Machine Learning and Regression Modelling of Dynamic Urban Soundscapes

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Declaration

I, Andrew Mitchell, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Impact Statement

The statement should describe, in no more than 500 words, how the expertise, knowledge, analysis, discovery or insight presented in your thesis could be put to a beneficial use. Consider benefits from **inside** and **outside** academia and the ways in which these benefits could be brought about.

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1 Introduction

1.1 Research Summary

Urban noise pollution affects 80 million EU citizens with substantial impacts on public health which are not well addressed by conventional noise control methods. Traditional noise control methods have typically limited their focus to the reduction of unwanted noise, ignoring the potential benefits of increasing positive sounds and remaining restricted by practical limitations of noise reduction. Modern approaches to achieve improved health outcomes and public satisfaction aim to incorporate a person's perception of an acoustic environment, an approach known as 'Soundscape'.

Soundscape studies strive to understand the perception of a sound environment, in context, including acoustic, (non-acoustic) environmental, contextual, and personal factors. These factors combine together to form a person's soundscape in complex interacting ways (Berglund and Nilsson, 2006). In order to predict how people would perceive an acoustic environment, it is essential to identify the underlying acoustic and non-acoustic properties of soundscape.

When attempting to apply soundscape in practical applications in the built environment, it is immediately apparent that a predictive model of the users' perceptual response to the acoustic environment is necessary. Whether to determine the impact of a design change, or to integrate a large scale data at neighbourhood and city levels, a mathematical model of the interacting factors will form a vital component of the implementation of the soundscape approach. This work is intended to identify methods for incorporating contextual and objective information into a useable and interpretable predictive model of urban soundscapes. In order to achieve this, a protocol for collecting the multi-level, multi-factor perceptual assessment data has been developed and implemented, resulting in a large soundscape database. Several avenues of investigation are then drawn from the database. The primary research questions are:

1. What are the primary acoustic features involved in soundscape formation and what are the driving interactions between acoustic features and soundscape assessment?

2. How does the sound source composition in a complex sound environment mediate this interaction and how can this effect be simplified and modelled?

3. How can the multiple levels of soundscape formation be simplified and integrated into a cohesive predictive model, and what interpretations about the cross-effects of these levels can be drawn from the model?

4. How does the soundscape of a place vary over time, is this variation driven by environmental features or by context, and can this variation be predicted?

1.2 The SSID Project

1.2.1 Project collaborators

1.2.2 Motivation for the SSID Project

1.3 Research Aims

1.4 Soundscape Indices and Metrics

1.4.1 Standardisation

The soundscape community is undergoing a period of increased methodological standardization in order to better coordinate and communicate the findings of the field. This process has resulted in many operational tools designed to assess and understand how sound environments are perceived and apply this to shape modern noise control engineering approaches. Important topics which have been identified throughout this process are soundscape 'descriptors', 'indicators', and 'indices'. Aletta et al. (2016) defined soundscape descriptors as "measures of how people perceive the acoustic environment"; soundscape indicators as "measures used to predict the value of a soundscape descriptor; soundscape indices can then be defined as "single value scales derived from either descriptors or indicators that allow for comparison across soundscapes" Kang et al. (2019).

This conception has recently been formalized and expanded upon with the adoption of the recent ISO 12813 set of standards (International Organization for Standardization, 2014, 2018, 2019). ISO 12913 Part 1 sets out the definition and conception of Soundscape, defining it as the "acoustic environment as perceived or experienced and/or understood by a person or people, in context". Here, the soundscape is separated from the idea of an acoustic environment, which encompasses all of the sound which is experienced by the receiver, including any acoustically modifying effects of the environment. In contrast, the soundscape considers the acoustic environment, but also considers the impact of non-acoustic elements, such as the listener's context and the visual setting, and how these interact with the acoustic environment to influence the listener's perception.

1.4.2 Soundscape Descriptors

In order to consistently discuss soundscape and the factors which influence it, it is important to understand what terms have been used to describe soundscapes and to construct a consistent framework within which to work. Both the traditional focus on the epidemiological impacts of noise and the development of the soundscape concept have used many different terms in order to describe the perception of a sound environment.

Noise annoyance is perhaps the best researched aspect of environmental sound perception.

Pleasantness

Quietness / Tranquillity

Acoustic Comfort

Perceived sound level

Music-likeness

Restorativeness

Soundscape quality

Appropriateness

Perceived Affective Quality (PAQ)

1.4.3 Soundscape Indicators

Several studies prior to the formalization of the ISO standards on soundscape demonstrated the general, but inadequate, relationship between traditional acoustic metrics, such as L_{Aeq}, with the subjective evaluation of the soundscape (Berglund and Nilsson, 2006; Yang and Kang, 2005; Rychtáriková and Vermeir, 2013; Aumond et al., 2017; Alsina-Pagès et al., 2021). These have typically aimed to address the existing gap between traditional environmental acoustics metrics and the experience of the sound environment. Yang and Kang (2005) showed that, when the sound level is 'lower than a certain value, say 70 dBA', there is no longer a significant change in the evaluation of acoustic comfort as the sound level changes. However, the perceived sound level does continue to change along with the measured sound level, showing that (1) measured sound level is not enough to predict soundscape descriptors such as 'acoustic comfort', and (2) there is a complex relationship between perceived sound level and soundscape descriptors which is mediated by other factors.

Subsequent studies have shown that, even with large data sets and several possible acoustic indicators examined, models that are based on objective/measurable metrics under-perform in predicting soundscape assessment when compared to models based on perceptual responses. Ricciardi et al. (2015), with a methodology based on smart phone recordings, achieved $R^2 = 0.21$ with acoustic input factors L_{50} and $L_{10} - L_{90}$, whereas the same dataset and model building method achieved $R^2 = 0.52$ with perceptual input factors overall loudness (OL), visual amenity (VA), traffic (T), voice (V), and birds (B). This indicates that merely examining the acoustic level is not sufficient for predicting the assessed soundscape quality, and that additional objective factors and a more holistic and involved method of characterizing the environment is required. These previous studies have generally been limited by one or many of the following factors:

- limited number or types of locations;
- limited responses sample size;
- no non-acoustic factors.

These factors generally limit the generalizability of their results beyond the investigated locations.

1.4.4 The need for predictive soundscape models

The ability to predict the likely soundscape assessment of a space is crucial to implementing the soundscape concept in practical design. Current methods of assessing soundscapes are generally limited to a post-hoc assessment of an existing environment, where users of the space in question are surveyed regarding their experience of the acoustic environment (Engel et al., 2018; Zhang et al., 2018). While this approach has proved useful in identifying the impacts of an existing environment, designers require the ability to predict how a change or proposed design will impact the soundscape of the space. To this end, a model that is built upon measurable or estimate-able quantities of the environment would represent a leap forward in the ability to design soundscapes.

Developing soundscape indices is a process that requires consideration of how people perceive, experience, and understand the surrounding sound environment. For the purpose of modelling and comparisons,

Previous soundscape research has demonstrated that perception of the acoustic environment, while primarily driven by sound level, is mediated heavily by non-acoustic factors which interact with the sound level, spectral information, and temporal acoustic behaviour in complex ways. The soundscape is influenced by several levels of factors: the immediate and long-term acoustic environment, other environmental factors (e.g. temperature, air quality), the physical / visual characteristics of the space, the type of architectural space, and even cultural and country-level expectations. When approached in a predictive model context, the acoustic data must form the core components, but a coherent framework for describing how the influence of the acoustic factors is affected by the non-acoustic factors is required.

Simpler analyses have taken a fragmented approach, for instance where separate acoustic-factor models are built independently for each type of architectural space considered in the data set and, separately, statistical models are built to investigate another non-acoustic factor, e.g. visual greenness vs lack of greenness. In order to properly extract the influences of all of these levels of factors as well as to build a generalisable model which can be used in practice, this fragmented approach should be combined into a single multi-level model.

The first key step for this approach is the creation of a coherent, large-scale, multi-factor database of objective environmental measurements and subjective perceptual responses. My research makes use of in-person field questionnaires, long-term manned questionnaires, and multi-factor characterisation of the environment as part of the ERC-funded project Soundscape Indices (SSID) and in collaboration with The French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) to collect this database across a wide range of locations and soundscape types. This work has already been mostly completed and the database is now ready to be put to use in building the overall soundscape predictive model.

This approach is unique in that it:

1. fundamentally incorporates all identified factors of soundscape perception in a coherent manner;
2. is extensible and interpretable;
3. considers how soundscape change over both multi-hour and multi-day timescales and incorporates this dynamic behaviour for increased accuracy.

1.5 Application of SSID

1.6 Summary of Novel Research

1.7 Chapter Summary and Thesis Overview

2 Literature Review

2.1 Impact of Urban Noise on Health and Wellbeing

Give a full formal background to why noise control is important for public health.

2.2 Current Methods of Assessing and Addressing Urban Noise

2.2.1 Acoustical Parameters

2.2.2 ISO Environmental Acoustics Standards

ISO 1996-1, esp sections on annoyance, e.g. Annex F, G, H

2.2.3 EU Noise Mapping

2.2.4 Shortcomings

2.3 Soundscape Studies

2.3.1 Soundscape Descriptors and Indices

2.3.2 World Soundscape Project

2.3.3 Swedish Soundscape Quality Protocol

2.3.4 Demographic differences

Several studies have attempted to study the degree to which personal and demographic factors influence a person's soundscape perception. In some conceptions (Kou et al., 2020) these personal factors are classed as 'contextual' soundscape indicators - features which influence or, in a modelling context, be used as independent variables to predict the value of a soundscape descriptor. The personal factors help to create a personal soundscape interpretation model which is individual to each person.

In this way, a person's individual state-of-mind, ethnic identity, educational background, gender identity, etc. form a pseudo-deterministic framework through which the physical inputs from their environment are filtered. Clearly, many of these personal factors could never be measured and even those which are measurable will have wide ranges of legitimate effects, however estimating the degree and type of effect they may have can both help us better predict individual soundscape assessments and understand how group identities influence sound perception.

Section on Erfanian et al. 2020, Psychological Well-being

Low-income and minority evidence A consistent limitation of soundscape studies investigating the influence of personal factors is a sampling bias towards majority ethnicities (typically White British for UK studies and ethnic Chinese for Chinese studies) and middle-class and highly educated groups. This results in not only incomplete information about how demographics influence soundscape perception, but also represents a systemic under-representation of certain environments. While it may be unclear to what extent ethnicity and social class internally influence a person's perception, it is clear that these groups are exposed to different sound environments and therefore studies which do not include under-represented groups are also by definition not including those sound environments which those groups inhabit.

A recent study by Kou et al. (2020) was successful in making inroads in these under-represented environments by studying the Humboldt Park neighbourhood in Chicago, USA. Their study included

2.4 Existing Predictive Models

(Lionello et al., 2020)

2.4.1 Models based on non-acoustic data sources

(Verma et al., 2020), (Gasco et al., 2020)

3 Methods

3.1 Data Collection (Protocol)

draft *From: Protocol paper* Soundscape studies strive to understand the perception of a sound environment, in context, including acoustic, (non-acoustic) environmental, contextual, and personal factors. These factors combine together to form a person's soundscape in complex interacting ways (Berglund and Nilsson, 2006). In order to predict how people would perceive an acoustic environment, it is essential to identify the underlying acoustic and non-acoustic properties of soundscape.

The ISO/TS 12913-2:2018 is the current reference document addressing data collection and reporting requirements in soundscape studies. In terms of methods, the ISO document covers two main approaches, namely: soundwalks combined with questionnaires (Methods A and B) and narrative interviews (Method C) (International Organization for Standardization, 2018), which relate to on-site and off-site data collection, accordingly. Part 3 of the ISO 12913 series builds on Part 2 and provides guidelines for analyzing data gathered using only those methods (International Organization for Standardization, 2019). However, the range of possible methodological approaches to soundscape data collection is much broader and it includes, for instance, laboratory experiments (Aletta et al., 2016; Sun et al., 2019; Oberman et al., 2018), pseudo-randomized experience sampling (Craig et al., 2017), and even non-participatory studies (Lavia et al., 2018). The protocol described in this paper was designed having in mind the need for a relatively large soundscape dataset that could be used for design and modeling purposes, thus trying to expand the scope of soundwalks that typically deal with much smaller samples of participants (Engel et al., 2018). For the sake of comparability and standardization with these methods, we chose to refer to the soundscape attributes reported in the ISO Part 2 (Method A).

The ability to predict the likely soundscape assessment of a space is crucial to implementing the soundscape concept in practical design. Current methods of assessing soundscapes are generally limited to a post-hoc assessment of the existing environment, where users of the space in question are surveyed regarding their experience of the acoustic environment (Engel et al., 2018; Zhang et al., 2018). While this approach has proved useful in identifying the impacts of an existing environment, designers require the ability to predict how a change or proposed design will impact the soundscape of the space. To this end, a model that is built upon measurable or estimate-able quantities of the environment would represent a leap forward in the ability to design soundscapes.

draft *Need to rephrase all of this, lifted wholesale from protocol paper* proof *hello!* Developing soundscape indices is a process that requires consideration of how people perceive, experience, and understand the surrounding sound environment. For the purpose of modeling and comparisons, it is important that such indices are numerical entities and that these quantities are collected consistently across all investigated spaces and soundscapes. Although the soundscape approach taken in this protocol represents a step-change away from existing methods of noise exposure measurements, strong cues particularly in the realm of acoustic measurement methods should be taken from existing standards both to make use of the significant knowledge and experience that has gone into the creation of these standards and to facilitate compatibility between soundscape and traditional measurements. In general, the measurement methods and best practice given in environmental noise standards such as ISO 1996-1:2016 and ISO 1996-2:2017 should be followed wherever possible, including the use of standardized acoustic equipment such as standard sound level meters.

An European Research Council (ERC) Advanced Grant project is ongoing to develop the proposed "Soundscape Indices" (SSID), which adequately reflect levels of human comfort and preference while integrating measurable and observable quantities. The framework proposed for the SSID project is laid out in detail by Kang et al. (Kang et al., 2019), the first step of which is generating a large-scale and coherent database of the required soundscape characterization data. Given the already recognized differences in soundscape assessment across various countries and cultures (Ren et al., 2018; Kang et al., 2016) and the success of existing international soundscape efforts such as the Soundscapes of the World project (De Coensel et al., 2017), the collection of soundscapes from many different countries and in many different contexts is an important component of the SSID project.

Therefore, the following protocol has been conceived and implemented within the SSID framework to collect data about urban soundscapes for use in general soundscape research and toward the design of Soundscape Indices. Thus far, the collected database includes nearly 4000 participants' responses from 59 locations in 10 cities and provinces across the UK, China, Spain, and Italy. This protocol has been refined and adjusted as needed during this extensive data collection process to arrive at this final version. This work was conducted by nine associated research groups and coordinated by the SSID group based at University College London and has already produced several pieces of published work towards the creation of Soundscape Indices (Aletta and Kang, 2018; Aletta et al., 2019a; Mitchell and Kang, 2019; Mitchell et al., 2019; Aletta et al., 2019b; Lionello et al., 2019; Aletta et al., 2019a; Oberman et al., 2018). Additional collaborations and data collection efforts are currently underway in France, the Netherlands, and Croatia.

3.1.1 Purpose

This protocol was designed to achieve two primary goals: (1) gather in situ soundscape assessments from the public, which can be further analyzed and utilized in designing a soundscape index; (2) conduct recordings needed to reproduce the audio-visual environment of a location in a laboratory setting for conducting controlled experiments on soundscape. These two goals represent two levels of data required for developing a general soundscape model. The first enables large scale data collection, resulting in a database with thousands of perceptual responses and their corresponding quantitative data which can be statistically analyzed on a large scale, or used for training in machine learning modeling. In situ assessments also represent the most holistic assessment, ensuring all factors that influence the soundscape are present, including those which cannot be reproduced elsewhere.

However, there are questions which cannot be practically addressed in situ, such as soundscape assessment of less- or un-populated areas, the influence of mismatched acoustic and visual cues, physiological and neural responses to various soundscapes, and so on (Kogan et al., 2017). Laboratory experiments with controlled environments are required to address these aspects. Toward the development of a coherent SSID, however, it is important that these two forms of data are collected simultaneously and with compatible methods, such that the results of the two approaches can be confidently combined and compared. In addition, since this protocol is intended to be used for the creation of a large-scale international database with additions carried out by several different and remote teams, it has been designed for efficiency, scalability, and information redundancy.

3.1.2 Protocol Design and Equipment

The first goal is achieved by conducting in situ questionnaires using a slightly altered version of Method A (questionnaire) from Annex C of the ISO/TS 12913-2:2018 technical specification (International Organization for Standardization, 2018) collected either via handheld tablets or paper copies of the questionnaire. Typically, a minimum of 100 responses are collected at each location during multiple 2-5-hour sessions over several days. During the survey sessions, acoustic data are collected via a stationary Class 1 Sound Level Meter (SLM) (as defined in IEC 61672-1:2013) running throughout the survey period and through binaural recordings taken next to each respondent. These acoustic and response data are linked through an indexing system so that features of the acoustic environment can be correlated with individual responses or with the overall assessment of the soundscape, as required by researchers.

The second goal is achieved by making First-Order Ambisonic (FOA) recordings simultaneously with 360°video which can be reproduced in a virtual reality environment. It has been shown that head-tracked binaural and multi-speaker ambisonic reproduction of recorded acoustic environments recorded in this way have high ecological validity (Davies et al., 2014), particularly when paired with simultaneous head-tracked virtual reality video (Hong et al., 2017, 2018; De Coensel et al., 2017).

The on-site procedure to collect these data are separated into two stages, which will be outlined in detail in Section **??**. The stage during which the spatial audio-visual recordings are made for lab experiments is called the **Recording Stage**, while the stage during which questionnaires and environmental data are captured is called the **Questionnaire Stage**.

The procedure has been designed to include multiple levels of data and metadata redundancy, making it robust to on-site issues and human error. The most crucial aspect of the redundancy is ensuring perceptual responses can be matched with the appropriate corresponding environmental and acoustic data even when some information is lost or forgotten.

Labeling and Data Organization

In order to be able to identify all of the many data components of the Recording and Questionnaire Stages and to associate these with their various corresponding data, the following labeling system is suggested. This system is focused on (1) relating all of the separate recordings and factors to specific questionnaire responses and (2) efficiency and consistency on site. A recent paper by Aumond et al. (Aumond et al., 2017) demonstrated the importance of addressing multiple levels of factors which influence perception, from individual-, to session-, to location-level. The successful pleasantness models built incorporating these information levels showed a marked improvement over the equivalent individual-level or location-level only models. The data organisation system proposed here was designed in order to maintain this important information, and the levels of information for the data collected on site are shown in Table 3.1.

At the top level is the **Location** information. This includes information about the location which does not change day-to-day, and generally characterizes the architectural character of the space, or typical climate conditions for the area. As described in Section **??**, each 'environmental unit' should be considered a new location. Therefore, if researchers want to investigate the differences in soundscape assessment in the middle of a small urban park and along the road next to the same park, these would be considered different locations since they would (typically) have different environmental factors, and should be given different names. The name chosen should be concise, but it should be obvious what location is referred to.

Table 3.1: Labeling system for on site data collection. Regent's Park Japanese Garden is used as an example location. SLM: Sound Level Meter (acoustical factors); ENV: Environmental factors; BIN: Binaural; QUE: Questionnaires; PIC: Site pictures.

Level of Information	Example Label					Factors Measured at This Level
Location	RegentsParkJapan					GPS, Architectural typology, visual openness, etc.
SessionID	RegentsParkJapan1			RegentsParkJapan2		SLM, session notes, ENV
GroupID	RPJ101	RPJ102	...	RPJ201	...	BIN, PIC
Questionnaire	1, 2, 3	4, 5	...	25, 26	...	QUE, Start & End time

The next level is information which is specific to each session, labeled with a **SessionID**. This SessionID should contain the name of the location and a numerical index which will increase with each repeated session at that location. The SessionID is associated with the data collected during the Recording Stage, and with the data which are continuous throughout the Questionnaire Stage, SLM, and ENV data. For easy automatic processing, correct spelling and consistency with the format is crucial so that data can be filtered according to the SessionID or the location, as is often necessary. In addition, for ease of automatic processing, it is recommended not to include spaces in the SessionID to avoid string splitting issues in analysis code.

Underneath each SessionID will be a set of **GroupID**s. One GroupID is assigned for *each group of participants*. This should correspond to a single binaural recording and a single 360° photo. This will be used to (1) relate multiple surveys taken simultaneously and (2) link the recording and photo with the surveys. The GroupID is particularly crucial as it allows commonly missing data to be shared across multiple collection methods. For instance, occasionally paper questionnaires will be missing start and end time information. In this case, this information can be pulled directly from other questionnaires with the same GroupID. Where no questionnaires have the times, it is possible to extract an approximate start time from the binaural recording or 360° photo and then estimate an average end time.

The GroupID should have the following format: [a set of letters representing the location name][the SessionID index number][an incrementing index for each group]. For example, for the second session at Regent's Park Japanese Garden, the location name is RegentsParkJapan, the GroupID letters might be 'RPJ'; the SessionID would be 'RegentsParkJapan2' so the GroupIDs for that session would start at '201'. Therefore, for example, the tenth group of participants for that session would be labeled 'RPJ210'. This format ensures that, if the location or SessionID are not recorded for a questionnaire, it is still obvious which session it belongs to.

Location and Measurement Point Selection

3.1.3 Equipment

3.2 Techniques for Field Data Collection

3.2.1 Spatial Recording

3.2.2 Ambisonic Encoding

3.2.3 Lab Design?

3.2.4 VR Reproduction

3.3 Questionnaire

3.4 Psychoacoustics and Auditory Perception

3.4.1 Psychoacoustic Parameters

Loudness

Zwicker and Fastl, Chap 8, see Mendeley notes and python-acoustics development notes.

3.4.2 Feature Selection

3.5 Machine Learning and Regression Techniques

3.5.1 Feature Selection

Mutual Information

draft *It appears that mutual information is related to the Bayes formula. I still need to read more into this, but it appears based on relative and overlapping probability distributions between the variables in question.*

From scholarpedia: quote *Based on entropy, where the uncertainty about a variable can be expressed as "the number of yes/no questions it takes to guess a random variable, given knowledge of the underlying distribution and taking the optimal question-asking strategy". "The mutual information is therefore the* reduction *in uncertainty about variable X, or the expected reduction in the number of yes/no questions needed to guess X after observing Y.".*

quote *"Mutual Information is just one way among many of measuring how related two variables are. However, it is a measure ideally suited for analyzing communication channels. Abstractly, a communication channel can be visualized as a transmission medium which receives an input x and produces an output y. If the channel is* noiseless, *the output will be equal to the input. However, in general, the transmission medium is noisy and an input x is converted to an output y with probability $P_{Y|X}(y|x)$.* misc *This seems very useful for my conception of sound perception / auditory processing, where the perception system is a noisy communication channel.*

Conditional Mutual Information

The Mutual Information between two variables, given another variable as a control.

3.5.2 Clustering Analysis

K-means

nbclust

3.5.3 Modelling Likert-type Data

Multiple Linear Regression

Ordinal Logistic Regression

Multi-output Regression

3.5.4 Multi-level Models

3.5.5 Bayesian Regression

4 Characterizing the Temporal Behaviour of Dynamic Urban Soundscapes

4.1 Introduction

4.2 Methods

4.3 Results and Discussion

4.3.1 Presence of 1/f in urban soundscapes

4.3.2 Statistical relationship to pleasantness ratings

4.3.3 Ordinal logistic models based on temporal and acoustic features

4.4 Conclusion

5 Combined Multi-level Regression Model for Predicting Soundscape

5.1 Introduction

5.2 Methods

5.2.1 Multi-level regression modelling

5.2.2 Feature Selection

5.3 Results

5.3.1 Simplified predictive soundscape models

COVID-19 Model

5.3.2 Multiple levels of soundscape formation

5.3.3 Feature selection

Acoustic features

Non-acoustic factors

5.3.4 Model design

5.4 Discussion

5.4.1 Interpretation

5.4.2 Implementation and use cases

6 The Influence of Sound Source Composition in Soundscape Formation

6.1 Introduction

6.2 Methods

6.2.1 Data collection

6.2.2 Clustering analysis

6.3 Results

6.3.1 Sound source profiles

6.3.2 Perceived affective quality ratings

6.3.3 Psychological well-being mediates soundscape formation within different sound source profiles

6.3.4 Regression models

6.4 Discussion

6.5 Conclusion

7 A Bayesian Hierarchical Predictive Soundscape Model and a Proposed Soundscape Index

7.1 Introduction

7.1.1 Probabilistic Distribution Thinking

The instruments described in the ISO 12913 Part 2 International Organization for Standardization (2018) were originally designed primarily for the context of individual or small group assessments. In these scenarios, the focus is on assessing the particular soundscape of the person in question. Recent advances in the soundscape approach since the development of the standards have shifted some focus from individual soundscapes to characterizing the overall soundscape of public spaces (Mitchell et al., 2020). In this context, a consideration of the natural variation in people's perception and the variation over time of a soundscape must be a core feature of how the soundscape is discussed. Boiling a public space which may have between tens and tens of thousands of people moving through it in a single day down to the mean (or median, or any other single metric) soundscape assessment completely dismisses the reality of the space. Likewise, this overall soundscape of a public space cannot possibly be determined through a 10-person soundwalk, as there is no guarantee that the sample of people engaged in the soundwalk are representative of the users of the space (in fact it is very likely they would not be).

This shift is part of a move towards a more holistic approach to urban noise and to integrating the soundscape approach into urban design and regulations.

7.2 Methods

7.3 Results

7.4 Discussion

7.5 Communicating SSID on the Basis of Percentages

7.6 Conclusion

8 Soundscape Modelling for Smart Cities: A case study

8.1 Introduction

8.2 Methods

8.2.1 SSID Data Collection

8.2.2 Sensor network and IFSTTAR data collection

8.3 Results

8.4 Discussion

9 Conclusions

9.1 Summary

9.2 Findings

9.3 Limitations and Recommendations for Future Research

Bibliography

Aletta, F., Astolfi, A., Di Blasio, S., Shtrepi, L., Kang, J., and Molinero, L. (2019a). Exploring associations between soundscape assessment, perceived safety and wellbeing: a pilot field study in Granary Square, London. In *23rd International Congress on Acoustics*, Aachen.

Aletta, F. and Kang, J. (2018). Towards an urban vibrancy model: A soundscape approach. *International Journal of Environmental Research and Public Health*, 15(8):1712.

Aletta, F., Kang, J., and Axelsson, Ö. (2016). Soundscape descriptors and a conceptual framework for developing predictive soundscape models. *Landscape and Urban Planning*, 149:65–74.

Aletta, F., Oberman, T., Mitchell, A., Erfanian, M., Lionello, M., Kachlicka, M., and Kang, J. (2019b). Associations between soundscape experience and self-reported wellbeing in open public urban spaces: A field study. *The Lancet*, 394:S17.

Alsina-Pagès, R. M., Freixes, M., Orga, F., Foraster, M., and Labairu-Trenchs, A. (2021). Perceptual evaluation of the citizen's acoustic environment from classic noise monitoring. *Cities & Health*, 5(1–2):145–149.

Aumond, P., Can, A., Coensel, B. D., Botteldooren, D., Ribeiro, C., and Lavandier, C. (2017). Modeling soundscape pleasantness using perceptual assessments and acoustic measurements along paths in urban context. *Acta Acustica united with Acustica*, 103(3):430–443.

Berglund, B. and Nilsson, M. E. (2006). On a Tool for Measuring Soundscape Quality in Urban Residential Areas. *Acta Acustica united with Acustica*, 92(6):938–944.

Craig, A., Moore, D., and Knox, D. (2017). Experience sampling: Assessing urban soundscapes using in-situ participatory methods. *Applied Acoustics*, 117:227–235.

Davies, W. J., Bruce, N. S., and Murphy, J. E. (2014). Soundscape reproduction and synthesis. *Acta Acustica united with Acustica*, 100(2):285–292.

De Coensel, B., Sun, K., and Botteldooren, D. (2017). Urban Soundscapes of the World: Selection and reproduction of urban acoustic environments with soundscape in mind. In *INTER-NOISE 2017 - 46th International Congress and Ex-*

position on Noise Control Engineering: Taming Noise and Moving Quiet, Hong Kong, China.

Engel, M. S., Fiebig, A., Pfaffenbach, C., and Fels, J. (2018). A Review of Socio-acoustic Surveys for Soundscape Studies. *Current Pollution Reports*, 4(3):220–239.

Gasco, L., Schifanella, R., Aiello, L. M., Quercia, D., Asensio, C., and de Arcas, G. (2020). Social Media and Open Data to Quantify the Effects of Noise on Health. *Frontiers in Sustainable Cities*, 2:41.

Hong, J. Y., He, J., Lam, B., Gupta, R., Gan, W.-S. S., Hong, Y. J., He, J., Lam, B., Gupta, R., Gan, W.-S. S., Hong, J. Y., He, J., Lam, B., Gupta, R., and Gan, W.-S. S. (2017). Spatial Audio for Soundscape Design: Recording and Reproduction. *Applied Sciences*, 7(6):627.

Hong, J. Y., Lam, B., Ong, Z.-T. T., Ooi, K., Gan, W.-S. S., Kang, J., Jing, F., Tan, S.-T. T., Feng, J., and Tan, S.-T. T. (2018). Quality assessment of acoustic environment reproduction methods for cinematic virtual reality in soundscape applications. *Building and Environment*, 149:1–14.

International Organization for Standardization (2014). *ISO 12913-1:2014 Acoustics – Soundscape – Part 1: Definition and conceptual framework*. Geneva, CH.

International Organization for Standardization (2018). *ISO/TS 12913-2:2018 Acoustics – Soundscape – Part 2: Data collection and reporting requirements*. Geneva, CH.

International Organization for Standardization (2019). *ISO/TS 12913-3:2019 Acoustics - Soundscape - Part 3: Data analysis*. Geneva, CH.

Kang, J., Aletta, F., Gjestland, T. T., Brown, L. A., Botteldooren, D., Schulte-Fortkamp, B., Lercher, P., van Kamp, I., Genuit, K., Fiebig, A., Bento Coelho, J. L., Maffei, L., and Lavia, L. (2016). Ten questions on the soundscapes of the built environment. *Building and Environment*, 108:284–294.

Kang, J., Aletta, F., Oberman, T., Erfanian, M., Kachlicka, M., Lionello, M., and Mitchell, A. (2019). Towards soundscape indices. In *Proceedings of the 23rd International Congress on Acoustics*, pages 2488–2495, Aachen.

Kogan, P., Turra, B., Arenas, J. P., and Hinalaf, M. (2017). A comprehensive methodology for the multidimensional and synchronic data collecting in soundscape. *Science of The Total Environment*, 580:1068–1077.

Kou, L., Kwan, M.-P., and Chai, Y. (2020). The effects of activity-related contexts on individual sound exposures: A time-geographic approach to soundscape studies. *Environment and Planning B: Urban Analytics and City Science*.

Lavia, L., Witchel, H. J., Aletta, F., Steffens, J., Fiebig, A., Kang, J., Howes, C., and Healey, P. G. T. (2018). Non-participant observation methods for soundscape design and urban panning. In Aletta, F. and Xiao, J., editors, *Handbook of Research on Perception-Driven Approaches to Urban Assessment and Design*, number April.

Lionello, M., Aletta, F., and Kang, J. (2019). On the dimension and scaling analysis of soundscape assessment tools: A case study about the "Method A" of ISO/TS 12913-2:2018. In *23rd International Congress on Acoustics*, Aachen.

Lionello, M., Aletta, F., and Kang, J. (2020). A systematic review of prediction models for the experience of urban soundscapes. *Applied Acoustics*, 170.

Mitchell, A., Aletta, F., Oberman, T., Erfanian, M., Kachlicka, M., Lionello, M., and Kang, J. (2019). Making cities smarter with new soundscape indices. In *The Journal of the Acoustical Society of America*, volume 146, pages 2873–2873, San Diego. Acoustical Society of America (ASA).

Mitchell, A. and Kang, J. (2019). The spectral structure of acoustic time series can predict the perceptual assessment of urban soundscapes. In *The Journal of the Acoustical Society of America*, volume 146, pages 2795–2795, San Diego. Acoustical Society of America (ASA).

Mitchell, A., Oberman, T., Aletta, F., Erfanian, M., Kachlicka, M., Lionello, M., and Kang, J. (2020). The Soundscape Indices (SSID) Protocol: A Method for Urban Soundscape Surveys–Questionnaires with Acoustical and Contextual Information. *Applied Sciences*, 10(7):2397.

Oberman, T., Šćitaroci, B. B. O., and Jambrošić, K. (2018). Towards a virtual soundwalk. In *Handbook of Research on Perception-Driven Approaches to Urban Assessment and Design*, pages 317–343. IGI Global.

Ren, X., Kang, J., Zhu, P., and Wang, S. (2018). Soundscape expectations of rural tourism: A comparison between Chinese and English potential tourists. *The Journal of the Acoustical Society of America*, 143:373–377.

Ricciardi, P., Delaitre, P., Lavandier, C., Torchia, F., and Aumond, P. (2015). Sound quality indicators for urban places in Paris cross-validated by Milan data. *The Journal of the Acoustical Society of America*, 138:2337–2348.

Rychtáriková, M. and Vermeir, G. (2013). Soundscape categorization on the basis of objective acoustical parameters. *Applied Acoustics*, 74(2):240–247.

Sun, K., De Coensel, B., Filipan, K., Aletta, F., Van Renterghem, T., De Pessemier, T., Joseph, W., and Botteldooren, D. (2019). Classification of soundscapes of urban public open spaces. *Landscape and Urban Planning*.

Verma, D., Jana, A., and Ramamritham, K. (2020). Predicting human perception of the urban environment in a spatiotemporal urban setting using locally acquired street view images and audio clips. *Building and Environment*, 186.

Yang, W. and Kang, J. (2005). Acoustic comfort evaluation in urban open public spaces. *Applied Acoustics*, 66(2):211–229.

Zhang, X., Ba, M., Kang, J., and Meng, Q. (2018). Effect of soundscape dimensions on acoustic comfort in urban open public spaces. *Applied Acoustics*, 133:73–81.