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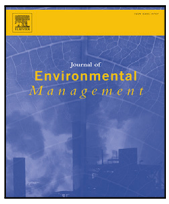

Research article

Urban background sounds under various weather conditions categorized for virtual acoustics

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ABSTRACT

One of the major problems in the auralization of complex urban scenarios is the creation of ambience, i.e. the diffuse background which represents the sound floor on which the acoustic scene of interest is created. Omitting a realistic ambience results in a sterile and implausible impression. To overcome this drawback, a hybrid approach with admixture of spatially recorded background sounds seems to be a promising approach. This paper provides a protocol to record and categorize background soundscapes for such applications. The freely accessible database contains 102 calibrated recordings at the IHTApark in Aachen (Germany) across various weather conditions, segmented into calibrated 30-second snippets. The categorization is performed based on the meteorological and acoustic parameters.

1. Introduction

1.1. Motivation

Critical listening to any urban environment reveals two important facts: (1) sound goes beyond what we can see, revealing details of the environment beyond our field of view (Krause and Payne, 2016; Monacchi, 2013); and (2) outdoor sound propagation is inherently time-variant due to weather-dependent atmospheric influence (Attenborough and Van Renterghem, 2021). For decades, acousticians have been developing algorithms to simulate such effects with the goal to synthetically generate soundscapes and sound fields that reflect the real-world experience. For example, the virtual acoustics technique, also known as auralization (Vorländer, 2008), is promising to simulate complex urban environments in planning processes. The efforts show great advances in that direction, however, with many remaining future challenges. A very important limitation of such simulations is weak plausibility when background sounds are not included. This is related to the high number of potential sound sources and the degree of spatial detail that would be necessary to be synthesized. This can be understood by imagination of an acoustical scene in an urban environment: on the one hand, there are sound sources that can be clearly distinguished from others or localized (Malmgren, 2022; Koutsoklenis and Papadopoulos, 2011), e.g. a car pass-by or a bird at some meters distance, as it can be seen at the upper sketch of Fig. 1. On the other hand, some sounds are arriving from far-away sources which are reflected, diffracted or absorbed by the environment (Valzolgher et al., 2024; Brungart et al., 2005; Good and Gilkey, 1996). With a sufficient number of distributed sources with a broadband spectral content, the resulting ambience is perceived by the listener with a diffuse and fluctuating character, e.g. a distant highway reflected through the surrounding environment and the mix with the rustling leaves of trees, as it can be seen at the lower sketch of Fig. 1. The combined simulation of both type of sources is currently a challenge and, certainly, the combination of both produces the characteristic urban soundscape. This manuscript aims to contribute to an efficient and more plausible auralization by proposing a hybrid and calibrated use of both.

It is known that traffic sound immission is affected by atmospheric conditions, so that a dependency of urban background sound can be expected, too (Attenborough and Van Renterghem, 2021; Dreier and Vorländer, 2021). According to Bass et al. (1995), atmospheric attenuation A_{atm} depends on several physical parameters:

$$A_{\mathrm{atm}} = \mathrm{f}(f, RH, T, p_{stat}) \tag{1}$$

where f is frequency, RH is relative humidity, T is temperature and p_{stat} is static pressure.

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URL: https://www.akustik.rwth-aachen.de (J. Llorca-Bofí).

[1] The recorded data can be interactively explored and listened to via https://paad-group.github.io/IHTApark-ambient-recordings/ and is publicly available for download at https://zenodo.org/doi/10.5281/zenodo.11184516.

[2] Klimamessstation Aachen-Hörn (2022).

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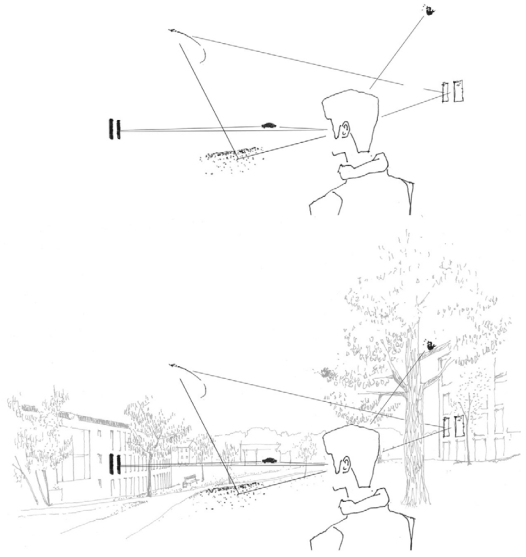

Fig. 1. Graphical representation of physically-based auralizations for singular and localizable sound sources, indicating the direct and first-order reflection paths of an aircraft, car and bird (top); with surrounding background sounds, including a relative high collection of sound sources and diffusely distributed around the listener (bottom) at the case study IHTApark.

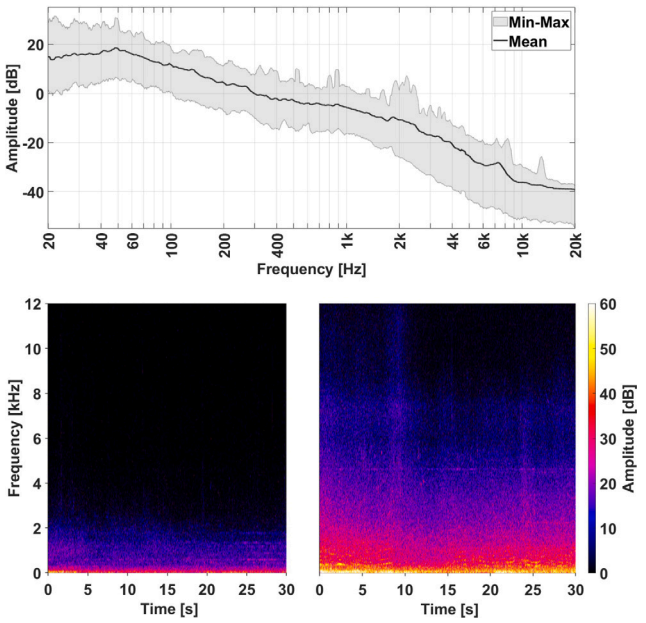

Fig. 2. Broadband spectra of the background sound recordings. Top: Mean and minimum–maximum variation of the sound pressure levels (SPLs) over all recordings at IHTApark at position 1 (see Fig. 3), derived from the time-averaged, 1/12-octave-smoothed frequency responses per recording. Bottom: Spectrograms of two selected background sound recordings. Left: Recording with the lowest SPL in the dataset. Right: Recording with the highest SPL in the dataset. The visualized signals are the omnidirectional W-channels of the Ambisonics B-Format.

In order to tackle the two issues we just described above – namely the improving spatial diffusivity and accounting to weather-dependent variations in outdoor auralizations – we collected the background sounds of the specific urban scenario IHTApark and correlate its psychoacoustic and weather indicators to categorize them for virtual acoustics.[1] The IHTApark environment was selected because it provides the laboratory conditions which make the study possible since it is located in the vicinity to a weather station.[2] This paper is structured as follows: Section 1.2 gives a broad overview of existing outdoor recording databases and highlights opportunities for the contribution of this work. Section 2 presents the materials and methods and serves as protocol for the data collection, calibration, postprocessing, sample selection, database accessibility, and integration of recordings into simulated auralizations. Finally, Section 3 describes the database using IHTApark as case-study, and the results of the correlations between psychoacoustic parameters and weather indicators, as well as the categorization of the recorded sounds. Section 4 presents a discussion highlighting the diffuse nature of background sounds, the main correlations, a comment on Just Noticeable Differences of the sound samples and potential applications of the actual work. Finally, Section 5 exposes the main findings and limitations of the study, as well as potential future developments.

1.2. State of the art and contribution of this work

In urban settings, listening occurs in complex environments containing different temporal, spatial and spectral sound field distributions due to numerous sound sources of different nature. It is known from soundscape studies that activities are influenced by the weather (Zhou et al., 2014; Kang et al., 2016). Notable weather impact on urban soundscapes are the wind direction and condition (upwind, downwind), surface wetness of pavements, building ventilation machinery, or the wind velocity that moves the trees' leaves and thus affects their rustling. For visual illustration, Fig. 2 reveals sound spectrograms of two background sounds recorded at the same location under variable weather conditions. The variations in level, as well as the frequency distributions illustrate the described effects. Therefore, incorporating these variations into outdoor auralization is the second aim of this work.

While field tests stay true to the complexity of the investigated environment and are more ecologically valid (Guastavino et al., 2005; Tarlao et al., 2022), they imply a loss of experimental control making reproduction a difficult task (Aletta et al., 2022). Integrating auralization into virtual reality allows users to be immersed in the virtual scene of the investigated environment (Vorländer, 2008). Thereby, vision and acoustics are stimulated and matched making the scene perceptually more authentic (Llorca-Bofí et al., 2022a; Jo and Jeon, 2022; Ruotolo et al., 2013; José Carles and de Lucio, 1992). This is a valuable method in laboratory research, compared to classical psychoacoustic experiments – which are usually based on pure tones or synthetic noise as stimuli –, as it increases ecological validity while maintaining control over the stimuli, background sounds, playback level and calibration (Maffei et al., 2016).

In this regard, auralization is becoming an increasingly more important aspect in the design process of architecture and environmental engineering (Thery et al., 2019). For example, it enables to experience and perceptively assess environmental noise pollution instead of using numerical values – such as loudness, level, or other psychoacoustic parameters (Fastl and Zwicker, 2007) – or graphical representations such as noise maps, as commonly done nowadays according to the ISO12913 (ISO 12913-3:2019, 2019).

In particular, open urban environments include a diversity of sounds originating from traffic, people, birds, etc., which are challenging to be simulated (ISO 12913-3:2019, 2019; Kang and Schulte-Fortkamp, 2016). These sounds travel over various distances and are exposed to the complexity of the environment including the variable physical properties of the medium, geometric characteristics of the surroundings, material absorption, phase shifts, etc. Outdoors, sound propagates through in-homogeneous media. Sound waves can be refracted through wind and by temperature layers and attenuated through atmospheric absorption. In addition, sound is reflected on the ground and at surfaces of buildings, diffracted at edges and barriers, and attenuated by vegetation. As a result, outdoor soundscapes are far more difficult to replicate than sound in closed rooms. Laboratories simulating outdoor

situations have recently become important for different acoustic purposes in order to study the behavior of sound in real conditions. As the presented work, several of the institute's research publications on auralization and visualization of urban scenes is based at the green area close to the institute's building, named IHTApark (Llorca-Bofí et al., 2022a; Llorca-Bofí and Vorländer, 2021; Heimes et al., 2022; Dreier and Vorländer, 2022; Dreier et al., 2022; Llorca-Bofí et al., 2022b). An audio–visual model as digital twin of the park already exists (IHTApark at Zenodo, 2021; IHTApark at gitHub, 2024), which uses synthesized sounds for the dominant technical transportation sounds and comprises visualizations of different weather scenarios. Hence, a database of recorded background sounds over various weather conditions became necessary to be included in the auralizations as noise floor to create the corresponding ambience.

The output of existing sound databases might be challenging to be integrated into a single comprehensive database due to the lack of standardized procedures. Often, these recordings are not publicly available, not calibrated and they lack environmental and/or acoustical documentation of the recorded scene (ISO 12913-1:2014, 2014). Most importantly for this work, detailed information on weather indicators are missing. Nevertheless, they lay a solid foundation for soundscape research. As suggested by Weisser et al. (2019), databases should fulfill the following four minimum requirements required for a database to be suitable for hearing research: (1) the recording files are provided in a format that allows accurate spatial reproduction of the scenes via headphones and loudspeaker arrays; (2) the sound pressure levels (SPL) are provided enabling reproduction at original levels; (3) scene descriptors are included allowing for selection according to preference and comparison between the databases; (4) recorded or simulated room impulse responses are provided or accessible to add other acoustic material to the scenes, as required, for instance for implementing a speech-in-noise test. Although these guidelines were developed for hearing research in the context of mainly speech communication, they serve well as basis for more general research on auditory perception.

There are a few existing databases containing structured recordings of typical acoustic environments. One of the most notable is The World Soundscape Project database (The world soundscape project, 1973), created by Schafer in the late 1960s, as it launches not only the research on environmental noise in urban places, but also the creation of databases of recordings. It includes recordings, detailed descriptors of the recorded environment as well as scene photos, exact location information, and occasionally a timeline description of sound events. However, these recordings are not calibrated making them problematic for accurate reproduction in controlled laboratory research. In 2010, the DESRA project focused on the development of the database for environmental sound research and application (DESRA, 2019; Gygi and Shafiro, 2010) and provided a diversity of calibrated sounds generated by various sound sources (localizable sound sources with and without background sounds) as well as detailed perceptual and psychoacoustical information for each sound file. Furthermore, the DEMAND database of diverse environments and multi-channel acoustic noise from 2013 (Thiemann et al., 2013) contains calibrated 16-channel recordings of everyday scenes from six broad classes, namely domestic, office, transportation, public, nature, and street, with each class containing 3 scenes. Similarly, the EigenScape database, created in 2017, provides spatial acoustic scene recordings in fourth-order Ambisonics format (EigenScape database, 2017; Green and Murphy, 2017), representing everyday scenes from eight classes, namely beach, shopping street, park, pedestrian zone, quiet street, shopping centre, train station and woodland. Each class contains eight scenes. While this database offers a considerable number of recordings with detailed comments and descriptors, they are also inadequate for auralization due to uncalibrated sound pressure levels and the lack of additional acoustic information. The ARTE database from 2019 consists of calibrated 62-channel Ambisonics recordings of 13 typical environments, such as office, library, church, living room, café, streets and train station (ARTE, 2019; Weisser et al., 2019). Being publicly available, acoustic properties including absolute level and room impulse response are additionally covered. Finally, the I Hear NY3D project from 2013 contains calibrated first-order Ambisonics recordings of six diverse locations in Manhattan, New York, as well as the corresponding acoustic parameters (Boren et al., 2013).

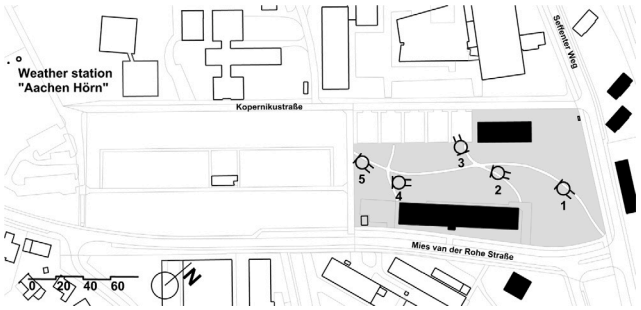

Fig. 3. Site map (IHTApark geolocation, 0000) of the IHTApark (gray) with five recording positions (frontal directions indicated by the microphone symbol), and the weather station. Street view available at: https://www.google.de/maps/@50.780904,6.0675193,3a,75y,250.3h,90.08t/data=!3m6!1e1!3m4!1s-rJSHXzz10-lQsPPKDzaIg!2e0!7i16384!8i8192?entry=ttu, last visited October 27th 2023.

The preceding review of the existing databases highlights the main contributions of this work:

1. Background sound database with additional weather data. Although several existing databases provide background sounds from urban scenes, they all lack meteorological information. Oftentimes, the recordings are mixed with other prominent sounds such as near pass-bys of cars, voices or machinery. Both, knowledge of weather conditions and the absence of unwanted prominent sound sources, is important to be able to later superimpose simulated sound sources.
2. Calibrated spatial background sound recordings according to the procedure explained in Section 2.2. This procedure allows for calibrated recordings without the need to use a reference microphone for the correct level information. Then, the recordings can be simply superimposed by the simulated individual sound sources.

Finally, a broader scope of this work is the current research on assessing urban environments through immersive audio–visual representations. In this regard, physically-based auralizations are crucial to keep the differences between scenarios close to the reality. Extensive research on audio–visual sensory monitoring of urban areas is being done in this regard (Garzón et al., 2023). Several approaches have been used to discover relationships between pleasantness and eventfulness in holistic audio–visual representations (Mouratidis, 2020; Mouratidis and Ziannakou, 2022) to assess what makes cities livable, focusing on the effects of contexts in urban residential areas on the pleasantness and appropriateness of natural sounds (Hong et al., 2020; Jeon et al., 2021). The variation of sound and visual–spatial metrics stimulates different feelings in people, and their relationship may enhance well-being in residential environments (Hasegawa and Lau, 2022). In this regard, this contribution aims to contribute to enhance plausibility of immersive audio–visual urban simulations, specially where sound matters.

2. Materials and methods

2.1. Recording locations

The selected study location is the IHTApark (50° 78′N, 06° 06′E) in the west of Aachen, Germany, next to the Institute for Hearing Technology and Acoustics (IHTA) in Kopernikusstrasse 5, 52074 Aachen.

The climate monitoring station (50°47'N,06°04'E, 222 m a.s.l.) is located approximately in a distance of 320 m from the IHTApark center. Due to this proximity, the data is representative of the weather conditions present in the IHTApark. The study site spans an area of about 9840 m^2 and is enclosed by the roads Kopernikustrasse to the north-west, the main road Seffenter Weg to the north-east, and Mies-van-der-Rohe-Strasse to the south-east, as shown in Fig. 3.

Five positions were chosen along the walking path. Thus, all positions present more or less the same surface sealing degree and the same vegetation cover in the surrounding area consisting of mostly grassland and deciduous bushes and trees with heights of approximately 20 m. Position **1** is next to the bench closest to the railway tracks and the main road Seffenter Weg, located closest to a highly trafficked area and the most open position, with only a small hill; position **2** next to the bench, situated centrally in the park at the crossing of the sand path, closest to air conditioning from the building at South-East; position **3** right at the entrance of the IHTApark from the parking slots, enclosed which might result in less wind exposure; position **4** at the highest altitude and closest to the air conditioning of the adjacent building; and position **5** situated in the park's corner.

2.2. Spatial microphone calibration

As introduced in Section 1.2, many of the existing databases of background sound recordings do not contain calibrated data. The Sennheiser AMBEO VR microphone does not have a documented frequency response, and thus, the frequency-dependent characteristics, specifically its free-field sensitivity, needs to be determined. Therefore, since there is no standardized calibration procedure for spherical microphone arrays, the calibration method proposed by Heck et al. (2022) was applied, which in turn refers to DIN EN IEC61094-8:2012-04 (2012).

2.3. Audio recording and post processing

The recordings consisted of simultaneous audio, video, and weather data collection. The setup consists of a vertically aligned Ambisonics microphone and 3D camera on a common tripod. For the data presented here, the following hardware was used:

- Portable Zoom H6 multitrack recording device to store the audio recordings;
- Sennheiser AMBEO VR microphone for first-order Ambisonics recordings;
- Voltage calibrator for recorder input gain calibration;
- Digital thermo-hygrometer KLIMA BEE 30.5036;
- Canon EOS R5 camera for photograph documentation.

The multichannel spatial sound field recordings were sampled with a rate of 48 kHz and a resolution of 24 bit. For each recording, the preamplifier gain of every channel was adjusted and individually re-calibrated for each recording in order to avoid clipping. For the spatial conversion of the audio signals, the native VST (Virtual Studio Technology) plugin from the microphone manufacturer (Sennheiser AMBEO A-B Converter, version 1.2.3) (AMBEO A-B Converter, 2023) was used for converting the captured Ambisonics A-format to AmbiX B-format (Zotter and Frank, 2019). Finally, for perceptually-correct reproduction with regard to spaciousness and timbre, the equalization method by Ahrens and Andersson (2019) can be applied.

2.4. Audio recordings segmentation

The final database includes a full 8-minute recording, referred to as "segment"; and a 30-second excerpt extracted from the 8-minute segment, referred to as "snippet", for each position from every recording session. These snippets are meant to be used in auralization. They serve the purpose of limiting clipping artifacts from wind noise or the predominance of individual sound sources, especially traffic noise.

Table 1
A-weighted levels in dB(A) as time-averaged mean value and its standard deviation (Std) over the recording positions 1-5. The 8-minute segments are compared to the 30-second snippets. Data is shown separately for weekdays (Week.) and weekends (Wnd.).

			1	2	3	4	5
Segments	Week.	Mean	40.70	39.30	38.02	38.53	36.72
		Std	10.95	9.81	9.91	9.83	10.32
	Wnd.	Mean	35.98	36.47	33.65	33.56	34.34
		Std	10.74	10.44	10.10	10.13	11.61
Snippets	Week.	Mean	33.05	32.10	33.25	30.83	30.83
		Std	9.96	9.80	9.55	9.834	10.67
	Wnd.	Mean	32.56	31.32	29.39	29.02	30.09
		Std	13.28	11.94	12.06	11.89	11.79

Meanwhile, they should also be representative of the scene and the corresponding ambience. To minimize unwanted sounds, the following exclusion criteria have been applied:

- wind noise,
- road noise,
- rail noise,
- other human-produced machine noises (e.g. leaf blowers, chainsaws, or lawn mowers),
- human conversation,
- walking footsteps.

In contrast, the segments should include:

- birds chirping,
- crows cawing,
- leaves rustling,
- antropophonic sounds such as the ringing of church bells or children playing and shouting in a distant schoolyard.

A manual selection and subjective evaluation of the segments has been carried out. An overview of the data after segmentation can be seen in Table 1.

2.5. Psychoacoustic parameters

The following (psycho)acoustic parameters are calculated for each sound snippet. The presented values are the average over the full length of each snippet (30 s).

- Sound Pressure Level (SPL) of unweighted (in dB) and A-weighted sound pressure levels (in dB_A) according to DIN EN 61672 (2013).

- Loudness (in sone) is a psychoacoustic quantity that maps the human perception of the sound level to a linear scale. Unlike a level description in dB, loudness values can intuitively be compared so that the ratio of two sone values correspond to their subjectively perceived ratio (ISO532-1:2017, 2017).
- Sharpness (in acum) is closely inverse related to sensory pleasantness and caused by high frequency components in a sound (Aures, 1985).
- Roughness (in asper) is caused by signal variations with very low modulation frequencies around its maximum at 70 Hz. With increasing roughness, noise emissions are perceived as increasingly noticeable and usually as increasingly aggressive and annoying (Sottek and Genuit, 2013).
- Fluctuation strength (in vacil) is caused by signal variations with very low modulation frequencies around its maximum at 4 Hz. These low-frequent modulations are typical in speech signals.
- Tonality (in tu_{HMS}) is a psychoacoustic calculation method for the identification and evaluation of tonal components in a sound (Sottek, 2018).

Throughout this work, for each parameter three values are computed:

- The time-averaged value (X).
- Its 5% percentile value (X5), aiming for a more robust estimator which excludes outliers over the time signal.
- The difference of both (X-X5), highlighting the parameter's variation over the time signal.

2.6. Weather data

Most of the meteorological data is obtained from the weather station Aachen-Hörn, (Klimamessstation Aachen-Hörn, 2022) (50°47'N, 06°04'E, 222 m a.s.l). Due to its proximity, the data is representative of the weather conditions present in the IHTApark (see location in Fig. 3). The following standarized indicators are registered in the corresponding units according to international standards:

- Atmospheric pressure [hPa].
- Air temperature [°C].
- Soil temperature [°C].
- Relative humidity [%].
- Solar irradiance $[\frac{W}{m^2}]$.
- Wind velocity $[\frac{m}{s}]$.
- Air absorption of sound, as a function of air temperature, relative humidity and atmospheric pressure (ISO9613-1:1993, 1993) $[\frac{dB}{km}]$. One value per octave-band has been calculated from 63 Hz to 8000 Hz.

The authors also collected additional non-standarized indicators. The aim of including them is to complete the meteorological description of the environments apart from the standarized indicators. They might provide intuitive descriptions of the environment that potentially indicate a relation to acoustic parameters:

- Foliage: presence of leaves on trees [0 Without leaves; 1 With leaves].
- Brightness: relative values to gray in RGB format [0–255]. Photograph perpendicular to the ground plane with the lens facing the sky. Camera properties were fixed across all takes. The photos are first converted into a gray-scale image. The intensity value is averaged over all pixels.
- Cloudiness: according to ISO/CIE Standard sky [0 Clear; 1 Partly cloudy; 2 Overcast; 3 Uniform].
- Surface wetness: by observation, in four categories [0 Dry; 1 Almost dry; 2 Partly wet; 3 Wet].
- Time category: three categories [1 Peak hours (8–9 am and 5–6 pm); 2 Daytime (9 am–5pm); 3 Nighttime (6 pm–8 am)].

The recorded weather data is gathered from the weather station's website, which provides them as 10-minute averages (Klimamessstation Aachen-Hörn, 2022). Additionally, relative humidity and air temperature are measured with a digital thermo-hygrometer KLIMA BEE 30.5036. Unlike the meteorological data from the weather station, the values from the digital thermo-hygrometer are instantaneously recorded at the measurement positions.

3. Results

3.1. Open database: Background sounds with weather information

The postprocessed measurements result in a database of 102 background sound recordings of 30 s ("snippets") and their corresponding weather data. The database is open access and available on the Zenodo repository (IHTApark background sounds, 2024). The distribution of the recordings across months and daytime is aggregated around the three measurement phases from 02.02.2022–18.02.2022, 20.04.2022–02.05.2022 and 05.12.2022–15.12.2022. Recordings are distributed throughout the day from early morning at 6 h 30 until midnight. Most of the recordings are concentrated around noon and the late afternoon. No recordings cover the time interval between 13 h 00 and 15 h 30.

The published spatial audio files are made available in different formats. The Ambisonics B-Format has been calibrated according to Section 2.2. It is delivered with and without a filtering accounting for better reproduction with regard to spaciousness and timbre, see Ahrens and Andersson (2019). The omnidirectional W-channel of the B-format is provided as one-channel/mono file. From this, the (psycho)acoustic parameters have been derived. Additionally, a binaural decoding is delivered (Bernschütz, 2013).[3] The binaural downmix can be listened via the website https://paad-group.github.io/IHTApark-ambient-recordings/ that allows to explore the dataset interactively by selecting the parameters according to which the dataset is displayed.

3.2. Correlation between psychoacoustic parameters and weather indicators

In this section, a categorization of the recorded data is presented with focus on accessibility and applicability for future users. To check which parameters are decisive to construct the categorization, a Pearson correlation between psychoacoustic parameters and weather indicators is performed. In Fig. 4, the X axis contains the weather indicators, and the Y axis the psychoacoustic parameters. The heat map shows the significant correlation values of indicator pairs with p-values lower than 0.05. The following observations can be made:

- Firstly, the strongest correlation is observed for relative humidity and sharpness. This might suggest that the more humid the weather is (Bass et al., 1995; Llorca-Bofí et al., 2022a) the wetter is the road and higher frequency content is audible due to the tyre contact on a road with water. In this regard, a similar correlation happens between sharpness and surface wetness, and between sharpness and cloudiness (see left-top plot of Fig. 5).
- Secondly, relative humidity correlates negatively with roughness. This weak trend is observable in the left-mid plot of Fig. 5. If this effect only relies on the source content or if the atmospheric sound propagation also has an impact, cannot be clearly concluded in this study.
- After these two important correlation observations, a connection between background sound and humidity as well as sound and surface wetness seems relevant. This is confirmed by observing a negative correlation between tonality T5 and surface wetness in Fig. 4 and can be observed in the right-top plot of Fig. 5. The high-frequency sound spectrum due to increased road surface wetness can potentially mask the tonal sounds of surrounding machinery. Furthermore, the results indicate that the variability of tonality (T-T5) increases in dry conditions. This can be understood as the result of birdsongs, which appear to grow with decreasing surface wetness. They usually show clear tonal components but with a fluctuating characteristic.
- Fourthly, air absorption in low, mid and high frequency regions (center frequencies of 125, 500 and 2000 Hz) negatively correlates with sharpness. The strongest correlation can be seen in the high frequencies, which could be expected since air absorption generally increases towards high frequencies (see the right-mid plot of Fig. 5). In contrast, roughness positively correlates with air absorption. In this case, the correlation becomes weaker for higher frequencies. An explanation for this could be that, as more energy from distant sources of any direction (which has the characteristics of a diffuse broadband noise) is absorbed, the more importance lies on closer sources which might be recorded with more detail including more time variances than those far-away sources. High frequency air absorption also shows negative

[3] Pluggin for binaural decoding from Bernschütz (2013): http://audiogroup.web.th-koeln.de/ku100hrir.html https://plugins.iem.at/ https://git.iem.at/audioplugins/IEMPluginSuite; https://plugins.iem.at/.

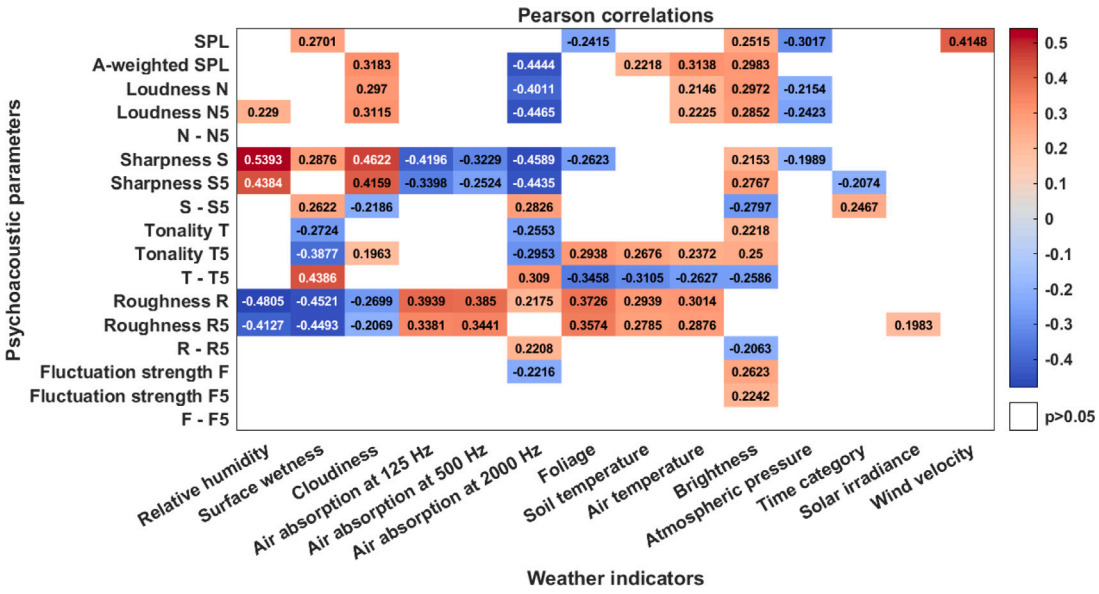

Fig. 4. Significant Pearson correlations between weather indicators and psychoacoustic parameters. Colors indicate correlation values in positive and negative scale. White cells indicate non-significant correlations ($p > 0.05$). On the X axis, the weather indicators are ordered from the highest (left) to the smallest absolute correlation values (right). On the Y axis, the indicators are ordered in triplets: indicator X, indicator X5 and their difference X-X5. To further explore the collected parameters, please visit the website https://paad-group.github.io/IHTApark-ambient-recordings/. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

correlations with tonality. This might be due to the same reason. The more the far-away broadband background noise is absorbed, the more closer sources like singing birds will gain importance. The correlations between level or loudness and air absorption appear to be inconsistent over the frequency bands which is why they are therefore not given any further importance here.

- A fifth important observation it that there is a strong correlation of sound pressure level with wind velocity. It can be explained by the strong low-frequency content which is induced at the microphone capsules by wind. This is confirmed by A-weighted SPL showing no correlation with wind velocity.
- The sixth observation is that foliage, soil temperature and air temperature show a similar pattern of correlations with tonality and roughness. For roughness, it behaves inversely to relative humidity, cloudiness and surface wetness (see first item).
- A seventh important finding is that loudness shows to correlate with less weather indicators and weaker than sharpness, tonality and roughness. Even though, e.g. more birdsongs appear with warm temperatures, those changes do not imply an increase in levels. This finding suggests that other parameters than loudness are important to consider in order to categorize the sound recordings according to weather conditions.
- Finally, the indicator brightness correlates with almost all the psychoacoustic parameters, which cannot be explained with the current analysis. Atmospheric pressure, time category and solar irradiance show only few and weak correlations and are not further explored. Fluctuation strength shows no meaningful correlation and is also not further considered.

The bottom part of Fig. 5 presents the categorization of all the recordings in the database. It is displayed as pairs between significant weather indicators (Y axis) and psychoacoustic parameters (X axis). The database spans a balanced distribution of sounds in all ranges of the weather and psychoacoustic parameters. The data have been categorized into three clusters per parameter, choosing a low, medium and high range for each according to the percentiles described in Table 2. In this way, the categorization highlights some correlations, e.g. surface wetness with tonality T5, by showing a diagonal (low–low to high–high). This suggests that the higher the surface wetness is, the less prominent are the tonality peaks (see Section 2.5 for further explanation on the psychoacoustic parameters). The explanation can be seen in the masking by the broadband spectrum of background sounds, which usually increases in the higher frequency range with higher humidity and wetness. Between roughness R and surface wetness, the negative correlation is also visible in the categorization plot by a diagonal in opposite direction.

Table 2
Value ranges for the selected parameters used for the categorization as per Fig. 5 (right). The low range comprehends data below the 0.35 percentile and the high range comprehends data above the 0.65 percentile.

	[Units]	Low	Medium	High
Temperature	[°C]	< 7.40	[7.40 - 10,63]	> 10.63
Relative Humidity	[%]	< 52.81	[52.81 - 68.90]	> 68.90
Surface wetness	[dry–wet]	< 1	[1 - 2]	> 2
Loudness N5	[sone]	< 6.12	[6.12, 7.16]	> 7.16
Roughness R	[asper]	< 0.11	[0.11, 0.14]	> 0.14
Tonality T - T5	[tu]	< −0.21	[−0.21, −0.08]	> 0.08
Sharpness S	[acum]	< 1.35	[1.35, 1.55]	> 1.55

4. Discussion

The large number of sound sources of similar acoustic spectral content (i.e. rustling of individual leaves or different cars in a very large distance) evokes a perception of background or ambience surrounding the listener. Additionally, this study reveals that the variation between background sounds – in terms of psychoacoustic parameters – is high across scenarios and weather conditions. This suggests that those factors should not be neglected and influence the soundscape composition. Important sound sources that contribute to the background sounds can be seen in birds, leave rustling and low-frequency spectral components, which originate mainly from human activity, such as traffic noise and ventilation machinery in adjacent buildings.

In this work, Pearson correlation coefficients are used to highlight to what extent audible features – by means of psychoacoustic parameters – relate to specific weather conditions. This is of practical importance for those who are searching a background sound for a virtual scenario.

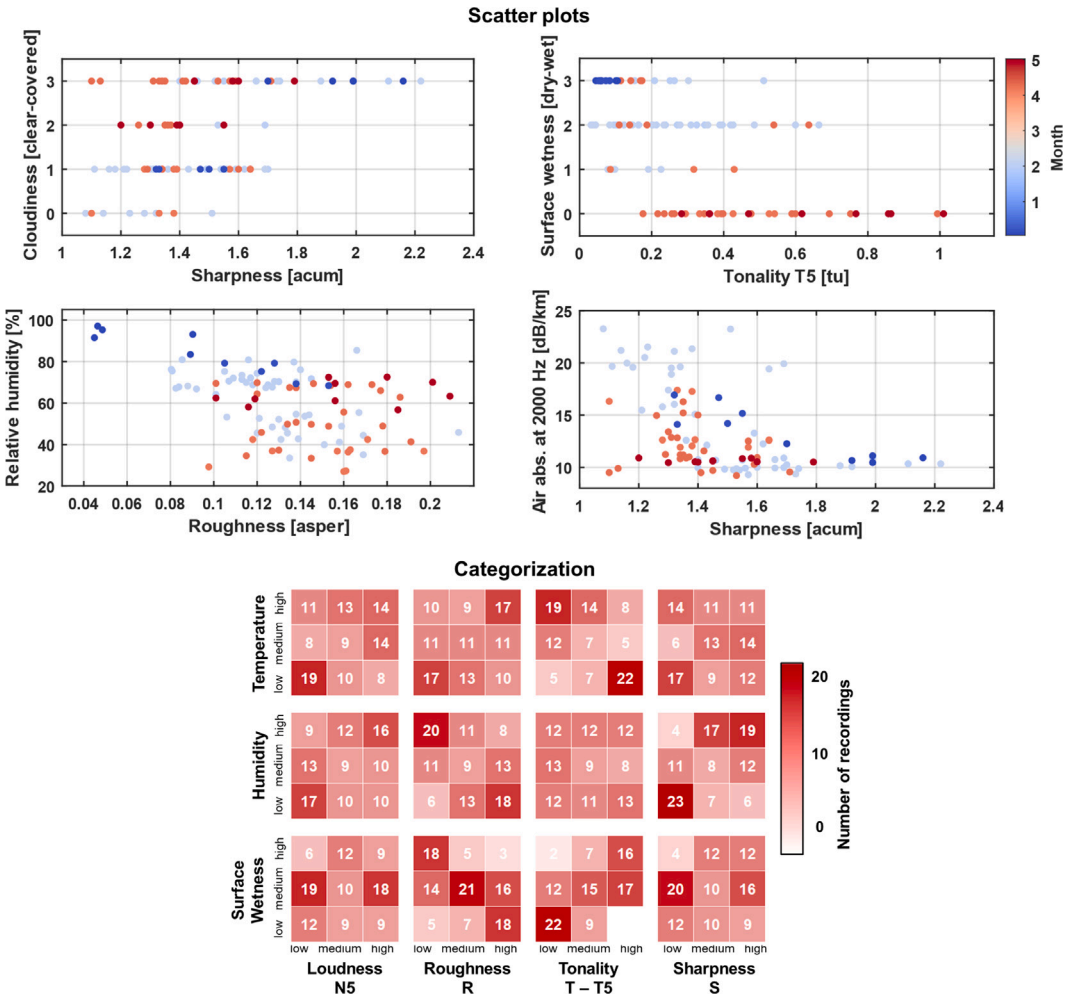

Fig. 5. Scatter plots and categorization map representing the dataset.
Up: The dots represent single measurements in terms of three different psychoacoustic indicators (X axis) in relation to a selected weather indicator (Y axis). The color scale indicates in which month the soundscape was recorded, from December (0) to May (5).
Down: The heat map categorizes the dataset of recordings according to four psychoacoustic parameters (X axis) and three weather indicators (Y axis). The indicators' value ranges are provided in Table 2. The numbers represent the number of recordings per cluster. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

With a specific weather condition in mind, it is easy to identify the most affected acoustic parameters within the dataset. Among the prominent correlations, a very interesting one resulted between sharpness and air absorption of sound. This gives a picture of the interaction of several weather indicators affecting the air absorption of sound, and how this correlates with the content of high frequencies (sharpness) arriving to the receiver.

A comment on the weakly correlating values should be added at this point: The weather indicators foliage, soil and air temperature show significant correlations with the psychoacoustic parameters tonality and roughness. Despite their significance, the correlation values are relatively low (between 0.37 and 0.2). Brightness appears to be an extreme case, correlating with almost all psychoacoustic parameters, but showing low correlation values. Brightness as such, however, does most probably not have a direct influence on sound. Sunlight will influence temperature, static pressure and humidity. For this reason, correlations are more relevant between those atmospheric conditions and psychoacoustic quantities. Therefore, brightness was not considered as relevant. Instead, the strongest correlations were highlighted, which correspond to relative humidity, cloudiness, surface wetness and wind velocity.

The results show that the acoustic parameter range of all recorded data is above just-noticeable differences (JND), thus confirming the assumption that weather-dependent features are audible. In comparison to a JND in SPL of about 1 dB, the recordings can differ by 20 dB (see Fig. 2). Sharpness was observed to vary between 1 and 2.2 acum for very cloudy skies and 1.1 to 1.5 acum for clear sky conditions. In comparison, the JND estimations of sharpness in case of complex sound with a long duration are reported to be 0.04 acum (Pedrielli et al., 2008). In the case of roughness, our data show a range of 0.1 to 0.2 asper, i.e. 200%. In comparison, a ratio of 17% has been reported as JND (Fastl and Zwicker, 2007; Valverde et al., 2018).

5. Conclusion, limitations and outlook

The presented database includes calibrated first-order Ambisonics background sound recordings that can be used to include weather-dependent background noise in order to create an ambience in (acoustic) virtual reality environments. The sounds are freely available via https://zenodo.org/doi/10.5281/zenodo.11184516 and presented for interactive exploration and binaural listening at https://paad-group.github.io/IHTApark-ambient-recordings/. This study characterized background sounds in terms of acoustic parameters and weather conditions, accompanying correlations of weather and acoustic indicators in order to understand which perceptual aspects can be associated with which weather indicators. In particular, results show that sharpness and

roughness present high and similar correlation values with relative humidity and cloudiness. Tonality correlates furthermore with surface wetness. In contrast, loudness correlates with less weather indicators and weaker. Hence, the use of background sounds in virtual soundscapes can be assumed to be important since the frequency and time content is affected, not only the perceived level.

This study has limitations. Firstly, the recorded data is limited to a period of time across the year and to the recording positions described in Fig. 3. Since this is a limited amount of data, no significant conclusions were drawn related to daytime. However, the time information is accessible via the Zenodo database. Moreover, the database is limited to the studied environment of IHTApark, for which reason the database might not be useful for any arbitrary location with different weather conditions. However, the described protocol can be used to extend the database. Finally, it should be noted that the "snippets" selection according to the exclusion guidelines for unwanted sounds was performed manually. Hence, it might be influenced by the authors' subjective perception and impressions. Further implementation on automatic detection of soundscape events could be included in future work.

CRediT authorship contribution statement

Josep Llorca-Bofí: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jonas Heck:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christian Dreier:** Writing – original draft, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Michael Vorländer:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors have added a link to the available data in the manuscript.

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