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What Does Air Quality Sound Like? On Exploring the impact of Data Sonification Versus Data Visualization

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Air pollution is currently a hot topic and a significant threat that impacts not only climate change but also the health of individuals. As a matter of fact, it was estimated that it causes 6.7 million premature deaths annually, and, in 2021, 97% of the urban population was exposed to particulate matter concentrations above the World Health Organization's health-based guideline. Generally, individuals have no perception of the air quality around them and in the city where they live, and their knowledge of the subject depends on what they learn from newscasts or newspapers. However, increasing awareness of the topic can help them make more conscious choices. To partly tackle this problem, we developed a web-based prototype exploiting two modalities to communicate air quality data: data sonification (through audio) and data visualization (through animated video). With the aim of investigating the best communication modality that, eventually, can raise awareness on the topic, we performed a preliminary study. To anticipate some findings, we found out that the videos were considered less mentally demanding and less frustrating, while the sound was considered more pleasant. At the same time, while the videos required less time to be understood and communicated a more precise level of pollution, the audios were considered, on hand, more involving, making the users also feel more immersed in the experience, and, on the other hand, gave the possibility to concentrate on something else while experiencing the data.

CCS Concepts: • **Human-centered computing → User studies**; **Web-based interaction**; **Visualization**.

Additional Key Words and Phrases: air quality, data visualization, data sonification

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1 INTRODUCTION

Air quality improvement is currently a much-discussed topic, especially in the recent period. First, with COVID-19, as a result of the lockdown, there was an improvement in the air quality [5], especially in the most polluted cities, then, with the Ukrainian war, there was a worsening in the affected areas [18], and finally, even more recently, with the fires in Canada, there is a subsequent worsening up to the New York areas [3]. A good air quality level is critical as intrinsically linked to public health. As a matter of fact, based on the report from the European Environment Agency, air pollution is the biggest health risk in Europe related to the environment as it can cause cardiovascular and respiratory diseases, inflammation, oxidative stress, immunosuppression, and cell mutation [14]. In addition to that, analyzing data from 2021, 97% of the urban population was exposed to an amount of particulate matter above the health level imposed by the World Health Organization [1]. To fight air pollution, governments and cities have put in place several policies, such as limiting traffic and reducing the pollutants produced by industries. Despite that, also public awareness can be part of the solution [11]. To increase awareness with the aim to lead individuals to make more informed decisions in everyday life, the communication of the air quality data is crucial, and the Air Quality Index (AQI) is often used with this aim. There are many variations of this index depending on the country in which they are used. Despite that, the most common is the U.S. AQI created by the U.S. Environmental Protection Agency (EPA) [2]. This AQI index is based on five different pollutants: ozone (O_3), particulate matter (PM), carbon monoxide (CO), sulfur dioxide ($SO2_2$, and nitrogen dioxide (NO_2). The index is represented by a value from 0 to 500 calculated from the pollutants just mentioned and identifies six categories of air quality: i) good (0-50) visually represented by green color, ii) moderate (51-100) visually represented by yellow, iii) unhealthy for sensitive groups or severe (101-150) visually represented by orange, iv) unhealthy for all (151-200) represented by red, v) very unhealthy (201-300) visually represented by purple, and vi) hazardous (>301) visually represented by maroon [2].

In this study, we were interested in discovering the best way to communicate the value of the AQI to eventually raise awareness of air quality and its effects on daily life. To do so, we proposed to the participants of our study two different methodologies (visualization and sonification) to better investigate the pro and cons of each one and identifies the one that works best in this case scenario. To evaluate the two modalities, we engaged 14 people in a preliminary study composed of a quantitative and qualitative evaluation carried on after exposing them to videos and audios representing the air quality of five different cities. The rest of the paper is organized as follows. Section 2 analyzed the studies that inspired our work in the context of air quality data, and Section 3 presents the system and the sonification process exploited in the study. Then, in Section 4, our preliminary study is presented along with our results. Finally, in Section 5, we presented some final remarks and future work.

2 RELATED WORK

Our approach was mainly inspired by previous literature on data visualization and sonification in the context of air quality. Concerning the perception of air quality, there is a body of literature that analyzes different approaches to making people aware of the air pollution around them. Kosmidis et al. exploited citizen science combined with low-cost sensing devices and map-based visualization to create a collective online platform to make available air quality data and raise awareness of them [7]. Zamri et al. also used data visualization in [20], where they created a web-based dashboard to provide information on air quality data and identify areas with low air quality. After development, the dashboard was evaluated in terms of user interface, ease of use, and data understanding.

Data understanding is crucial to raise awareness on a specific issue; however, cognitive overload or capacity limits of attention can undermine the effectiveness of data visualization [6]. Nevertheless, data visualization is often used to communicate the mentioned data, so we decided to compare it against a sonification-based approach. In fact, sonification is often used to raise society's awareness of important issues [9, 13]. At the same time, data sonification is exploited to overcome some limitations of traditional data visualizations and reach a wider population, including people with visual impairments and with little expertise in scientific data [16]. Moreover, in relation to the context of air quality data, in the analysis made by Pauletto and Bresin, they mentioned health and environmental data as an emerging theme in data sonification [15]. This is also proven by the systematic review made by Lindborg et al. who analyzed 32 recent projects (18 of them also integrated visualization) involving climate data sonification and visualization based on atmosphere, biosphere, and hydrosphere [10]. Also, using sonification in the context of air quality data is not new. Zhao et al. created a smart earphone charging case (AirCase) able to measure several environmental data, including

CO_2 and volatile organic compounds and proposed a soundscape sonification strategy with the air quality data [21]. However, the authors did not perform an evaluation with users so the effects of this sonification are unknown. The idea of using a smart object in combination with sonification is also exploited by Selfridge et al. [17]. They investigate how to increase awareness of indoor air quality to make users take preventive actions. In particular, the authors augmented with sonification an office gadget that provides information on air quality data when a user interacts with it. The prototype is evaluated by analyzing four sonification models, but not in contrast to different modalities to provide the same information.

In summary, data visualization and data sonification are both used in the context of air quality data and, with this study, we wanted to investigate how users perceive the data in these two different approaches to gain some insight into the best approach to use with this type of data.

3 THE SYSTEM

This section presents the architecture of our system, with a focus on the sonification component and on how sound tracks are generated from air quality data. The system is made up of three main components: i) the web application, ii) a set of REST APIs, and iii) the sonification algorithm. The application runs entirely on the client's browser, and displays the world map thanks to OpenStreetMap [1]. As the user zooms on any location on the map, real-time geolocated air quality data is loaded by contacting AQIcn [2] and overlayed as circles that are colored based on the level of pollution in that area. When clicking on a circle, historical air quality data is fetched from weatherbit.io [3] and displayed in a bar chart, along with input fields to tweak the time range. Additionally, the sonification of the data in the chart can be requested by clicking on a dedicated button. This triggers an HTTP request to the server, which includes the air quality data as a JSON payload and triggers the sonification process, detailed in the following subsection.

3.1 Sonification process

We adopted a combination of two approaches for our air quality sonification strategy: audio synthesis and sound design. The first technique consists in generating a new sound track from scratch, without the usage of any acoustic instrument. Audio synthesis can create interesting and unique, but usually not very expressive sounds, mainly due to the lack of harmonics. A harmonic is a wave whose frequency is a positive integer multiple of the fundamental frequency, and it's usually responsible for defining the stamp of an instrument or a human voice. To overcome the drawback of audio synthesis, we have resorted to sound design, which consists of the usage of sounds from real musical instruments to induce certain feelings in the listener. For example, musical theory suggests that higher musical chords and scales express positivity, while dissonances and lower pitches express negative emotions [8].

Two aspects of pollution have been sonified: pollution trend and residual pollution. The first, as the name suggests, is a series of AQI measurements and makes up for the lead track of the sonification output. This dataset is prone to spikes, as the level of pollution can suddenly change in response to certain events, so each value must be represented by an individual note. We chose a major scale to sonify the pollution trend, which is the graver the higher the value of the pollution is. Since major scales transmit positivity, we introduced dissonances that get gradually stronger and more frequent at higher pollution levels, to break the harmony and convey a sense of tension to the listener. The sub track is generated from residual pollution data, which indicates a health risk that continues over time following a

[1] https://www.openstreetmap.org/
[2] https://aqicn.org/
[3] https://www.weatherbit.io/

particularly polluted day. This value is subject to high increments, sonified with an arpeggio of ascending notes, and gradual decrements, represented by less frequent notes that slowly decrease in pitch and volume over time.

To make the synthesized track more interesting, we applied some audio effects to it, picking them from Archetype Gojira, a software made by Neural DSP in combination with the french metal band Gojira. The following effects were chosen: i) delay, to give the residue an echo effect which highlights its persistence over time; ii) reverb, which emulates the bouncing of sound waves in a room; and iii) shimmer, the harmonization of a sound that creates a "many-voices choir" effect. Audio synthesis is not without complications. The most common is probably the presence of some "pops" and crackling while playing the track. These unpleasant sounds are caused by playing discordant notes, when the speaker travels too great a distance in too short a time. To avoid this issue, we used an envelope, which is a filter that enables handling the volume in a gradual manner.

The format of choice that has been used during sonification is MIDI (Musical Instrument Digital Interface). Creating, editing and exporting MIDI tracks is a simple procedure that does not require prior knowledge of how sound works at a hardware or software level, nor does it need any programming skill. A MIDI track is a sequence of events, each with a distinct function, start time, end time, channel and value. Additionally, the MIDI standards include General MIDI, a specification for electronic musical instruments that respond to MIDI events. This enabled the possibility of just choosing a set of General MIDI compliant instruments, delegating the actual synthesis to a third party software. Finally, after the sonification procedure is complete, the audio track is converted to WAV format and stored on the disk.

The entire sonification process, as well as the generation of the animated charts (videos), is carried out by a Python program that can be interacted with through a set of REST APIs. MIDI tracks are generated thanks to the MIDIUtil library [4], audio effects are loaded with the Pedalboard library by Spotify [5], audio is synthesized with Timidity++ [6], and Matplotlib [7] is used to generate the animated charts for the demo.

4 PRELIMINARY STUDY

To understand how the air quality data are perceived through the two different approaches of sonification and visualization, we planned a four-step online study exploiting a website (ad-hoc created for the evaluation), and a Google Form questionnaire.

(1) introduction (website homepage): it involved a brief explanation of the AQI [2] and an introduction to the two modalities we exploited to convey the data (audios for the sonification and animated videos for the visualization);
(2) sonification (website second page): we exposed the participants to five audios (automatically generated exploiting our REST APIs), each one representing one of the 5 selected cities;
(3) visualization (website third page): we exposed the participants to five animated videos (automatically generated exploiting our REST APIs), each one representing one of the 5 selected cities;
(4) (Google Form) questionnaire: we asked the participants to answer a questionnaire made of six sections (as visible in Figure 1), asking i) their knowledge and perception of AQI (Q1-Q10), ii) the perception related to the audios (sonification) (Q11-Q26); iii) the perception related to the videos (data visualization) (Q27-Q31); iv) the comparison between audio (sonification) and video (data visualization) (Q41-Q53); v) demographics (Q54-Q55);

[4] https://github.com/MarkCWirt/MIDIUtil
[5] https://github.com/spotify/pedalboard
[6] https://timidity.sourceforge.net/
[7] https://matplotlib.org/

ID	QUESTION	
Q1	In the past 12 months, was there a time when you thought or felt that the air quality where you live was bad?	
Q2	In the last 12 months, was there a time when you or were informed that the air quality where you live was bad?	
Q3	Did you do something different when you thought or were informed that the air quality where you live was bad?	
Q4	If you answered yes to the question above, what did you do?	
Q5	Have you ever heard or read about the "Air Quality Index" (AQI)?	
Q6-Q10	In your opinion, on average, what is the air quality in	New Delhi?
		Rome?
		Beijing?
		Cesena?
		London?
Q11-Q15	In your opinion, how would you rate on average the air quality heard in	Audio 1?
		Audio 2?
		Audio 3?
		Audio 4?
		Audio 5?
Q16	Map each audio with one of the city (New Delhi, Rome, Beijing, Cesena, London)	
Q17	Please rate the following statements.	Understanding air quality trends via sonification required a lot of mental effort
Q18		I was frustrated with not understanding air quality trend via sonification
Q19		I'm sure I understood air quality trend from the audios I listened to
Q20		I think it's easy to understand air quality trends by sound
Q21		I was able to understand the differences in air quality between the various audios I listened to.
Q22		The variations of trend within a sonification are easily distinguishable
Q23		It takes little time to understand the sonification
Q24		The sound is aesthetically pleasing (and not annoying)
Q25	Do you think sound should be used more often to communicate data?	
Q26	Can you motivate your answer?	

ID	QUESTION	
Q27-Q31	In your opinion, how would you rate on average the air quality seen in	Video 1?
		Video 2?
		Video 3?
		Video 4?
		Video 5?
Q32	Map each video with one of the city (New Delhi, Rome, Beijing, Cesena, London)	
Q33	Please rate the following statements.	Understanding air quality trends via visualization required a lot of mental effort
Q34		I was frustrated with not understanding air quality trends via visualization
Q35		I'm sure I understood air quality trend from the videos I watched
Q36		I think it's easy to understand air quality trends through the visualization
Q37		I was able to understand the differences in air quality between the various videos I watched
Q38		The variations of trend within a visualization are easily distinguishable
Q39		It takes little time to understand the visualization
Q40		The visualization is aesthetically pleasing
Q41	Map each video with one of the audio listened	
Q42	Please rate the following statements about sonification.	The data on air quality remains more impressed on me if listened to
Q43		I can concentrate on other things while listening to air quality information
Q44		I feel involved in the sonification experience
Q45		I feel "immersed" in the sonification experience
Q46		I perceive air quality data more precisely with sonification
Q47	Please rate the following statements about visualization.	The data on air quality remains more impressed on me when viewed on the screen
Q48		I can concentrate on other things while looking at air quality information
Q49		I feel involved in the visualization experience
Q50		I feel "immersed" in the visualization experience
Q51		I perceive air quality data more precisely with the visualization
Q52	Thinking about the pollution data you hear and see, which modality would you prefer to use?	
Q53	Could you motivate your answer?	
Q54	What gender do you identify with?	
Q55	What's your age?	
Q56	If you want, share a comment or suggestion about the project.	

Fig. 1. Questions asked in the last step of our process. **Q1-Q10** are the questions related to the knowledge and perception of AQI (in yellow), **Q11-Q26** are related to the perception of audio and sonification (in light blue), **Q27-Q40** are related to videos and data visualization (in green), **Q41-Q53** are related to the comparison between audio and videos, **Q54-Q55** are the demographics questions (in pink) and **Q56** is to collect feedback on the project (in white).

and vi) feedback (Q56). The questions were inspired by various studies in the research area of sonification [4, 12, 13, 19].

For our case study, we selected five different cities with different degrees of pollution, as shown in Figure 2. In particular, we selected: Beijing (with, on average, an unhealthy AQI with spikes of very unhealthy), New Delhi (with, on average, an unhealthy AQI), London (with, on average, a moderate AQI with severe spikes), Cesena (with, on average, a moderate AQI with good spikes), and Rome (with, on average, a good AQI with moderate spikes). We selected the hourly data for a day and a half, between 18/04/2023 and 19/04/2023, which were working days in the middle of the week.

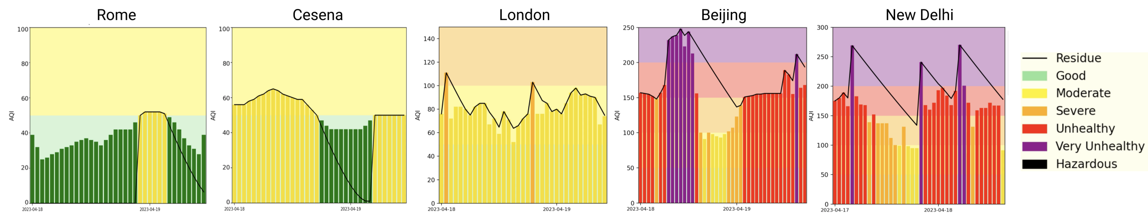

Fig. 2. Air quality data of the five selected cities.

4.1 Results

We had 14 participants in our study (engaged exploiting snowball sampling). All participants were between the ages of 18 and 45 and 12 of them were male.

Knowledge and perception of AQI. Concerning the air quality perception of our participants, 9 of them (64.3%) felt that the air quality of the area where they lived was not good (Q1). Despite that, 3 of them have not informed themselves or were not informed about the actual data (Q2). At the same time, one participant, although informed about poor air quality, did not perceive it. Moreover, notwithstanding the answers to Q1, only 2 participants did something different when they perceived the poor air quality (Q3): one looked for spots in the city where the air was better or moved to a city nearby where the air was better for that day, the other one wore a surgical mask (Q4). Regarding the knowledge of AQI, 9 of the participants (64.3%) already knew about it before the interaction with our system (Q5). Finally, analyzing the answers related to the city exploited in this case study, on average, the participants considered the air quality between unhealthy and very unhealthy in New Delhi (in line with our data), between severe and unhealthy in Rome (incorrect based on our data), very unhealthy in Beijing (in line with our data), moderate in Cesena (correct according to our data), and severe in London (incorrect according to our data) (Q6-10).

Mapping between audio, video, and city. Concerning the air quality data perceived from the audio (Q11-Q15), we noticed that there is no clear majority on the average perceived level, but various nuances were perceived by the participants (Figure 3). Despite this, the emerged nuances, in most cases, reflect all the levels visible in the graphs representing the actual data (Figure 2). For example, looking at Rome, it clearly emerges an average good (green) level from the visualization (Figure 2), although yellow levels are also present. Analyzing the answers, the audio of Rome was perceived as good for 5 participants and moderate for 7. Moreover, comparing the actual data and the answers on the left of Figure 3, we noticed that participants tend to associate a more severe level to the data listened to if compared with the actual level. These results can have two explanations: i) the audio is more subjective to individual interpretation; and ii) the audio makes one perceive all the nuances, creating a more complete narrative, but from which it is more difficult to extract an accurate average value. Looking at the videos, almost all participants answered correctly about the average level for each video (Q27-Q31), proving that it is easier to understand an exact value through a visualization.

The nuances perceived with the sonification and the prior belief on the selected cities have conditioned the mapping between the audio and the city (Q16). While 8 participants (57.1%) guessed the audio for Beijing and 6 (42.9%) the one for New Delhi, just one guessed Rome and Cesena, and two London. As a matter of fact, participants considered Beijing as the most polluted city, so the majority of them correctly mapped the city with the audio considered worse. The same applies to New Delhi, believed to be the second worst. Concerning Rome and London, the participants had an incorrect idea of the average pollution value, so they had more difficulty with the mapping.

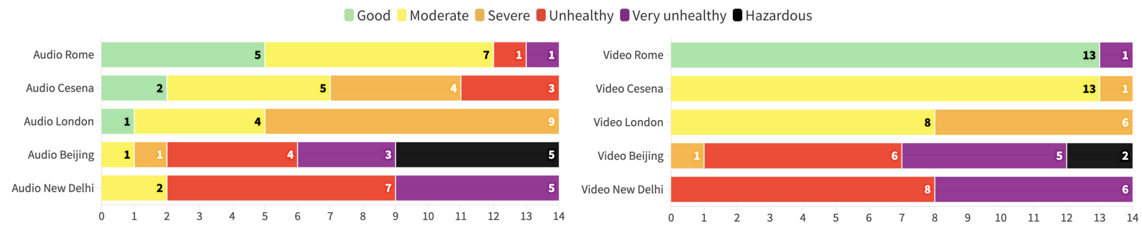

Fig. 3. Answers to Q11-Q15 (on the left) and to Q27-Q31 (on the right) about the air quality data perceived from the audios (left) and videos (right).

Analyzing the mapping between the video and the city (Q32), also in this case, the results were clearly influenced by the prior belief. In relation to the sonification, the results were worst for 3 cities: New Delhi (guessed by 5 participants), Rome (not guessed by anyone), and Beijing (guessed by just 3 participants). We had better results for Cesena (guessed by 2) and London (guessed by 4). This outcome suggested that the nuances perceived through the sonification can help in some way the mental mapping with the city, limiting a bit the effects of the prior belief.

Concerning the mapping between video and audio (Q41), we noticed better results for cities with worse air quality values like Beijing (7 guesses - 50%) and New Delhi (6 guesses - 42.9%), followed by Rome (5 guesses), London (4 guesses) and Cesena (1 guess). This finding suggested that the algorithm exploited to convert data into sound worked best for high values of AQI.

Comparison between audios (sonification) and videos (data visualization). To analyze the differences between audios and videos, we selected 13 dimensions investigated through a set of questions; whose answers are visible in Figure 4. Through their analysis, we found that visualization scored higher for 9 dimensions. In particular, the visualization was considered less mentally demanding than the sonification (Q17-Q33) and less frustrating (Q18-Q34). The frustration derived from the thought to have not correctly understood the data (Q19-Q35). To help with that, one participant suggested having samples of the sounds with an indication of the meaning to obviate any subjective interpretation. This preference is reflected in the answers about ease of understanding (Q20 and Q36). Despite that, the majority of the participants (71.4%) have found it easy to understand the variations between the five audios (Q21), and 8 of them (57.1%) have found it easy to understand the variations and trends inside the same audio (Q22). However, the values were higher for the visualization, as all participants found understanding the differences between the videos easy (Q37), and 11 of them easily recognized the variations inside the same videos (Q38). About the time required to fully understand the data, the answers reflected what we expected, as they showed a clear preference for visualization (Q23-Q39). Considering how much data remains impressed and against our belief, the participants generally preferred visualization (Q42-Q47). However, the sound was considered more pleasant than the visualization (Q24-Q40). Based on the answers, compared to visualization, sonification was preferred for other three dimensions. First, it allows users to concentrate on something else (Q43-Q48), second, increases the level of engagement (Q44-Q49), and, third, makes the users feel more immersed in the experience (Q45-Q50). Despite that, the visualization gives more precise information on the data (Q46-Q51). However, half of the participants believed sound should be exploited more often to communicate data (Q25), as also proven by qualitative feedback (Q26). P1 stated: "Sound is very intuitive, so it is easy to understand its trend and get a general idea of the situation, also because some sounds 'give an idea of pollution' (e.g. the pulsations of some of the audios in this study). However, sound also has an uncertain semiotic content and it is difficult to assign an absolute

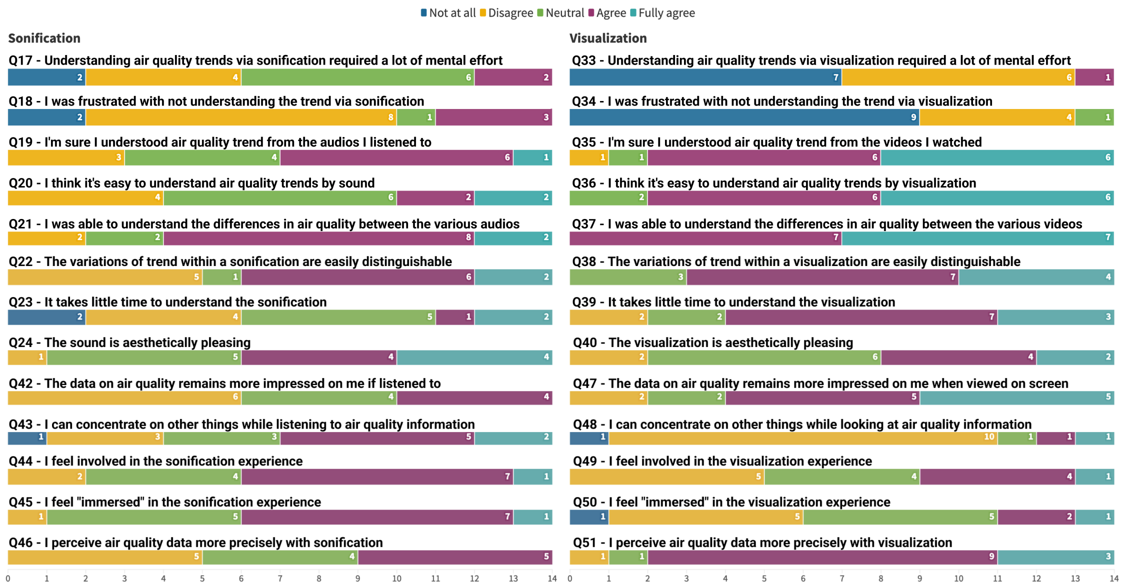

Fig. 4. Answers to Q17-Q24 and Q42-Q46 (on the left), and to Q33-Q40 and Q7-Q51 (on the right) about the selected 13 dimensions to better investigate the differences between sonification (audio) and data visualization (video).

value to it, so each person's actual interpretation is perhaps less predictable than in other means of representation.", P8: "With sound, you can involve the person more, sound can influence mood changes and I believe it is effective for communicating data even to people who cannot read graphs (boring and sometimes badly formatted). The difference in the pitch of the sounds makes it possible to perceive a difference in air quality", and Q13: "Sound leaves a sharper memory and information than a graph, although it requires more initial time to understand how it works". In addition to that, 71.4% of the participants believed that visualization and sonification should be used together (Q52) to exploit the benefits of each methodology. As proof of that, P3 stated: "Visualisation helps one understand the data. Sonification makes them more expressive. If they are used together they give very good results in my opinion.", and P13: "Both modes have advantages that the other lacks: for example, visualization is more immediate, but sonification remains more imprinted after understanding it". We also had an alternative from P7: "Billboards scattered around the city with visual indicators would be more effective. Sound elements would contribute to noise pollution".

5 CONCLUSION AND FUTURE WORK

This paper presents a preliminary study on the perception of air quality data through two different methodologies: visualization and sonification. Based on our results, visualization is generally preferred, even though sonification is more engaging and makes the users more immersed in the experience. However, if possible, the combination of the two methodologies should be better investigated. Also, we noticed that the prior belief in the pollution level in a city influences the mapping between data and the city. This study is still a work in progress. Concerning the next steps, we plan to: i) test the combination of the two methodologies, and iii) investigate if the exposure to the system can increase the actual awareness of AQI.

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