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Towards soundscape indices

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ABSTRACT

The growing field of soundscape studies considers sound environments as perceived, in context, with an interdisciplinary approach. This paper outlines an ongoing European Research Council (ERC) Advanced Grant project, which aims to establish "soundscape indices" (SSID). By taking psychological, (psycho)acoustical, neural and physiological, and contextual factors into account, SSID will adequately reflect levels of human comfort to integrate side-by-side with (and eventually replace) decibel-based metrics into existing (international) regulations, shifting the focus from noise control to a more holistic approach. Steps to achieve this include: to characterise soundscapes, by capturing acoustic environments and establishing a comprehensive database; to identify key factors and their influence on soundscape quality based on the database, by conducting laboratory psychological evaluations, acoustical/psychoacoustic factors analysis, and also, to research the neural and psychophysiological underpinnings of soundscape experience, by applying techniques such as functional Magnetic Resonance Imaging (fMRI) and Skin Conductance Response (SCR); to develop, test and validate the soundscape indices, by analysing the influences of various factors; to demonstrate the applicability of the soundscape indices in practice, by establishing frameworks for soundscape prediction, design, and standardisation. Ultimately, the findings of SSID will allow for an easy assessment of public spaces and the increase of the noise management impact.

Keywords: Soundscape database, Neural and physiological, Contextual factors

1. INTRODUCTION

For environmental sound quality, it is widely recognised that reducing the sound level is not always feasible or cost-effective. More importantly, with only ~30% of noise annoyance depending on physical aspects, such as acoustic energy, sound level reduction will not necessarily lead to improved quality of life (1). Soundscape research represents a paradigm shift in that it combines physical, social and psychological approaches and considers environmental sounds as a "resource" rather than a "waste", by relating to perceptual constructs rather than just physical phenomena (2–4).

The decibel (dB) is the most commonly used index to evaluate environmental sound quality, but there have been numerous criticisms on its effectiveness, as the correlations between dB and perceived sound quality (e.g. noise annoyance) are often low (2). Psychoacoustic parameters, including loudness, fluctuation strength, roughness, sharpness, and pitch strength, which are effective for evaluating the sound quality of industrial products, have rather limited applicability in environmental acoustics (5) where a significant feature is that there are multiple and dynamic sound sources. While it has been demonstrated that people perceive/experience acoustic environments differently, there must be fundamental factors which determine their perceptions, including psychological, acoustic/psychoacoustic, neural and physiological, and contextual factors.

This paper outlines an ongoing European Research Council (ERC) Advanced Grant project, which aims to establish "soundscape indices" (SSID), adequately reflecting levels of human comfort while integrating decibel-based metrics. It first presents a framework of developing SSID, including relations among soundscape descriptors, correction factors, and indicators, as well as the modelling process. It then describes a protocol for capturing acoustic environments and consequently establishing a comprehensive database to characterise soundscapes. This is followed by a description of the main research themes that are being pursued to identify key factors and their influence on soundscape quality based on the database. Finally, the SSID development and application are discussed.

2. FRAMEWORK FOR SOUNDSCAPE INDICES DEVELOPMENT

There is an ongoing process of methodological standardization in the soundscape community. The urgent need for solutions to overcome (or rather integrate) noise control engineering approaches in environmental management policies is prompting increasing efforts in both soundscape research and practice to come up with operational tools that can be used to assess and anticipate how urban acoustic environments will be perceived. These include soundscape descriptors, indicators, and indices, which have been acknowledged as important topics to address. Aletta et al. (6) proposed a definition of soundscape descriptors and indicators, where the former are "measures of how people perceive the acoustic environment", whilst the latter are "measures used to predict the value of a soundscape descriptor". Taking a further step, soundscape *indices* can then be defined as single-value scales derived from either indicators or descriptors that allow for comparisons across soundscapes. This process is schematically described in Figure 1.

Developing soundscape indices is a process that requires consideration of how people perceive, experience and understand the surrounding sound environment (7). For the purpose of modelling and comparisons, it is important that such indices are numerical entities. Aletta et al. (6) have highlighted that the framework for developing soundscape indices could be organised into a three-step process based on: (a) collecting soundscape data; (b) characterising the (acoustic) environment; and (c) modelling.

Collecting soundscape data relates to quantifying soundscape descriptors: this process can be carried out on site, in simulated and/or reproduced environments, or via recalling the experience in memory. Characterising the acoustic environment relates to physical entities of sound phenomena and relies on established (psycho)acoustic metrics, such as equivalent sound level, loudness, and other related parameters. There is a growing consensus that other non-acoustic factors (e.g., vision, smell, etc.) should also be considered in this context (8, 9). The third step relates to modelling the relationship between descriptors and indicators. This will, in turn, pave the way for the definition of the soundscape indices that will be used as single-value representations of the soundscape quality of a place.

Overall, soundscape indices are important to implement the soundscape approach in urban planning and design, with the ultimate goal of creating spaces of high acoustic quality. For this to happen, it is therefore required that the soundscape international community makes more efforts to identify and to agree on relevant soundscape descriptors and corresponding affecting factors.

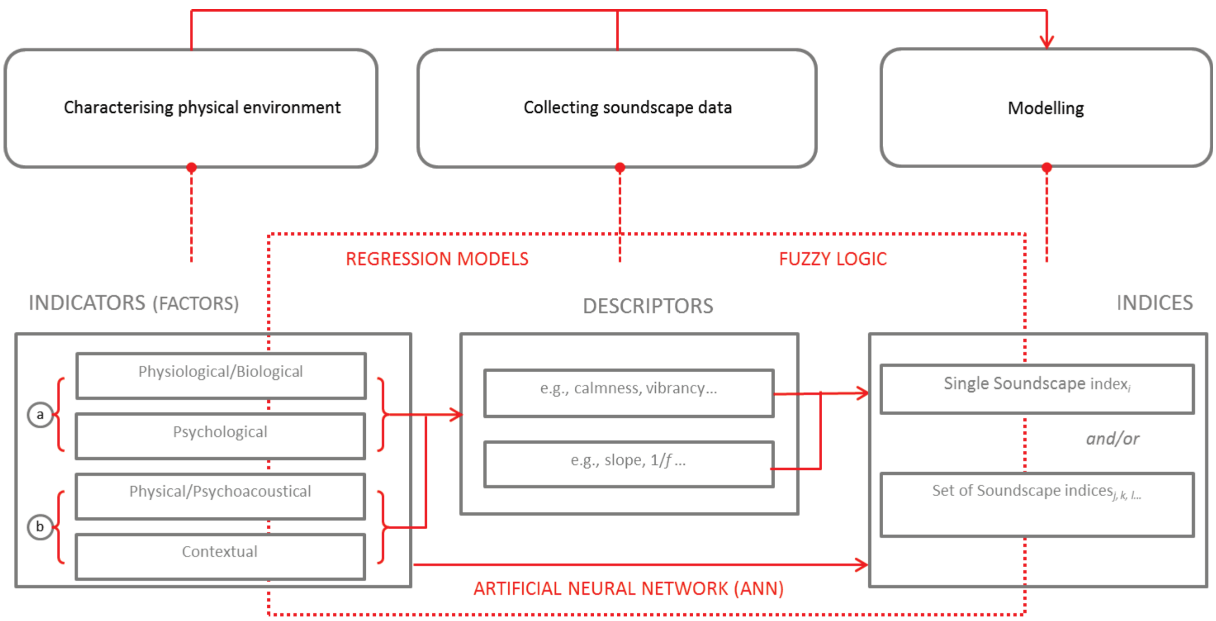

Figure 1 – A visual schematization of the overall framework for developing soundscape indices

3. SOUNDSCAPE DATABASE

3.1 Protocol for On-site Data Collection

In order to build a useful soundscape database for the prediction model shown in Figure 1 and to cover a reasonable variety of auditory and non-auditory factors, a number of sites around the world are being surveyed in the context of the SSID project. A protocol for data collection has been established to gather comparable soundscape-related parameters at each site. It comprises soundscape descriptors but also a number of other parameters which are speculated to influence human perception of the acoustic environment. The protocol gathers subjective and objective data, all quantified to serve as soundscape descriptors and indicators. The protocol is being applied on-site following the measurement-point approach, where all the metrics are related to a delimited area, i.e. a measurement point in an urban open space.

The subjective responses are being collected on-site in two stages: via questionnaires handed out to the untrained participants and via researcher's notes. The survey questionnaire is based on Method A of the ISO/TS 12913-2:2018 (10) and the WHO-5 Well-Being Index (11) and it comprises sound source identification, soundscape descriptors, assessment of the overall environment, participants' demographic and socio-economic data, and self-reported well-being. The researcher's notes describe dominant sound events observed by the researchers and comments on participants' activities prior and during the survey (e.g., was a participant part of a group, was he/she passing by or staying in the measurement-point vicinity?).

The objective measurements are being collected in three stages:

- representative spatial, audio-visual recording directly preceding the collection of subjective data;
- reference binaural recording during the subjective data collection;
- continuous 'monitoring-type' monaural audio and environmental data logging during the whole survey session (during both representative and reference recordings).

The audio-visual recording and environmental data logging are performed using the 360-camera (for spatial and reference visual data), a sound level meter, a 1st order ambisonic microphone with the accompanying portable audio recorder, binaural recording system and an environmental meter (measuring light, humidity, and temperature amongst other parameters). The setup is conceived to capture both industry-standard monaural recording needed for calculating environmental sound pressure level and psychoacoustic parameters (12) and multichannel recording needed to assess static and dynamic spatial characteristics, i.e. movement, localisation, etc.

The representative spatial recording will serve as the basis for the reproduction of a VR simulation in laboratory conditions and for testing physiological responses. It is performed to capture a consistent and representative five-minute period.

Figure 2 – The research team conducting a survey at Byng Place/Torrington Square in London in March 2019

3.2 Case Study Sites

Over 40 case study sites have been selected in cities all over the world to provide a variety in the auditory and non-auditory (physical-contextual and social-contextual) factors. While a majority of sites providing physical-contextual (visual and morphological) and auditory diversity have been identified in London, being the project's base location, a number of sites are being surveyed in China, Netherlands, Spain, Italy, Croatia, and France. The sites include different urban scales, uses, activities, and ambiances – from pocket squares in residential parts of Shenzhen and communal gardens in London to vast monumental squares in Harbin and Shenyang; from an anonymous residential street in Granada to the iconic Piazza San Marco in Venice. All physical-contextual factors are being measured from a single point of view, using the data available from the 360-camera and the environmental meter.

The meaning embedded in the observed stimuli (qualitative data) has been one of the trademarks of the soundscape approach (13). This can be applied to both auditory and non-auditory factors and is reflected in keeping track of culturally conditioned soundmarks (music, bells, and signals) and landmarks (architectural setting distinguishable as traditional, historical, international or neutral).

Auditory factors considered for site selection are based on sound source types (human, natural and sounds). They are being characterised regarding their level, dominance in the overall acoustic environment, and meaning.

The main physical-contextual factors considered are: the amount of the visible vegetation within the view-field, openness (defined either as the amount of the visible sky or visible horizon), spatial complexity (featuring topography and the sky vs ground ratio), the amount of visible water surface and the layer of 'urban and architectural meaning' (number of items identified as historical/traditional or international). Physical-contextual factors have a major influence on soundscape descriptors, especially the visually related ones (9, 14). Probably the crucial factor for determining vibrancy is the presence of people (8, 9). It can be measured using the video data, either as the number of visible people or as the area covered by people. Although being a social factor per se, here it is considered a part of the physical context as it is being measured using visual data.

Social-contextual factors are considered to be influenced by sensorial sensitivity, behavioural expectations, and intentions, all expected to be related to participant's cultural background (2, 13), which is the main reason for sampling sites across the world.

Table 1 –Auditory and non-auditory factors observed for site selection

Auditory factors	Non-auditory factors	
	Physical-contextual factors	Social-contextual factors
Sound source type (dominance in the acoustic environment)	Visual (built environment and social presence)	Socio-economic and demographic (status, gender)
Sound source meaning (soundmark, music, signal)	Environmental (illuminance, temperature, humidity, wind speed)	Pre-conception and personal preference (cultural background)
	Visual meaning (cultural heritage, signalisation)	Intention (activities)

4. EFFECTS OF PSYCHOLOGICAL, ACOUSTICAL/PSYCHOACOUSTICAL AND NEURAL AND PHYSIOLOGICAL FACTORS

4.1 Acoustic/Psychoacoustic Metrics and Non-Auditory Factors

The relationship between physical attributes of the environment and the perception of the sound as assessed by the people exposed to the environment will be crucial to any proposed soundscape index.

Previous work on identifying the key acoustic and psychoacoustic parameters has so far yielded conclusive results only in the realm of soundscape identification (15) and has indicated that traditional acoustic parameters and analysis are insufficient metrics for subjective assessment of a soundscape's overall pleasantness (16). However, progress has been made in determining the relationships between (psycho)acoustic parameters and more targeted perceptual attributes such as vibrancy and eventfulness (9, 17).

Although some research has indicated that aspects of the temporal structure of the acoustic environment may be related to attributes such as "chaotic" or "boring", the current methods for evaluating the influence of the temporal structure on soundscape perception are lacking and struggle to generalise soundscape assessments over longer timescales. This study will apply modern advances in time series analysis and regression computing toward the development of a metric describing the complex temporal structure of measured sound environments. This temporal metric will enable us to investigate the relationship between medium- and long-timescale patterns in the acoustic environment and components of the assessments of the soundscape. Further regression analysis can contribute to improved forecasting of the behaviour and characteristics of acoustic environments, allowing for extrapolations of the expected soundscape quality based on relatively short measurements.

4.2 Perceptual Factors and Target Population Assessment Simulation

Rating of perceptual attributes is a strategy commonly used in soundscape research. One proposed method uses a trigonometrical projection over the mean or the median of the distribution of perceptual attributes (10, 18). However, some observations (19) show that cross-distributions of ratings across paired attributes show patterns that could possibly hide further features to complement or to extend the results. Considering the current direction of the state of the art, a pilot study (19) has focused on the scaling deviances across ratings of pairs of bipolar attributes. The information from the bivariate distribution of these attributes has been examined by means of clustering analysis across multiple combinations of features. The results will be used for feature selection to understand the most influential combination of features to describe differences between soundscapes which share particular properties. These features will be used to highlight psychoacoustic, physical and contextual factors, which possibly lay behind distribution patterns of ratings between paired bipolar attributes. This information will be further considered in order to choose the best model strategy to be implemented in the SSID framework (see section 3.1).

A further important point is to understand the perceptual differences in the assessment between untrained and soundscape-expert subjects. A study to map the differences between these two categories (i.e., trained vs. untrained) of subjects will also be taken into account to optimise resources in terms of the number of subjects and amount of time needed. This step aims to predict the responses in a large scale of casual users by only using the assessment of a few trained people. On the other hand, the prediction of general subjects' assessment can also be implemented and estimated by using a dataset augmentation technique by means of Generative Adversarial Networks (20). This strategy makes it possible to automatically fill hundreds of surveys, given particular contextual, psychoacoustic and environmental parameters/measurements, by simulating a target population which can be characterised by age, education, socio-economical distribution, and gender proportions.

4.3 Psychophysiological substrates of soundscape

The impact of the acoustic environment on humans' nervous system functionality and structure, manifesting as psychological and physical health issues has been long established (21, 22). However, the explicit peripheral and central psychophysiological mechanisms underlying this impact are far from understood. The psychophysiology behind soundscape may be described as unbalancing the state of equilibrium or homeostasis, causing altered behaviours, cognition, and emotions (23, 24). It is therefore important to shed light on the impact of sounds on the human nervous system at the unconscious level by quantifying the physiological and neurophysiological responses such as heart rate (HR), Skin Conductance Response (SCR), and spectral bands/electrical activity of the brain.

The quantification of the physiological and neurophysiological basis of soundscape, taking into account the physical properties of the acoustic environment in a similar context, will be valuable in the development of a robust groundwork for determining why individuals perceive acoustic environment the way that they do, and in the prediction of the perceptual appraisals.

The SSID project aims at measuring HR and SCR in response to spatially recorded sounds, representing three main categories/sound sources, namely nature, mechanical, and human, in order to extrapolate physiological patterns that arise from those sound sources. Additionally, the electrical activity of the brain will be probed in response to sounds from single vs. complex sources, back- vs. foreground sounds, and short vs. long sounds, respectively, for the purpose of taking one closer step toward characterising soundscape at the brain level. Overall, understanding the perception of the acoustic environment at the unconscious level may create a beneficial foundation for psychophysiological modelling of soundscape and the characterization of soundscape regarding the type of evoked responses. Such results will form a key element in the model for soundscape indices, determined by physiological and neurophysiological considerations.

4.4 Neural correlates of soundscape experience

Based on the results from complex acoustic analyses of the acoustic environment recordings it is possible to attempt predictions about people's perception of sounds present in the environment (25), but yet very little is known from a neuroanatomical perspective about why those predictions might be true. Many psychoacoustic parameters, such as loudness, pitch, timbre, and sound location, depend on complex spectral and temporal aspects of sounds, and so result in multidimensional perceptual sensations (26–28). It is important to understand how the relationships between physical properties of acoustic stimuli, neural processing, and their connection with perceptual attributes may be reflected in brain processes and how subjective perception might be shaped by contextual modulation of auditory connectivity. The use of functional magnetic resonance (fMRI) offers an opportunity to study the relationship between physical stimulus properties, stimulus representation in the brain, and their connection with perceptual attributes more directly by identifying patterns of activation in response to selected sound samples. Since neural responses are not correlated with a listener's perceptual reports until the level of the cortex (29), it is expected that modulations of the cortical activity can be linked to the subjectively determined state of soundscape quality. Therefore, the magnitude and extent of the cortical activation can be described as a function of physical sound properties and equivalent perceptual attributes to provide insights into the relationship between fMRI activation, the characteristics of the stimulus, and its perceptual outcome (i.e., the soundscape).

In order to analyse the acoustic scene, our auditory system needs to be able to extract certain stimulus attributes while generalising across other properties. The effectiveness of those processes and the ability to listen selectively in complex and noisy environments is crucial to our everyday behaviour and effective communication. Since the process of selectively directing attention to a single auditory stream in a complex multisensory scene may shape our perceptual organisation of the elements present in this scene, attention might be one factor crucial for understanding those processes (30). It is thus important to explain how human attention is drawn, and what are the consequences of the sustained attention or lack of it, in a dynamic process of perceiving the acoustic environment. Another approach employed in this study will be the use of virtual reality and eye-tracking technologies which would help to understand the interactions between the auditory and visual signal processing (31, 32) as well as to tackle the role of saliency, feature characteristics, and goal-directed behaviour in shaping attention distribution. By manipulating sound samples and visual features present in the virtual environment, it is possible to extract the information about the existing cross-modal audio-visual effects and attentional effects driven by different attributes and their influence on soundscape.

Understanding neural mechanisms behind sound perception will feed directly into the proposed soundscape indices by explaining the relationship between physical attributes of the environment and the perception of the sound as assessed by the people exposed to this environment and providing neuroanatomical validation of the results yielded by the current research.

5. SOUNDSCAPE INDICES DEVELOPMENT AND APPLICABILITY

Based on the statistical examination of the interrelationships among factors in different facets, formula(s) and/or model(s) for soundscape indices can be derived/constructed. The soundscape indices may take the form of a single index or a set of indices (also see Figure 1). For the former, it could be SSID = *f*(physical factors) + *f*(contextual factors) + …, with corrections by socio-demographical factors and modifications with psychological, neural, and physiological considerations. SSID could be a single numerical indicator or a fuzzy indicator of possibilities. The SSID could also be calculated with a computer model, rather than an analytical/empirical formula, if there are multiple/complex correlations among the determining factors, where artificial intelligence (AI) or machine learning (ML) techniques could also be considered (33) For the latter, the SSID will be based on a set of formulas or computer models, reflecting multiple attributes (e.g. loudness, calmness, sound preference, vibrancy), which could also be regarded as intermediate indices.

The SSID project is also addressing soundscape prediction and design. With the above SSID models, soundscape prediction tools could be established, with SSID as the key output. The inputs, as designable factors, could include various sound sources and their spatial and temporal conditions for predicting sound levels, people movements and spatial distribution, and 3D acoustic animation of scenarios. Such tools will lead to the future generation of soundscape mapping, going beyond the current noise mapping. The development of SSID will provide the foundations for relevant standards and policies in sound environment design and regulation.

6. CONCLUDING REMARKS

In this paper, the framework and basic steps of developing soundscape indices have been discussed. It is expected that this will enhance the underpinning science of soundscape studies, by fostering interdisciplinary cross-breeding of emerging scientific ideas. The soundscape indices will support the implementation of soundscapes - by integrating into planning policies to better inform the management and planning of acoustic environments, allowing for better tailored improvements to design the built environment, contributing to creating healthier, more enjoyable and liveable environments, with respect to the planning of new living and recreational areas and to the reshaping of unsustainable older developments.

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