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Research Paper

Virtual Reality Technology in Analysis of the Sarek National Park Soundscape in Sweden

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The paper presents an in-depth analysis of the soundscape within Sarek National Park, the oldest national park in Europe, situated in Lapland, northern Sweden. The comprehensive acoustic measurements, ambisonic recordings, and 360° video recordings were carried out during a scientific expedition in the summer of 2020. The aim of the paper is to show the soundscape analysis of carefully selected characteristic locations in various parts of the valley. The paper extensively discusses the findings derived from the recorded data using both classical acoustic methods and the soundscape approach. The classic acoustic parameters, commonly employed in environmental acoustics as well as eco-acoustic indices such as: ACI (acoustic complexity index), ADI (acoustic diversity index), AEI (acoustic evenness index), NDSI (normalized difference soundscape index), BIO (energy level of biophony), amplitude index (M), and total entropy (H) were calculated. To gain further insights, listening tests, facilitated through virtual reality tools, were conducted, enabling participants to engage in soundwalk experiences. By employing a combination of traditional acoustic methods and innovative soundscape approaches, the paper presents a holistic evaluation of the auditory environment in Sarek National Park. The main contribution of the presented research is providing new data from the unique, geographically inaccessible region of the world, the Sarek National Park. This research not only enriches our understanding of the national park's soundscape but also offers valuable insights into the interaction between the natural environment and human perception of sound.

Keywords: virtual soundwalk; Lapland; UNESCO; natural soundscape; virtual reality technology.

1. Introduction

Unique sounds should be treated as intangible heritage worthy of protection and preservation. The idea of the value of sounds found in the acoustic environment is closely related to the concept of soundscape. The soundscape method was first introduced in the work of authors such as Southworth (1969), Schafer (1977), Krause (2012), Brown *et al.* (2015). The data collection methods and soundscape descriptors for the soundscape assessment have been introduced by Aletta *et al.* (2016; 2019), Kang *et al.* (2016).

The perception of sounds in the environment is a complex creative process, involving the active perception, analysis, and interpretation of sensory phenomena. In this process, incoming sensory signals are processed in a manner consistent with previously acquired experience. Some techniques to scale the perception of specific sounds are described by Berglund and Nilsson (2006), Davies *et al.* (2013), De Coensel and Botteldooren (2006). A principal component model of the soundscape perception is portrayed by Axelsson *et al.* (2010). An extensive set of 116 soundscape attributes were well integrated into three basic components or dimensions of the soundscape perception: pleasantness, eventfulness, and familiarity.

In 2008, the Working Group at the International Organization for Standardization [ISO] was established and was named "Perceptual assessment of soundscape quality" (Mitchell *et al.*, 2022). The results of the work of this team have been published in the form of standards within the ISO 12913 series on soundscape. Part 1 is a full standard and provides a general framework and definitions of soundscape concepts (ISO, 2014), while part 2 and part 3 are technical specifications and offer guidance on how data should be collected and analysed, accordingly (ISO, 2018; 2019).

Psychoacoustic research on the soundscape is difficult and complex. It is difficult to determine the values of variables that will define not only acoustic preferences, but also the mood and emotional state of an individual person. Different subcultures can be identified in each area, which are further influenced by individual preferences (Farina, 2014). A soundscape only defined as friendly to some people may be neutral or annoying to others. The determination of what is a friendly and beneficial soundscape and what is not, is also determined by the level of social acceptance (Jiang *et al.*, 2022). The following eco-acoustic indices are currently used: acoustic complexity index (ACI), acoustic diversity index (ADI), acoustic evenness index (AEI), normalized difference soundscape index (NDSI), energy level of biophony (BIO), amplitude index (M), and total entropy (H) (Bradfer-Lawrence *et al.*, 2019; Flowers *et al.*, 2021; Pieretti *et al.*, 2011). These indices are quantitative measures used in environmental research to assess acoustic properties of ecosystems. The calculation of these indices is based on the analysis of the acoustic energy distribution in soundscape recordings. Through monitoring and such analysis, biodiversity patterns, habitat and ecosystem health, and ecological changes can be studied.

The ACI quantifies sound complexity by assessing the variability of intensities between time samples within a specific frequency band. The higher ACI values the higher level of bird or insect activity. The ADI is calculated by applying the Shannon diversity index to the relative proportion of signals occurring in each 1 kHz frequency band. The higher ADI values the greater evenness soundscape and number of occupied frequency. The AEI assesses the balance of sound sources by estimating the Gini coefficient based on the signal proportion in each 1 kHz band. The lower AEI values the less saturated soundscape. The NDSI calculates the ratio of signal power in the frequency bands between 1 kHz–2 kHz (anthrophony) and 2 kHz–8 kHz (biophony). The higher NDSI values the higher level of biophonic activity. The BIO quantifies the signal power specifically within the 2 kHz–8 kHz frequency band, representing the biophony. The higher BIO values the higher levels of biophonic activity in the soundscape. The amplitude index (M) is a metric that assesses the variations in signal amplitude within a designated frequency band, providing a measure of the intensity or strength of acoustic signals present in a given environment. The higher M value, the greater the amplitude variations within the specified frequency band. Total entropy (H) quantifies the overall unpredictability and complexity of acoustic signals in a given system, reflecting the diversity across different frequency bands. The higher H value, the greater the unpredictability and complexity of acoustic signals, indicating a more diverse sound environment.

The dynamic development of civilisation and the huge number of anthropogenic noise sources in the environment makes silence of particular value. Silence, understood as the audibility of the sounds of nature, is becoming a much sought after value. Numerous scientific studies show that recording acoustic environments captures their phonic richness and the unique sound features of the environment (De Coensel, Botteldooren, 2006; Scarpelli *et al.*, 2021; Bernat, 2013; Rychtáriková, Vermid; 2013; Czopek *et al.*, 2019; Małecki *et al.*, 2020; Borkowski *et al.*, 2021).

This paper presents the results of measurements and analysis of survey data recorded in Sarek National Park, in Lapland in Sveden during a 10-day research expedition (Czopek *et al.*, 2022).

The analysis was carried out using the classical method and the soundscape method. Basic classical acoustic parameters used in environmental acoustics (the A-weighted, equivalent continuous sound level, spectrograms, spectra) were calculated. Also, basic soundscape attributes "pleasant", "eventful", "annoying", "calm", etc., were used to assess the sound environment. The virtual reality (VR) technology was used to perform listening tests. Furthermore, eco-acoustic indices including: ACI, ADI, AEI, NDSI, BIO, M, and H were employed. These research methods facilitated the comparison of multi-temporal acoustic patterns across various sections of the valley, as well as their correlation with the subjective evaluations provided by the listeners.

2. Lapland and the Sarek National Park

In present times, Lapland (also named Sápmi) spans across the northern parts of the Scandinavian Peninsula and the Kola Peninsula. This ethno-cultural region boasts vast expanses of land. It covers approximately 390 thousand square kilometres across four countries: Norway, Sweden, Finland, and Russia. The indigenous people living in the Lapland region are the Saami, whose population is estimated around 60 000–90 000. At present, they are a minority among the inhabitants of Lapland – approximately 2.3 million people. Most of the Lapland's territory is situated north of the Arctic Circle. Its western region encompasses fjords, deep valleys, glaciers, and mountains, including the highest peak, Kebnekaise (2111 m) located in Swedish Lapland. The Swedish part of Lapland is distinguished by the presence of major rivers that flow from the northwest to the southeast.

Sarek National Park was established in 1909. It is located in northern Sweden about one hundred kilometres beyond the Arctic Circle and covers an area of 1970 km^2. Sarek National Park is approximately circular in shape with a diameter of approximately 50 km. It is adjacent to two other national parks, namely Stora Sjöfallet and Padjelanta National Park. In December 1996, the adjacent national parks of Sarek, Stora Sjöfallet (1278 km^2), and Padjelanta (1984 km^2) were inscribed on the UNESCO World Heritage List collectively as the Laponian Area. It met the five demanding criteria (iii, v, vii, viii, ix) for Outstanding Universal Values. The Laponian Area, located in northernmost Sweden, is a magnificent wilderness of high mountains, primeval forests, vast marshes, beautiful lakes, and well-preserved river systems. It contains areas of exceptional beauty such as the snow-covered mountains of Sarek, the large alpine lakes of Padjelanta, and the extensive river delta in the Rapa Valley. Also, the Laponian Area is an outstanding example of traditional land-use, a cultural landscape reflecting the ancestral way of life of the Saami people based around the seasonal herding of reindeer (UNESCO, n.d.).

Sarek National Park is distinguished by its breathtaking alpine scenery, featuring majestic mountain ranges, narrow valleys, glaciers, swift rivers with abundant rapids and waterfalls. Six of Sweden's thirteen highest mountains, nearly 100 glaciers, and long, deep, and narrow valleys are located in the park. It is renowned for its diverse wildlife, including large elk and numerous predators. The meltwater from the numerous glaciers feeds the main Sarek river, the Ráhpaädno, forming the most renowned delta in the alpine world. However, the park does not boast a wide variety of plant species. This is primarily attributed to the fact that most of the park lies above the tree line, approximately 500 m in altitude, limiting the presence of coniferous vegetation. Within the park, there are no tourist facilities, marked trails, or shelters for overnight stays. The landscape of the area bears the unmistakable imprint of the ancient ice sheet, and traversing Sarek is akin to embarking on a journey through Sweden's geological past. In Sarek National Park, many places have names derived from Sami languages. The most common Sami names for locations or objects in the park are tjåkkå or tjåkko (mountain), vagge (valley), jåkkå or jåkko (stream), lako (plateau), and ätno (river), e.g., Rapaätno means Rapa River.

Sarek is a challenging measurement and research environment. The terrain and the weather can be very hard and changing. Measurements and recording of soundscapes were carried out in 8 places located between: Aktse and Skárjá. Among which, the soundscapes captured in three places of the Sarek National Park: Tjasskávárvásj, by the Rådnik, Skárjá were analysed further (Figs. 1 and 2). At each point, 30-minute ambisonic and 360° video recordings were made and, except for Akste, where a 10-day sound recording was carried out.

Tjasskávárvásj – the location on the left bank of the Rapadalen Valley, near a section of the Kungsleden (King's Trail) leading to the summit of Skierffe, famous for its magnificent view of the Valley of the Rapaätno River and its picturesque delta. The measurement site is already within the boundaries of Sarek National Park, shortly after branching off from the Kungsleden Trail and heading up the Rapaätno River.

By the Rådnik – the location on the left bank of the Rapadalen Valley, northwest of the Rådnik peak. From the slope, there is a view extending over the valley.

Skárjá (Smaila Moot) – the central location of the park, was previously used as a pasture by the Saami. Now, there is a small cabin equipped with an emergency phone. The cabin is not open to hikers but

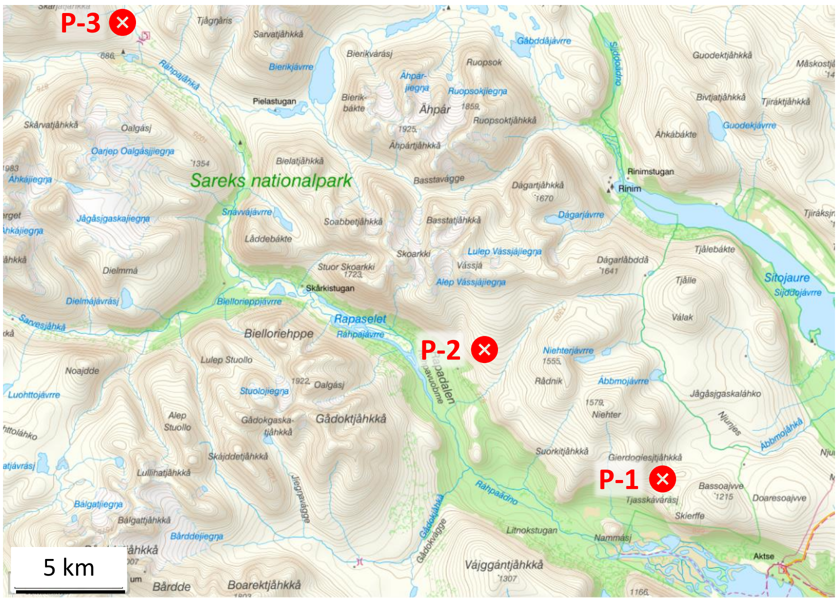


Fig. 1. Location of measuring points in Sarek National Park: P-1 Tjasskávárvásj, P-2 by the Rådnik, P-3 Skárjá.

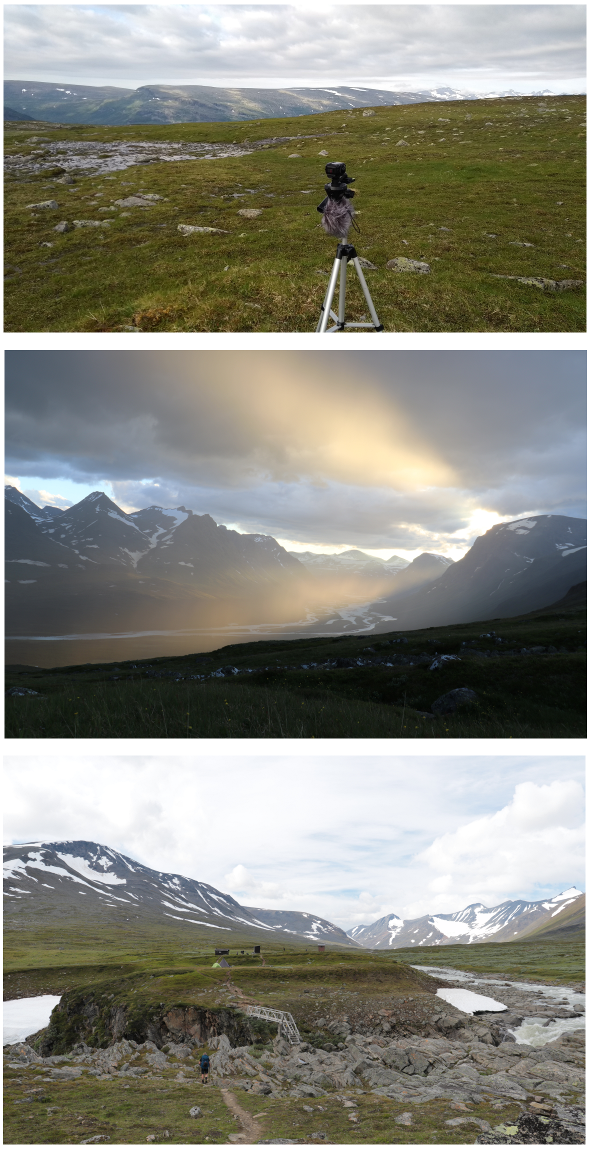


Fig. 2. Sarek National Park landscape measuring points: a) Tjasskávárvásj; b) by the Rådnik; c) Skárjá.

can be used as an emergency shelter. It is a place where many hikers can be found. There is also a bridge over the Smailajåkk canyon which allows hikers to cross the stream. The bridge is removed every winter and put back in the spring, after the spring flood.

There were minimal anthropogenic sounds in the soundscapes used to recreate and simulate the natural environment. At the initial location, Tjasskávárvásj, the primary sound sources are birds with quite high frequencies. There is also sound of wind and streams. At the site named "by the Rådnik" the wind is the predominant sound source. The soundscape of Skárjá is the only one with anthrophony. Here, the main source of sound emanates from the water, accompanied by the whispers of the wind, the gentle rustling of grass, and occasional sounds of human origin. In this rich audio tapestry, one can also discern the singing birds.

3. Virtual reality method and measurement

The analysis of the recorded soundscapes was carried out using the method of recording the acoustic environment and later recreating it in a laboratory with a sound system and using the VR technology (LaValle, 2019; Wang, 2020). Virtual reality is created with the use of hardware and software. After donning the goggles and headphones, our senses are cut off from the outside world and we experience the phenomenon of immersion, i.e., full immersion in a virtual world. This allows us to experience simulations of unusual places, objects or activities. Environmental recordings were made using an ambisonic microphone, 360° camera and sound analyser SVAN957. Laboratory tests were carried out using a VR set – Oculus Quest 2. The realisation of a suitable VR project requires the spatial image recording and the sound recording made with an ambisonic microphone to be converted and synchronised due to the different formats of the recorded data. The obtained files were rendered and then submitted to a final conversion in Spatial Media Metadata Injector, resulting in 360° videos with spatialised sound. The next stage of the work was to calibrate the playback level so that it was possible to play the films on the Oculus Quest 2 at the same sound level as in real life.

Calibration was carried out in an anechoic chamber with the use of the HATS (Head and Torso Simulator) simulator with built-in microphones in the ears by Bruel&Kjaer 1/2″ type 4189 and the DAW – Pro Tools software (Fig. 3).

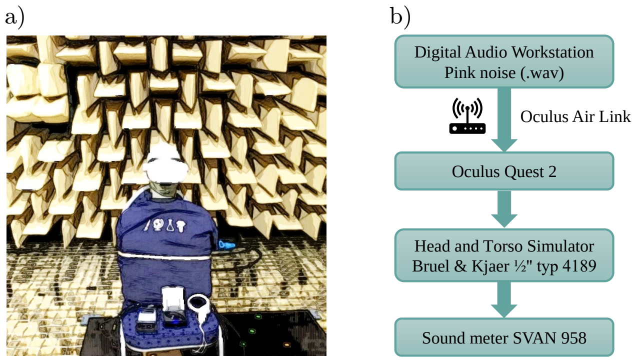


Fig. 3. Calibration of the Oculus's sound level for listening tests: a) photograph of the equipment in an anechoic chamber; b) block diagram of the calibration process.

The sound level was similar – around 30 dBA – for the by the Rådnik and Tjasskávárvásj soundscapes. For the third soundscape (Skárjá) used in simulations, the sound pressure level was over 50 dBA.

The qualitative evaluation of the soundscape was carried out with the use of questionnaires (ISO, 2018). The questions concerned the issues of loudness assessment, general impression, adjusting the sound to the environment, describing emotions experienced at a given moment, but also specifying the existing sound sources. There were questions verifying the context and considering the extent to which the studied environment is perceived as monotonous, dynamic, varied, unvaried, irritating, pleasant, calm or chaotic. The survey included basic personal information and seven questions. The Likert scale was used for all survey questions. Numerical values from 1 to 5 were assigned to the responses increasing with the nature of the characteristic under investigation.

Psychoacoustic research was carried out on a group of 30 people using a questionnaire that was completed by each participant after simulating the soundscape in the auralization laboratory. The study participants included 13 men and 17 women. The age of the respondents ranged from 21 to 23 years old, the largest part of which were 22-year-old. Each examined person completed the questionnaire three times.

The research was carried out in the auralization laboratory of the Department of Mechanics and Vibroacoustics of the AGH University of Krakow. The examined person sat on a swivel seat that allowed him to turn freely during the simulation. Then, the test participant put on the VR goggles – Oculus Quest 2 and received one of the two controllers compatible with the VR headset (Fig. 4).

Fig. 4. Tested person wearing VR goggles during an auditory test at the Auralization Laboratory at AGH University of Science and Technology.

The controller allowed each person to set individual characteristics for each played file. Navigating through cyberspace and switching on subsequent films was also made possible by the controller. Playback levels were calibrated individually for each participant and recording, so that each test participant perceived the same sound level as was actually present in the location.

The examined person was presented three spherical films with spatial sound depicting three different sound landscapes. Each simulation lasted three minutes and was completed with a survey. The movies were played in the following order: Tjasskávárvásj, by the Rådnik, Skárjá the same sound level that was actually present in the given place.

4. Results

The following four figures show the results of the assessment of the surrounding environment. Figure 5 summarises the comparative characteristics of the variation in responses regarding the overall assessment of the studied acoustic environments.

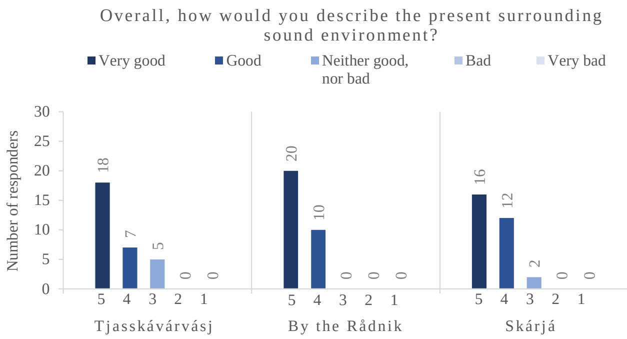


Fig. 5. Distribution of votes for the assessment of the surrounding sound environment of the tested sites.

It is noticeable that none of the soundscapes were generally perceived as bad or very bad by the survey participants. The significant majority of respondents rated the soundscapes presented as good or very good. A very small number of participants described the perception of the acoustic environment occurring at the sites: Tjasskávárvásj and Skárjá as neither good nor bad. The median values calculated for all those three places are the same – very good. Comparing the distribution of votes for Tjasskávárvásj and Skárjá, it can be seen that there is very little difference between the overall perception of the studied soundscapes. It is noteworthy that the respondents rated the soundscape of Rådnik as the best, resulting in the highest number of votes for a very good assessment and no votes for a neither good, nor bad, bad or very bad. In contrast, the acoustic environment recorded at the Tjasskávárvásj site was generally received as the worst.

Distribution of responses assessing appropriateness of the surrounding sound environment of the tested sites is shown in Fig. 6.

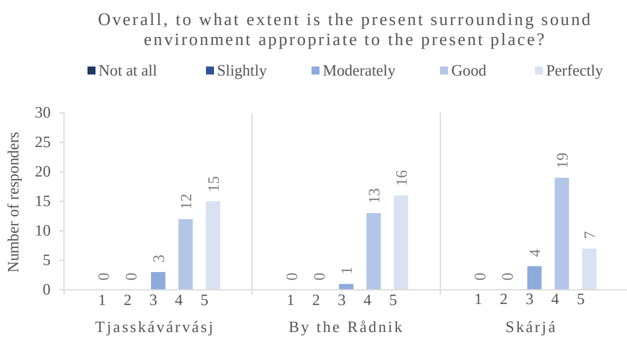


Fig. 6. Distribution of votes assessing appropriateness of the surrounding sound environment of the tested sites.

None of the sites analysed were rated by respondents as matching the surroundings slightly or not at all. A small number of respondents rated the sound fit at each analysed site as moderate.

The significant majority described the fit of the soundscapes as very good or ideal. The best match between sound and surroundings with median value equals 5.0 was recorded for the soundscape of by the Rådnik. The soundscape of Tjasskávárvásj received a slightly lower rating, with a median of 4.5. The acoustic environment documented for Skárjá was the worst in this comparison and had a median value equal 4.0.

The distribution of votes regarding the loudness of a site is shown in Fig. 7.

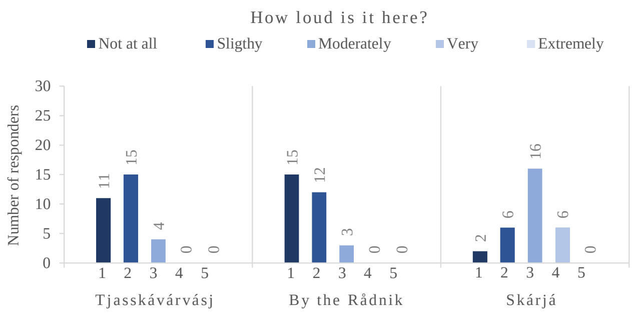


Fig. 7. Distribution of votes assessing a loudness of the sound environment.

None of the three analysed soundscapes were rated as extremely noisy. Most people described the places surveyed as slightly or moderately noisy or quiet. Out of those surveyed, only the soundscape of Skárjá was rated as noisy by six respondents.

When comparing the median values of the loudness ratings of the surveyed soundscapes, it is clearly noticeable that Skárjá's soundscape was described as the loudest. The median value is 3.0, indicating that the soundscape was considered moderately loud. The other two landscapes were rated very similarly – as not at all or slightly noisy. Median value for Tjasskávárvásj is 2.0 and for by the Rådnik is 1.5.

The distribution of votes regarding willingness to return to the surveyed places is shown in Fig. 8.

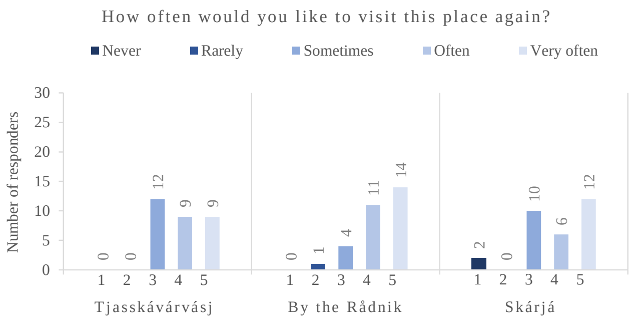


Fig. 8. Distribution of votes assessing a willingness to return to the surveyed places.

The great majority of respondents would like to be able to visit the presented places again. The median for all locations is 4.0, indicating that respondents would like to visit all places with similar frequency, and often. Only two respondents would not like to visit the Skárjá landscape again. Analysing the distribution of votes, it is noticeable that by the Rådnik was considered by far the most visitable place.

Figures 9 and 10 present selected results of the survey related to the eight perceptual attributes of the acoustic environment of the three tested places.

The analysis of the results presented in Fig. 9 shows that none of the respondents described the studied acoustic environments as definitely unpleasant. The Tjasskávárvásj and by the Rådnik soundscapes were also not rated as rather unpleasant. Only three of the study participants characterized Skárjá's soundscape as rather unpleasant, and two as moderate unpleasant. The second landscape by the Rådnik was definitely the most pleasantly perceived, the median of which was 5.0. For the other two locations – the median was 4.0. Generally, all soundscapes were found to be pleasant.

The next question of the survey questionnaire examined the extent to which the analysed soundscape is perceived as annoying. The soundscape of by the Rådnik was rated by all 30 respondents as definitely non-annoying. None of the three locations was identified as being clearly annoying. The third soundscape Skárjá was found to be the most annoying place. The median for Tjasskávárvásj soundscape is 2.0 and for by the Rådnik and Skárjá is 1.0, which means that the respondents defined a small or very small degree of compliance with the examined statement.

As in the previous question, all of 30 respondents described the by the Rådnik soundscape as calm. Only one person rated the last soundscape Skárjá as definitely restless. The median of compliance was the highest for the second soundscape – 5.0, followed by the first – 4.5 and third – 3.0 – soundscapes.

None of the soundscapes was considered chaotic by the respondents. Twenty-six of respondents indicated the soundscape of by the Rådnik as the least chaotic. The median was the highest for the third soundscape, which of the three was considered to be the most consistent with the examined statement.

Figure 10 shows respondents' answers regarding to what extent the surveyed acoustic environments are perceived as monotonous, vibrant, uneventful and eventful. None of the landscapes were rated as definitely monotonous, with the exception of only three people describing by the Rådnik's acoustic environment in this way. The median was the highest for this landscape. On the other hand, the soundscape of Skárjá was considered to be the least monotonous.

The most vibrant soundscape was found to be the last, third soundscape, with a median of 3.0. By the Rådnik's soundscape was rated as the least vi-

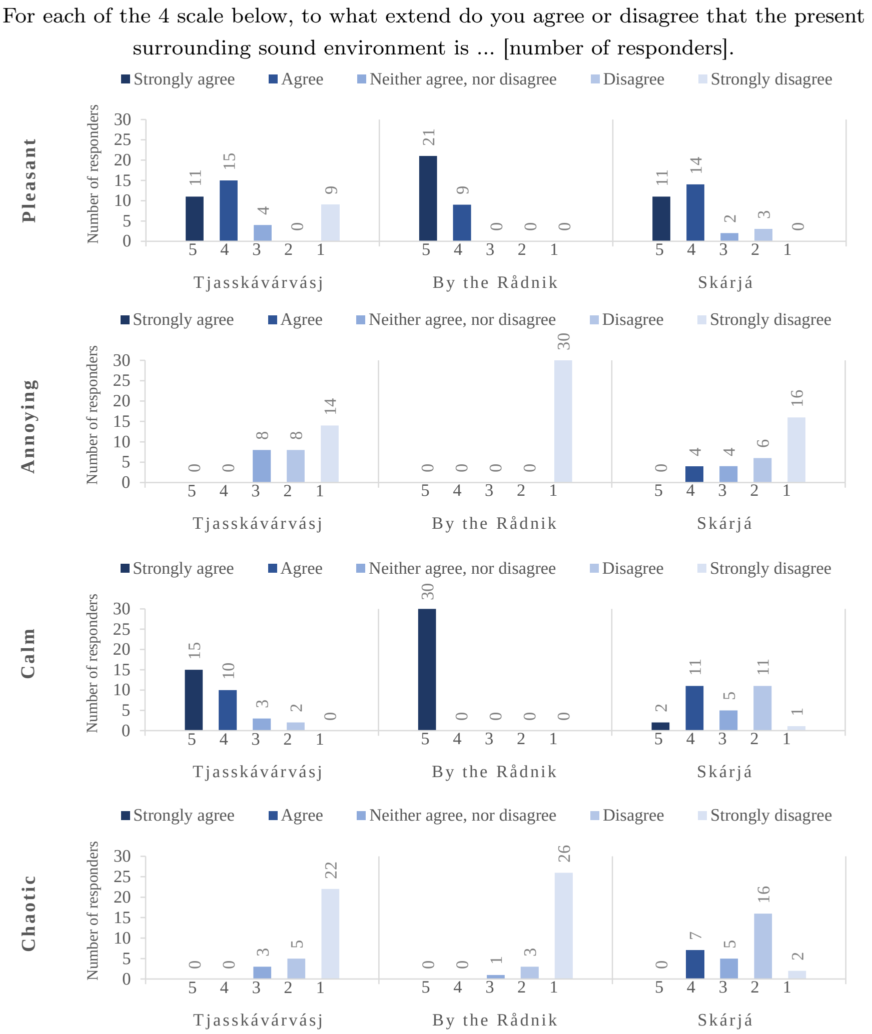


Fig. 9. Distribution of votes regarding the perception of the surveyed place as pleasant, annoying, calm, and chaotic.

brant – median is 1.0. The highest median – 4.0 – was achieved by the soundscape of by the Rådnik receiving the title of the most uneventful soundscape. None of the sites surveyed were identified as definitely eventful. Feedback from participants identified the third landscape as the most eventful.

Results shown in Figs. 9 and 10 could be reported in a two-dimensional scatter plot with coordinates for the two dimensions: pleasantness and eventfulness (Fig. 11). In order to calculate the position of the individual soundscapes, values from 5 (strongly agree) to 1 (strongly disagree) are taken for the individual perception assessments (ISO, 2019). The coordinates for the pleasantness axis – P – are then obtained by substituting the mean values for pleasant (p), annoying (a), calm (ca), chaotic (ch), vibrant (v), and monotonous (m) into Eq. (1). The coordinates for the eventfulness axis – E – are obtained by substituting the mean values for eventful (e), uneventful (u), chaotic (ch), calm (ca), vibrant (v), and monotonous (m) into Eq. (2):

$$P = (p - a) + \cos 45^\circ \cdot (ca - ch) + \cos 45^\circ \cdot (v - m), \quad (1)$$

$$E = (e - u) + \cos 45^\circ \cdot (ch - ca) + \cos 45^\circ \cdot (v - m). \quad (2)$$

Comparing results is much easier if the range of values is ± 1. Therefore, the resulting coordinates can be normalised by dividing by $\left(4 + \sqrt{32}\right)$.

All tested acoustic environments were described as pleasant. The soundscape of by the Rådnik turned out to be the most calm and uneventful of all. The reason for this could be the small number of sound sources present. The sounds of wind and grass were predominant in the soundscape. The singing of the birds was inaudible when listening with a VR system.

The soundscape of Skárjá, which is much more eventful and vibrant due to the presence of more varied sounds, is different from the rest. In the acoustic environment, not only sounds of natural origin, but also those of human origin appear. The more sound sources, the more vibrant and eventful the place is.

In Fig. 12, the comparison of National Park Sarek's soundscape with a sample of London's soundscape is presented (Mitchell *et al.*, 2021). The values obtained in the park closely resemble those obtained

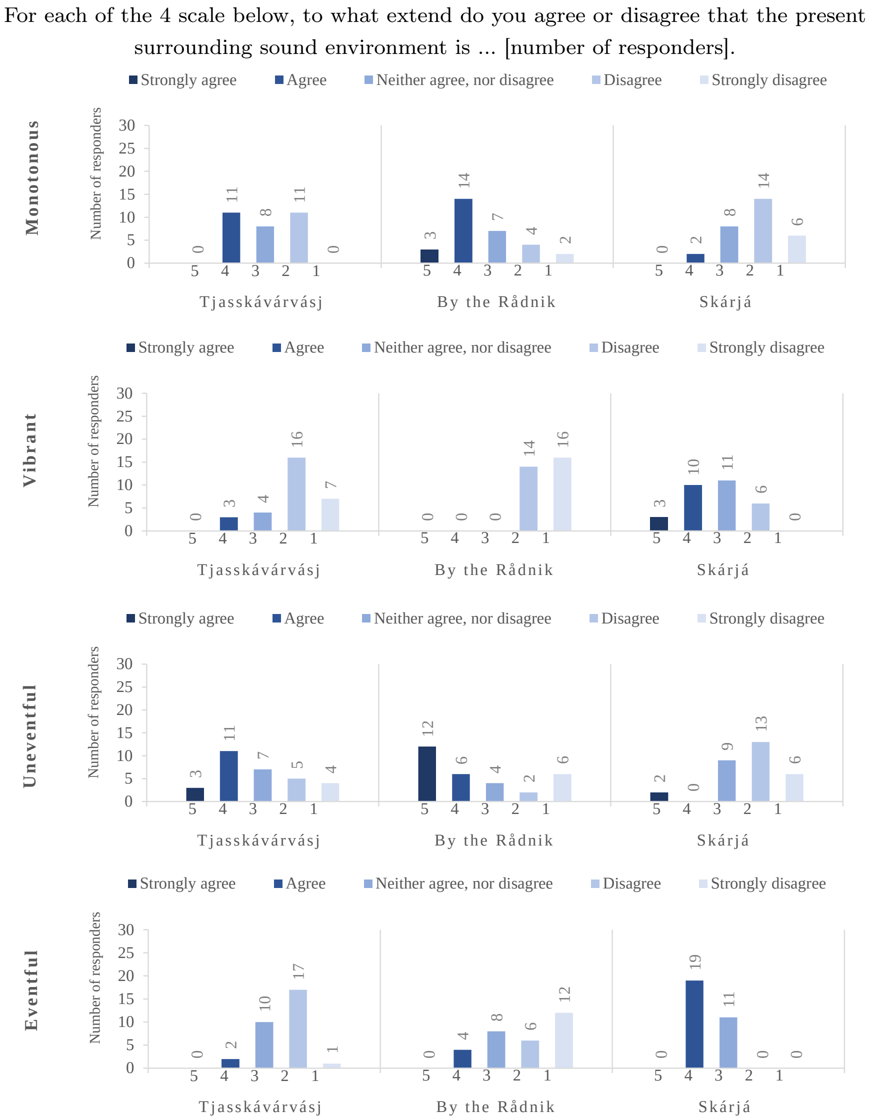
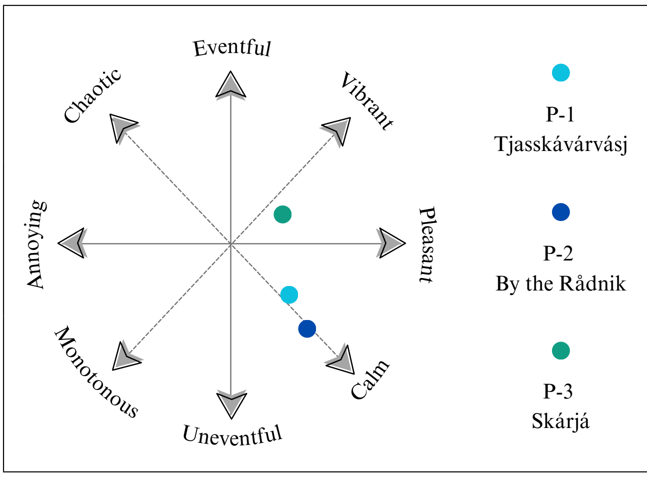


Fig. 10. Distribution of votes regarding the perception of the surveyed place as monotonous, vibrant, uneventful and eventful.



	Pleasantness	Eventfulness
P-1 Tjasskávárvásj	0.40	−0.35
P-2 By the Rådnik	0.52	−0.57
P-3 Skárjá	0.35	0.18

Fig. 11. Graphic classification of pleasantness and eventfulness of Sarek's soundscapes calculated using ISO Eqs. (1) and (2). The values have been normalised (by dividing the coordinates by $\left(4+\sqrt{32}\right)$).

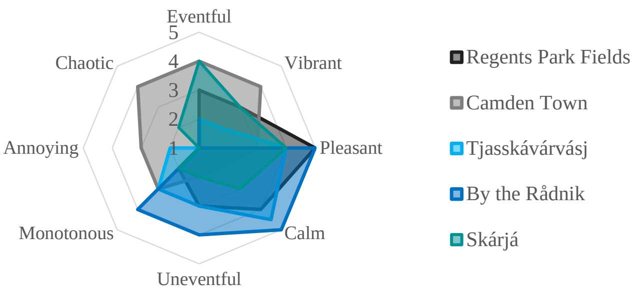


Fig. 12. Comparison of Sarek's soundscapes (Tjasskávárvásj, by the Rådnik, Skárjá) with soundscape of London park (Regents Park Fields) and square (Camden Town) on a radar plot of median value of perceptual attribute ratings on the Likert scales from 5 to 1 (Mitchell *et al.*, 2021).

in National Park Sarek. However, it is essential to note that different research groups participated in the studies, and they were not conducted simultaneously. The assessment of Camden Town's soundscape is significantly shifted towards the Eventful coordinate axis. This location received relatively high ratings for chaotic, eventful, and vibrant.

Skárjá's landscape was louder than the other two landscapes (Fig. 13), which may have made it perceived as less pleasant. In Skarja's landscape, anthropogenic noises such as tourists' footsteps and conversations disrupt the natural harmony of the environment, leading to a more negative perception and a decreased desire to return frequently. All studied landscapes are generally classified as pleasant, calm and not very eventful.

The A-weighted, equivalent continuous sound levels, spectra and spectrograms – classical acoustic parameters commonly used in environmental acoustics – were used to objectively characterise the soundscapes studied. Figure 13 shows the average spectra (left) and spectrograms (right) measured at the study sites.

In Fig. 13a, the bi-modal energy distribution in the frequency domain at Tjasskávárvásj can be observed. The highest SPL values are found at frequencies 160 Hz and 2000 Hz. The equivalent A-weighted sound pressure level was 32 dB. At by the Rådnik acoustic energy is accumulated in the low-frequency range, here there is a rapid decrease in value from 42 dB to 12 dB, in the frequency band from 50 Hz

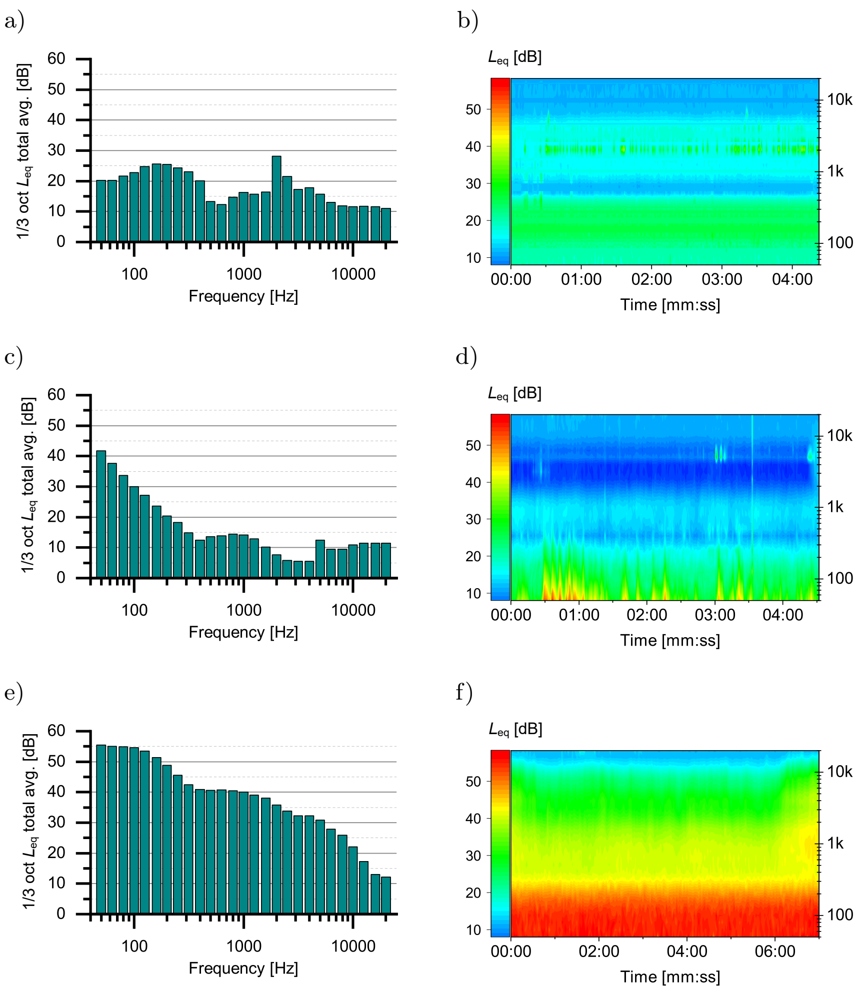


Fig. 13. The Tjasskávárvásj's ((a) and (b)), by the Rådnik's ((c) and (d)) and Skárjá's ((e) and (f)) sound level: average spectrum (on the left) and spectrogram (on the right).

Table 1. Basic eco-acoustic indices calculated for 300 s recording window.

Indicator	Place		
	Tjasskávárvásj	By the Rådnik	Skárjá
	Index value		
Acoustic complexity index (ACI)	1785.92	1823.25	1794.31
Acoustic diversity index (ADI)	0.85	0.003	0.78
Acoustic evenness index (AEI)	0.81	0.90	0.82
Normalized difference soundscape index (NDSI)	0.69	0.11	0.51
Energy level of biophony (BIO)	3.39	1.53	4.76
Amplitude index (M)	0.042	0.016	0.023
Total entropy (H)	0.75	0.35	0.66

to 400 Hz (Fig. 13c). In the remaining frequency range 500 Hz–20 000 Hz, 1/3 octave SPL values oscillate around 7 dB–12 dB. The equivalent A-weighted sound pressure level was 24 dB. Figure 13e shows a broadband distribution of acoustic energy at Skárjá, with a drop in 1/3 octave SPL values from 70 dB to approximately 14 dB as the frequency increases. The equivalent A-weighted sound pressure level was 50 dB.

For comparison purposes, calculations of basic eco-acoustic indices were also carried out. The calculation results are presented in Table 1.

The calculated values of the indicators confirm that the acoustic activity is not high at the presented measurement points. High NDSI values, around 0.8, at Skárjá and Tjasskávárvásj indicate that signals do not contain anthrophony.

Slightly higher values of ACI and BIO factors (4.76 in Skárjá and 3.39 in Tjasskávárvásj) indicate a slightly higher activity of birds comparing to by the Rådnik. Slightly higher values of the ADI index (Skárjá, Tjasskávárvásj) indicate the occurrence of higher wind comparing to by the Rådnik. Also, low ADI values (by the Rådnik) show that the soundscape is not containing many vocalizing species.

Higher values of the NDSI coefficient (Tjasskávárvásj) indicate greater biophonic activity and minimal anthrophonic noise in 1 kHz–2 kHz and indicate higher levels of biophonic activity in the soundscape. Similar values of the AVE coefficient show that all three soundscapes are similarly saturated.

5. Summary

The conducted research allowed for the mapping of three unique soundscapes in the VR technology. The VR technology allows for a very realistic representation of any acoustic environment. In total, approximately 160 hours of audio recordings were gathered, including 100 hours of ambisonic audio and 360° video recordings in Sarek National Park. Sound level measurements accompanied all the recordings. Modern VR devices can significantly facilitate the organization of soundscape research, or even enable it. The executed recordings facilitate subsequent soundscape research in inaccessible regions such as Sarek National Park. This affords the opportunity to conduct comparative studies and investigate the influence of natural soundscapes on humans' wellbeing within laboratory environments, thereby opening new avenues for research.

In the conducted study, respondents generally classified the three tested soundscapes as pleasant and calm. This was confirmed by both the analysis of the voice distribution and the median on the radar chart. Graphic classification of pleasantness and eventfulness of Sarek's soundscapes shows that all three soundscapes surveyed were classified as pleasant and peaceful. However, the louder and more varied the soundscape (e.g., presence of pulse biophones) the more annoying and eventful the rating.

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References

1. Aletta F., Kang J., Axelsson O. (2016), Soundscape descriptors and a conceptual framework for developing predictive soundscape models, *Landscape Urban Planning*, **149**: 65–74, doi: 10.1016/j.landurbplan.2016.02.001.

2. Aletta F., Guattari C., Evangelisti L., Asdrubali F., Oberman T., Kang J. (2019), Exploring the compatibility of "Method A" and "Method B" data collection protocols reported in the ISO/TS 12913-2:2018 for urban soundscape via a soundwalk, *Applied Acoustics*, **155**: 190–203, doi: 10.1016/j.apacoust.2019.05.024.

3. Axelsson Ö., Nilsson M.E., Berglund B. (2010), A principal components model of soundscape perception, *The Journal of the Acoustical Society of America*, **128**(5): 2836–2846, doi: 10.1121/1.3493436.
4. Berglund B., Nilsson M.E. (2006), On a tool for measuring soundscape quality in urban residential areas, *Acta Acustica united with Acustica*, **92**(6): 938–944.
5. Borkowski B., Suder-Dębska K., Wiciak J., Szlachta A.M. (2021), Acoustic panels inspired by nature, *Archives of Acoustics*, **46**(1): 135–146, doi: 10.24425/aoa.2021.136567.
6. Bradfer-Lawrence T., Gardner N., Bunnefeld L., Bunnefeld N., Willis S.G., Dent D.H. (2019), Guidelines for the use of acoustic indices in environmental research, *Methods in Ecology and Evolution*, **10**(1): 1796–1807, doi: 10.1111/2041-210X.13254.
7. Bernat S. (2013), Awareness of noise hazards and the value of soundscapes in polish national parks, *Archives of Acoustics*, **38**(4): 479–487, doi: 10.2478/aoa-2013-0057.
8. Brown A.L., Gjestland T., Dubois D. (2015), Acoustic environments and soundscapes, [in:] *Soundscape and the Built Environment*, Kang J., Schulte-Fortkamp B. [Eds.], pp. 1–16, CRC press.
9. Czopek D., Małecki P., Piechowicz J., Wiciak J. (2019), Soundscape analysis of selected landforms on Spitsbergen, *Archives of Acoustics*, **44**(3): 511–519, doi: 10.24425/aoa.2019.129266.
10. Czopek D., Lichoń S., Małecki P., Wiciak J. (2022), The Soundscape of the Sarek National Park – Case study, [in:] *Proceedings of the 24th International Congress on Acoustics*.
11. Davies W.J. *et al.* (2013), A Perception of soundscapes: An interdisciplinary approach, *Applied Acoustics*, **74**(2): 224–231, doi: 10.1016/j.apacoust.2012.05.010.
12. De Coensel B., Botteldooren D. (2006), The quiet rural soundscape and how to characterize it, *Acta Acustica United with Acustica*, **92**: 887–897.
13. Farina A. (2014), *Soundscape Ecology: Principles, Patterns, Methods and Applications*, Dordrecht, Springer.
14. Flowers C., Le Tourneau F-M., Merchant N., Heidorn B., Ferriere R., Harwood J. (2021), Looking for the -scape in the sound: Discriminating soundscapes categories in the Sonoran Desert using indices and clustering, *Ecological Indicators*, **127**: 107805, doi: 10.1016/j.ecolind.2021.107805.
15. International Organization for Standarization (2014), *Acoustics – Soundscape – Part 1: Definition and conceptual framework* (ISO Standard No. 12913-1:2014), https://www.iso.org/standard/52161.html.
16. International Organization for Standarization (2018), *Acoustics – Soundscape – Part 2: Data collection and reporting requirements* (ISO/TS Standard No. 12913-2:2018), https://www.iso.org/standard/75267.html.
17. International Organization for Standarization (2019), *Acoustics – Soundscape – Part 3: Data analysis* (ISO/TS Standard No. 12913-3:2019), https://www.iso.org/standard/69864.html.
18. Jiang L. *et al.* (2022), Ten questions concerning soundscape valuation, *Building and Enviroment*, **2019**: 109231, doi: 10.1016/j.buildenv.2022.109231.
19. Kang J. *et al.* (2016), Ten questions on the soundscapes of the built environment, *Building and Environment*, **108**: 284–294, doi: 10.1016/j.buildenv.2016.08.011.
20. Krause B. (2012), *The Great Animal Orchestra: Finding the Origins of Music in the World's Wild Places*, New York, Little, Brown and Company.
21. LaValle S.M. (2019) *Virtual Reality*, Cambridge University Press.
22. Mancini S., Mascolo A., Graziuso G., Guarnaccia C. (2021), Soundwalk, questionnaires and noise measurements in a university campus: A soundscape study, *Sustainability*, **13**(2): 841, doi: 10.3390/su13020841.
23. Małecki P., Czopek D., Piechowicz J., Wiciak J. (2020), Acoustic analysis of the glacier caves in Svalbard, *Applied Acoustics*, **165**: 107300, 1–9, doi: 10.1016/j.apacoust.2020.107300.
24. Mitchell A. *et al.* (2021), The International Soundscape Database: An integrated multimedia database of urban soundscape surveys – Questionnaires with acoustical and contextual information, https://zenodo.org/records/10672568 (access: 15.02.2024).
25. Mitchell A., Aletta F., Kang J. (2022), How to analyse and represent quantitative soundscape data, *JASA Express Letters*, **2**(3): 037201, doi: 10.1121/10.0009794.
26. Pieretti N., Farina A., Morri D. (2011), A new methodology to infer the singing activity of an avian community: The acoustic complexity index (ACI), *Ecological Indicators*, **11**(3): 868–873, doi: 10.1016/j.ecolind.2010.11.005.
27. Rychtáriková M., Vermeir G. (2013), Soundscape categorization on the basis of objective acoustical parameters, *Applied Acoustics*, **74**(2): 240–247, doi: 10.1016/j.apacoust.2011.01.004.
28. Scarpelli M.D.A., Ribeiro M.C., Teixeira C.P. (2021), What does Atlantic Forest soundscapes can tell us about landscape?, *Ecological Indicators*, **121**: 107050, doi: 10.1016/j.ecolind.2020.107050.
29. Schafer R.M. (1977), *The soundscape: Our Sonic Environment and the Tuning of the World*, Destiny Books, Rochester, VT.
30. Southworth M. (1969), The sonic environment of cities, *Environment and Behavior*, **1**(1): 49–70, doi: 10.1177/001391656900100104.
31. UNESCO (n.d.), *Laponian Area*, https://whc.unesco.org/en/list/774/ (access: 21.07.2023).
32. Wang M. (2020) Social VR: A new form of social communication in the future or a beautiful illusion?, *Journal of Physics: Conference Series*, **1518**: 012032, doi: 10.1088/1742-6596/1518/1/012032.