Machine Learning and Regression Modelling of Dynamic Urban Soundscapes: A multilevel approach

PhD Upgrade Report
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Abstract

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'.

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 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 can then be 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 affect 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?

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1 Introduction and Literature Review

Traditional noise control methods face several challenges in decreasing noise pollution in modern cities. In many cases, these challenges stem from an approach primarily focussed strictly on decreasing the noise levels or noise exposure in a given space. This approach can often prove impractical in situations where a problematic noise source cannot be moved or decreased, or where mitigation methods such as building a sound wall to block the sound transmission are expensive, infeasible, or merely undesirable. This can result in many urban spaces which are intended to provide a restorative space in the city being unpleasant due to the unwanted noise and going underutilised with little way to address the issue. When applied to urban sound and specifically to noise pollution, the soundscape approach introduces three key considerations beyond traditional noise control methods: 1) considering all aspects of the environment which may influence perception, not just the sound level and spectral content; 2) an increased and integrated consideration of the varying impacts which different sound sources have on perception; and 3) a consideration of both the positive and negative dimensions of soundscape perception. This approach can enable better outcomes by better identifying existing positive soundscapes (in line with the Environmental Noise Directive's mandate to 'preserve environmental noise quality where it is good' [1]), better identify specific sources of noise which impact soundscape quality and pinpoint the characteristics which may need to be decreased, and illuminate alternative methods which could be introduced to improve a soundscape where a reduction of noise is impractical. These can all lead to more opportunities to truly improve a space by identifying the causes of positive soundscapes, while also potentially decreasing the costs of noise mitigation by offering more targeted techniques and alternative approaches.

However, the soundscape approach also introduces new challenges, one of which is the difficulty in consistently measuring the perception of an urban space. To address this, 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. [2] 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"; and soundscape indices can then be defined as "single value scales derived from either descriptors or indicators that allow for comparison across soundscapes" [3].

This conception has recently been formalized and expanded upon with the adoption of the recent ISO 12913 standard series [4]–[6]. 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.

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), which relate to on-site and off-site data collection, respectively [5]. A soundwalk is a participatory group exercise wherein participants are led through the environment while focussing on listening to the environment and was first used in the World Soundscape Project by Murray Schafer, co-creator of the term soundscape [7]. When applied to practical soundscape assessments, this process will typically involve a researcher leading a group of 10-15 participants on a pre-planned walk through several locations of interest [8]. The participants will be instructed to "pay attention to what sounds are heard during the soundwalk, what they liked and disliked, why, and how they believe the acoustic environment could be improved" and their responses are collected by the researchers either through narrative interviews or by filling in a questionnaire [5]. Methods A and B present two questionnaires with slightly differing approaches to capture a person's perception.

Method A is built on a series of descriptors referred to as the Perceived Affective Quality (PAQs), proposed in soundscape studies by Axelsson, Nilsson, and Berglund in 2010 [9]. These PAQs are based on the pleasantness-activity paradigm present in research on emotions and environmental psychology, in particular Russell's circumplex model of affect [10]. As summarised by Axelsson: "Russell's model identifies two dimensions related to the perceived pleasantness of environments and how activating or arousing the environment is." This circumplex model is formed of two dimensions, pleasantness (often referred to as valence) and activity (or arousal), which are orthogonal to each other. When applied to soundscape, Axelsson re-termed these main axes as 'Pleasant' and 'Eventful', and also identified a set additional axes which are rotated 45° from the main axes. This rotated axis contains additional attributes

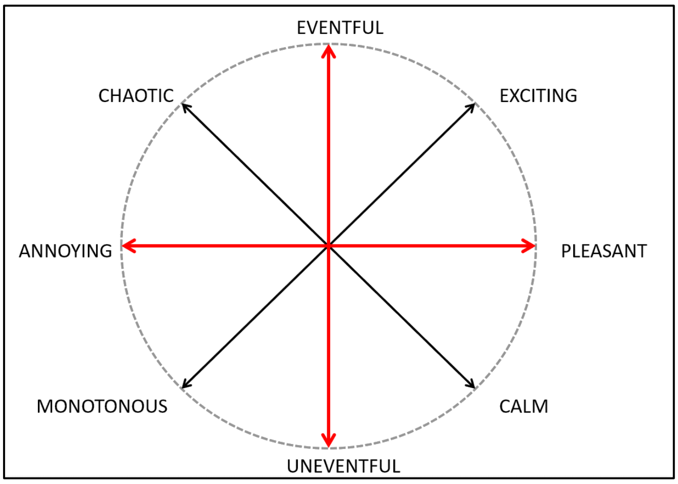


FIGURE 1 – CIRCUMPLEX MODEL OF SOUNDSCAPE

which represent various mixtures of the pleasant and eventful attributes: ‘Exciting’, ‘Chaotic’, ‘Monotonous’, and ‘Calm’. This circumplex model of soundscape can be seen in Figure 2. In Method A, these PAQs are collected through a series of questions with 5-point Likert-type responses where participants are asked to what extent they agree or disagree that the present surrounding sound environment is pleasant, exciting, etc. for each of the 8 descriptors. Method A also includes questions on: the sound source composition of the space, broken down into ‘Traffic noise’, ‘Other noise’, ‘Sounds from human beings’, and ‘Natural sounds’; overall soundscape quality; appropriateness of the sound environment to the place. Method B extends these questions to include: ‘How loud is it here?’, and ‘How often would you like to visit this place again?’. The circumplex model, along with the sound source and general soundscape questions represent a relatively comprehensive method for assessing the soundscape of a space.

The perception of a sound environment, in context, includes acoustic, (non-acoustic) environmental, contextual, and personal factors. These factors combine together to form a person’s soundscape in complex interacting ways [11]. 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.

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 [12]. 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.

Several studies conducted 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 [11], [13]–[15]. These have typically aimed to address the existing gap between traditional environmental acoustic 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 [16], 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, and no non-acoustic factors, generally limiting the generalizability of their result beyond the investigated locations. 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 in a single, multi-level modelling framework. This work is trying to extend the scope of objective measurements that are being collected in conjunction with perceptual responses by including other environmental and visual data in an attempt to extend the inclusion of contextual information in a soundscape model.

2 Goals

In order to address this, a protocol for collecting this multi-level, multi-factor perceptual assessment data has been developed [17] and implemented, resulting in a large soundscape database. Several avenues of investigation can then be drawn from the database. My 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 affect 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?

The relationship of these research questions to the rest of my work and my planned thesis is shown in Figure 1, below. A proposed thesis outline is included as Appendix A.

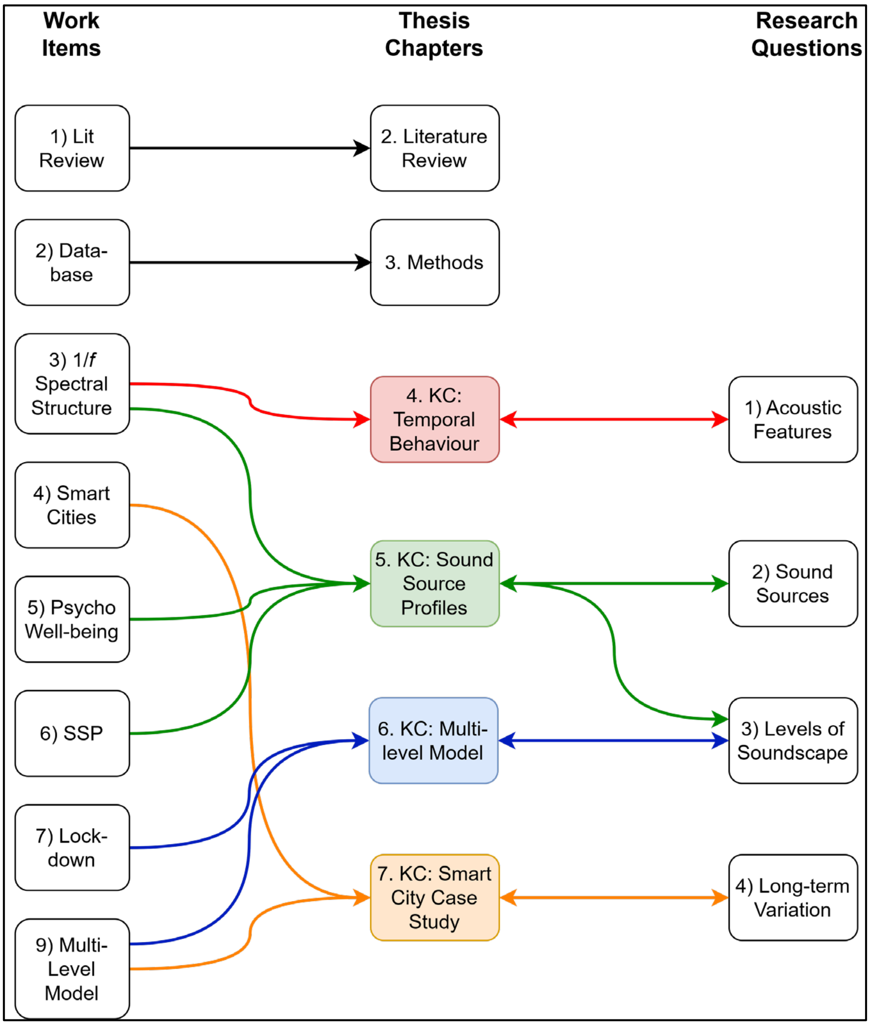


FIGURE 2 – GRAPH OVERVIEW OF THESIS WORK.
See Table 1 and Table 2 for the full labels of the Work Items and Appendix A for the Thesis Chapters.

3 Methodology

The first stage for this work is to collect a large database of soundscape assessments which can be used to build the predictive models. A protocol was designed for this work, and the broader SSID project, having in mind the need for a relatively large soundscape dataset that could be used for design and modelling purposes, thus trying the expand the scope of soundwalks that typically deal with much smaller samples of participants [8]. The data collection protocol was designed to gather in situ soundscape assessments from the public, which can be further analysed and utilised in designing a soundscape index.

In particular, this method enables large scale data collection, resulting in a database with thousands of perceptual responses and their corresponding quantitative data which can be statistically analysed on a large scale, or used for training in machine learning modelling. In situ assessments also represent the most holistic assessment, ensuring all factors that influence the soundscape formation are present, including those which could not be reproduced elsewhere (e.g. in a laboratory setting). For in depth details of how this data collection is carried out and what subjective and objective data are included, please see the journal paper attached in Appendix B.

Once collected, this database will be analysed with a series of machine learning and statistical methods. Multivariate linear regression is commonly used both for determining relationships between environmental factors and soundscape perception and for implementing predictive soundscape models [17], [18]. Specifically, when addressing Likert-type data, ordinal logistic regression is commonly used in fields such as education studies but has been less commonly used in soundscape studies [20], [21]. Although it has not yet been investigated in detail, Bayesian regression analysis may represent a powerful method for improving the accuracy and validity of soundscape models, as it can incorporate the degree of variation in responses inherent in dealing with perceptual data. Thus far, it does not appear that Bayesian analysis has been applied to any urban soundscape studies, and has only been used in one study within soundscape ecology [22], so it represents a novel avenue of investigation in urban soundscape modelling. Regression models may be applied with objective environmental features as input, or with other perceptual factors (i.e. visual amenity prediction soundscape comfort) [16], however this research will primarily focus on using metrics derived from objective measurements as independent variables. Clustering analysis has also been applied in several of the studies discussed below, most notably for Item 6: Sound Source Profiles, and is widely used within the field for classifying various soundscapes [14], [23].

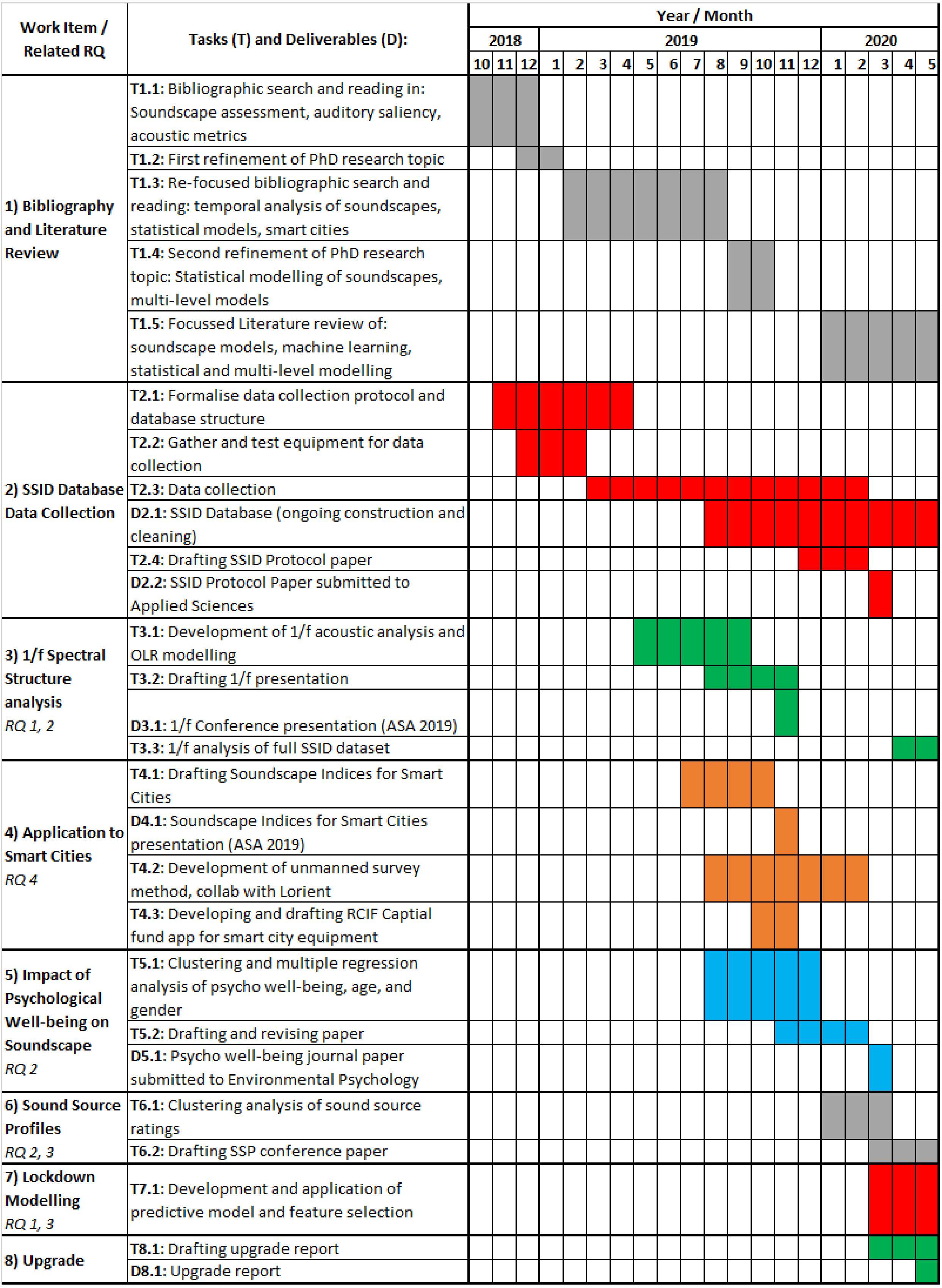
4 Completed Work

The following section presents the tasks (T) and deliverables (D) of the research project. Table 1 summarizes the work carried out thus far. Items 6 and 7 are currently ongoing and are included as both completed and proposed work.

4.1 Item 2: SSID Database data collection, organisation, and analysis

Finalising the form, content, and process for constructing a soundscape assessment database was one of the first tasks for this research. During the first several months of my PhD work, I worked with the rest of the SSID team to decide on the procedure for on-site data collection, gathered and tested the required equipment, and built the infrastructure and metadata system for organising the final database. The final protocol and much of the justifications and decisions which went into it were published as [17], included in Appendix B. The database was specifically constructed to address the needs of the SSID project, but the data included in it offers a wide range of possible investigations and is intended to be supplemented by work from other research groups.

Once the protocol was settled on and the database structure setup, data collection was started. This involved conducting on-site soundscape surveys, which were carried out by the entire SSID research team and were typically led by myself or Dr Tin Oberman. To date, the team at UCL has collected over 1,000 soundscape survey responses, along with their accompanying acoustic, visual, and environmental data, at 13 locations in London and Venice. Throughout this process, I performed the data cleaning, organisation, and analysis required to include these data into the database. This includes: setting up and managing the survey collection software (RedCap); implementing data security and quality measures for the surveys; listening to all of the binaural recordings made in London and cleaning the recordings; performing acoustic analysis on all of the London recordings; and combining the surveys and binaural analysis into a single, useable results table. So far, this overall results table includes all the London sites but will soon be expanded to include all of the data collected in Europe.



Work Item / Related RQ	Tasks (T) and Deliverables (D):	Year / Month																			
		2018			2019												2020				
		10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5
1) Bibliography and Literature Review	**T1.1:** Bibliographic search and reading in: Soundscape assessment, auditory saliency, acoustic metrics	▨	▨	▨																	
	T1.2: First refinement of PhD research topic			▨	▨																
	T1.3: Re-focused bibliographic search and reading: temporal analysis of soundscapes, statistical models, smart cities					▨	▨	▨	▨	▨	▨	▨									
	T1.4: Second refinement of PhD research topic: Statistical modelling of soundscapes, multi-level models												▨	▨							
	T1.5: Focussed Literature review of: soundscape models, machine learning, statistical and multi-level modelling																▨	▨	▨	▨	▨
2) SSID Database Data Collection	**T2.1:** Formalise data collection protocol and database structure		🟥	🟥	🟥	🟥	🟥	🟥													
	T2.2: Gather and test equipment for data collection			🟥	🟥	🟥															
	T2.3: Data collection						🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥			
	D2.1: SSID Database (ongoing construction and cleaning)											🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	T2.4: Drafting SSID Protocol paper															🟥	🟥	🟥			
	D2.2: SSID Protocol Paper submitted to Applied Sciences																		🟥		
3) 1/f Spectral Structure analysis *RQ 1, 2*	**T3.1:** Development of 1/f acoustic analysis and OLR modelling								🟩	🟩	🟩	🟩	🟩								
	T3.2: Drafting 1/f presentation											🟩	🟩	🟩	🟩						
	D3.1: 1/f Conference presentation (ASA 2019)														🟩						
	T3.3: 1/f analysis of full SSID dataset																			🟩	🟩
4) Application to Smart Cities *RQ 4*	**T4.1:** Drafting Soundscape Indices for Smart Cities										🟧	🟧	🟧	🟧							
	D4.1: Soundscape Indices for Smart Cities presentation (ASA 2019)														🟧						
	T4.2: Development of unmanned survey method, collab with Lorient											🟧	🟧	🟧	🟧	🟧	🟧	🟧			
	T4.3: Developing and drafting RCIF Captial fund app for smart city equipment													🟧	🟧						
5) Impact of Psychological Well-being on Soundscape *RQ 2*	**T5.1:** Clustering and multiple regression analysis of psycho well-being, age, and gender											🟦	🟦	🟦	🟦	🟦					
	T5.2: Drafting and revising paper														🟦	🟦	🟦	🟦			
	D5.1: Psycho well-being journal paper submitted to Environmental Psychology																		🟦		
6) Sound Source Profiles *RQ 2, 3*	**T6.1:** Clustering analysis of sound source ratings																▨	▨	▨		
	T6.2: Drafting SSP conference paper																		▨	▨	▨
7) Lockdown Modelling *RQ 1, 3*	**T7.1:** Development and application of predictive model and feature selection																		🟥	🟥	🟥
8) Upgrade	**T8.1:** Drafting upgrade report																	🟩	🟩	🟩	🟩
	D8.1: Upgrade report																				🟩

TABLE 1 - COMPLETED WORK PLAN TIMETABLE

4.2 Item 3: 1/*f* Spectral Structure Analysis

This study is focussed on characterising the temporal behaviour of a complex sound environment and draws on previous studies which have conflicting findings on the degree to which urban sound environments exhibit a semi-random time structure. The perception of a sound environment depends not only on the average or overall acoustic properties (typically defined by $L_{Aeq,t}$) but also relies on the temporal properties of the sound. This seems to be especially true in complex sound environments, where sound events overlap and compete for attention to form a complete soundscape.

This was addressed through spectral structure analysis of time series of (psycho)acoustic metrics calculated from recordings in the London SSID database. The study aimed to address two research questions:

1. To what extent is a 1/f structure present in the power spectrum of time series of various acoustic parameters of urban sound environments?
2. Which perceptual attributes of the soundscape can be accurately predicted based purely on the temporal behaviour of the acoustic time series (as measured via the spectral structure)? How does this model compare to one based on typical average / overall acoustic parameters?

The results of the spectral structure analysis were then paired with the perceptual responses of their corresponding in-situ surveys in order to determine the relationship between the degree of randomness vs predictability in the various acoustic characteristics to the perceived soundscape attributes. In addition, to determine to what extent this temporal metric could predict the perception when compared to the average acoustic metrics traditionally used, separate ordinal logistic regression models were built and compared, which suggested that the *1/f* metric provided an improvement in models predicting perceptual attributes of soundscape.

This study was presented at the Fall 2019 Conference of the Acoustical Society of America, in San Diego and was well-received [24]. The work done for the 1/*f* spectral structure conference presentation is currently being compiled to be submitted as a short journal paper to the JASA - Express Letters.

4.3 Item 4: Soundscape Indices for Smart Cities

The core objectives of smart city design are to increase quality of life, enhance efficiency, and move towards the sustainability of cities. While this will involve increased integration of new and smarter technologies into urban design, the implementation of these technologies as applied to acoustics should be made within a design approach which considers these core objectives. Soundscape strategies have a focus on people's perception and experience, considering the many factors which influence their perception. A recognised demand in the field of soundscape is a new set of metrics that can reliably measure both the acoustic environment and its perception. The European Research Council acknowledged this need and recently funded the Advanced Grant project "Soundscape Indices" (SSID), which aims at providing more advanced tools, compared to conventional dB-based metrics, taking into account psychological, psycho(acoustical), neurophysiological, and contextual factors for soundscape assessment. The SSID project will: characterise soundscapes, by capturing acoustic environments and establishing a comprehensive database; identify key psychological evaluations, acoustical/psychoacoustical factors analysis; and research the neural and psychophysiological underpinnings of soundscape experience. It is expected that SSID will provide a vital tool in guiding the implementation of the technological infrastructure of smart cities.

Although the smart city concept is rapidly advancing toward both an increase in the deployment of sensor networks for monitoring and the proliferation of a more holistic design approach, within acoustics only the former has been able to be technologically implemented. Acoustics in smart city design need to focus on the whole system, considering the interaction of several characteristics of the design. Soundscape studies strive to incorporate the influence of not just the sound environment, but of other factors such as environmental conditions, contextual, demographic, and psychological factors.

How people interact with city spaces (e.g. how often they visit an urban green space, or for how long), is driven by their perception of the space, rather than by the raw characteristics of the space. Kruize et al [25] recently showed that perceived greenness and satisfaction with the space were strong predictors of increased minutes of physical activity, increased social contacts with neighbours, and better mental well-being. On the other hand, the GIS-derived measures of the space (i.e. greenness of the space calculated from satellite photos) were found not to be associated with these improved uses of the space. In acoustics, soundscape therefore provides a powerful middle step for re-contextualising the objective information gathered in a smart city in order to better assess that city's characteristics impact on health and well-being.

In order to effectively integrate the soundscape approach with smart city sensor networks, an index based on measurable parameters is required which can make use of sensor network data. A more in-depth discussion of the framework for this index can be found in [3], [17]. The successful implementation of an SSID based on multi-factor environmental sensor networks would allow the unmanned implementation of soundscape concepts. One of the challenges of dealing with smart city sensor networks is integrating all the data from various types of environmental sensors, but because SSID will be constructed from the start to consider non-acoustic influencing factors, it allows us to incorporate this spread of information. Applying SSID to smart city design will support the implementation of the soundscape approach by tackling two main challenges: 1) predicting how design changes will manifest in changes to the soundscape, and 2) integrating information from sensor networks in a more holistic way.

Finally, SSID provides new tools for investigating the influence of the sound environment on the use and impact of a space by refocusing on perception.

This paper was presented at the Fall 2019 ASA meeting in San Diego, and was awarded a Best Paper Award by the Noise technical committee [26].

Prior to the COVID-19 lockdown, a plan was in place to implement unmanned soundscape surveys alongside an existing sound sensor network in Lorient, France. This plan was formulated with Pierre Aumond and Catherine Lavandier at The French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) and involved the deployment of fliers with printed QR codes leading to an online questionnaire with a request for participants to assess their current soundscape. These fliers were to be deployed at several public urban spaces around Lorient for a period of several months in an attempt to gather long-term assessment data of the city's soundscape. This unmanned method would be paired with one or two manned surveys carried out according to the SSID protocol, ideally at the beginning and end of the unmanned survey period.

These data would allow us to build a baseline soundscape model from the manned survey data, and deploy and validate it across a long timescale using the sensor network data and the unmanned surveys. This method serves three purposes: 1) investigate how the city soundscape changes over long (multi-month) timescales in a continuous manner, while also 2) testing the possibility of conducting unmanned soundscape surveys using distributed signage and online surveys; and 3) demonstrating a method of combining a soundscape approach with stationary smart city sensor networks.

Unfortunately, due to the COVID-19 shutdown this planned study could not be carried out and the form of this collaboration between the SSID team and the team at IFSTTAR is uncertain at the moment.

4.4 Item 5: The impact of psychological well-being, age, and gender on soundscape

Again drawing from the London SSID database, in depth analysis was performed to determine the degree to which respondents' psychological well-being and demographic factors impact the perceived pleasantness and eventfulness of the soundscape. To assist in this, clustering analysis was performed to separate the dataset according to the dominant sound source in the soundscape. Multivariate linear regression models were then built to investigate the impact of the factors of interest on the soundscape and how these impacts were dependent on, and varied across, the sound source contexts. The clusters were identified as: 'Natural-dominant', 'Traffic-dominant', and 'Mixed-sources' locations, and the mean Pleasantness and Eventfulness ratings were found to show significant variation across the clusters (as measured by a Kruskal-Wallis test). The linear regression analysis demonstrated that psychological well-being was positively associated with Pleasantness in All-locations and the Mixed-sources cluster, and with Eventfulness in the Traffic-dominant cluster. This study, included as Appendix D, was co-written with Mercede Erfanian and is under review at the Journal of Environmental Psychology. My contribution to this paper was the compilation and cleaning of the dataset, performing the clustering analysis and multiple linear regression, and drafting small sections of the text.

4.5 Item 6: Sound Source Profiles of urban public spaces and their influence on the assessment of soundscape pleasantness and eventfulness

By extending the clustering analysis done for the previous study, a set of Sound Source Profiles (SSP) was developed to describe various common urban public spaces across the full SSID database. In situ soundscape surveys (N=3,537) were conducted across 27 urban public spaces in the UK, China, Italy, Spain, and the Netherlands in which respondents assessed the dominance of four sound source types (Traffic noise, Human sounds, Natural sounds, and Other noise) as well as the Perceived Affective Quality and perceived loudness of the soundscape. Hierarchical agglomerative clustering was performed using the mean response to each of the 4 sound source dominance questions within each location, producing 5 clusters. These clusters form the SSPs into which each location can be sorted based on the composition of sound sources in the space. The relationships of perceived loudness with pleasantness and eventfulness are then investigated within each SSP, revealing significant and meaningful information about the relationship between loudness and the perceived affective quality of a soundscape.

Significant differences in both perceived pleasantness and eventfulness ratings were found across the five identified SSPs, with the Natural-dominant and Low-noise profiles being both the two most pleasant and least eventful profiles. However, this inverse relationship is not consistent across all of the SSPs; the Human-dominant profile has the highest eventfulness rating and also has a relatively high pleasantness rating. Significant differences in the relationship between perceived loudness and perceived pleasantness were also found across the various SSPs. Although all SSPs show a negative correlation, the Natural-deficient profile has the strongest negative correlation (R = -0.41), while the Mixed-sources (R = -0.12), Human-dominant (R = -0.14), and Low-noise (R = -0.16) profiles have a weaker correlation.

These results suggest that the SSP classification is capturing some amount of the contextual information which informs the complex interactions in soundscape formation. For modelling and practical purposes, this method simplifies the inclusion of the effects of sound sources. When applying a model to a proposed urban space, it would likely be difficult for the modeller to accurately predict the precise dominance of each sound source to be included in a model. The profile system would instead involve sorting the space into one of five SSPs depending on the general expected sound source composition, then inputting the expected SSP as an input variable into the model.

This analysis in this section reveals many of the relationships between sound sources and soundscape formation and proposes a method for usefully incorporating this information as an upper level in a predictive multi-level model. The analysis for this paper has been completed and an abstract has been submitted for the Inter-Noise 2020 conference (now online). If this is successfully accepted, the conference paper will be submitted in June 2020 and presented in August.

4.6 Item 7: Changes in the London soundscape under the COVID-19 Lockdown

Investigating the soundscape of a city under a lockdown order is very difficult, as standard soundscape assessment methods require conducting either in-person surveys or lab studies using high-quality recordings, both of which are not possible while social distancing. This presents exactly the type of challenge a soundscape index is designed to address - assessing or predicting the soundscape when it is impractical or impossible to ask people their perception. For my part of this SSID group work, I am building a regression model based on the SSID dataset collected prior to the lockdown which is designed to predict a person's perception of the dominance of Natural sounds and the overall quality of the soundscape, based on acoustic features calculated from a set of 30s binaural recordings. This model can then be applied to new recordings made in the same locations during the lockdown to predict how people would have perceived this new soundscape and determine how the soundscape has changed under the lockdown.

The analysis and drafting of this paper are currently underway with the rest of the SSID team. As of writing, a Multi-level linear regression model structure for predicting a limited number of sound source dominance and PAQ responses has been selected, and the feature selection and training process has begun. My model forms a key part of this study and represents a novel application of a soundscape model for determining the change in soundscapes in a situation where the soundscapes could not be directly measured, demonstrating a vital use of the SSID. This paper will be submitted to a COVID-19 special issue of JASA in the next few months, as data collection is completed.

5 Planned work:

Table 2 provides the work plan for the remaining duration of the project.

Work Item / Related RQ	Tasks (T) and Deliverables (D):	Year / Month																					
		2020								2021												2022	
		5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2
1) Bibliography and Literature Review	**T1.5**: Focussed Literature review of: soundscape models, machine learning, statistical and multi-level modelling	▨	▨	▨	▨	▨																	
2) SSID Database Data Collection	**D2.1**: SSID Database (ongoing construction and cleaning)																						
3) 1/f Spectral Structure analysis	**T3.3**: 1/f analysis of full SSID dataset	🟩																					
	T3.4: Draft final 1/f paper (for JASA-EL)	🟩	🟩																				
	D3.2: Submit 1/f paper to JASA-EL			🟩																			
4) Application to Smart Cities *RQ4*	**T4.3:** Apply model to sensor network data (Lorient)													🟨	🟨	🟨	🟨						
	T4.4: Draft sensor network case study paper																🟨	🟨	🟨				
	D4.2: Submit paper																			🟨			
6) Sound Source Profiles *RQ 2, 3*	**T6.2**: Drafting SSP conference paper	▨	▨																				
	D6.1: SSP conference paper		▨																				
	T6.3: Extending SSP based analysis to incorp. acoustic features		▨	▨	▨	▨																	
	T6.4: Draft SSP journal paper					▨	▨	▨															
	D6.2: SSP Journal paper (to JASA)								▨														
7) Lockdown Modelling *RQ 1, 3*	**T7.1**: Development and application of predictive model and feature selection	🟥	🟥																				
	T7.2: Drafting and revising paper (w/ Tin)		🟥	🟥																			
	D7.1: Journal paper (to JASA special issue)			🟥																			
9) Multilevel Model / Turing Institute *RQ 1, 2, 3*	**T9.1**: Lit review of modelling techniques					🟨	🟨	🟨	🟨														
	T9.2: Development of the model									🟨	🟨	🟨	🟨	🟨									
	T9.3: Drafting of journal paper												🟨	🟨	🟨	🟨							
	D9.1: Submit Journal paper																🟨						
10) Thesis	**T10.1**: Compile literature review															🟦	🟦	🟦					
	T10.2: Writing of thesis																		🟦	🟦	🟦		
	T10.3: Final edits																				🟦	🟦	
	D10.1: Submit Thesis																					🟦	
	D10.2: Viva																						🟦

TABLE 2 - ESTIMATED WORK PLAN TIMETABLE

5.1 Item 4: Soundscape Indices for Smart Cities

As stated in the completed work section above, this item was intended to involve a collaboration with a team at IFSTTAR for conducting unmanned soundscape surveys alongside an acoustic sensor network deployed in Lorient. Since the interruption of the COVID-19 lockdowns, this plan has had to be re-adjusted and given the current uncertainty at the time of writing, it's impossible to know what shape it will take. It seems certain we will need drop the unmanned survey portion of the work, as the lockdown conditions likely drastically limit the number of people using the proposed spaces and their likelihood to linger and participate in a study. The lockdown also postpones any manned surveys as the conducting them would break social distancing rules.

The most likely proposal is to postpone the usage of the sensor data from Lorient until a usable soundscape model has been built (see Item 9). This model could then be applied to the long-term acoustic and environmental data from the Lorient sensor network, thus tracking the change in soundscape over a long period of time, possibly even revealing changes in soundscape during the lockdown periods. This may even capture changes in soundscape over several periods and varying levels of severity of lockdowns, if the region adopts an intermittent lockdown strategy, as some studies have discussed [27]. Careful thought will need to be given to validating this implementation of a model, given that no perceptual data has been collected in Lorient. By this point, it is hoped that the situation will have improved enough to allow manned surveys to be carried out in Lorient to establish baseline soundscape assessments in the proposed locations against which the model can be compared before being applied to long-term sensor data.

5.2 Item 6: Sound Source Profiles

In order to refine the SSP analysis and implementation, the conference paper will be expanded upon for submission as a journal paper. Key to this expansion is the inclusion of the acoustic features from the SSID binaural recordings. Where the conference paper is focussed on looking at the relationship between perceived loudness and soundscape pleasantness and eventfulness within each SSP, the journal paper will investigate how the relationship between the physical acoustic level and the perceived level, and how this varies across different SSPs. This paper is intended to be submitted (likely to the Journal of the Acoustical Society of America (JASA) or a special Soundscape issue of Frontiers in Psychology) by the end of 2020.

5.3 Item 9: Combined multi-level model and Turing Enrichment Scheme

Starting in January 2021, I will begin a 9-month placement at the Turing Institute as part of their Turing Enrichment Scheme. While there I will continue to progress my PhD research while making use of the resources and expertise available at the Institute. Due to the nature of the scheme, it’s difficult to know how it will affect the direction of my research, however, this stage in my research will involve combining the available acoustical/environmental factors with the Sound Source Profile method to build a multi-level model which incorporates contextual information in a practical way. I expect how this will be achieved and what structure the model takes will depend on what I learn while on the Enrichment Scheme. The intention is for the nine months at the Institute to be focussed on building this model and drafting a journal paper based on it, to be submitted in September 2021.

5.4 Item 10: Thesis

The Turing scheme will take me through to the end of my 3 years. Data collection for my thesis work has already been completed, and by September 2021 the analysis work will be finished and formalised as a series of papers. After this, I will focus on writing up the thesis, planning to submit in early 2022. A proposed thesis outline is included as Appendix A.

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Appendix A: Proposed Thesis Outline

Appendix B: SSID Protocol – First Author (Published)

Appendix C: Impact of Psychological Well-being – Co-author (Under review)