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A MULTI-DOMAIN COMFORT WALK: CROSS-MODAL INTERACTIONS ON ACOUSTIC PERCEPTION

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ABSTRACT

Although human comfort is influenced by several environmental factors, multi-domain comfort remains largely unexplored, particularly regarding the cross-modal effects of acoustic perception. Addressing this gap, this study presents a multi-domain comfort analysis in urban areas. Comfort walks were conducted between an urban park and a commercial hub located in Perugia, central Italy, over four consecutive days, at 2 pm and 6 pm, with three different participants answering a comfort survey at each location. Acoustic environments were evaluated in terms of sound pressure level and spectral content, revealing that the park was noisier than the commercial area. However, the sound of water from the park's fountain likely masked unpleasant anthropogenic sounds due to its broad spectral distribution. As a result, acoustic quality was perceived as better in the park. Furthermore, recognition of natural sounds was found to be associated with improved air quality perception and higher levels of visual and overall comfort, underscoring the significance of the water fountain in enhancing multi-domain comfort. In conclusion, this study highlights the importance of considering multi-domain comfort in urban resilience under climate change scenario. By considering the interplay between various environmental stimuli, we can create more pleasant outdoor spaces that promote human well-being.

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1. INTRODUCTION

Noise pollution is an inevitable issue of urban environments, which is augmented considering the rapid urbanization process and the consequent transport, industry, and community activities [1]. Given this problem, the concern about the negative impact of noise on people's well-being and health has increased [2], thus boosting the interest in assessing acoustic comfort and strategies to mitigate these impacts. In particular, soundscape (i.e., "acoustic environment as perceived or experienced and/or understood by a person or people, in context" [3]) research has been growing as it provides a holistic approach that connects physical, social, and psychological perspectives aiming at characterizing, managing, and designing acoustic environments [4].

Outdoor environments are complex and characterized by several environmental settings. Changing one of these settings can impact others and, consequently, influence human comfort level [5]. For this reason, environmental comfort studies are moving towards multi-domain investigations nowadays, that is, the interactions and crossed effects between different comfort domains are gaining attention. For example, Geng et al. [6] found significant interactions between acoustic perception and sound types with thermal comfort. Jin et al. [7] also concluded that there are cross-modal effects between thermal and acoustic environments that can affect overall comfort levels as well. However, studies applying this approach to outdoor environments are still few [8] but should be further explored as the overall comfort cannot be fully comprehended by analyzing the impact of individual domains on human comfort [5].

Under this context, this study presents an outdoor comfort assessment through a multi-domain comfort walk inspired by the soundwalk, a technique for evaluating soundscapes currently standardized by ISO/TS 12913-2:2018 [9], in which participants are asked to walk along a predefined path and stop in some locations to listen and provide their evaluations and comments. The main objective of this method is to catch human sensations and responses regarding the acoustic environment [9], which cannot be simply measured by environmental units as they can be also influenced by social, demographic, and behavioral characteristics, as well as by different sound sources [10]. As this study proposes a multi-domain comfort analysis, the walk here presented focused on all comfort domains instead of only acoustics, both in terms of environmental monitoring and subjective assessments.

The aim of this study is to provide a detailed comparison of two outdoor areas in terms of their acoustic environments and evaluate how spectral audio-content of different sources affect human perception not only in terms of acoustics, but also referring to other comfort domains (namely, thermal, visual, and air quality). In detail, the two places refer to an urban park and a commercial hub located in Perugia, central Italy, and were selected because they are areas dedicated to leisure activities but with different morphological and anthropological characteristics. The acoustic environments were described in terms of sound pressure level and spectral content. The multi-domain analysis was performed by comparing the subjective assessments provided for the two places through a dedicated survey, specifically verifying how the perception of different sound sources affected citizens' comfort from a multi-domain perspective.

2. MATERIALS AND METHODS

2.1 Monitoring campaign

This study was based on a multi-domain comfort walk. This method consists of completing a pre-defined path monitoring the environmental parameters and accompanied by people who provide their subjective assessments about environmental perception. The experiment was repeated twice a day (at 2 pm and 6 pm) for four consecutive days (from June 12th to 15th, 2021), for a total of eight comfort walk sessions. The walks always started at one of the places under investigation and ended at the other.

For environmental monitoring, a wearable device was used to record data related to thermal, visual, and air quality domains, while acoustics were monitored with a digital sonometer and microphone recordings.

Three persons participated in each walk, for a total of 24 people involved in the campaign. The limited number of participants was due to the COVID-19 pandemic contingency in effect when the experiment was conducted. Participants' information was handled anonymously in accordance with the General Data Protection Regulation (GDPR). In each of the places under investigation, participants were invited to complete a survey about their environmental perception and comfort. They spent at least 10 min in these places before answering the survey, as silently as possible and within a few meters of the monitoring devices, to acclimatize to the surroundings.

2.2 Data collection

During the walks, a wearable device [11] was used to monitor the environment in terms of thermal, visual, and air quality domains. In detail, this system monitors air temperature, relative humidity, wind velocity and direction, atmospheric pressure, global solar radiation, illuminance, and CO_2 and particulate matter concentration. In addition, it has a GPS to track the specific position of its records, which are made every 5 s. This device was built to monitor environmental parameters on a hyperlocal scale and catch pedestrians' real exposure to the environment, providing data with high spatial and temporal granularity. Regarding the acoustic domain, the sound pressure level was measured with a digital sound level meter (model C.A. 832, accuracy = ± 1.5 dB) using the weighting curve A. Moreover, during the 10 min in which participants waited to acclimatize with the surroundings, an audio recorder (model Zoom H2n Handy Recorder) was used to record the acoustic environment of the places under investigation in bi-channel stereo audio configuration.

Subjective assessments of both places were collected through a multi-domain comfort survey based on the guidelines of ISO 10551:2019 [12], with questions about the level of thermal, visual, and overall comfort and air quality perception, all answered in a 5-point Likert scale (from "very uncomfortable" to "very comfortable"). Concerning the acoustic domain, the survey followed the recommendations of ISO/TS 12913–2:2018 [9]. First, participants were asked about the level of noise perception ("very noisy" to "very silent") and how they describe the acoustic environment in terms of quality ("very bad" to "very good"), again on a 5-point Likert scale. Moreover, the survey included questions about sound source identification, where participants should classify to what extent they heard traffic, natural, anthropic, and other sounds, on a 5-point scale ("not at all", "a little", "moderately", "a lot", or "dominates completely").

2.3 Data analysis

First evaluations of the acoustics environment of the two locations were done using the sound pressure levels measured with the A-weighted filter. Then, a qualitative analysis was carried out to extend the analysis involving the spectral content of the recorded audio signals during the experiment. The stereo signals have a sampling frequency of 48 kHz and they were cross averaged between the two channels to gain a single signal. A power-frequency spectral analysis with a Hann window was carried out in Matlab environment. To enhance the definition of the spectrogram, the weighted power-frequency range threshold was set between -70/-100 dB. Then, to evaluate the power-frequency contribution of the water sound in the spectrum, the water sound was isolated from recordings and a non-linear power spectrum subtraction was performed on the recorded signals by a nonlinear multi-band Bark scale frequency spacing approach [13].
Then, as a multi-domain analysis, a qualitative assessment of the relationship between acoustic environment perception and the other comfort domains was performed. In particular, it was evaluated how the perception of different sound sources (especially traffic and natural sounds) influenced the acoustic perception as well as the level of thermal, visual, and overall comfort, and air quality perception.

2.4 Case studies

This research was conducted in Perugia, a city in central Italy characterized by a humid subtropical climate (Cfa climate zone [14]). Two places dedicated to leisure activities were under investigation: an urban park (UP, always the starting point of the walk) and a commercial hub (CH, ending point). Figs. 1 and 2 present the places. These places are near to each other, then the walk length was approximately 1 kilometer and lasted around 56 min, including the 10 min of acclimatization in each place.

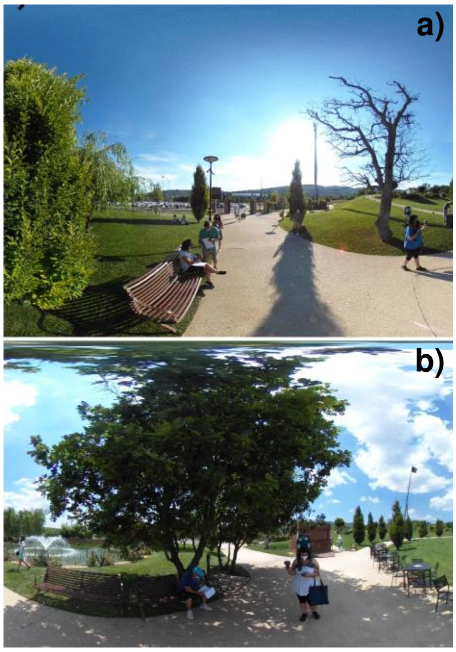


Figure 1. Monitored urban park (UP): a) walking path; b) resting area close to the fountain.

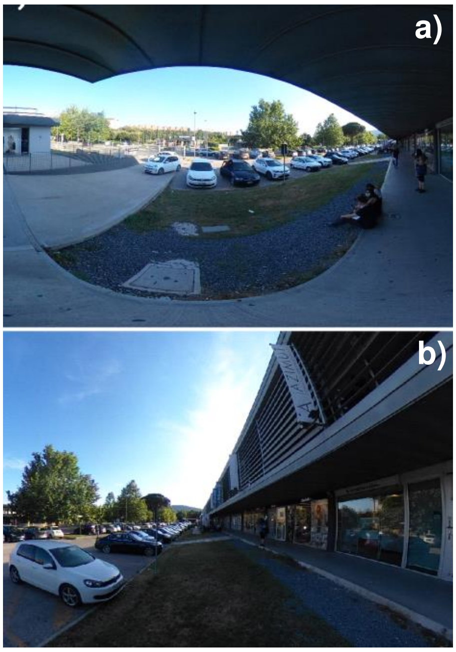


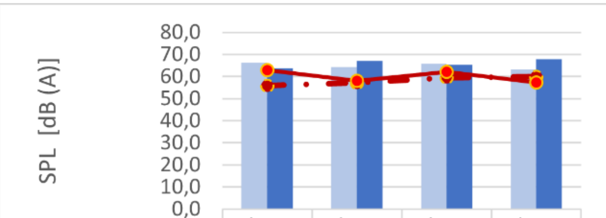
Figure 2. Monitored commercial hub (CH): a) covered area; b) parking lot.

The UP is an open area that incorporates greenery with sidewalks and seats (Fig. 1a). The spot where participants stayed for acclimatizing is close to an artificial lake with a fountain (Fig. 1b). Moreover, there is background music in the entire park area. The CH (Fig. 2) is a building with two floors, the first one dedicated to stores and restaurants and the second to offices. It is located on a very busy road and has a parking lot between the building and the street to serve the customers. It is also close to the rails of a public transportation system. In front of the building, there is a covered sidewalk where the participants stayed to acclimatize to the environment, close to the building façade.

3. RESULTS AND DISCUSSIONS

3.1 Acoustic data

A summary of the acoustic conditions during the experiments is reported in Fig. 3, with the sound pressure level measurements reported in function of the location, day, and time. During all days, sound pressure levels at the UP were higher than at the CH ones with a maximum difference of 10,6 dB(A) at 2 p.m. on day 1. During the same day, it was reported the smallest difference of 0,9 dB(A) at 6 p.m. However, generally, the difference between UP and CH is >5 dB(A). The listening and the spectral analysis of the two environments highlighted the presence of water in the UP, which may prevail on other noisy sounds like traffic (Fig. 4).



	day 1	day 2	day 3	day 4
UP 2 p.m.	66,4	64,2	65,9	63,2
UP 6 p.m.	63,7	67,1	65,3	67,8
CH 2 p.m.	55,8	57,2	59,5	59,9
CH 6 p.m.	62,8	58,1	62,2	57,2

Figure 3. A-weighted sound pressure levels at the two locations, with the day and measuring time.

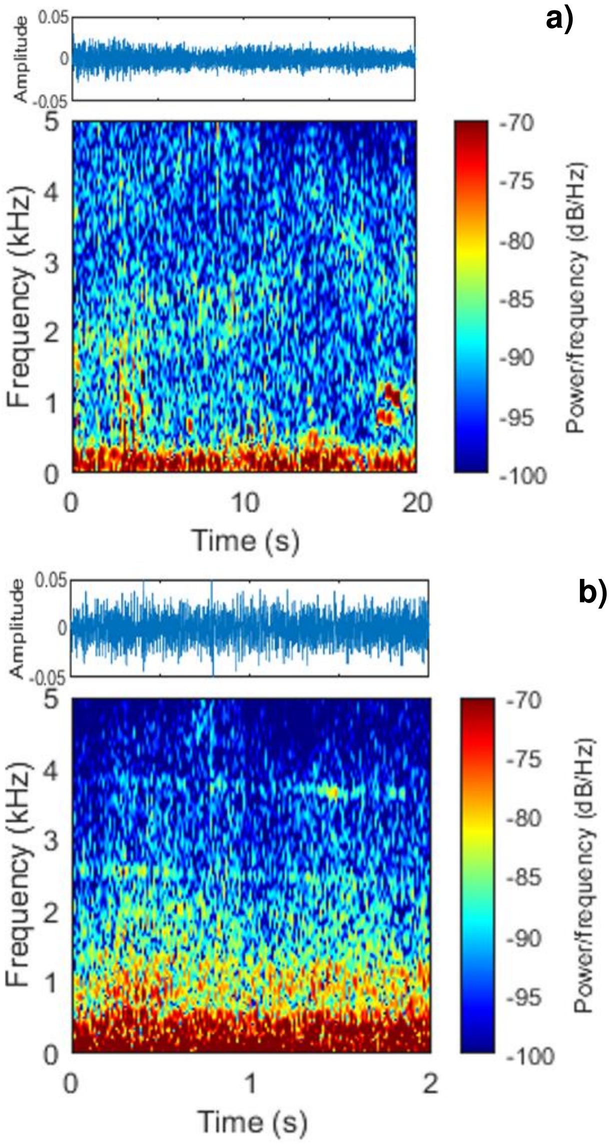


Figure 4. A 20 s segment of the amplitude and power-frequency spectrogram of the sound signal between 20Hz to 5 kHz for UP a) and CH b).

Given the potential acoustic masking effect of water sound reported in literature [15], the water power-frequency spectrum was isolated from the recordings. Fig. 5 points up the water sound contribution on the spectrum and reports a flickering sound with a quasi-harmonical distribution starting from the low-frequency range (<250, 750, 1500, 2000, 3000 Hz). Subtracting the power data on the recording noise and the water spectrum in the initial sound signal from recordings, the resulting spectrum is reported in Fig. 6 where the same time window of Fig. 4 is there reported without the power-frequency contribution of the water sound.

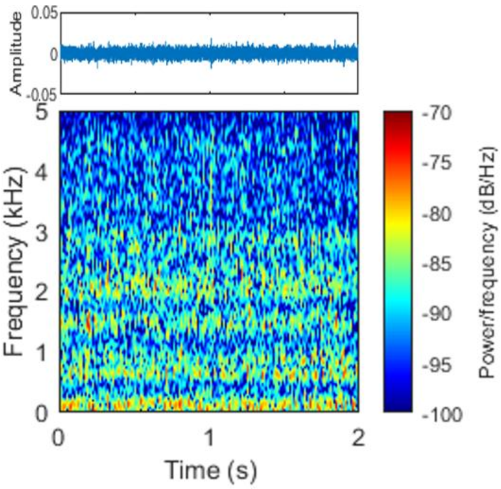


Figure 5. A 2 s segment of the amplitude and power-frequency spectrogram of the sound signal of water at UP between 20Hz to 5 kHz.

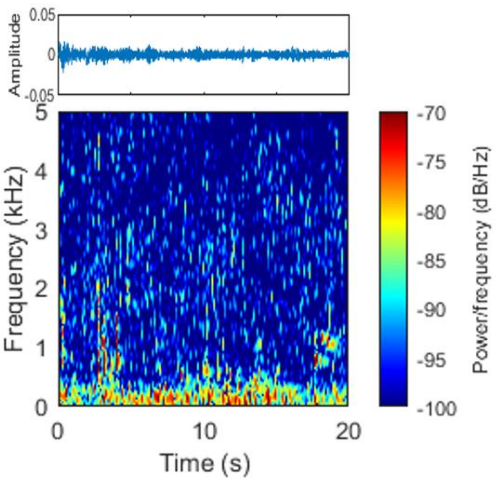


Figure 6. A 20 s segment of the amplitude and power-frequency spectrogram of the sound signal (from Figure 4a) with the water spectrum subtraction between 20Hz to 5 kHz.

Without it, Fig. 6 highlights the lack of spectral power in the considered frequency range, in the lower part of the spectrum too (<250 Hz). Indeed, in that section, the maximum reported value is -75 dB(A), 5 dB lower than the previous spectrogram (-70 dB(A) in Fig.4).
Therefore, the highlighted differences between the two spectra can prove the contribution of water in terms of power frequency and in terms of potential masking of any noisy content like cars, transportation, motorways etc. Unfortunately, any quantitative comparison is not possible because no calibration file is available for the audio recordings, only spectrum-averaged sound pressure levels at the moment of the recordings are available.

3.2 Subjective assessments

Tab. 1 presents the mean votes relative to the subjective assessments of each place. It is important to highlight that all these questions were answered on a 5-point Likert scale, so negative values represent bad evaluations, 0 is neutral, and positive values mean good assessments. Additionally, Fig. 7 presents the detailed subjective assessments regarding acoustics at both places, considering the votes from all walks. The UP was better evaluated in all comfort domains, which also resulted in a better overall comfort evaluation. In fact, the CH was always hotter than the UP (mean difference of 1.5 °C, sd = 0.9), and higher wind speed was registered at the UP (mean difference of 3.3 km/h, sd = 1.0), which improves thermal comfort at the UP considering that the monitoring campaign was performed during hot days. Moreover, the UP also had lower $PM_{2.5}$ (mean difference of 1.7 µg/m^3, sd = 1.2) and PM_{10} (mean difference of 1.8 µg/m^3, sd = 1.1) concentrations, which can lead to better air quality perception at this place. In addition, the better visual comfort level in the UP can be due to the natural landscape. Indeed, greenery and water elements have already been found to enhance visual satisfaction [16].

Table 1. Mean votes regarding every comfort domain at the UP and CH.

Question	UP	CH
Thermal comfort	0.6	-0.3
Visual comfort	1.2	0.0
Air quality perception	1.3	-0.8
Noise perception	-0.6	-1.0
Acoustic quality perception	0.7	-0.7
Overall comfort	1.0	-0.4

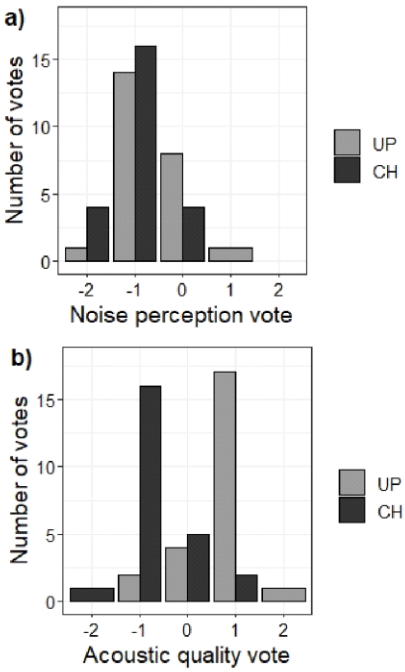


Figure 7. Subjective assessments regarding acoustics at the UP and CH: a) noise perception; b) acoustic quality perception.

Both places were perceived as noisy (negative mean votes), with a slightly worse assessment for the CH, even though the sound pressure level was higher in the UP. Despite the sound pressure, participants also better evaluated the acoustic quality in the UP. Then, the sound source perception was evaluated to investigate whether it could affect the different acoustic environment assessments. Fig. 8 presents the results of this assessment. In both periods, natural sounds were predominant in the UP, while traffic was the main distinguished source in the CH. At 6 p.m., anthropic sounds were more perceived than in the earlier sessions, a result of the greater presence of people during this period of the day in both places. Therefore, it can be concluded that even though the UP was noisier than the CH (higher A-weighted sound pressure level) and people recognize that the place is noisy (negative mean vote for noise perception), the fact that the main perceived source is from natural sounds contributes to increasing their level of acoustic comfort (positive mean vote for acoustic quality perception). In fact, in the UP, participants stayed close to the water fountain, which can somehow mask other unpleasant noise sources.

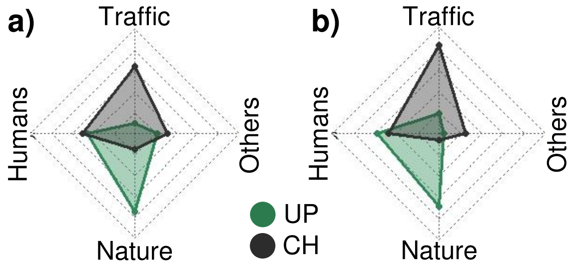


Figure 8. Perceived sound sources at the UP and CH at a) 2 p.m. and b) 6 p.m.

From the sound pressure level analysis (Fig. 3) the difference between UP and CH is >5 dB(A), and this is in contrast with the perceived noise conditions by the subjects (Fig. 7). It is not true that where the sound pressure level is higher, the perceived noise is higher, and the acoustic quality is lower. Indeed, although subjects rated CH nosier than UP for a few votes (Fig. 7a, -1.0 vs -0.6 Tab. 2), the acoustic quality vote clearly rated positively the UP over CH (Fig. 7b, 0.7 vs -0.7 Tab. 2). From the spectral analysis of the recordings, it was shown that the water contribution prevails in the 20-5000 Hz frequency range potentially masking the effect of anthropic noises. This result is in accordance with other studies that concluded that natural sounds are preferred and enhance acoustic comfort [5,17,18]. At the CH, on the contrary, the absence of natural sound could have led to lower acoustic comfort levels.

When comparing the sound source perception with other comfort domains, it was observed that, at the UP, as the natural sound was more perceived (i.e., more votes for "a lot" and "dominates completely"), enhanced visual and overall comfort (more votes for "comfortable" and "very comfortable") and air quality perception. Conversely, all the negative air quality perception votes at the CH are associated with lower natural sound perception (i.e., "not at all" and "a little"). Moreover, all people who declared to feel "very comfortable" overall in the UP also voted for "not at all" when evaluating the traffic sounds perception. In the CH, those who perceived air quality as "very bad" had a high perception of traffic sounds (i.e., "a lot" and "perfectly"). Therefore, it can be inferred that the natural sound perception contributed to improving not only acoustic but also the other comfort domains, especially air quality and overall comfort, while traffic sounds harmed air quality perception. For the park under investigation, the prevalent natural sound source was the water fountain. Then, water masking could be an interesting strategy for enhancing human comfort outdoors in general. It is important to highlight that this study is based on a small sample of participants. Therefore, additional data collection should be performed to verify the significance of these findings through statistical methods.

4. CONCLUSIONS

This paper presents a multi-domain comfort analysis in two different urban contexts located in Perugia: an urban park and a commercial hub. A total of 24 subjects were involved in the study, providing their thermal, acoustic, visual, air quality, and overall comfort perceptions in the two places. In addition, acoustic data were gathered by a sonometer (dB(A)) and audio recordings. The UP was better perceived in all comfort domains, which was expected since parks are well recognized for mitigating urban overheating [8] and reducing air pollution [19], as well as enhancing visual and acoustic satisfaction [20]. Matching the acoustic sound pressure level data with the acoustic comfort perception reported by the subjects, overall, the sound pressure levels at the UP were observed to be higher than at the CH, whereas the acoustic perception was opposite (better acoustic evaluations for the UP). Investigations on the spectral content of the post-processed audio signals highlighted the contribution in terms of power-frequency level in the UP recorded audio signal. By a non-linear power subtraction approach, water was targeted as the sound-signal masker on any anthropic activities, improving the perceived acoustic quality of the site. Moreover, it could be inferred that as natural sound was more perceived at the UP (mainly attributed to the water sound from the fountain), air quality perception, visual, and overall comfort also improved. Therefore, highlighting the benefits of fountains and water flows in the multi-domain perception, they may represent a suggestion on the design for urban outer areas. This finding is in line with other studies in the literature that have demonstrated the efficacy of water sound masking in mitigating extreme annoyance in industrial settings. For instance, research has shown that the noise of a water fountain can reduce the annoyance caused by electrical welding processes by up to 29% [21]. This underscores the potential of water sound masking as a viable solution for managing noise pollution in industrial environments. Moreover, in the current study, the UP configuration provides the opportunity to view the fountain from various angles during a walk, which can serve as an added advantage in reducing perceived noise, in addition to frequency masking. The literature confirms correlations between the benefits of water soundscape and fountain shapes [22]. Future developments involve a quantitative analysis of spectral content by water by acquiring calibration data and developing a more precise power spectral subtraction algorithm in terms of frequency windowing. Additionally, the small number of subjects hinders the statistical analysis of their perception. Therefore, further monitoring campaigns should be carried out to enhance the results.

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