficulty of the task, the disaggregated data is shown in Figure 6(a). When considering the ease or difficulty with which participants performed the task in more detail, the effort required to complete method AR was due to GPS instability (3 participants), the attention required to view all the presented information to obtain the desired result (2 participants), and a lack of experience with mobile applications (1 participant). The effort required due to GPS instability was evident in the challenge of initially detecting the road to be travelled and in adjusting the pace of movement to the pace of the GPS data update. Two participants did not feel the need to make any effort. Regarding method AR+3D virtual map, the effort required was due to the lack of familiarization with the application (2 participants), GPS instability (2 participants), and difficulty in combining the information given in the two interfaces (AR and 3D virtual map). There were 3 participants that did not feel the need to make any effort. The analysis of the results obtained by the participants revealed an issue with the inaccuracy of the mobile devices GPS. As previously mentioned, each participant had to identify the GPS coordinates of the location with the highest pollutant concentration on the least polluted path. The comparison of GPS coordinates obtained during the methods AR and AR+3D virtual map showed an average differential of 7.29 metres (SD = 6.6). Figure 6(b) shows the disaggregated data for the difference in GPS coordinates, obtained by each participant, between each task performance by the participants.

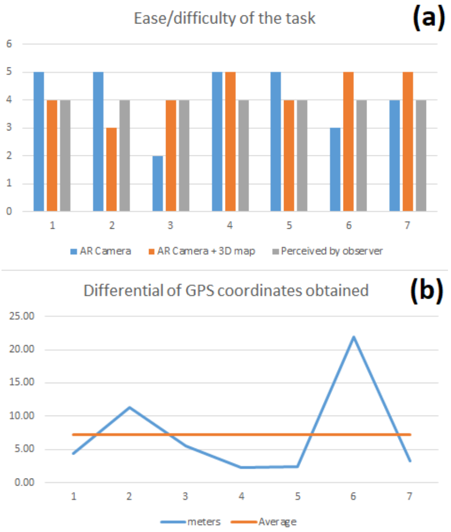


Figure 6: *Questionnaire results on (a) task difficulty and (b) GPS coordinate differences between performances.*

For each participant, the task execution was timed separately each time they performed it. The average task time in the method AR was 382 seconds (SD = 121.2). For the method AR+3D virtual map, the average was 159 seconds (SD = 45.2). It could be argued that the decrease in task completion time, which was on average 42.31%, was due to the task having already been done once. However, participants' feedback, supported by their explanation of how they would perform the task, validates the idea that the use of side-by-side dynamic AR and VR camera feeds made the task much easier to perform. Some discrepancies in task completion times between participants resulted from the strategy used to complete the task. A detail that may have increased execution time refers to requests for help to the observer, mainly for assistance with GPS issues, button usage, and Portuguese translations (the language used in the AR application is English). The duration of time taken by each participant to complete the task with the methods AR and AR+3D virtual map, as well as the difference between the two durations, are presented in Figure 7.

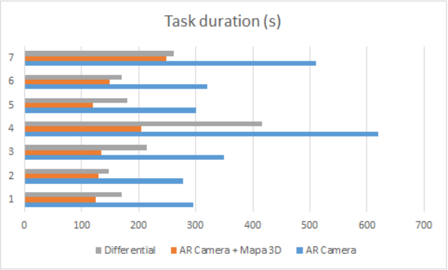


Figure 7: *Participants' times with each method (AR and AR+3D virtual map) and the difference between them.*

According to the unanimous opinion of the study participants, the most comprehensive method for completing the task would be AR+3D virtual map, utilizing the AR camera and the 3D map. This method was, also, deemed the most useful and preferred by 85.71% of the participants (6 out of 7). The reasons for this preference include its intuitiveness, perceptibility, the information it provides (complementary to the one given by the AR camera), and the reduction of movements required. However, to eliminate the possibility that this preference was due to the task being performed last, study participants could have been divided into two groups, each one starting to perform the task differently and then comparing the results between the groups. When it came to the most practical way of performing the task, the participants were divided, with 57.14% voting for using the AR camera and 3D map, and 42.86% opting for using only the AR camera. The reason for this unexpected outcome is that 42.86% of the participants felt that using only the AR camera simplified the task, allowing for better focus and a clearer understanding of the visualized information, with fewer points of distraction.

Concerning the answers to the open questions from the surveys given to the participants, the advantages of using only the AR camera are that it is a practical and familiar way, since there is experience of using the camera for other purposes (1 participant), it offers relevant information (2 participants) and being able to see it in real-time (1 participant), and also that it does not require as much attention since it has less information (1 participant). Two participants found no advantages. On the other hand, the disadvantages found were having less information (2 participants), the instability of the GPS (1 participant), and the fact that it is more laborious, as it forces the participants to walk the entire paths (3 participants). Only one participant found no disadvantages. The advantages of using the AR camera and the 3D map together were having more information available (6 participants) and the possibility to visualise the information for the whole area where the task was taking place, obtaining the requested result faster (1 participant). The importance of representing the pollution concentration levels with differently sized and coloured spheres (which better demonstrate the possible severity of the situation) was also emphasised. Finally, the disadvantage found in using the AR camera and 3D map, according to 2 participants, was the difficulty of coordination between both interfaces (AR and 3D virtual map). Five participants found no disadvantages.

Regarding the air quality information provided by the AR mobile application, participants rated the ease of understanding the information (median = 4), the complexity of the information (median = 2), and the sensation of involvement with the information presented after using the AR component of the application (median = 4) on a Likert-type scale ranging from 1 (none) to 5 (a lot). The values obtained in the first two ratings validate each other, and the response obtained on the participant's sense of involvement highlights the usefulness of the AR technology in alerting to environmental issues and creating a strong connection between users and the information provided. Disaggregated data on air quality information can be found in Figure 8(a). Concerning the distinction of pollutant concentration levels representation, participants rated the use of spheres, with a standard colour code and size scale, in the 3D virtual map (median = 5), as shown on the right side of Figure 5(a), the use of planes with only a standard colour-code scale in the 3D virtual map (median = 4), as shown on the right side of Figure 5(c), and the use of 3D representations of the pollutant molecule in the AR camera (median = 4) on a Likert-type scale ranging from 1 (not understandable at all) to 5 (very understandable), as shown in Figure 5. The difference between the obtained results for the greater understanding of the representation of the pollutant by spheres and planes could initially be attributed to the fact that the representation by spheres was the default option in the AR application. However, the analysis carried out revealed that the difference was in the fact that the representation with planes only uses colour (regardless of the concentration levels), while the representation of spheres also changes the size of the spheres depending on the concentration levels – comparison between the representations of pollution levels on the right side of Figure 5(a) and Figure 5(c). The lower score obtained in the representation used in the AR camera is due to the complexity of the 3D model, which was not very perceptible to all participants. The disaggregated data for the representation of pollutant concentration levels is shown in Figure 8(b).

The participants classified the created mobile application as simple, intuitive, interesting, and easy to understand. They found it useful for everyday life and relevant for changing behaviours related to air quality, such as deciding to walk instead of driving to reduce pollution. However, one participant felt that the intended purpose of the application was unclear.

Regarding overall improvements that could be made to the application, participants mentioned the following: increase the size of the applications buttons, improve the stability of the GPS, ensure that latitude and longitude information is always visible, and allow the visualization of the application from any position of the mobile phone, regardless of the gyroscope information. Specifically for the use of the 3D camera, the suggested improvements are: display the pollution concentration level in colour and bold font, introduce alerts when pollution levels increase or decrease as the user moves, and improve the appearance of the 3D models of the molecules. For the use of the AR camera and 3D map, the proposed improvements are: adjust the virtual feed (3D map) based on the user's movement to make it more perceptible, increase the size of the pollution concentration level representations on the 3D map, mark the current concentration level on the 3D map, according to the user's location, display the concentration level values on the 3D map, and allow the user to save pollution concentration level records for future comparisons or compare with current data for recurrently travelled paths.

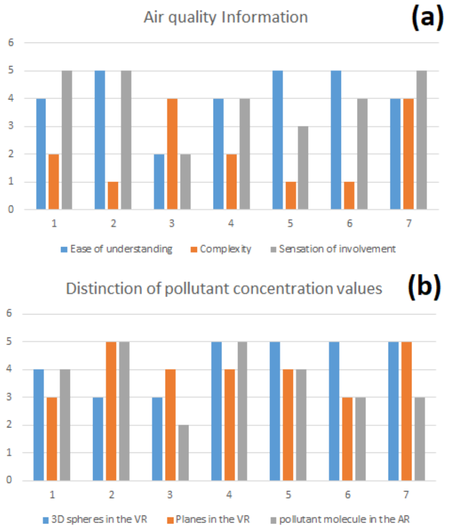


Figure 8: *Questionnaire results regarding: (a) air quality information. (b) the distinction of pollutant concentration levels representation.*

During the brief interview with the participants after completing the task, they revealed that they only used the two cameras of the mobile device to cross the roads more safely. This was because they were primarily focused on viewing the air quality data and walked on the paths along the sidewalks. However, the general opinion was that this feature would be very useful in various situations, particularly to give a sense of social presence [MSDS22], to keep them safe, or to provide a greater field of view.

6. Concluding remarks and future work

This paper presents an application based on SV aimed at helping increase the awareness concerning air pollution using two methods to mitigate the limitation of the egocentric viewpoint. The results of an exploratory user study suggest that the proposed solutions enable users to access more information from their current location without needing to relocate. This conclusion is supported by the unanimous agreement among participants that they felt better informed, safer, and wasting much less time carrying out the task assigned to them when using all the functionalities of the created mobile AR application.

Despite being an exploratory user study with a small number of participants, the results suggest that society is still not adequately aware of the issue of air quality, and urgent educational interventions are required. This idea should be further validated through a larger sample size in future research. Our participants' sample showed that having a higher level of education does not necessarily result in greater awareness of the issue. in fact, 57.1% of the participants held Ph.D. degrees, and only one had consulted information on air quality. During the interview, participants realized the impact that air quality can have on their health and expressed willingness to use mobile applications, such as the one used in the study, if they provided real-time information about air quality covering the whole area where they regularly move.

The study developed was only preliminary to gather feedback and not to prove any hypothesis. When the application is finalized, a future controlled experiment with more participants and tasks given randomly to each participant must be done. This evaluation of the effectiveness and usability of the final application would use the System Usability Scale (SUS).

In addition to implementing the suggestions mentioned by the participants, future work to improve the created application should include: the use of more 3D content, a questionnaire (to evaluate the impact of pollution on people's daily life), the possibility to explore other types of hardware (to overcome GPS issues), the possibility to share information about the air quality of their location (which will be validated by the application managers and used as educational content), multimodal input and output (such as visual and auditory elements to increase inclusion and accessibility), integration with public transportation (routes and the pollution they emit) and weather reports, and Artificial Intelligence (AI). These improvements imply the characterization of the Situated Sonorization model, the analysis of longer and alternative routes, and collaborative interfaces to allow more than one user to view and analyze the same data. The inclusion of AI could help provide a more comprehensive view of air quality and assist users in making more informed decisions and choosing the best course of action. By leveraging machine learning, the application could continuously improve over time, providing even more efficient and accurate information.

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