ASSOCIATIONS BETWEEN
URBAN SOUNDSCAPE PERCEPTION AND EMOTIONAL STATES

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Abstract

Urban soundscape design represents a research area still in development, with gaps, such as influences on human response and practical application. Research on natural soundscapes, such as urban parks has demonstrated their benefits to society, however, other soundscape types are less studied. Additionally, the presence of people has been suggested from previous work to contribute to the sense of eventfulness to a place. Given this, a variation of soundscape types and population densities using physiological experiments consist of a reasonable strategy to tackle the research. The aim of this thesis is to investigate the relationships between soundscape perception and emotional state in urban locations (park, plaza, and pedestrian street) that may indicate changes on responses to the sonic environment. Methods involved subjective self-reports and brain activity observations when exposed to real audio-visual soundscape stimuli reproduced in virtual reality (VR) via internet and laboratory experiments. Participants scores confirmed that the perception of eventfulness increased when higher number of people where in the scene. Similarly, the studied park and plaza with children playing on a sunny day were classified as a Vibrant soundscape. Electroencephalogram (EEG) responses showed increases in the Alpha Power when locations were empty. Contributions of this work are based around the concepts of identifying that population density changes perceptual and emotional responses in urban soundscapes, real site VR can be a tool to collect these subjective responses, and EEG could complement these self-reports. EEG responses to soundscapes are still rare among soundscape studies, especially since population density has demonstrated an effect on EEG alpha power readings. Thus, population density and the design of Plazas should be considered in assessing, planning, and designing urban soundscapes towards livelier sounding cities. The benefits from this kind of research impact not only alternative solutions for environmental noise issues, but also improvements in public health, quality of life, and cultural heritage.

Keywords: urban soundscape perception; emotional states; virtual reality; population density; EEG.

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Abbreviations

- Acoustic related

PAQs – Perceived Affective Qualities

$L_{Aeq,60}$ – one-minute A-weighted equivalent continuous sound pressure

DAW – Digital Audio Workstation

FOA – First Order Ambisonic

SPL – Sound Pressure Level

- Others

SDI - Simpson's Diversity Index

EEG – Electroencephalogram

VR – Virtual Reality

HMD – Head mounted device

PANAS – Positive and Negative Affective Schedule

SAM – Self-Assessment Manikin

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Declaration

This thesis contains previously published text. When the material is used, the paper is referenced. Below is a list of all published papers, posters and expanded abstracts related to the thesis topic.

- First author

Carvalho, M. L., Davies, W. J., & Fazenda, B. (2019). Investigation of emotional states in different urban soundscapes through laboratory reproductions of 3D audio-visual samples. In proceedings of 14th INTERNATIONAL POSTGRADUATE RESEARCH CONFERENCE 2019: Contemporary and Future Directions in the Built Environment (p. 326). Conference paper received a Dean's Award.

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Carvalho, M. L. D. U., Davies, W. J., & Fazenda, B. M. (2021, June). EEG approach to Urban Soundscape responses: An experimental proposal. In the 30th EEGLAB workshop online. University of California, San Diego. Workshop Poster.

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- Co-author

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Antunes, S., Michalski, R. L. X. N., de Ulhôa Carvalho, M. L., & Alves, S. (2021). Validated translation into Portuguese of perceptual attributes for soundscape assessment. In Proceedings of the 12th European Congress and Exposition on Noise Control Engineering (pp. 710-718).

Michalski, R. L. X. N., Alves, S., Antunes, S., & Carvalho, M. L. D. U. (2022). Atributos perceptivos para avaliação da paisagem sonora: tradução para a língua portuguesa. In Proceedings of XII Congresso/Congreso Iberoamericano de Acústica & XXIX Encontro da Sociedade Brasileira de Acústica - SOBRAC.

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Antunes, S. M., Michalski, R. L. X. N., de Ulhôa Carvalho, M. L., Alves, S., & Ribeiro, L. C. (2023). A European and Brazilian cross-national investigation into the Portuguese translation of soundscape perceptual attributes within the SATP project. Applied Acoustics, 211, 109472.

1. CHAPTER ONE: Introduction

This chapter starts with an overview of soundscape topics addressed in the thesis. Then, subsections navigate from the motivation to the study objectives and end with the links among the five experiments included in the thesis.

1.1 Overview

Soundscapes consist of a transdisciplinary field of research that relates physical, social, cultural, and psychological aspects of sound (Dubois, Guastavino, and Raimbault, 2006; Kang, 2007; Davies *et al.*, 2013; Aletta and Xiao, 2018). In this thesis, the soundscape is investigated from urban design, sound perception, and emotional response perspectives.

Urban planning has gradually included good soundscape design into practice (Kang *et al.*, 2016; Aletta and Xiao, 2018). Some applied design solutions incorporate functional approaches dealing with noise barriers, water structures, surface acoustic treatment, and use of vegetation (Dzhambov and Dimitrova, 2014; Rehan, 2016), while others have an additional aesthetic components, such as music interventions, sound installations, and sculptures (Lavia *et al.*, 2012; Witchel *et al.*, 2013; Meng, Zhao, and Kang, 2018; Steele *et al.*, 2019). These solutions focus on enhancing the human sonic experience to achieve an improved quality of life, healthier places, and restore the natural environment. However, these experiences also demonstrate the need to bridge the gap between academic work and practice, so that design can embrace soundscape in urban planning (Aletta and Xiao, 2018).

To approach the characteristics and preferences of soundscape, studies use self-report surveys in *soundwalks* (site visits to observe the acoustic environment) to identify sound sources, human expectations, their appropriateness to space (Davies, Bruce, and Murphy, 2014), and their relations to activities (Steele, Steffens and Guastavino, 2015). Questionnaires mark soundscape through semantic differential scales within two-dimensional axes--arousal and valence--with origins from psychological studies (Russell, 2003) which evolved to the emotional dimensions of eventfulness and pleasantness (Axelsson, Nilsson and Berglund, 2010). These terminologies gained space among researchers (Davies, Bruce, and Murphy, 2014) and became standard in 2014 (BS ISO 12913-1, 2014; ISO 12913-2, 2018; PD ISO 12913-3, 2019).

Nevertheless, questionnaires and surveys may threaten the validity of results, since the attention of participants shifts to the examination, interpretation, understanding, and judgment of sounds (Bell *et al.*, 2001; Lavia *et al.*, 2018). The validity of results is influenced by factors including how responses can create biases, such as the "social desirability" of appearing good in the responses (Paulhus, 1991), and the "experimenter effect" where subjects' attention is brought to things they never reflected consciously (A. L. Brown, Kang, and Gjestland, 2011), among other distortions. These occurrences can weaken the credibility of the results when projecting their application in urban design.

Alternative methods to assess soundscape perception can be the non-participatory observation of the public (Lavia *et al.*, 2018) and psycho-physiological measurements of human responses to soundscapes. The spontaneous responses to the acoustic environment, such as behaviours or physiological responses, can represent real-life results that may provide greater reliability to planners. These findings can establish new guidelines for urban soundscape planning and assist urban development.

From a psychophysiological perspective, studies on human responses to soundscapes appeared gradually (Erfanian *et al.*, 2019). Experiments include respiration rate, skin conductance level, heart rate (Gomez and Danuser, 2004; Alvarsson, Wiens and Nilsson, 2010; Medvedev, Shepherd and Hautus, 2015), Functional Magnetic Resonance Imaging (fMRI), Positron Emission Tomography (PET) (Irwin *et al.*, 2011), and Electromyography (EMG) (Hume and Ahtamad, 2013). These efforts to observe spontaneous responses to soundscape through physiological experiments contribute to identifying scenarios that may improve public well-being.

These experiments are mostly developed in laboratory conditions and have developed into virtual reality (VR) reproductions, because of the controlled conditions that do not exist in-situ and the complex equipment set-up. Still, soundscape assessment integrates other elements, such as temperature, odour, *character*, and "meaning of place" which influence may be missed when using such a tool. For this reason, the "ecological validity" of the immersive experience is considered to be of vital importance in soundscape research (Maffei *et al.*, 2016a). Up to now, most studies have confirmed similar soundscape perceptions among in-situ and laboratory VR listening tests (Maffei et al., 2016b; Puyana-Romero et al., 2017; Jo and Jeon, 2021; Tarlao, Steele and Guastavino, 2022), thus, in this thesis VR was applied as the main audio-visual stimuli in experiments. Considering these points, the present thesis investigated the relationships between soundscape perception, and emotional state that may indicate changes for a healthier environment through physiological measurements reproduced in a virtual environment using a head-mounted device. The document includes chapter one with introduction, chapter two with literature review, chapter three with experimental methods, chapter four with results and discussions, and, finally, chapter five with conclusions and future works.

1.2 Motivation

Until now, main urban soundscape research assesses general frameworks, definitions, practical, and methodological issues of “soundscaping” (Aletta and Xiao, 2018). However, since the urban design is intrinsically of a practical nature, there remains the question of whether soundscapes can impact or modify emotional states in a healthy way at public spaces. Here, "healthy" refers to those soundscapes that contribute to enhancing feelings of happiness and engagement in activities (high in behavioural options) as in Vibrant sites that the public considers to be promoters of well-being. This differs from observations identified in a systematic review on associations between positive soundscapes and health-related effects referring mainly to calm and silent scenarios. These studied papers declared healthier self-reported conditions when in reduced noise sites and faster recovery from stress when in pleasant and calm settings (Aletta, Oberman and Kang, 2018). That is, they concentrated on how calm soundscapes effect human health and not so much on how vibrancy may affect health.

Considering the worldwide trend of population growth in urban centres, quality of life through urban sound treatment becomes necessary since noise pollution is among the world's biggest pollutants. Reviewed environmental noise studies point negative health effects, such as high levels of annoyance, sleep deprivation, cardiovascular effects, and reduce in children cognitive development (Brown and van Kamp, 2017). Hence, it is considered that positive soundscapes where people feel less annoyed may improve public health. Furthermore, once spotted positive emotions to sounds, can these identified sounds be used as tools in soundscape design?

The majority of soundscape studies investigate parks where natural sounds indicate psychological restoration (Payne, 2013) and improvement in the sonic environment (Van

Renterghem *et al.*, 2020). However, responses to Exciting or Vibrant soundscapes remain with fewer studies. According to the soundscape perceptual dimension (Axelsson, Nilsson and Berglund, 2010), Vibrant soundscapes can be characterised as eventful and pleasant (Figure 1). Additionally, psychology describes this quadrant as potentially high in quality affordance (Andringa and Bosch, 2013) (Figure 2). In other words, places with plenty of events considered pleasant can flourish sentiments of joy and facilitate the public into engaging in fulfilling self-selected activities. Given the eventful scale has been indicated to represent locations busy with human activities (PD ISO 12913-3, 2019), this study included population density as a controlled factor.

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Figure 1: Component scores of soundscape excerpts in Pleasantness and Eventfulness (Axelsson, Nilsson and Berglund, 2010, p. 2844). Emphasis added to the top right for focused area of study are a personal adaptation to the two-dimension plots.

Furthermore, previous works demonstrated that the "presence of people" in places lead a soundscape into the Eventful dimension and defines as a fundamental factor in the Vibrant experience (Aletta and Kang, 2018; Sun et al., 2019). Modulation on population densities from empty to busy is believed to contribute to soundscape perception changing from one dimension to another. For example, an empty street may be considered a monotonous soundscape while, when full, the place may shift to a Vibrant or Chaotic scenario. The aspects that establish a

Vibrant soundscape as pleasant are still not clear in the literature and, therefore, worth investigating.

Graph removed due to copyrighted restrictions.

Figure 2: Core affect in terms of complexity of behaviour selection and affordance content. The upper-left to lower-right diagonal corresponds to the middle column and to arousal (Andringa and Bosch, 2013, p. 7). Emphasis added to the top right for focused area of study are a personal adaptation to the two-dimension plots.

Furthermore, previous works demonstrated that the “presence of people” in places lead a soundscape into the Eventful dimension and defines as a fundamental factor in the Vibrant experience (Aletta and Kang, 2018; Sun et al., 2019). Modulation on population densities from empty to busy is believed to contribute to soundscape perception changing from one dimension to another. For example, an empty street may be considered a monotonous soundscape while, when full, the place may shift to a Vibrant or Chaotic scenario. The aspects that establish a Vibrant soundscape as pleasant are still not clear in the literature and, therefore, worth investigating.

Moreover, how can the different conditions--soundscape types and population densities--be assessed with scientific control and genuine fidelity to human responses of soundscape experiences? Here, the outcomes were tested with physiological responses to VR reproductions of real soundscapes in the different conditions. In short, the aim of the study is to identify soundscapes cases that evoke healthy perceptions and emotions so to support good soundscape design practices towards healthier sounding cities and urban quality of life.

1.3 Contributions to Knowledge and Novelty

It is considered that emotional changes when exposed to different soundscapes still lack studies. The soundscape perceptual dimension types, mainly those quiet with natural sounds, are studied isolated so to identify their benefits (Payne, 2013; Herranz-Pascual *et al.*, 2019). Additionally, Vibrant scenarios are not clearly characterised as pleasant (Hall *et al.*, 2013; Aletta and Kang, 2018) and the majority of studies rely on self-report approaches (questionnaires) where a bias may occur due to "social desirability" (Paulhus, 1991), or "experimenter effect" (A L Brown, Kang, and Gjestland, 2011), among other errors.

Hence, contributions of this study can be listed as:

- the study of population density in perceptual and emotional responses to urban soundscapes;
- the use of VR for collecting perceptual and emotional responses of real urban spaces in different population densities, and;
- the use of Electroencephalogram (EEG) to complement self-reported perceptual and emotional responses of urban locations in different population densities.

From these perspectives, the findings of this study will reveal a new understanding for designers on how soundscapes can trigger emotions that support or undermine healthier behavioural options to users in urban places.

1.4 Research Questions, Aims, & Objectives

The research questions consisted of the following:

1. How can real-time EEG measurements be compatible with VR method in urban soundscape studies?
2. How to overcome electric line noise in EEG data originated from VR HMD?
3. How does different human occupancy and nature sound in different urban scenarios effect EEG alpha power?

4. Can higher educated individuals differ in brain activity when assessing urban soundscapes through VR?
5. Can the university community identify places that represent the ISO's 4 PAQs quadrants?
6. Can the number of people shift ISO's PAQ responses in different urban areas?
7. Can children's sounds induce vibrancy?

The aims are:

- Investigate if different urban soundscapes and population densities affect human perception, emotional state, and brain responses, and
- Explore if urban soundscapes may contribute to the design of healthier sounding cities.

The objectives are:

- To assess how people perceive and how they feel when exposed to VR audio-visual stimuli of different urban soundscapes in different population densities through self-reports, and
- To observe brain activity through EEG readings when exposed to VR audio-visual stimuli of different urban soundscapes in different population densities.

1.5 Links between experiments

The thesis is composed of five experiments as illustrated in the diagram of Figure 3. The first experiment was to identify the most representative locations in Manchester for the four quadrants of the ISO's Perceived Affective Qualities (PAQ), e.g., Vibrant, Calm, Monotonous, and Chaotic attributes (ISO 12913-2, 2018). This experiment was vital to indicate where footage would be done and influenced all following experiments.

The second experiment was done during field recordings. It was an opportunity to test how people reacted to the questionnaire in situ. Even though some participants were intrigued with the exercise of paying attention to the sonic environment--something they were not familiar with--, there were demonstrations of impatience to respond the 20 soundscape descriptors. Thus being, the next experiment reduced from 20 to the eight ISO's PAQs, e.g. Vibrant, pleasant, calm, uneventful, monotonous, annoying, chaotic, and eventful attributes in the questionnaire (ISO 12913-2, 2018).

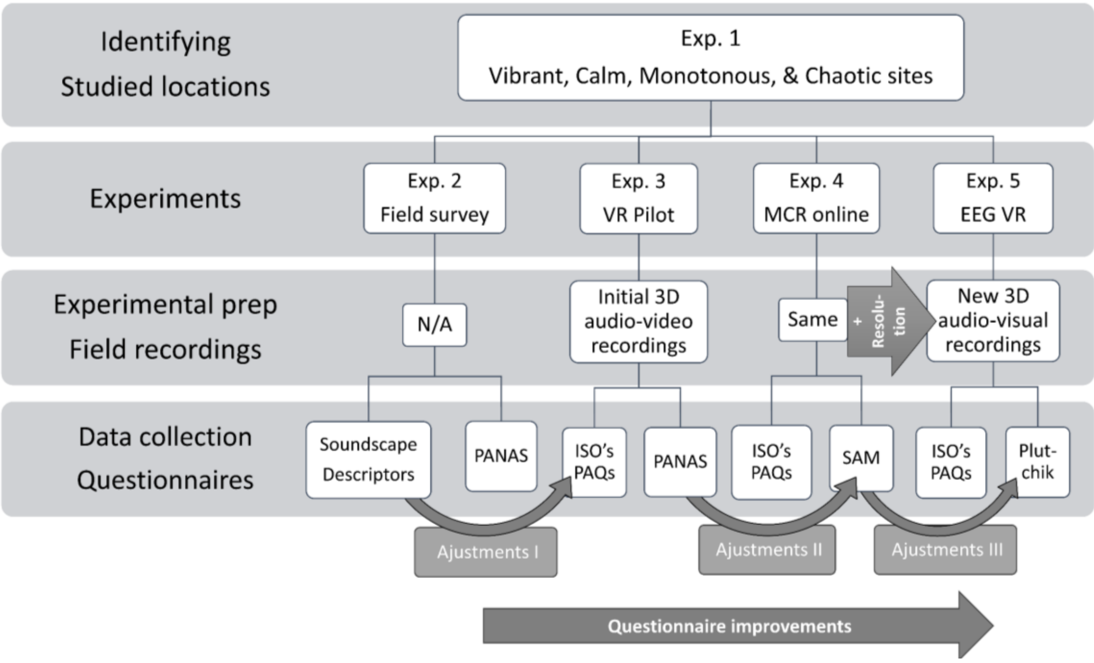

FIGURE 3: DIAGRAM ILLUSTRATING LINKS AMONG EXPERIMENTS.

Differently from the second experiment, the third experiment included virtual reality (VR). In this experiment, soundscape questions were changed while the emotional states was maintained with the Positive Affect Negative Affect Schedule (PANAS). Skills on VR were put into practice so to reproduce the three dimensional audio-visual soundscapes in a head mounted device (HMD). Although the experiment was a pilot, results were published and received a Dean's Award, hence it was relevant to present in the thesis. PANAS outputs demonstrated weak results with one significant result out of ten scales which led to changing the emotional state scale to the Self-Assessment-Manikins (SAM) in the next experiment.

The fourth experiment maintained the ISO's PAQs and used the SAM scale for the emotional assessment. "Arousal" was significant different at the pedestrian street and urban park, but not in the bus stop and plaza. Meanwhile, "Valence" and "Dominance" had no effect in the four locations. Many participants declared to not understand how dominance was related to soundscapes. In addition, a study with different emotional assessments demonstrated that the Plutchik's Emotion Wheel (Plutchik, 1982) managed to classify emotions in a similar way independent of nationality (Engel, Carvallho, *et al.*, 2021). Considering that only two out of the 12 SAM results were significant, and there are intentions to replicate these experiments in Brazil, the Plutchik's taxonomy was used in the last experiment.

Regarding experimental preparations for VR reproductions, the pilot and MCR online experiments were vital for refinements of the EEG VR experiment. For instance, in the pilot audio-visual alignments and audio calibrations to field sound levels demanded corrections. On the MCR online, video resolutions were considered poor which led to new recordings for the EEG VR test.

In brief, the first experiment indicated the locations to be studied in all experiments. The second tested questionnaires on field which led to changes towards the ISO's PAQs that was maintained from the second to the last experiment because of the expressive results as presented in Chapter 4. The different taxonomies tested for the emotional states changed in each experiment and still demands more investigation to identify new ways to assess soundscapes with more consistent results. As form VR preparations, gradual improvements occurred among experiments. Finally, the five experiments were linked among themselves as described above.

2. CHAPTER TWO: Literature Review

This chapter brings together the literature review done throughout the doctoral journey. It starts with a general background of soundscapes, moves towards subjective responses to them, processes of soundscape design, and finishes with EEG responses to soundscapes.

2.1 Soundscape Background

Sounds in recent contemporary cities include a cacophony considered by many as noise. However, Raymond Murray Schafer (1933-2021, *in memoriam*) believed these signals composed potential parts of a harmonized orchestration that he called as soundscape. Given his musical background, he described it as all sounds in space and used them in his compositions (Schafer, 1977). Historically the terminology originated from Southworth and his studies on urban sound design (Southworth, 1967), but Schafer brought the term to popularity with the World Soundscape Project[1]. On a more technical perspective, the International Standard Organization defines soundscapes as the perception of a sonic

[1] https://www.sfu.ca/~truax/wsp.html

environment by people in a context (BS ISO 12913-1, 2014). Regardless of definitions, soundscape studies have increased in the last decades worldwide becoming relevant to indoor and outdoor sound planning.

R. Murray Schafer classified the various sounds in the environment into *Soundmarks*, *Signals*, and *Keynotes*. *Soundmarks* are an analogy to a landmark representing sounds with value within a specific community (Schafer, 1977). Given this distinction, these sonic elements gather ecological preservation and health restoration values to people constructing the intangible cultural heritage of a society (Kytö *et al.*, 2012). Another word used by the author is the *Sound Signal,* also called foreground, which indicates an audible element alerting or contrasting to other sounds in the acoustic ambience. These sounds have meaning regardless of location, such as police, ambulance, or fire sirens. Finally, *Keynote* represents the background sound that combines all sounds not identified as predominant, such as traffic noise, or rustling of leaves emanating from a distance (Schafer, 1977).

In addition, he arranged soundscapes by qualitative references (natural, human, mechanic, among others) and quantitative aspects. For classifying soundscapes to a categorical reference, both Schafer (Schafer, 1977) and Brown and colleagues (Brown, Kang and Gjestland, 2011), who influenced the ISO 12.913 part 2 (ISO 12913-2, 2018), arrived at a common taxonomy, that is: human, mechanical, and natural sounds.

Regarding the quantitative aspects of soundscapes described by Schafer, the physical classification was closely related to music notations. The duration of the signal separated the sound into attack, body, and decay. Frequency, which he called by mass, given possible entangled mixtures of frequencies creating chunks, was represented over a pentagram from very high to very low frequencies. Fluctuations of the sonic stimuli were named grain. He categorized them as steady-state, transient, multiple transients, rapid warble, medium pulsation, and slow throb, giving the sense of touch to audition as perceived in smooth contours through amplitude modulations (*tremolo*) and flickering states of frequency modulations (*vibrato*). Additionally, the dynamics represented in sheet music from fortissimo (*ff*) to pianissimo (*pp*) included decrescendo (when sounds become quieter) and crescendo (when sounds become louder) progressions. Further, he characterized the sonic settings by estimating the sound source distance, intensity in decibels (dB), the distinction of the perceived sound, the texture of the sonic environment, the contextual aspect of the audio event, and environmental conditions (Schafer, 1977).

From another view, ISO 12.913-2:2018 (ISO 12913-2, 2018) establishes descriptors and indicators for soundscape assessments where people, the sonic environment, and context construct the fundamental instruments to manage such resource. Whether in *soundwalks* (an audio-guided walk), field surveys, interviews, or laboratory studies, participant responses are classified and evaluated through self-reports or non-participatory observations to obtain their opinions about the investigated site. The acoustic environment evaluation derives from environmental noise studies where sound pressure levels are assessed (ISO 1996-1, 2003), and additionally integrates the psychoacoustic metrics of loudness, sharpness, roughness, tonality, and fluctuation strength (PD ISO 12913-3, 2019). However, further investigations still need to prove the efficiency of these metrics in soundscapes studies, given that a recent study demonstrated psychoacoustic percentile parameters could not clearly establish reciprocity to the temporal auditory perception in context (Engel, Fiebig, *et al.*, 2021).

Differing from the objective characterization of the sonic environment, the context in soundscape research introduces several elements related to the cognitive processes of auditory perception, which includes correlations among people, activities, and places in time and space. Specifically, the standard indicates that context influences auditory sensation, its interpretation, and the responses to the sonic environment, embracing features not related to sounds, such as climate, cultural background, personal differences, other sensory stimuli, among other factors (BS ISO 12913-1, 2014). Given the broad list of influential components of context, studies still need to expand investigations on what elements of context will be vital to report, in order to contribute a complete soundscape assessment.

In contrast to environmental noise control, only reducing sound levels does not guarantee acoustic comfort and good soundscape practices (Cain, Jennings and Poxon, 2013). Efforts go further physically observing sound source types and their characteristics towards noticing human expectations (Bruce and Davies, 2014) and activities of those who live in the cities (Davies *et al.*, 2013). The positive impacts include public health, quality of life, cultural differences, and global variety (Kang *et al.*, 2016), being a contemporary subject that points to innovating fields.

Within the sources of the soundscape, natural sounds have proven as preferred among urban users (Yang and Kang, 2005; Kang, 2007). Benefits such as stress reduction come with exposure to bird sounds (Ratcliffe, Gatersleben and Sowden, 2013) and water streams (Annerstedt *et al.*, 2013). The walking speed slows down while adding to the sense of trail enjoyment (Franěk *et al.*, 2018). All these aspects demonstrate how soundscape can develop healthier sonic experiences in the environment for society.

With the increased interest in soundscape application, different research projects have tackled varied frontiers with vast potential. Among them, the multidisciplinary experience of "The Positive Soundscape Project" (Davies *et al.*, 2009, 2013) demonstrated the variety of terms used to describe soundscapes and how this field can be complex. Among the various conclusions, researchers noted that people seem to describe sounds relating to the activity (e.g., clapping, whistling) and human behaviour (e.g., quiet, agitated).

Another research project consists of the "Urban Soundscapes of the World" project, performed by ASA sense and Ghent University, supported by Head-Genuit-Stiftung[2]. Up to the moment, the initiative compiled a database of over 125 high-quality 1-minute 360° videos and spatial audio files of locations worldwide varying from urban parks to historic sites. Their goal resides in becoming a reference database for soundscape research (De Coensel, Sun and Botteldooren, 2017). Additionally, they have researched procedures for identifying and hierarchically classifying urban locations (De Coensel, Sun and Botteldooren, 2017), evaluating the degree of realism and immersion of database recordings (Sun *et al.*, 2018), validating the hierarchical soundscape method mentioned above (Sun, De Coensel, *et al.*, 2019; Sun, Filipan, *et al.*, 2019), and testing a soundscape intervention using the database material (Van Renterghem *et al.*, 2020). If the project continues and future researchers follow their procedure, this archive can contribute to future comparisons of soundscape changes over time. This concept was defended by Schafer (Schafer, 1977), given that the majority of efforts on eco-preservation are physical, and ignore how sounds, wanted or unwanted, change over time.

In conclusion, soundscape research resides in a complex human-based evaluation of the sonic environment in a context that should tackle sound planning through a holistic approach (Alves *et al.*, 2015). Good progress came with the publication of the international standard

[2] http://urban-soundscapes.org/

ISO 12.913 composed of 3 parts specifically, part 1 related to definitions (BS ISO 12913-1, 2014), part 2 regarding methods (ISO 12913-2, 2018), and part 3 on data analysis and reports (PD ISO 12913-3, 2019). Furthermore, the ISO committee is joining efforts to launch an additional fourth part concerning soundscape interventions (Moshona *et al.*, 2022). Nevertheless, these standards represent a starting point, deserving reviews and adjustments to reach an optimized reference for soundscape researchers and practitioners.

2.2 Emotional responses to Soundscapes[3]

Emotions can be complex to analyse given the many influential factors constructed from personal experiences. Through special moments, humans process emotions into categories that are reflected into behaviour. However, it all begins with a meaningful affect process where internal senses of the body trigger a feeling (Barrett, 2017). For example, involuntary chills when hearing a cry for help that makes one feel fear, or a spontaneous smile when listening to a child's laugh resulting in a happy state.

Differently from mood, emotions are caused by a specific object or event (Beedie, Terry and Lane, 2010), which can be an audible event in context, time, and space, also considered as a soundscape. Differences are identified by duration, with mood being more constant, while emotions are short-lived with specific purpose (Fiebig, Jordan and Moshona, 2020).

Given the relations of emotions and the auditory system, studies have also argued that sounds indicate the perception of safety (Andringa and Bosch, 2013; Sayin *et al.*, 2015; van den Bosch, Welch and Andringa, 2018; Calleri *et al.*, 2019). And therefore can change public behaviour towards liberty to attend to their own matters when normalness is indicated, or to become vigilant, when safety is so uncertain that it results in difficulty to relax and concentrate on other self-chosen activities (Andringa and Bosch, 2013). In short, the auditory perception evokes emotions which serve to determine what environment people are attracted to or repelled from (van den Bosch, Welch and Andringa, 2018).

[3] In this section, part from (Carvalho, W.J. Davies and Fazenda, 2019; Engel, Carvallho, *et al.*, 2021) papers are included.

The emotion of fear related to the lack of audible safety in public spaces increases the emotion of anxiety, resulting in the public avoiding the place and, consequently, creating financial depreciation of the venue (Sayin *et al.*, 2015). On the contrary, the influence of natural sounds has been demonstrated to stimulate the emotion of tranquillity (Watts and Pheasant, 2015) and to induce stress recovery (Annerstedt *et al.*, 2013). Also, ambient sounds demonstrated influence on perceptions of social presence, perceived safety, satisfaction, and willingness to purchase (Sayin *et al.*, 2015).

The English language has a few hundred words for describing emotions (Plutchik, 2001). Theories of emotion describe it as a complex construct of various classes of evidence (Plutchik, 1982) or components (Scherer *et al.*, 2013) which includes verbal reports of feelings. Here, different taxonomies for emotional responses to urban soundscapes are addressed so that, by better understanding how people feel about sounds, support can be given to healthier design decisions (Engel, Carvallho, *et al.*, 2021).

Russell (Russell and Pratt, 1980; Russell, 2003) has influenced most taxonomies for soundscape affective evaluations (Axelsson, Nilsson and Berglund, 2010; Barrett, 2017; ISO 12913-2, 2018). Along with Mehrabian (Mehrabian, 1995), they established three emotional dimensions: Pleasure, Arousal, and Dominance denominated as PAD scale. However, the first two are more cited as Russell's circumplex model (Figure 4 for environments, and Figure 5 for core affects). Arousal represents the degree of alertness in someone's emotional state which can go from positive (frenetic excitement) to negative (sleepy), while pleasure consists in the degree of ecstasy (positive) to agony (negative emotion) (Russell, 2003).

Axelsson et al. (Axelsson, Nilsson and Berglund, 2010) proposed a model for soundscape perception which has resemblances with Russell's circumplex model for environments (Figure 4) (Russell and Pratt, 1980). The authors initially used a predetermined set of 189 adjectives developed from interviews for assessing aesthetic features of photographs that was reduced to 116 words for better representation of soundscape characteristics. The group of words was used in the evaluation of 50 different soundscapes by 100 participants. Variance in the results were explained by three principal components: pleasantness, eventfulness, and familiarity. The small variance of the last component led to its elimination given possible perceived similarities among used soundscapes resulting in a limited application in soundscape assessments. Finally, the authors suggest outdoor soundscapes can be represented within a two-dimensional space constructed by the two components, pleasantness, and eventfulness (Figure 6). These soundscape attributes were later adopted in the soundscape standard ISO 12913-2:2018 in method A as the Soundscape Perceived Affective Qualities (PAQ) (ISO 12913-2, 2018).

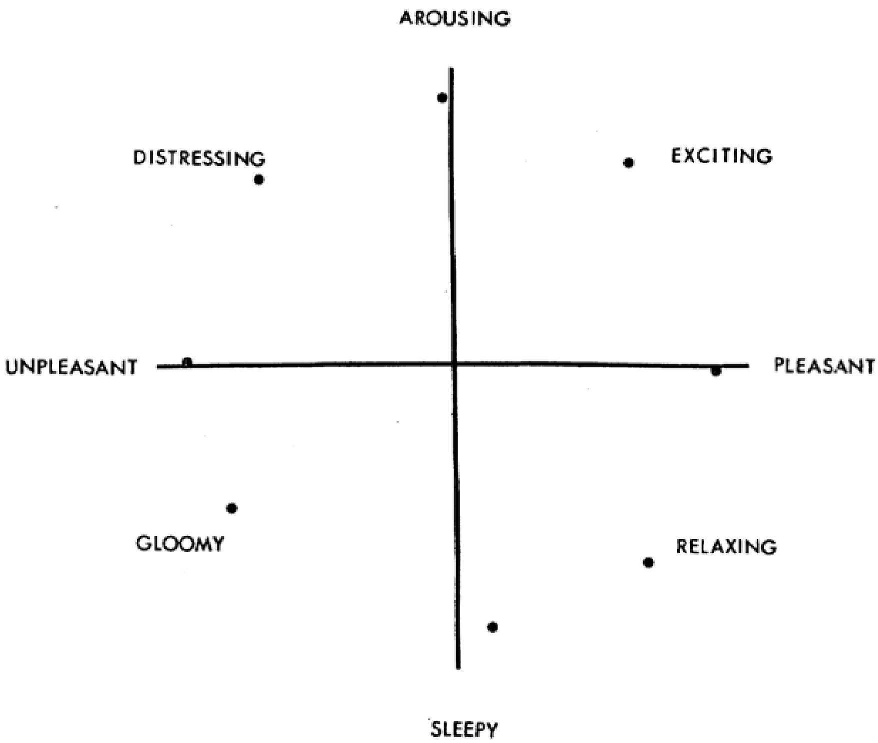

FIGURE 4: PROPOSED TWO-DIMENSIONAL REPRESENTATION OF THE AFFECTIVE QUALITY ATTRIBUTED TO ENVIRONMENTS (RUSSELL AND PRATT, 1980), P.281.

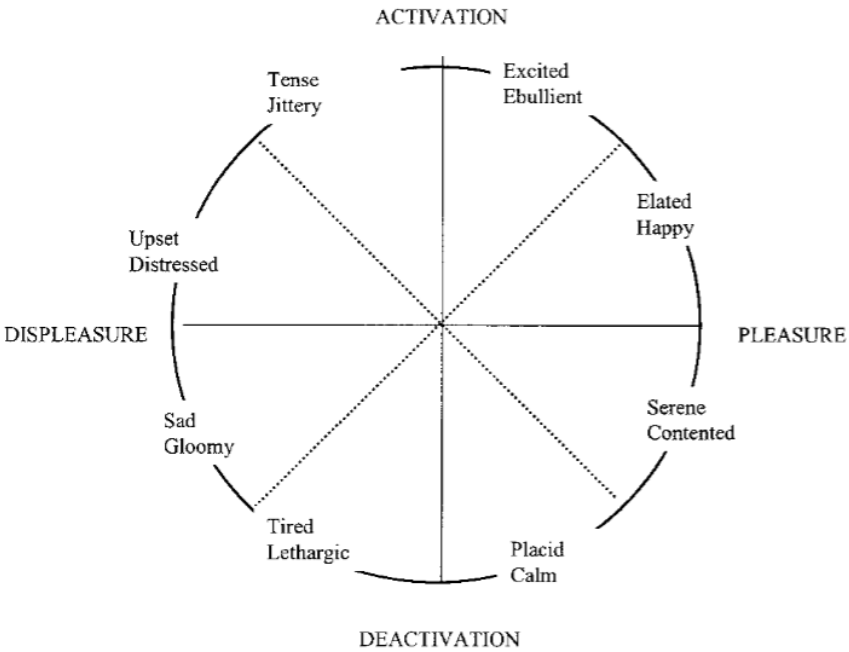

FIGURE 5: RUSSELL'S TWO-DIMENSIONAL MODEL FOR "CORE AFFECT" (RUSSELL, 2003), P.148.

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Figure 6: Component scores of the 50 soundscape excerpts in Pleasantness and Eventfulness. Symbols represent dominant sound-categories: human sounds (filled squares), technological sounds (filled circles), natural sounds (open squares), and no dominant sound-category (open circles) (Axelsson, Nilsson and Berglund, 2010) p. 10.

Cain et al. (Cain, Jennings and Poxon, 2013) achieved emotional dimensions through a factor reduction obtained from three preliminary experiments using open questions of how and why participants felt about different sounds and locations. Authors summarized results into five dimensions (Calmness and Relaxation; Comfort and Reassurance; Vibrancy and Arousal; Informative; and Intrusiveness and Sense of Self) including their semantic descriptors. Their conclusions were that urban soundscapes have two principal emotional dimensions (Calmness and Vibrancy - Figure 7) which must come together with their semantic descriptors to be adequately expressed (Cain, Jennings and Poxon, 2013). Such dimensions can be considered as a rotation of Axelsson's dimensions (Axelsson, Nilsson and Berglund, 2010), as illustrated in Figure 6.

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Figure 7: Independent soundscape dimensions: “Calmness” and “Vibrancy” (Cain, Jennings and Poxon, 2013), p.237.

The ISO 12913-2:2018 (ISO 12913-2, 2018) standard introduces and describes the soundscape Perceptual Affective Qualities (PAQs) by eight attributes: eventful, vibrant, pleasant, calm, uneventful, monotonous, annoying, and chaotic (Figure 8). These semantic scales, in theory, are traced back to the arousal-valence scales of Russell (Russell, 1980), who inspired Axelsson and colleagues (Axelsson, Nilsson and Berglund, 2010) to develop the mentioned attributes. In part 3 of the ISO 12913-3:2019 (PD ISO 12913-3, 2019), each attribute has an additional definition and some terms are correlated to different sound environments (Carvalho, Davies and Fazenda, 2022). As stated in the standard, this two-dimensional model is still under investigation and validation in other languages (PD ISO 12913-3, 2019). also, it was considered relevant to continue to explore other emotional and affective taxonomies.

Largely used in music assessments, the Emotional Self-Assessment Manikins (SAM) adopt Russell and Mehrabian PAD dimensions and gives it a graphic representation (Bradley and Lang, 1994), see Figure 9. Here, pleasure is valence, and can be sonically represented by sounds of joyful laughter or birds singing. Arousal may relate to the sounds of an energetic cheerful group. Dominance reports how in control the participant feels toward the experience. In soundscape studies, the feeling of dominance can be hard to correlate, but an example would be a quiet library where the individual felt compelled not to speak, reflecting a dominating sonic environment (Carvalho, Davies and Fazenda, 2022).

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FIGURE 8: GRAPHICAL REPRESENTATION OF PLEASANTNESS AND EVENTFULNESS SCALES (PD ISO 12913-3, 2019), P.6.

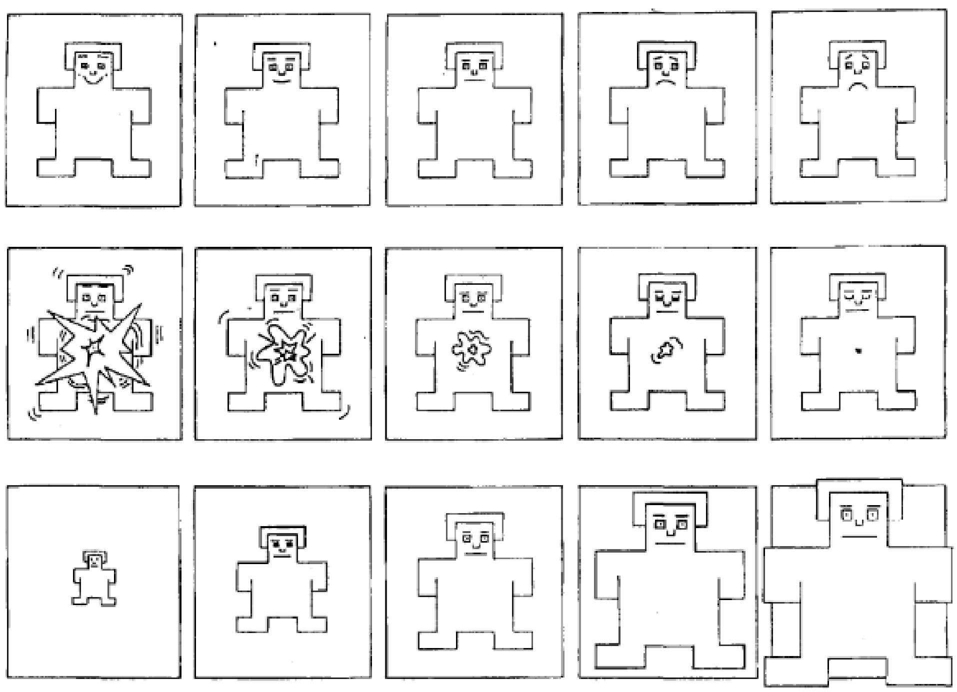

FIGURE 9: THE SELF-ASSESSMENT MANIKIN (SAM) USED TO RATE THE AFFECTIVE DIMENSIONS OF VALENCE (TOP PANEL), AROUSAL (MIDDLE PANEL), AND DOMINANCE (BOTTOM PANEL) (BRADLEY AND LANG, 1994), P.51.

Other emotional taxonomies less common to urban soundscapes studies are the Positive and Negative Affect Schedule (PANAS) (Watson, Clark and Tellegan, 1988), Plutchik's wheel of emotions (Plutchik, 1982) and the Geneva Emotion Wheel (GEW) (Scherer *et al.*, 2013). Initially developed for mood analysis with 20 negative and positive terms (Watson and Clark, 1988), the PANAS scales were summarized to 10 words (Thompson, 2007). They were determined, attentive, alert, inspired, active, afraid, nervous, upset, ashamed, and hostile scored in the Likert scale of one (1) for never to five (5) for always. In this thesis, these affective scales were tested to observe if they would point to meaningful results other than the standard soundscape descriptors PAQs (ISO 12913-2, 2018).

Plutchik (Plutchik, 1982) define emotions as a complex chain of reactions in the following sequence: stimulus event, inferred cognition, feeling, behaviour, and effect. Their work (Plutchik, 1982) arranged eight basic feelings into an emotion three-dimensional circumplex colour wheel (Figure 10) according to pairs of opposites and similarities of emotional terms, such as "fear / terror", "anger / rage", "joy / ecstasy", "sadness / grief", "acceptance / trust", "disgust / loathing", and "anticipation / surprise". Other 24 emotions are displayed in a cone form (third dimension) where stronger feelings are placed in the centre and gradually decrease in intensity when moving away from the centre. Between coloured sections, Plutchik mixed emotions which he called primary dyads, such as "joy" and "acceptance" created "love". He emphasizes that other emotions can be defined with different mixtures in different levels of intensity. Colours reference are not psychologically related but refer to the colour theory where the mixture of yellow and blue result in green (Plutchik, 2001).

In a similar form, Scherer et al. (Scherer *et al.*, 2013) also established a circular distribution of emotional terms. However, these authors arranged the words according to a discrete (emotion words) and a two-dimensional (valence and control/power axis) approach. After many enhancements in ten different languages, their work is summarized in the Geneva Emotion Wheel (GEW) that includes 20 emotion terms distributed along four quadrants of the circle varying from positive to negative valence, and high to low control. The emotion words (Figure 11) are labelled clockwise as follows: "involvement / interest", "amusement / laughter", "pride / elation", "happiness / joy", "enjoyment / pleasure", "tenderness / feeling love", "wonderment / feeling awe", "feeling disburdened / relief", "astonishment / surprise", "longing / nostalgia", "pity / compassion", "sadness / despair", "worry / fear", "embarrassment / shame", "guilt / remorse", "disappointment / regret", "envy / jealousy", “disgust / repulsion”, “contempt / scorn”, and “irritation / anger”. Opposite from Plutchik (Plutchik, 2001), the more intense the feeling is, the closer to the rim the rating is placed in the wheel (Scherer *et al.*, 2013).

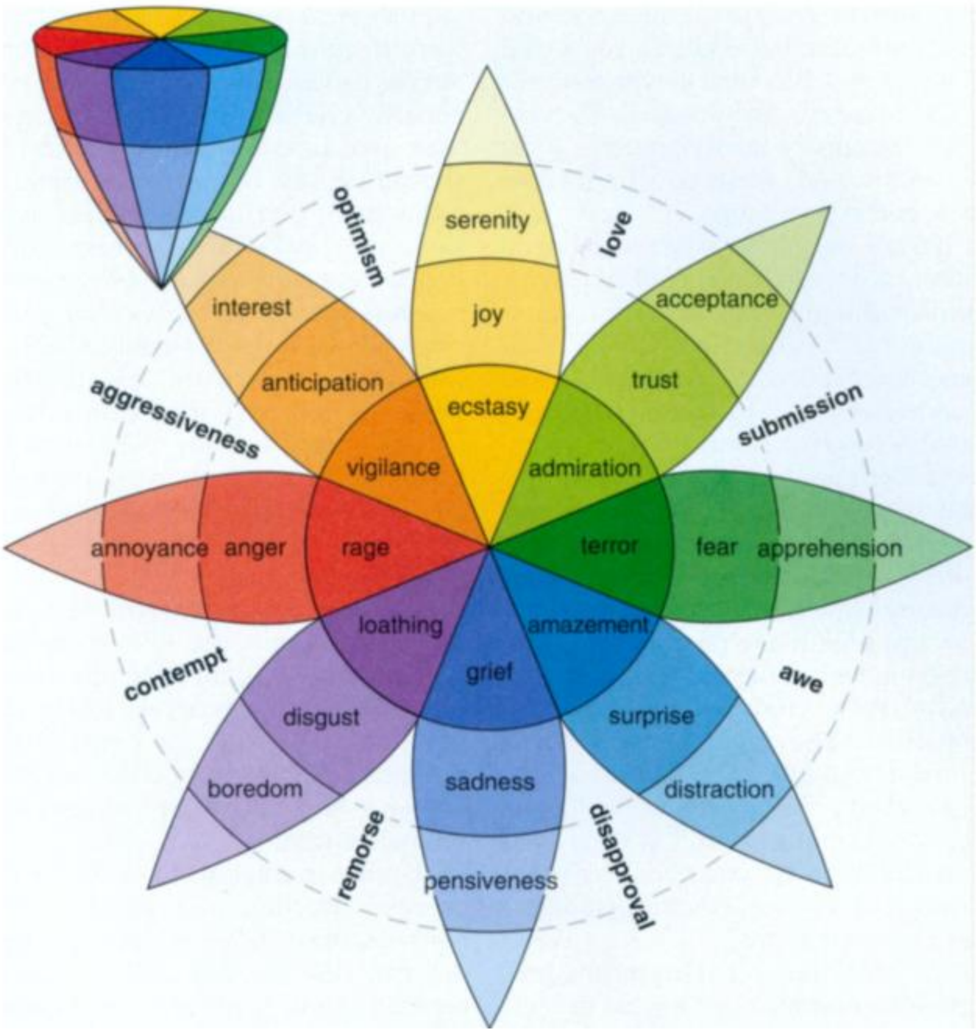

FIGURE 10: PLUTCHIK’S THREE-DIMENSIONAL CIRCUMPLEX MODEL […] ANALOGOUS TO THE […] COLOUR WHEEL. THE CONE’S VERTICAL DIMENSION REPRESENTS INTENSITY, AND THE CIRCLE REPRESENTS DEGREES OF SIMILARITY AMONG THE EMOTIONS. […] (PLUTCHIK, 2001), P.349.

All in all, soundscape research still lack consensus in assessing emotional responses to sounds (Fiebig, Jordan and Moshona, 2020). Forces to identify enjoyable and pleasant emotions towards places, situations, and people should be aimed for and maintained to create flourishing behaviours (van den Bosch, Welch and Andringa, 2018) for a healthier society. Further, studies point out that understanding emotional responses to soundscape gives support to design decisions, a better opportunity of achieving users’ satisfactions (Cain, Jennings and Poxon, 2013), and quality of life (Andringa and Bosch, 2013).

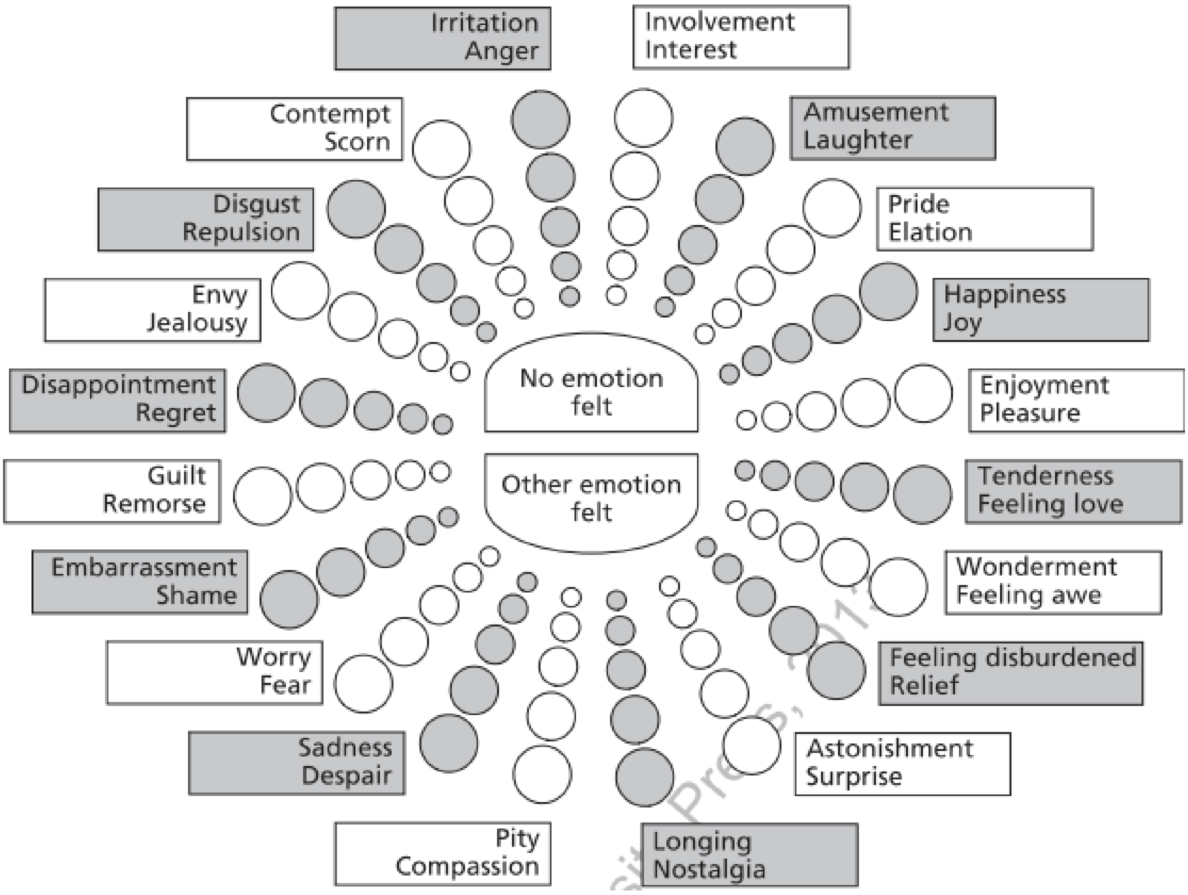

FIGURE 11: TEMPLATE OF VERSION 2.0 OF THE GEW (SCHERER *ET AL.*, 2013), P. 289.

2.2.1 Soundscape influences on Human Behaviour

Soundscape research has focused on understanding how people perceive and evaluate the acoustic environment, but how they react in behaviour and psychologically to different sounds in contexts is still reduced to "… Anti-social behaviours, use of spaces [, and] crowd's movements " (Aletta and Xiao, 2018, p.7). Here, some studies on how people behave in urban public places are presented (Tables 1 and 2) through their methodologies and discoveries, specifically in the perspective of behavioural analysis correlated to soundscapes.

TABLE 1: SUMMARY OF REVIEWED PAPERS.

Reviewed papers	Objectives		Metrics	Stimuli	Type of Site	Findings
(Lavia *et al.*, 2012; Lavia, Dixon, *et al.*, 2016)	To integrate soundscape approach to solve noise problems and enhance public awareness.	To observe the influence of sound on users	(1) Body language (2) police feedback	3D outdoor soundscape installation	Public street	(1) Public responses were more relaxed (pro-social behaviour) (2) area reduced noise levels, reduced noise complaints, and the public felt an increase in the sense of safety.
(Witchel *et al.*, 2013; Lavia, Dixon, *et al.*, 2016; Lavia, Witchel, *et al.*, 2016)		To test pro-social and territorial-controlling behaviour	(1) Walking speed (2) Loitering behaviour	No music (control) & music (classical, jazz, & contemporary dance)	Pedestrian subway public tunnel	(1) Speed decreased with music (2) fewer loitering events occurred with classical & jazz music when entering the tunnel while classical music induced people to exit the tunnel which might indicate that classical music prevents loitering behaviour.
(Aletta *et al.*, 2016; Lepore *et al.*, 2016)	(1) To observe the influence of music in number or duration of stay (2) the association between music and behaviour.		(1) Activity (2) group (3) posture behaviour	No music (control) & Recorded music (classical, jazz, & ambient electronic)	University pedestrian place	(1) Music did not increase the number of people, but the duration of stay (loitering) (2) chatting and eating/drinking increased with classical and ambient electronic music as well as smoking with any type of music.
(Meng, Zhao, and Kang, 2018)	To study how music influenced specific crowd behaviour.		(1) Walking speed (2) paths (3) sitting	No music (control) & familiar pop song with lyrics	Typical Urban Leisure Chinese Square	(1) Music made people (walking by, walking around, or sitting) come closer to the sound source (2) walking speed was reduced for those "walking around" the square.

TABLE 2: SUMMARY OF REVIEWED PAPERS (CONTINUATION).

Reviewed papers	Objectives	Metrics	Stimuli	Type of Site	Findings
(Franěk, van Noorden, and Režný, 2014)	To observe (1) walking synchronization with music (2) effects of motivational and non-motivational music on walking speed (3) masking effect of music in visual stimuli.	(1) Walking pace (2) walking speed	(1) One world pop music in different tempos (2) two different types of music	Real outdoor urban route	(1) Occasionally synchronize walking pace to music (2) Motivational music increased speed while non-motivational the speed was slower and calmer in different ways according to individual personality traits (3) music did not mask visual stimuli but enhanced to a pleasant walking experience.
(Meng and Kang, 2016)	To observe how sound-related activities influenced human behaviours.	(1) Standing & watching (2) passing by (3) doing exercise (4) sitting	Sound-related activities (1) four activities with music (2) three human-made sounds	Typical pedestrian street	(1) Music-related activities increased attention and encouragement of people to pass, stand, and watch while those that wanted to sit preferred quieter places (2) when the number of people in human-related activities was six or more, standing and watching behaviour increased (3) no influence of sound-related activities in exercising behaviour.
(Maculewicz, Erkut, and Serafin, 2016)	To investigate the influences of soundscape and footstep sounds on walking pace.	Walking pace	(1) 3 footsteps (2) 4 soundscapes + control (silence)	An aerobic stepper in laboratory condition	(1) Both conditions influenced on walking pace, but soundscape influenced more than footstep sounds (2) the complexity of soundscape could mask the sound of footsteps.
(Franěk *et al.*, 2018)	To investigate the effect of listening to diverse environmental sounds on walking speed.	Walking speed and route evaluation	(1) Traffic noise (2) forest birdsong	Real outdoor urban route	(1) Traffic increased while birdsong slightly decreased walking speed (2) negative evaluation when listening to traffic noise while more pleasant evaluation when birdsong.

Most studies use music interventions to observe the effect before and after the intervention (Lavia *et al.*, 2012; Easteal *et al.*, 2014; Franěk, van Noorden and Režnỳ, 2014; Aletta *et al.*, 2016; Lavia, Dixon, *et al.*, 2016; Lavia, Witchel, *et al.*, 2016; Lepore *et al.*, 2016; Meng, Zhao, and Kang, 2018) while others test if sound-related activities affect movement behaviour (Meng and Kang, 2016), and correlate how different sounds influence walking speed (Maculewicz, Erkut, and Serafin, 2016; Franěk *et al.*, 2018).

In the "Sounding Brighton" program developed by the Noise Abatement Society (NAS), even though the intervention was not announced, the two-hour event (“White Night”) could be characterized as an “outside party” in the queuing area before entering the clubs which resulted in a positive public interaction (Lavia *et al.*, 2012). This experience effectively demonstrated the shift from negative (anti-social) to positive (pro-social) behaviour that can be considered healthier for society. However, even though the second part of the project (Lavia, Witchel, *et al.*, 2016) had a more controlled method, it did not identify behaviours that symbolize happiness, such as laughter and hugging as did the first part. Still, the change in walking speed due to music may indicate pleasantness in the individual as music research asserts that music effectively changes human emotions (Krumhansl, 1997; Husain, Thompson and Schellenberg, 2002; Perlovsky, 2010; Fiegel *et al.*, 2014).

In contrast, loitering behaviour was controversial among studied articles. While in the University pedestrian place (Aletta *et al.*, 2016) this behaviour was considered as a possible reference of environmental pleasantness to people. On the other hand, it was considered an anti-social behaviour that kept the public away in a pedestrian subway tunnel (Lavia, Witchel, *et al.*, 2016).

Regarding the effect of music intervention on walking speed in public spaces, most studies claimed that people changed speed (Lavia *et al.*, 2012; Franěk, van Noorden and Režnỳ, 2014; Lavia, Witchel, *et al.*, 2016; Meng, Zhao and Kang, 2018). This conduct may be justified by the possible environmental safety reported in some works (Lavia, Witchel, *et al.*, 2016; Van Den Bosch and Andringa, 2016). Additionally, some results indicated that people only occasionally synchronize their walking behaviour to music (Franěk, van Noorden, and Režnỳ, 2014), differently from other works in controlled situations (open-air athletics track) where synchronization of walking with music had a good response with a broad range of tempo (Styns *et al.*, 2007)(Styns et al., 2007). However, different types of music had different effects on the walking speed behaviour (Franěk, van Noorden, and Režnỳ, 2014; Lavia, Witchel, *et al.*, 2016; Meng, Zhao and Kang, 2018). Franěk argued that music enhanced the walking experience into a more pleasant and private activity instead of creating the masking effect (Franěk, van Noorden, and Režnỳ, 2014). This result corroborates findings of the effects of music on environmental assessment where positive music enhanced environmental ratings (Yamasaki, Yamada and Laukka, 2015).

However, musical interventions in soundscapes can create problems, such as limited social accessibility to the healthier soundscape, as the use of sound equipment or personal headphones are not always accessible to all social classes. These solutions are temporary and not sustainable in the long term for urban planning. Soundscape research must achieve more permanent solutions to gain better acceptance among urban designers. Not all local authorities and communities can fund the equipment, pay for maintenance, or prevent vandalism. Furthermore, it can be said that music can increase sound levels and change the natural settings of the soundscape.

From the perspective of human sounds, people seemed to be more attracted to sound-related activities when there were six or more individuals in a group (Meng and Kang, 2016). This conduct might be because people find it more interesting to observe a crowd that can symbolize liveness and diversity in a space than to watch fewer individuals in a calmer and more monotonous atmosphere. The phenomenon was also observed by Whyte concerning people's preference to be closer to other groups (Whyte, 1980). In contrast, a survey on members of the public practicing physical exercise showed they were not attracted to these activities (Meng and Kang, 2016), which could be because they are isolated in an "audible bubble" with their portable audio system (Bull, 2001; Franěk, van Noorden, and Režnỳ, 2014) so concentrate on their own audio to the extent that their behaviour is not influenced by the external environment. Also, they may persistently focus on the task of running, obscuring the need to participate or interact with the soundscape.

Moreover, the selection of reviewed papers concentrated on studies related to influences of soundscape on behaviour studies around the period of 2019, and later the research shifted to investigate emotions. Given that the individual must first feel and process, before making the decision to act reflecting on the behaviour. Most works used music as a stimulus, with other examples including seashore, street, office, restaurant (Franěk *et al.*, 2018), traffic noise, and forest birdsong (Maculewicz, Erkut, and Serafin, 2016). Still, only two of these sounds--seashore and forest birdsong--can be considered soundscapes that improve public well-being, thus demonstrating the lack of studies on other possible healthy soundscapes that may contribute to behavioural changes in society.

2.3 Soundscape Design

The soundscape topic has gained space among environmental noise discussions on urban quality of life, public health, and ecological restoration. It mainly received influence from noise management, but, due to its complexity, new parameters, such as user´s sonic experience and context issues became relevant. Planning and designing processes work with frameworks and diverse stages that are oriented by user-centred decisions, such as human sound preferences and expectations. Good practices are still moderately growing and are mostly only accomplished due to research support. In this chapter, soundscape design issues will be discussed considering some studies developed in recent years.

2.3.1 Environmental Noise influences

Since noise became one of the highest pollution issues in contemporary cities, the main Environmental Agencies in the world (Europe, USA, Australia, Brazil among others) established guidance with noise level limits to manage noise. However, studies demonstrate that only reducing noise levels may not achieve the human expectation of the sonic environment, and soundscape strategies began to be approached to help mitigate noise problems (Aletta and Kang, 2015). Consequently, soundscape research developed due to this approximation. Some influences are noise maps, acoustic measurements of sound levels, noise control solutions, such as noise barriers, and sound source control as well as noise annoyance surveys.

Noise maps give a graphic distribution of sound levels in two-dimension (2D) representations. They are good practices to present existing or simulated noise propagation in drawings to facilitate visual comprehension to non-expert public. However, in soundscape studies, there still is no standard in what should be represented in them. Publications vary in plots of *soundmarks* (high community valued sounds) and *sound signals* (foreground sounds) - Figure 12 (Vogiatzis and Remy, 2017), survey results - Figure 13 (Aletta and Kang, 2015), different sound levels of *anthrophony*, *biophony* and *geophony* - Figure 14 (Liu *et al.*, 2013) and sound topologies - Figure 15 (Boubezari and Bento Coelho, 2012).

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Figure 12: *Sound signals* (black colour) and *soundmarks* (red colour) of the studied district (Vogiatzis and Remy, 2017).

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Figure 13: Soundscape maps for the overall assessment of the sound environment (left) and the appropriateness of the sound environment to the place (right) (Aletta and Kang, 2015).

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FIGURE 14: SOUNDSCAPE COMPOSITION WHERE *ANTHROPHONY*, *BIOPHONY*, AND *GEOPHONY* ARE ORIGINALLY DESCRIBED IN RED, GREEN AND BLUE RESPECTIVELY, AND THE INTERMEDIATE COLOURS STANDS FOR AN AREA THAT RECEIVED COMBINED SOUNDS (LIU *ET AL.*, 2013).

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FIGURE 15: SOUNDSCAPE TOPOLOGICAL LAYERS OF ESTRELA PARC IN LISBON (BOUBEZARI AND BENTO COELHO, 2012).

To represent *soundmarks* and signals in maps is coherent to the initial soundscape definitions (Schafer, 1977) while to plot people´s preferences is less common (Aletta and Kang, 2015). Additionally, it may be complicated to understand what the map represents when many different sound source levels blend in colours (Liu *et al.*, 2013). Sound topology maps also demonstrate sound levels of sources in maps, including how traffic noise masks these sources (Boubezari and Bento Coelho, 2012). Nevertheless, these tools contribute to the description of the acoustic environment through the quantification of sound levels (noise maps), identification of sound sources (sound or sound topology maps), and qualification of sound preferences (soundscape maps). This constitutes, in part, the knowledge needed to understand and assess soundscapes.

Another procedure coming from environmental noise assessment to soundscape analysis is to measure loudness, average, and percental values of sound levels. However, sound level averaged for long periods is considered not suitable for the soundscape analysis, since preferred sounds mainly happen in a short time (Bento Coelho, 2016). Also, mean values blend all sound sources, which will not help in distinguishing wanted from unwanted sounds. Brown and Muhar consider it more useful to have a separate time-history sound level of each sound so to manage possible masking effects (Brown and Muhar, 2004). Nevertheless, the PD/ISO 12913-3:2019 (PD ISO 12913-3, 2019) suggests psychoacoustic metrics extracted from binaural recordings as listed in Table 3.

TABLE 3: METRICS AND REPRESENTATIVE SINGLE VALUES ACCORDING TO ANNEX D OF PD/ISO 12913-3:2019 (PD ISO 12913-3, 2019).

Parameter	Metrics to be determined for each channel separately	Determination of representative single value	Reference
Sound pressure level	$L_{Aeq,T}$, $L_{Ceq,T}$, $L_{AF5,T}$, $L_{AF95,T}$	higher value of left and right metric values	ISO 1996-1
Loudness (time-variant loudness)	N_5, $N_{average}$, N_{rmc}, N_{95}, N_5/N_{95}	higher value of left and right metric values (or the average of left and right metric values)	ISO 532-1
Sharpness	S_5, $S_{average}$, S_{95}		DIN 45692
Psychoacoustic tonality	T		ECMA 74
Roughness	R_{10}, R_{50}		Fastl H., Zwicker E., (2007)
Fluctuation strength	F_{10}, F_{50}		

Regarding noise control solutions, soundscape studies inherited the concepts of noise barriers, noise source treatment, surface treatment, and masking unwanted sounds. According to Brown, the masking effect consists of the main element for managing and designing soundscapes (Brown, 2012). Also, a large number of interventions use water structures, such as fountains to mask unwanted sound (Kang, 2012). Nevertheless, these interventions must consider the sound *character* of the place, or the possible impact of *soundmarks* so that the inserted sound is coherent with context.

Another contribution from noise assessment is the noise annoyance surveys (ISO15666, 2003) that brought the experience of questionnaires with scales from "not at all" to "extremely" annoyed with noise, but shifting from annoyance to pleasant or comfortable. These parameters are present in part 2 of the ISO 12.913 (ISO 12913-2, 2018), along with other procedures.

2.3.2 Design Processes and Solutions

Given the recent application of soundscape resources in urban planning, design processes still vary in procedures. Here some researchers and their design process were discussed. They are the "steps" by Brown and Muhar (Brown and Muhar, 2004; Brown, 2012), the "points and elements" of Sieben (Siebein, 2011, 2013), the "roadmap" of Bento Coelho (Bento Coelho, 2016), and the "mixed-method approach" of Cerwén (Cerwén, Wingren, and Qviström, 2016; Cerwén, 2017; Cerwén, Kreutzfeldt, and Wingren, 2017). Some are more objective and others more artistic. In all cases, sound source identification and people´s responses to them are present.

The steps of Brown and Muhar to approach soundscape design are identifying activities, setting acoustic objectives, identifying and assessing sounds of preference on-site, and investigating design options (Brown and Muhar, 2004; Brown, 2012). First, the desirable activities are established for the considered site. Smaller places in the city may have one function, but diversity in activities tend to give a more dynamic atmosphere to urban places. In these circumstances, the practice of zoning is suggested by giving the distance in space, time, or both. An example of the first can be isolating quiet areas of a park from the playground areas so that the calm surrounding can be preserved for people to relax while children can still play further away. For the time zoning activities, there can be arrangements for a pedestrian street to be a market during the day and become a place for restaurants or clubs at night. In either way, the "local experts"--people who live and use the studied location willing to share their opinion with researchers--(Brooks *et al.*, 2014), local authorities, planners, designers and whoever is related to the site, should discuss what their interests are (Brown and Muhar, 2004).

Secondly, the authors (Brown and Muhar, 2004) introduce the concept of “Proposed Acoustic Environment” integrated with the “acoustic objectives” (the acoustic aims in the project) for each zone. These goals are a combination of wanted or unwanted sounds being enhanced or masked, respectively. Some examples are as follows: to have only sounds of nature heard, to hear mostly human sounds, or have an acoustic sculpture clearly audible among other features. The objective is to have the presence of one sound prevailing over another resulting in the masking effect. According to Brown, “Masking is a key principle of soundscape planning and design.” (Brown, 2012, p.79). However, to what extent should the insertion of a new sound go and not be "intrusive" or new pollution to the environment? This issue must be taken into consideration so that soundscape interventions do not become a noise problem, and still, achieve people´s sonic expectations.

Brown and Muhar following steps are the identification and assessment of wanted and unwanted sounds on-site, and, finally, the proposition of design options (Brown and Muhar, 2004). With enough knowledge of the wanted and unwanted sounds together with the “Proposed Acoustic Environment” initially defined, planners can discuss strategies to solve initial goals. Among the acoustic solutions cited by the authors, there is the acoustic treatment of pavements to increase the sounds of people passing by, and the increase of plants that attract birds intending to reach the acoustic objectives to hear more people and natural sounds. It is also mentioned that these steps are not to be linear and can be revised with feedbacks through communication and co-work among planners, designers, and acoustic specialists (Brown and Muhar, 2004).

The approach of Brown and Muhar (Brown and Muhar, 2004; Brown, 2012) can be simple to understand and transmit. However, can the acoustic objectives stimulate artist sonic creations to the soundscape designer? Better still, can the "local expert" identify the novel sounds that can be pleasant and enhance their sonic experience and quality of life? Some of these gaps can be filled with the next author, Siebein (Siebein, 2011, 2013).

Given Siebein's architectural background, his design approach to soundscape design is enhanced with aesthetical judgment and elements (Siebein, 2013). His five points of the creating process of soundscape are the *inspiration*, planning, conceptual structure, *tectonics*, and *details*. The seven elements of his theory are to identify the acoustical community that will relate to the project, develop the taxonomy of the acoustic events, map their itineraries (paths and sounds in time and space), list the *acoustic rooms* or zones with their *coloration*, establish the rhythm of the acoustic calendar, design sonic interventions that suit niches, and transform the objective data into unique aesthetic acoustic solutions (Gary W Siebein *et al.*, 2006a; Gary W. Siebein *et al.*, 2006b; Siebein, 2013). Some of these elements, such as mapping sounds and identifying the community, are similar to procedures from other authors (Brown and Muhar, 2004; Bento Coelho, 2016; Cerwén, 2017), although not all have the aesthetic approach.

The author (Siebein, 2013) indicates that the inspiration for soundscape design relies on the concept of a "place of being", where the designer aesthetically explores and translates the culture, context, program, and location of the place into the acoustical *identity* and *character* of the soundscape. Still, this point technically depends on advanced acoustical systems, such as computer modelling and simulations of the proposed acoustic concept (named acoustical *sketches* of sounds) for the acoustical community to discuss preferences through their aesthetic judgment. These simulations integrate the "planning" point where the seven elements are applied, and, additionally, the *acoustical rooms*, zones, or *acoustic arena* (Blesser and Salter, 2007) are identified and developed. Together, all information organized into the conceptual structure establishes how and where the complex network of sound sources communicates to the listeners through space in time. It is a moment of giving shapes and sounds to the intellectual and poetic aspects of the project, to materialize into the *tectonic*, and *detail* stages (Siebein, 2013).

Physical components of the architecture and how they influence the sonic experience, such as enclosures, structures, and textural treatment exist in the *tectonic* points, while the subtleties of how the environment responds to it and how the listener perceives the complexity of soundscape are the *details* (Siebein, 2013). This last stage is where the author mentions that soundscape design gives "colour" to sounds that are aesthetically different in "… qualities… regardless of function" (Siebein, 2013, p.161), and technically obtained by the variations of reflection, diffusion, and absorption in space. These *details* can be the sonic result of all the poetic materialization of the design inspiration into the complex soundscape to stimulate different aesthetic sonic experiences. It is important to notice that the *character* and *identity* given to soundscape by the designer are unique and that is considered "… the most fundamental aspect of the creating and designing process of soundscape" (Siebein, 2013, p.160). In this sense, this design method gives opportunities for designers to create as well as develop their own soundscape *signature* embedded in artistic values.

Within the creative solutions given by Siebein, there is the proposition of allowing sounds to flow from one acoustical room to another. It is mentioned that this phenomenon can encourage people to participate in different activities. There is also the suggestion of promoting "net-zero noise impacts" solutions which are those where noise pollution does not become a consequence of the new urban activity. These solutions are considered non-conventional solutions for soundscape design (Siebein, 2011).

On the other hand, the roadmap by Bento Coelho (Bento Coelho, 2016) combines some ideas of Brown, Muhar (Brown and Muhar, 2004; Brown, 2012) and Siebein (Siebein, 2013). The suggested steps are to establish the acoustical *character* of the place, to plan, to design and to optimise. The acoustical *character* includes the purposes and activities of the place that shape the acoustic objectives considering the listener's expectations which is similar to the acoustic objectives of Brown and Muhar (Brown and Muhar, 2004). Unlike Siebein (Siebein, 2013), his acoustical *character* (Bento Coelho, 2016) does not have the same poetic point of view but goes towards function, users, expectations, and attractiveness of the sonic environment.

The planning and optimizing steps by Bento Coelho (Bento Coelho, 2016) unite again authors (Brown and Muhar, 2004; Siebein, 2011, 2013). He points out to identify sound sources, listening places, itineraries, sound components, sound propagation paths, preferred and unwanted sounds (Bento Coelho, 2016). One of his contributions to this stage is the sound topology maps, as presented previously in Figure 14 (Boubezari and Bento Coelho, 2012; Bento Coelho, 2016), where sound pressure levels of unwanted and wanted sounds are combined to represent the limits of identified sound sources. It is also reported that an existing sound catalogue or sound identity map should be developed, where sounds are correlated to functions, activities, other senses, and preferred sounds of the place.

Finally, Bento Coelho defines the design options and optimizations for a soundscape that, through uses of prediction and simulation tools, present solutions to be discussed by stakeholders, planning technicians, and decision-makers (Bento Coelho, 2016). As mentioned by Brown (Brown, 2012), masking techniques are also indicated as a solution, not only the traditional phenomena but also the “mental masking” that consists of shifting the listener's attention to a more pleasant sound (Bento Coelho, 2016). Additionally, noise control measures and strategies, as well as soundscape composition, are recommended. In whichever selected solution, the author indicates to have caution in adjusting to the initial *character* (project aims), including attention to distinguish the different sonic subareas within the soundscape composition (Bento Coelho, 2016). These design processes presented up to here integrate characterization and planning stages of design, however, other than those regarding noise control, they present more procedures than solutions. These solutions can be found in the next author (Cerwén, 2017) where they are called “soundscape actions”.

Through four articles, Cerwén developed a “mixed method” composed of three categories in a comprehensive model of the soundscape for the landscape architecture process (Cerwén, 2017). Here, special attention will be given to two papers, II and IV: one regarding soundscape intentions in a landscape architecture competition for a new cemetery in Sweden (Cerwén, Wingren, and Qviström, 2017); and the other presenting the analysis results of three workshops that summarizes soundscape tools for possible practice application (Cerwén, Kreutzfeldt, and Wingren, 2017).

The new cemetery competition had many participants demanding a structure for proper analysis that resulted in the three categories: localization of functions, reduction of unwanted sounds, and the introduction of wanted sounds (Cerwén, Kreutzfeldt, and Wingren, 2017). Results demonstrated that sound had low relevance in projects, with approximately a quarter of participants not mentioning sound at all. Within those that used sound solutions, the main occurrences were for the reduction of unwanted sounds characterized as a “defensive approach” to soundscape treatment with 63.5%. The authors believed that this could be because the competition summary mentioned only sounds like noise and traditional urban sound management. That is, sound as a matter of nuisance in which attention has been diverted from the sound of work as an enhanced experience. Interesting to mention is that the winning proposal had little soundscape solutions, and, given its lack of proper sound analysis, the cemetery had to be replaced in a quieter area due to noise problems (Cerwén, Wingren, and Qviström, 2017). This reinforces the importance of having soundscape specialists participating in the early stages of the design process.

On the paper concerning the workshops (Cerwén, Kreutzfeldt, and Wingren, 2017), it should be mentioned that they were different in context, purpose, and participants. The first was a collaborative project among academics, urban planners, and decision-makers regarding potentialities of applying soundscape to planning. The second consisted of a research project around the new cemetery competition in Sweden and the third was developed with students in a landscape architecture course at Master's degree (Cerwén, Kreutzfeldt, and Wingren, 2017). Keyword summaries were developed by the groups within all workshops; then, these were correlated to the three previous categories (localization of functions, reduction of unwanted sounds and introduction of wanted sounds). Within these, 22* different "soundscape actions" were clustered and considered as assets for urban planning and design (Figure 16) (Cerwén, 2017). Furthermore, authors (Cerwén, Kreutzfeldt, and Wingren, 2017) also mention that further studies should occur to identify overlap and interactions of these actions that may result in different sound effects. They also suggested the development of other soundscape actions based on sound as a resource, and not as noise as occurred at the previous workshops (Cerwén, 2017; Cerwén, Kreutzfeldt and Wingren, 2017).

Graph removed due to copyrighted restrictions.

FIGURE 16: THE 23 "SOUNDSCAPE ACTIONS" IDENTIFIED BY CERWÉN. P.92 (CERWÉN, 2017). *NOTE: ADDITIONAL ACTION (EMBRACE WANTED SOUND) WAS INCLUDED AFTER THE FINAL ANALYSIS TO COMPLETE 23.

To resume, the three initial design processes presented in this section give support to project development (Brown and Muhar, 2004; Siebein, 2011, 2013; Brown, 2012; Bento Coelho, 2016) while the last (Cerwén, 2017) presents solutions for urban planners. Brown, Muhar

(Brown and Muhar, 2004) and Bento Coelho (Bento Coelho, 2016) have a more objective and pragmatic approach that establishes and describes the steps of the design process. Siebein, on the other hand, opens up to creativity with aesthetic values as *inspiration*, *identity*, *signature*, *details* and *coloration* within the whole process (Siebein, 2011, 2013). In the first three, there is the presence of characterization of soundscape that includes the diagnosis of the wanted and unwanted sounds, and participation of different communities (not just designers) on decision making during the design process. It should be noted that the latter gives many soundscape options that are still to be tested but may represent a significant contribution to innovative soundscape practices. Nevertheless, even though the study (Cerwén, Kreutzfeldt, and Wingren, 2017) systematically classifies the keyword summaries into clusters, there can still be other soundscape solutions or creations that may not have been identified. Together, these references are only some perspectives of the design process and solutions for the soundscape, and, due to recent diversity of methods and procedures, there can still be other alternatives.

2.3.3 The use of VR in Soundscape studies[4]

The use of VR has increased in soundscape assessments (Li *et al.*, 2018) with research groups creating databases of 360 audio-visual recordings of all over the world so to facilitate studies using different soundscapes scenarios. Additionally, to test the existent soundscape solutions through VR can optimize the identification of the best soundscape intervention that may compose the future part 4 of the ISO 12.913 (Moshona *et al.*, 2022). From this perspective, VR has a promising position to contribute to soundscape research.

Benefits have been shown, such as using VR soundscape approaches to assess no-go urban areas that may contribute to urban planners in security interventions since it can be used as a low-cost and non-intrusive strategy (Calleri *et al.*, 2019). Similarly, a street management strategies for vibrant areas where a shared-street design and traffic restrictions was simulated in an online VR survey, indicated improvements on the soundscape quality rating (Jiang *et al.*, 2018). Also, physiological stress recovery was achieved using birdsong and the sound of water in a green forest simulated in VR (Annerstedt *et al.*, 2013).

[4] In this section, part from (Carvalho, Davies and Fazenda, 2022) paper is included.

VR has proven "ecological validity" when representing urban scenes (Maffei *et al.*, 2016a). To be "ecologically valid" means guaranteeing that laboratory reproduction of real-life audio-visual stimuli creates the same sense of immersion and realism as in the original scenery (Loomis, Blascovich and Beall, 1999). If similarities between real and VR reproductions are maintained, laboratory experiments can support research with controlled factors. However, this may amplify results and bias conclusions. Thus, it should be interpreted cautiously (Tarlao, Steele and Guastavino, 2022). Up to now, most studies have confirmed similar soundscape perceptions among in-situ and laboratory VR listening tests (Maffei *et al.*, 2016b; Puyana-Romero *et al.*, 2017; Jo and Jeon, 2021; Tarlao, Steele and Guastavino, 2022).

For example, Maffei (Maffei *et al.*, 2016a) concluded that field and VR soundscape experiences are congruent enough to be used as a tool to understand human actions, movement, and perception towards the complexity of the environment. Therefore, VR soundscape experiments may reproduce real-life situations in conditions, such as laboratory which increases experimental control and still have high "ecological validity" (Loomis, Blascovich and Beall, 1999).

With technological advances, the reproduction of the real world in virtual environments became so realistic that the user, immersed into the experience, has the sense of being in a real-life place, also called the "sense of presence" (Slater, 2009). The sensation can be created through multimodal sensors, such as audio, visual, and tactile. In specific, the virtual sonic environment can be reproduced in different formats from mono to spatial audio (Rumsey, 2001), changing the perception of how immersive and realistic the sound is perceived. Derived from spherical harmonics, first order ambisonics (FOA) is composed of the four audio signals and can be understood through the simplified components presented in the Equations 1 to 4 (Hong *et al.*, 2017). The equations for the FOA are omnidirectional (W), front-back (X), left-right (Y), and up-down (Z), as follows:

$$W = \frac{S}{\sqrt{2}} \tag{1}$$

$$X = S \cdot cos\theta \cdot cos\phi \tag{2}$$

$$Y = S \cdot sin\theta \cdot cos\phi \tag{3}$$

$$Z = S \cdot sin\theta \tag{4}$$

where the S is the source signal with the azimuth angle θ, and elevation angle Φ.

The Urban Soundscapes of the World (USW) project has vastly contributed to methods of site selection, 3D soundscape field recordings, and creation of a high-quality audio-visual database of different urban soundscapes around the world. Table 4 presents a few papers produced by the group. Results from site selection method (De Coensel, Sun and Botteldooren, 2017) indicated lack of site representation for the annoying and uneventful quadrant of the ISO's PAQs. Their proposed hierarchical classification scheme embraces identifying fore and background sounds where the foregrounded ones are further analysed as disruptive or supportive, and calming or stimulating. Background sounds are not usually assessed in most subjective scales and experiments achieved in validating the proposed hierarchical soundscape perceptual method for classifying locations to be recorded (Sun, De Coensel, *et al.*, 2019; Sun, Filipan, *et al.*, 2019). Field recordings include 360-degree videos and spatial audios (binaural and FOA) for head-mounted reproduction with detailed procedure presented in papers (Sun, Botteldooren and De Coensel, 2018; Sun, De Coensel, *et al.*, 2019). When testing audio reproduction, binaural or FOA did not influence participant's sense of immersion or realism so either method could be used according to authors (Sun, Botteldooren and De Coensel, 2018; Sun, De Coensel, *et al.*, 2019).

No doubt, VR facilitates experiencing places by anyone, reducing time and expenses with travel which can aid in testing urban design with simulations or real-life reproductions. Benefits increase when experts and lay urban agents participate in the design, leading to better solutions (Berger and Bill, 2019), becoming more efficient, and gaining urban policy legitimacy. Thus, VR is considered a powerful tool to support soundscape design and reduce the gap between theory and practice.

Table 4: Summary of reviewed papers from the Urban Soundscapes of the World project.

Reference	Objectives	Methods	Principal Findings
(De Coensel, Sun and Botteldooren, 2017)	To report the perception-based protocol developed for a systematic site selection of the USW project regarding the cities of Montreal and Ghent.	Bottom-up community-driven online survey on locations within the four quadrants of the 2D perceptual dimensions of soundscape. Circulated among universities, websites, and Facebook of the cities. 27 participants from Ghent and 36 from Montreal.	The 2D central affect-based model did not equally represent urban locations, the "lifeless and boring" quadrant (uneventful and unpleasant) had the least consistent result. A hierarchical perceptual classification of urban soundscape locations is presented to better reflect the influence and expectations of the listener when choosing the location.
(Sun, Botteldooren and De Coensel, 2018)	To report an immersive perception experiment of (1) soundscape classification based on activity according to De Coensel *et all, 2017* (2) assess binaural and FOA techniques in terms of the degree of realism and immersion.	11 participants using an Oculus Rift head-mounted display watched 1-minute 360-degree videos of locations from project database (1) 30 videos with FOA audio and answered to questions based on Axelsson *et al*., 2010 and De Coesel *et al*., 2017. (2) 5 videos with FOA and binaural audio track, and answered to questions according to Guastavino *et al*., 2007.	(1) 71% of locations fitted in one of the four soundscape classifications suggested by De Coesel *et al*., 2017 which considers the existence of background soundscapes (2) The differences between soundscape types are larger than the influence of audio reproduction techniques that presented no significant differences.
(Sun, De Coensel, *et al.*, 2019)	To validate the hierarchical soundscape perceptual method for classification De Coensel *et all, 2017* that distinguishes between background and foreground, disruptive and supportive, and calming and stimulating soundscapes.	40 participants watched to 50 different 1-minute stimuli through an HMD and responded verbally to questionnaires regarding: (1) proposed hierarchical classification, memorability of sounds, perceptual dimensions of Axelsson et al., 2010, and quality of immersivion and realism (2) development of prediction models for soundscape classification based on acoustic parameters	(1) questionnaires validated proposed hierarchical soundscape perceptual classification (2) acoustical model classified the soundscapes into the four different categories with 88% accuracy.
(Sun, Filipan, *et al.*, 2019)		Same as above (1) perceptual dimensions of Axelsson et al., 2010 (2) proposed hierarchical classification (3) development of prediction models for soundscape classification based on acoustic and non-acoustic parameters (presence of people and greenness)	(1) proposed hierarchical soundscape classification method demonstrated distinct classes (2) classes can be interpreted by parameters derived from the acoustic environment and scene.

2.4. Electroencephalogram responses to Soundscapes

In this thesis, exploratory observations of how the brain responds to the studied soundscapes will be presented. To better understand these results, basic principles of the electroencephalogram (EEG) technique, a non-invasive procedure to record brain activity, are presented in section 2.4.1, and a brief review of EEG works related to auditory stimuli and emotional responses is introduced in section 2.4.2.

2.4.1 Basic EEG principles relevant to this study

The EEG uses electrodes placed over the head to capture the brain activity happening in the central nervous system. These sensors placed externally at the scalp usually adopt of conductive gel to pick up the neuronal activity. Initially, a neuron component called dendrite transmits electric currents along the neuronal membrane. When many neurons are activated synchronously, a local field potential creates a volume that can be recorded by the EEG scalp sensors. These potentials can be an excitatory postsynaptic potential (EPSP) or an inhibitory postsynaptic potential (IPSP) along the extracellular space of the brain. They are distinguished by the ionic flow direction (arrows) inward by cations (positively charged) and outward by anions (negatively charged) respectively illustrated at figure 17. The way in which these activities are synchronized determines the amplitude and rhythm of the EEG signal (Speckmann and Elger, 2005).

The synchronized field potentials fluctuation generates the brain rhythms or waves (Speckmann and Elger, 2005). There are four basic groups as follow: delta (0.5 to 4Hz), theta (4 to 8Hz), alpha (8 to 13Hz), and beta (>13Hz). Alpha wave resides in the most studied human brain rhythm and can be induced by relaxation and drowsiness normally detected at the posterior brain region (Teplan, 2002).

According to Buzsáki (Buzsáki, 2006), enhanced alpha activity in Westerners brains have become evidence of relaxation. Sharma and Singh demonstrated a significant increase in alpha power when subjects were in eyes-closed relaxed states compared to attention tasks in frontal and occipital regions of the brain (Sharma and Singh, 2015). Furthermore, focused minds with internal attention or deep mental states of meditation can also be associated with the increase of alpha rhythm (Buzsáki, 2006). Given the rise of alpha rhythm in ‘relaxation’ training and meditation states, Buzsáki considers that benefits of such behaviour need further investigations (Buzsáki, 2006).

As EEG reads the brain activity externally, the region which mostly influences these readings is the cerebrum that consists of a complex surface with irregular emminences and furrows distinguised in hemispheres named frontal, parietal, occipital and temporal lobes (Gray, 1918). Figure 18 illustrates these brain lobes and how the EEG electrodes are positioned over these regions.

EEG readings are knowned to be highly contaminated with patient or technical interferences called artefacts or artifacts. They vary from eye movements to external electrical line noise. To clean noisy EEG data, experts can remove from experience, use automated techniques, or both, such as plug-ins to eliminate line noise, and Independent Component Analysis (ICA) for artifact removal (Teplan, 2002). It is vital to discard them so to avoid baises of data analysis and potential results.

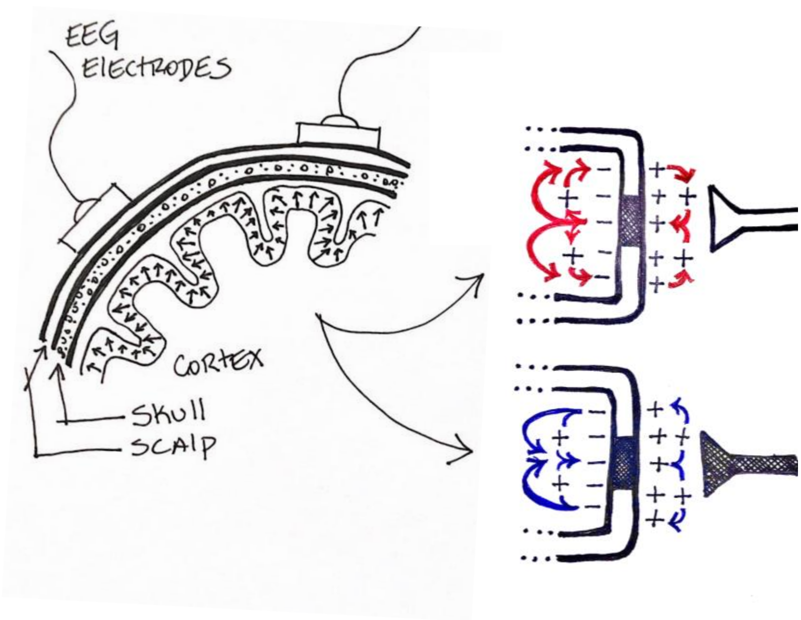


FIGURE 17: ON THE LEFT, SCHEMATIC VIEW OF EEG ELECTRODES, SCALP, SKULL AND CORTEX. ON THE RIGHT, EXCITATORY (TOP) AND INHIBITORY (BOTTOM) BRAIN ACTIVITY AT NEURONAL MEMBRANE (IMAGES ADAPTED FROM (SPECKMANN AND ELGER, 2005)).

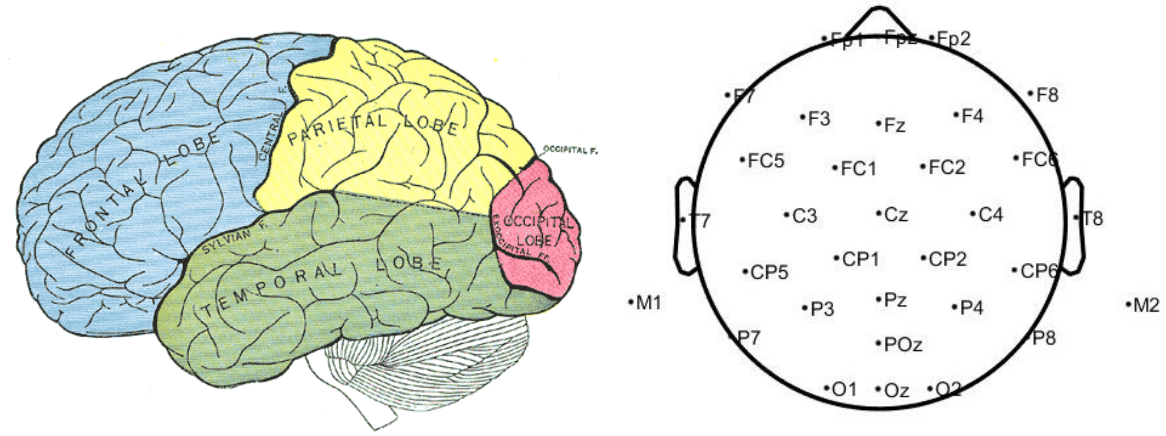


FIGURE 18: BRAIN REGIONS AT LEFT (GRAY, 1918) AND EEG ELECTRODE POSITIONS AT RIGHTSIDE (IMAGEM FROM EEGO™ SPORTS SYSTEM SOFTWARE OF ANTNEURO TECHNOLOGIES).

With many advantages, an open source MATLAB toolbox named EEGLab (Delorme and Makeig, 2004) facilitates EEG researches on the data processing for cleaning and analysis. The software has a friendly interface, large series of YouTube tutorials, mailing list and GitHub database with codes which facilitates the understanding of EEG for non-experts.

Within the EEG research community, there is a lack of universal method to clean and process EEG data. However, some similar steps can be observed in the literature. Here a selection of seven papers were reviewed to better understand procedures and to aid on final adopted procedure. Selection and order presentation of papers used criteria regarding users of EEGLab toolbox (Delorme & Makeig, 2004), more detailed steps in the procedure, and papers correlating EEG to auditory (noise or music), emotional responses of the brain, or both. Table 5 presents a summary of their pre-processing procedures numbered as follows:

1. Makoto's suggested pipeline "Alternative, more automated pipeline using ASR (11/13/2019 updated)". [5]
2. Makoto's suggested pipeline "Further optimizing the preprocessing order? (02/28/2020 updated)". [3]
3. Eqlimi, E., Bockstael, A., De Coensel, B., Schönwiesner, M., Talsma, D., & Botteldooren, D. (2020). EEG correlates of learning from speech presented in environmental noise. Frontiers in Psychology, 1850. (Eqlimi et al., 2020)

[5] Makoto's preprocessing pipeline. (n.d.). Retrieved November 13, 2022, from https://sccn.ucsd.edu/wiki/Makoto's_preprocessing_pipeline

4. Daly, I., Malik, A., Hwang, F., Roesch, E., Weaver, J., Kirke, A., Williams, D., Miranda, E., & Nasuto, S. J. (2014). Neural correlates of emotional responses to music: an EEG study. Neuroscience letters, 573, 52-57.(Daly et al., 2014)
5. Hsu, S. H., Lin, Y., Onton, J., Jung, T. P., & Makeig, S. (2020). Unsupervised learning of brain state dynamics during emotion imagination using high-density EEG. NeuroImage, 249, 118873.(Hsu et al., 2022)
6. Koelstra, S., Muhl, C., Soleymani, M., Lee, J. S., Yazdani, A., Ebrahimi, T., ... & Patras, I. (2012). Deap: A database for emotion analysis; using physiological signals. IEEE transactions on affective computing, 3(1), 18-31.(Koelstra et al., 2012)
7. Shepherd, D., Lodhia, V., & Hautus, M. J. (2019). Electrophysiological indices of amplitude modulated sounds and sensitivity to noise. International Journal of Psychophysiology, 139, 59-67.(Shepherd et al., 2019)

All examined references ran finite impulse response (FIR) filters and re-referenced the EEG data. Filtering varied from high-pass, band-pass to Butterworth filters. To high or low pass filter means to preserve data above or below cut-off frequency while atenuates signals below or above it. Band-pass filters lets frequencies pass within a frequency range. Butterworth filter has a flat pass band with a 20dB decay at each order, that is, second order Butterworth filter has a roll-off from the pass band to the stop band of 40 dB per decade. Most re-referenced to average with exception to references 3 (Eqlimi et al., 2020) and 7 (Shepherd et al., 2019) that re-references the data to an extra electrode positioned at the nose and to electrode Cz at the middle of 10/20 location system, respectively. When re-referencing channels to average, a charge conservation occurs where the positive and negative currents sum to zero.

ICA consists in an analysis where signals are identified by their similarities and separated in groups which in EEG helps identify artifacts. In EEGLab, a library for detecting these independent components, ICLabel plug-in, have classes for Brain, Muscle, Eye, Heart, Line Nosie, Channel Noise, and Other components (Pion-Tonachini, Kreutz-Delgado and Makeig, 2019). Line noise refers to a specific frequency such as 50/60Hz and relates to interference of electrical currents around EEG cap during data collection.

TABLE 5: RESUME OF REVIEWED EEG PRE-PROCESSING PIPELINES FOR DECISION MAKING OF ADOPTED PIPELINE FOR THESIS.

Review	Filter	Line noise	Bad chan removal	Re-reference	Down-sample	ICA	EEGLab	Details: a) Filter type, b) Line noise removal, c) Bad channel removal, d) Re-reference, e) Down-sample, f) ICA, and g) Other procedures.
1	x	x	x	x	x	x	x	a) High-pass filter 1Hz, c) Bad channel removal and interpolate removed channels, f) generate IC labels for rejection, and g) Double precision; import data; [...] import channel info; […]; correct continuous data using Artifact Subspace Reconstruction (ASR) [...]; estimate dipoles (15% RV);[...] epoch IC-rejected data to -1 to 2 s to event onset; and create final Study.
2	x	x	x	x	x	x	x	a) High-pass filter 1Hz, c) Bad channel removal and interpolate removed channels, and g) Double precision; import data; [...] import channel info; [...] correct continuous data with ASR; re-reference to average again; [...]; estimate dipoles (15% RV); and search and estimate symmetrically constrained bilateral dipoles.
3	x	Ø	x	x	x	x	x	a) FIR bandpass filter at 0,5-134Hz, c) Bad channel removal with power spectrum plots, visual inspection, and automatic method (median-based criteria), d) Re-referencing to nose electrode, e) Down-sample to 512Hz FIR low-pass filter, and g) Visual inspection and a shift of all channels with estimated delay of audio latency.
4	x	x	Ø	x	x	x	Ø	a) Band-pass filter at 0.1-45Hz, b) Line noise removal at 50Hz, e) Down sample to 100Hz, and f) ICA de-mixing for reconstruction of line noise EEG data and trials marked for final analysis.
5	x	Ø	x	x	x	Ø	x	a) Digitally filtered above 1Hz, b) Bad channel removal and interpolate removed channels, e) Down sample to 128 channels, and g) Periods broadly distributed, high-amplitude muscle noise and other irregular artifacts were tested for high-kurtosis or low probability activity; and ASR with cut-off parameter 20 to automatically remove large-amplitude artifacts like electrode pops and motion artifacts.
6	x	Ø	Ø	x	x	Ø	x	a) High-pass filter at 2Hz, e) Down sample to 256Hz, and g) Eye artifacts removed with blind source separation technique.
7	x	Ø	x	x	Ø	Ø	Ø	a) 0-phase-shift 3-pole Butterworth filter with corner freq. of 0,1 and 30Hz, and d) Re-reference to mean reference (Cz).
	Abbreviations: * Re-reference to average / freq. = frequencies / ch. = channels / FIR = anti-aliasing finite impulse response / Ø = empty							

Majority of observed studies declared to down-sample when necessary with the exception of reference 7 (Shepherd et al., 2019), but each group proceeded differently some reducing by frequency ranging from 1000 to 100 Hz (Daly *et al.*, 2014), and 2048 to 512 Hz (Eqlimi *et al.*, 2020), while Hsu et al. reduced channels from 134-235 to 128 channels per subject (Hsu *et al.*, 2022)

Only reference 7 (Shepherd et al., 2019) did not use the EEGLab toolbox (Delorme & Makeig, 2004). Two studied authors did not claim to have removed bad channels (Daly et al., 2014; Koelstra et al., 2012), but their removal could be have been achieved by eye inspection. Three observed studies did not state the use of ICA for artifact removal. However, reference 5 (Hsu et al., 2022) described other procedures including tests for high-kurtosis or low probability activity, and Artifact subspace reconstruction (ASR) to remove artifacts. Meanwhile, reference 6 (Koelstra et al., 2012) relied on eye artifact removal with blind source separation technique.

2.4.2 EEG approach to auditory and emotional responses

In this section, a brief review is presented with an emphasis on findings from EEG readings that indicate brain wave behaviour to emotion-related auditory stimuli, similar studies, or both. For this, the right hemisphere and valence hypothesis suppositions regarding emotional processes of the brain was considered relevant and are presented followed by the studied papers.

Right hemisphere hypothesis declares that the right side of the brain is responsible for expressions and processes of emotions. Borod et al. (Borod *et al.*, 1998) demonstrated through facial, prosodic, and lexical emotional perception of right and left damaged, and normal brain subjects that those participants with right brain damage had significantly different task results when compared to left damaged and normal brain individuals.

Valence hypothesis says that positive emotions, such as happiness and joy are processed in the left side of the brain while the negative emotions like sadness and anger activate the right side. Schmidt and Trainor study (Schmidt and Trainor, 2001) revealed left frontal EEG activity when participants were exposed to positive valence musical stimuli, and right frontal EEG activity when listening negative valence musical excerpts.

Most EEG experiment methods record brain activity of participants while they are exposed to a stimulus followed by emotional self-reports (Koelstra *et al.*, 2012; Daly *et al.*, 2014). EEG electrodes set to international 10-20 system, impedance checks, training session and baseline readings are also common across experiments. Tests are divided into sessions with breaks including non-caffeinated, non-alcoholic, or both drinks and snacks, EEG data is pre-processed, and responses are analysed by brain frequency bands.

The work done to create the Database for Emotion Analysis using Physiological signals (DEAP), demonstrated significant correlations among spontaneous emotions evoked by music video clips and EEG brain waves (Koelstra *et al.*, 2012). With 32 participants, authors presented stimuli selection procedure, SAM emotional self-report (valence, arousal, dominance and liking), analysis of EEG readings, correlations of SAM ratings and EEG results, peripheral physiological signals (galvanic skin response, blood pressure, breathing pattern, skin temperature, electromyography, and electrooculogram) and multiple content analysis (MCA, e.g., lighting key, colour variance, video rhythm, and other visual cues), as well as tests on fusion of these modalities. The 40 music video clips were equally distributed among four quadrants created by high or low levels of valence and arousal emotional dimensions (Figure 19). They were high valence and arousal (HAHV), high valence and low arousal (LAHV), low valence and arousal (LALV), and low valence and high arousal (HALV) (Koelstra *et al.*, 2012), that have similarities with the ISO 12913-3:2019 two-dimensional PAQ model (PD ISO 12913-3, 2019).

When comparing emotional reports with EEG data, authors observed strong correlations among the valence scale and all analysed brain frequencies. In specific, the increase in valence demonstrated increase of power for alpha band at occipital cortex, for beta band at right temporal, and a meaningful increase of gamma power at left and specially right temporal area. For the arousal scale, a negative correlation was reported at theta, alpha and gamma frequencies. The liking scores revealed correlates with all frequencies reporting an increase of theta and alpha power at the left frontal-central region. Fusion of self-report, EEG, and peripheral results produced a modest increase in performance, indicating better complementarity between EEG scores and arousal, peripheral and valence, and MCA and liking (Koelstra *et al.*, 2012).

Daly et al. studied neural correlates of emotional responses to a set of 110 music excerpts with 31 participants (Daly *et al.*, 2014). EEG readings with asymmetry and connectivity analysis, emotional ratings (pleasant, energy, sadness, anger, tenderness, happiness, fear, and tension) with principal component analysis (PCA), and demographic details were observed. The PC outcomes contained 75.8% variance with significant correlations to valence in PC1, energy arousal in PC2, and tension arousal in PC3. The valence hypothesis was supported with the beta and gamma asymmetry results correlations to PC1 for valence. Prefrontal and occipital cortices, and right-left hemispheres results modulated with valence and tension of music in a large and sparse range of brain connections. Emphasis was made that all neural responses to musical evoked emotions involved prefrontal cortex activation (Daly *et al.*, 2014).

Graph removed due to copyrighted restrictions.

Figure 19: The mean locations of the stimuli on the arousal-valence plane (AV plane) for the four conditions (LALV, HALV, LAHV, and HAHV). Liking is encoded by color: Dark red is low liking and bright yellow is high liking. Dominance is encoded by symbol size: Small symbols stand for low dominance and big for high dominance (Koelstra *et al.*, 2012) p.25.

In Li and Kang' study (Li and Kang, 2019), four typical soundscape types (forest, beach, shopping street, and high traffic street) were analysed through a combination of physiological measurements (electrocardiography, EEG, electrooculogram, respiratory wave, skin conductance, and body surface temperature) and subjective evaluation (Perceived Restorativeness Soundscape Scale, PRSS, in a total of 19 scales) of 66 participants. Audio and video were presented through headphones and screen in laboratory conditions.

Physiological outcomes and correlations with subjective responses from the 5-minutes audio-visual stimuli were analysed over time at 0.5, 1, 3, and 5 minutes with inflection point and stronger relations among results after one minute of the soundscape immersion. Alpha and beta EEG of nature soundscapes (beach and forest) were higher than noisy sites (shopping street and high traffic street). Alpha scores was more stable while beta wave increased with time (Li and Kang, 2019).

An in-situ EEG soundscape experiment conducted at a mountainous urban park with 12 participants demonstrated alpha (α) and beta (β) differences among audio only (AO) and audio-visual (AV) conditions (Li, Xie and Woodward, 2021). Two locations classified as worst and best audio-visual comfort were rated by subjects and visited for the EEG experiment. EEG-α was lower while EEG-β was greater in the worst location when compared to the best location in both conditions. Authors considered that participants were more stressed at the worst location where traffic noise was dominant. In addition, they reported that their participants had higher restorative brain responses when in the best location with dominant birdsong sounds. EEG-α was higher while EEG-β was lower at AO than the AV condition for both locations indicating a depreciation of restorative state and increase of stress with the inclusion of visual stimuli (Li, Xie and Woodward, 2021).

The studied papers presented are a small illustration of the wide range of EEG studies related to emotions, auditory stimuli, or both. It would be interesting to review EEG responses to noise disturbance during sleep. However, emotional responses to the music and soundscape were prioritized. The results of the emotionally evoked musical stimuli of the studied papers highlighted the EEG responses in beta and gamma frequencies at occipital, frontal, and temporal regions of the brain when exposed to high valence stimuli. Although the studied soundscape works did not include emotional responses, it was relevant to identify natural locations had higher EEG alpha than noisy environments. All in all, EEG alone does not predict emotions (Daly *et al.*, 2015), but studied works contributed to the final discussions.

3. CHAPTER THREE: Experimental methods

Much soundscape research investigate how natural sounds can increase health and quality of life (Annerstedt *et al.*, 2013; Cerwén, Pedersen and Pálsdóttir, 2016; Deng *et al.*, 2020). However, other than just looking for calm natural urban places, would it be possible to investigate other healthy emotional responses to urban soundscapes? The challenge in tackling this question lies in the multidimensional aspects that constitute soundscapes. Differently from environmental noise where actions go towards noise control for reducing numeric goals, soundscapes have semantic values where empirical data are referenced in experiences, expectations, and human responses to the sonic environment. From this perspective, the present investigations considered other pleasant urban sites to assess urban sounds, such as vibrant soundscapes.

The standard ISO 12913-2 (ISO 12913-2, 2018) suggests soundscape assessments to be in situ integrating human perception, characterization of the sonic environment, and context. In the thesis, two elements of context were considered: locations with different urban functions, and the number of people in the place, referred to as “population density” ranked in "empty", "medium", and "busy".

In this chapter, methods of five experiments are presented: 1) a survey to identify study locations, 2) a field questionnaire at Peel Park and Clifford Whitworth Library, 3) a VR pilot experiment with Piccadilly Gardens, 4) the Manchester Soundscape online experiment (MCR 2020), and 5) an EEG-VR soundscape laboratory experiment. The last four experiments involve emotional and soundscape perception questionnaires. In each section, the motivation for the experiment with hypothesis and methods are shown. Nevertheless, the independent variables for experiments three to five are the same: different locations and population density. This allowed to observe the advantages of each method to form an overall view and increase confidence in the findings.

Formal ethical approval for this thesis was granted by the University of Salford committee through document STR1819 -31. An information sheet and consent form were given individually to each participant in each experiment.

3.1 Experiment 1: Survey to identify locations

Soundscape management (Bento Coelho, 2016) is known to be a human centred assessment. Additionally, as observed in a socio-cultural soundscape urban study (Engel, Fels and Pfaffenbach, 2020), residents tend to have a better diagnosis of the sonic environment than those participant that are not familiar with the location. Thus being, Manchester residents were considered to point out more successfully the sites representative of the four quadrants created from the ISO 12913 (PD ISO 12913-3, 2019) PAQs (Vibrant, Calm, Monotonous, and Chaotic).

For this experiment, the hypothesis/research question was:

- Can residents identify distinctly the four types of soundscapes (e.g., Vibrant, Calm, Monotonous, and Chaotic) within Manchester public places?

Partial results of this survey were published in the Salford Postgraduate Annual Researcher Conference 2019 as a poster (Carvalho, William J. Davies and Fazenda, 2019).

3.1.1 Methods

Through a printed and structured survey, several places with the soundscape categories--Exciting, Calm, Chaotic, and Monotonous--in the Manchester (UK) region were identified. The category "Exciting" was used, because when the questionary was developed, the term for Vibrant was still not consolidated into to the part 2 of the ISO 12913 (ISO 12913-2, 2018).

Participants were students and staff among the Acoustic Research Centre and PGR students within the School of Science, Engineering, and Environment of the University of Salford approached randomly. The printed questionnaires were left with respondents to respond at their most convenient time and returned to the researcher when finished. Aimed sample size was 20 participants considering ISO 12913-2 (ISO 12913-2, 2018) minimum number of individuals for assessing each soundscape site in soundwalks.

The questionnaire consisted of four open questions asking for participants suggestions on the public spaces which best characterised the above-listed categories (Appendix 1). The questions had the same structure: "Think about the times when sounds in public spaces have contributed to your sense of […]. Are there places in Manchester that represent them? Could you name them?" Each question had one of the soundscape types, for example, how the sound "[…] contributed to your sense of CALM" or "[…] sense of CHAOTIC" and so on. Given the open question format, some participants included descriptions of indicated places opening the opportunity to better select and reaffirm studied locations.

Once collected, answers written on paper were transcribed to a spreadsheet in which the words with the same meaning were unified. Then, the group of words formed by the four soundscape types composed a separate file. Next, a word cloud was developed for each PAQ using *TagCrowd*, an online free software for building word clouds (https://tagcrowd.com/).

3.2 Experiment 2: Soundscape Field questionnaires at Peel Park and Clifford Whitworth Library

Field questionnaires are a part of the soundwalk procedure applied in soundscape assessments (ISO 12913-2, 2018). Given the top-rated Calm soundscapes from experiment 1 (section 3.1) were Peel Park and Clifford Whitworth Library, a field survey was held at these locations. Data collection gave the opportunity to test the questionnaire efficiency on the soundscape perception (Davies, Bruce and Murphy, 2014) and PANAS emotional (Thompson, 2007) responses to soundscape.

For this experiment, the hypothesis was:

- There are differences among subjective ratings of the soundscape perception and PANAS self-reports between Peel Park and Clifford Whitworth Library.

Partial results of this survey were published in the Salford Postgraduate Annual Researcher Conference 2019 as a poster (Carvalho, William J. Davies and Fazenda, 2019).

3.2.1 Methods

During audio-visual recordings of the selected locations, local experts were approached randomly to participate in a survey concerning how they perceived and felt while experiencing the sonic environment. These participants agreed to share freely their expertise with researcher after a short research explanation supported by an information sheet, and signing the consent form that clarified the ethic procedures with their data. Both locations were within the Peel Park Campus of the University of Salford, Manchester.

The printed questionnaires and pens were given to the respondents while the researcher waited nearby to receive them back when they were finished. The average time to complete the survey was 15 minutes. Aimed sample size was 20 participants considering ISO 12913-2 (ISO 12913-2, 2018) minimum number of individuals for assessing each soundscape site in soundwalks.

Questionnaires in the park were gathered in random places including locations where users were in passive activities and parents were accompanying their children in the playground, while in the library it was possible to systematically collect ten forms per floor. The floors were as follows: ground floor with entrance and study area; “studying out loud” floor where people can talk while studying; and “silent” floor where behaviour should be as quiet as possible.

The questionnaire (Appendix One) was divided into the semantic differential scales for soundscape assessment (Davies, Bruce and Murphy, 2014; Ikhwanuddin *et al.*, 2017) and the Positive and Negative Affect Schedule (PANAS) analysis for emotional traits (Thompson, 2007). The first part consists of 19 contrasting words which described different attributes of the soundscape, while the second portion contains ten words representing feelings; both questionnaires used the Likert scale. Less common in soundscape assessments, PANAS questions were included to collect emotional responses that could complement the other descriptive soundscape attribute questions.

Given data collection was done in two different sites, the Park and library (independent factor with two levels), with two different groups (independent samples) using a Likert scale questionnaire (ordinal variable), a Mann-Whitney U test representing a between subject design to observe group differences was used (Field, 2018). All statistical tests were processed in IBM SPSS (SPSS Statistics, 2016).

3.3 Experiment 3: VR pilot experiment with Piccadilly Gardens

This pilot experiment collected field recordings, prepared the audio-visual stimuli, and applied it in a VR environment so participants could respond to questionnaire. In addition, the ISO’s PAQs (ISO 12913-2, 2018) were tested while the emotional questions were maintained with the PANAS scales (Thompson, 2007).

Here, the hypothesis was:

- There are differences among the subjective ratings of the ISO’s PAQs and PANAS self-reports when experiencing different population densities of Piccadilly Gardens through a VR audio-visual stimuli accessed in an individual use of an HMD.

Notice, partial results of this pilot experiment have been published in the 14th International Postgraduate Research Conference 2019 as a conference paper and received a Dean's Award (Carvalho, Davies and Fazenda, 2019).

3.3.1 Methods

Figure 20 illustrated the workflow for the experiment. Stage 1 has been presented in section 3.1. The following stages are described hereafter.

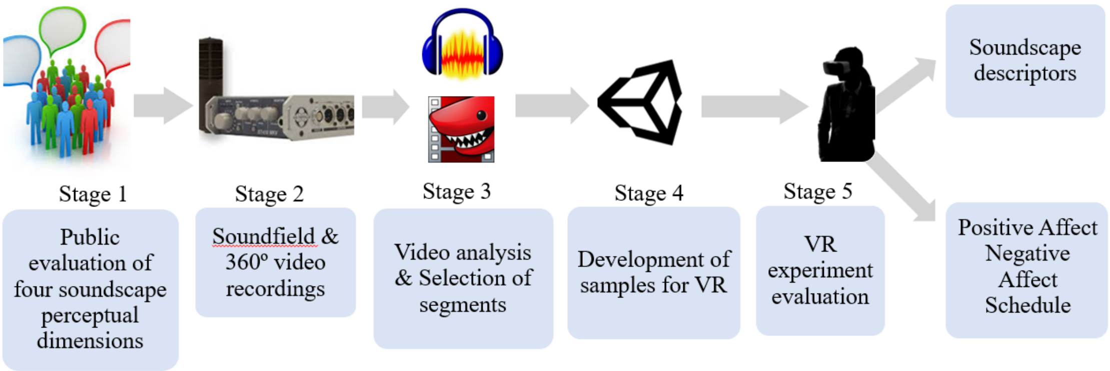


FIGURE 20: WORKFLOW METHODOLOGY FOR PILOT LABORATORY VR EXPERIMENTS.

3.3.1.1 Field recordings

The identified urban areas in section 3.1 were visited and recorded with the Sound field microphone ST250 at 44.1 kHz sampling rate and 24 bits plugged into a ZOOM H6 Handy Recorder for the audios, and Ricoh Theta S camera for the 360° videos. Audio recordings were captured in B-format in four channels with W for omnidirectional, X for front-back, Y for left-right, and Z for up-down. Equipment setup is illustrated in figure 21. The camera was positioned approximately 1.20 m from the ground and the microphone placed close to the ground under the camera to avoid wind sound interference on the recordings (Carvalho, Davies and Fazenda, 2019).

So, to not compromise equipment with exposure to rain, the weather forecast was observed in the website: https://www.accuweather.com/en/gb/manchester. Meanwhile the population density was selected in three weekdays as follows: during an early hour (4 to 6 am) of a weekday for empty, in the afternoon (2 to 4 pm) of a weekday for medium, and the afternoon (2 to 4 pm) at a weekend for busy population density. Once on the arrival to the location, the place chosen to set up the equipment was established according to a representative view which would not interrupt circulation. Recordings were repeated in the same position for every population density condition (Carvalho, Davies and Fazenda, 2019).

Given ethical approval restrictions, a sign warning “Filming in progress” was displayed with the equipment for public awareness before recordings, and the video recording resolution setting was low to reduce face recognition (Aletta *et al.*, 2016). Next, with a previous calibrated sound pressure level meter, type BSWA 308, an one-minute sample of A-weighted equivalent continuous sound pressure ($L_{Aeq,60}$) was registered to adjust sound levels from field to laboratory reproductions at the same height of the field microphone. Then, audio tests were done so to adjust gain level. Subsequently, the audio and camera were initiated, and the researcher clapped two to three times in front of the equipment for future audio-visual alignment. The recordings lasted approximately ten to twelve minutes. While recording, the researcher would either hide or blend in the environment so to not stand out in the scene. Many of these procedures are also done by the Urban Soundscapes of the World project group (Sun, De Coensel, *et al.*, 2019). Further details available at check lists for field recordings in Appendix Two (Carvalho, Davies and Fazenda, 2019).

FIGURE 21: EQUIPMENT SETUP AT PICCADILLY GARDENS WITH RICOH THETA CAMERA (1), SOUND FIELD MICROPHONE ST250 (2), AND ZOOM H6 HANDY RECORDER (3).

3.3.1.2 Audio & video editing

With recordings in hand, the 360° videos were transformed into equirectangular format through the Ricoh Theta S camera software to be analysed on a PC. Then, the audio and video were synchronized in time using the free version of Lightworks x64 (14.5.0.0 version) software.

For stimuli selections, recordings were analysed in sections of 30 seconds for foreground and background sounds representing local *characters* (Bento Coelho, 2016), *soundmarks*, and representative sound signals (Schafer, 1977) of each location. Stimuli duration followed previous work (Berglund and Nilsson, 2006) with the length of 30 seconds. For the crowded conditions, a people counting criteria was used similar to Ballesteros et al. work (Ballesteros et al., 2014), where they measured people by counting the number of individuals from a photo. To support this procedure, a short experiment with participants counting the number of people in the Piccadilly Gardens and Market Street medium and busy conditions was done as illustrated in figure 22. Eight participants came to the listening booth, put on the HTC VIVE VR system, watched each of the four videos in random order and reported to the researcher the estimate number of people identified in the 30 seconds footage.

FIGURE 22: INITIAL TEST FOR PEOPLE COUNTING IN THE SCENE.

With final selected audio and visual stimuli size ready, a fade-in and fade-out of half a second (.15 second) was inserted to sample using Audacity for audio and Lightworks for video.

3.3.1.3 VR preparation

The audio and video were imported separately into Unity 3D for adjusting head and audio head-tracking, that is, for the video and audio to move together in the virtual environment. The plugins installed for these procedures were VIVE port SDK (VR software development kit used in this experiment), Steam Audio, Steam VR, and Steam VR Ambisonic. Figure 23 presents final equipment distribution.

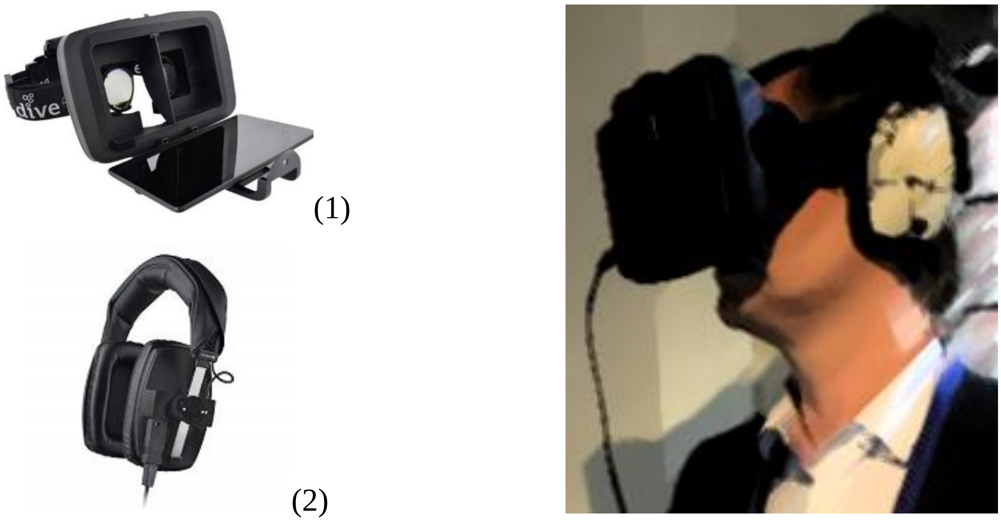


FIGURE 23: SHIELD TABLET K1 WITH DIVE HEAD-MOUNTED DEVICE (1) PLUGGED TO A HEADSET BEYER DYNAMIC BT100 (2) USED IN THE PILOT TEST.

First, a Sphere was created to insert the 3D video. Video was inserted, flipped to “normal” for camera visualization, switched horizontally to correct direction, and resized to enhance view. To make the audio-visual stimuli rotate, the original camera was replaced with a Camera Rig from Steam VR prefabs which was applied over the video Sphere.

For audio head tracking, the audio source installed had the Steam Audio Ambisonic added to audio source with Spatial Blend to one (1, 3D) and Ambisonic selected. Additionally, the Steam Audio Listener and Steam VR Ears plugin were applied to the CameraRig. At this point, it is important to certify that only one Audio Listener is turned on.

Also, for audio and video to run in Unity, the “Scene” and “Built and Run” of the Steam VR in the Built Settings were applied. Furthermore, “Project Settings” were set with Steam Audio Ambisonic Decoder and Steam Audio Spatializer to guarantee audio playback. The Ambisonic decoder plugin performs a filter that changes the ambisonic audio into binaural.

Finally, stimuli were sent to the VR HMD. For the experimental project to run in the used VR HMD, settings in the XR Plug-in Management selected the Open VR Loader, Window Mix Reality, and Mock HMD. Finally, each soundscape condition was exported as a file to run in a SHIELD Tablet K1 which was adapted to a Dive head-mounted device while the audio was played back through a Beyer Dynamic BT100 headset.

3.3.1.4 Other procedures

Participants were individuals attending in the IMMERSE event on July 10th 2019 at the University of Salford, Manchester, UK. They were approached randomly on coffee breaks and asked to come to a separate room to do the experiment. Each respondent individually watched pseudo-randomly to three audio-visual samples with different population densities (empty, medium, and busy) of the Piccadilly Gardens. While executing the experiment, participants were encouraged to stand up and look around. After each video, the subjects answered two short questionnaires on a sheet of paper. In the first questionnaire, they rated in a 11-point Likert scale the samples in the paired PAQs (Pleasant to Unpleasant, Eventful to Uneventful, Vibrant to Monotonous, and Calm to Chaotic) according to the ISO 12913-2:2018 (ISO 12913-2, 2018). For the second survey, the PANAS (Positive Affect Negative Affect Schedule) model was used to assess emotional states in a small version of ten emotional states (upset, hostile, alert, ashamed, inspired, nervous, determined, attentive, afraid, and active) (Thompson, 2007). Subjects were asked to respond to what extent they would generally feel the presented feelings in a 5-point scale of “never” to “always”. Full questionnaire is presented in Appendix Two (Carvalho, Davies and Fazenda, 2019).

Given all participants rated all samples and there were more than two conditions as independent variables, Friedman’s ANOVA was used to assess the significance of the crowd density as an independent variable (Field, 2018). Separate tests were done to determine if there were significant differences among the three conditions for each of the four PAQ axes and ten emotional states ratings, that is 14 individual tests. Once identified the significant difference among the three conditions, results were followed up with the Wilcoxon test for the effect size (Carvalho, Davies and Fazenda, 2019). All statistical tests were processed in IBM SPSS (SPSS Statistics, 2016).

3.4 Experiment 4: The Manchester Soundscape online experiment (MCR 2020)

Given the difficulties of face-to-face experiments during the pandemic, some researchers adapted their methodology to an online approach as done here. Additionally, the social media advertisement and engagement facilitated an international access of participants to the study resulting in a high number of respondents and range of nationalities. Furthermore, the four locations identified in Experiment 1 (section 3.1) were recorded, edited, and launched in the YouTube platform for the experimental execution. The ISO's PAQs (ISO 12913-2, 2018) was maintained, and the emotional assessments changed to the Self-Assessment-Manikins (SAM) emotional scale (Bradley and Lang, 1994).

In this experiment, the hypotheses were:

- There are differences among the subjective ratings of the ISO's PAQs and SAM emotional scales when experiencing different population densities (empty, medium, and busy) in different locations of Manchester (Piccadilly Gardens, Market Street, a bus stop, and Peel Park) through a VR reproduction online; and
- There are differences among the subjective ratings of the ISO's PAQs and SAM emotional scales when experiencing different population densities (empty, medium, and busy) in different locations of Manchester (Piccadilly Gardens, Market Street, a bus stop, and Peel Park) through a VR reproduction online between Brazilian and Non-Brazilian participants.

Notice, partial results of this experiment have been published in the Urban Sound Symposium 2021 as a poster (Carvalho, Davies and Fazenda, 2021b) and at INTERNOISE 2022 as a conference paper (Carvalho, Davies and Fazenda, 2022).

3.4.1 Methods

Figure 24 illustrates the workflow for the experiment. Field recordings used the same equipment and procedures as described in section 3.3.2.1.

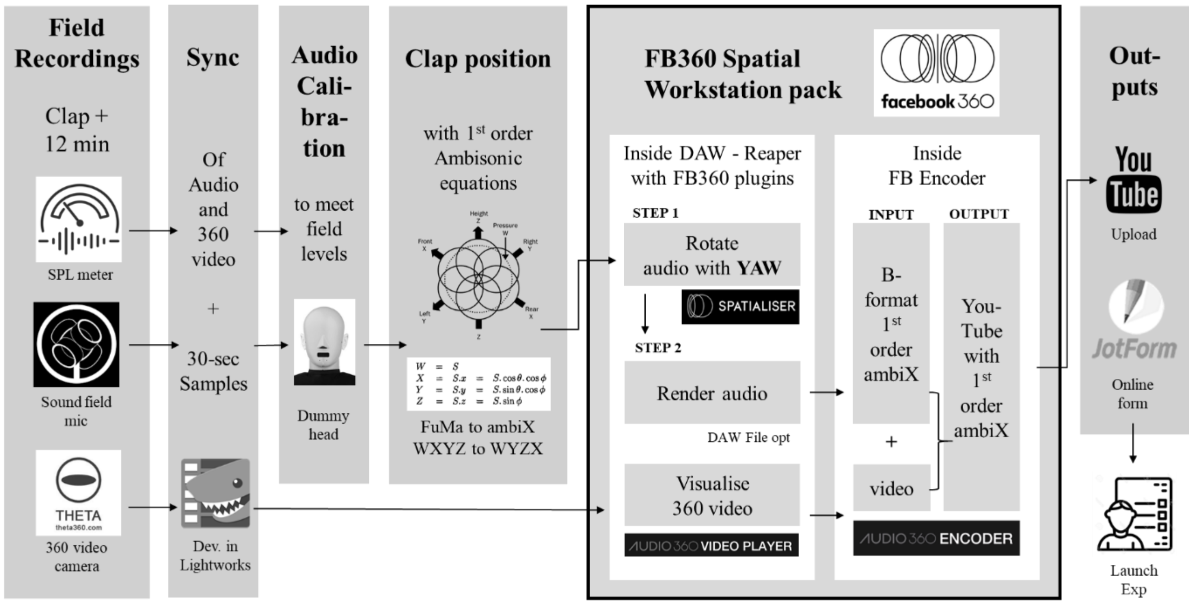


FIGURE 24: PIPELINE OF AUDIO-VISUAL PREPARATION FOR LAUNCHING THE EXPERIMENT.

3.4.1.1 Audio & video editing

Given Piccadilly Gardens samples were used in this experiment, sample selection method is the same, but here also applied to Market Street, a bus stop in front of the University of Salford, and Peel Park locations. Nevertheless, some improvements took place, such as audio calibration with field $L_{Aeq,60}$ in dB(A) and angle alignment among video and audio. Furthermore, the Facebook 360 Spatial Workstation[6] was used to convert the spatial audio from FuMa (WXYZ) to ambiX (WYXZ) (Audio 360 Encoder), rotate and align the audio with the video (Spatialiser), visualize the video (Audio 360 Video Player) and encode the audio with the video (Audio 360 Encoder).

Initially, the time of the clap in each recording was identified. The audio and video were then synchronized in time using the free version of Lightworks x64 (14.5.0.0 version) software. Then, sample selection was done as described in session 3.3.2.2. Following, audio files were calibrated to the field sound levels using a pre-calibrated High-frequency Head and Torso Simulator (HATS) with a PULSE software, both from Brüel & Kjær. Figure 25 at left represents internal microphones of the HAT for the right and left ear calibrated to 93.5 dB at 1 kHz before measurements. Figure 25 at right illustrates stimuli calibration with Beyer

[6] https://facebookincubator.github.io/facebook-360-spatial-workstation/

Dynamic BT100 headset headphones over the HATS. For the audio reproduction, signal came from a laptop driven by an M-audio Mobile Pre sound card and sent to the headphones. Once with calibrated audio files, the first order ambisonic signals were converted from FuMa (WXYZ) to ambiX (WYXZ) using the Audio 360 Encoder from the Facebook 360 Spatial Workstation.

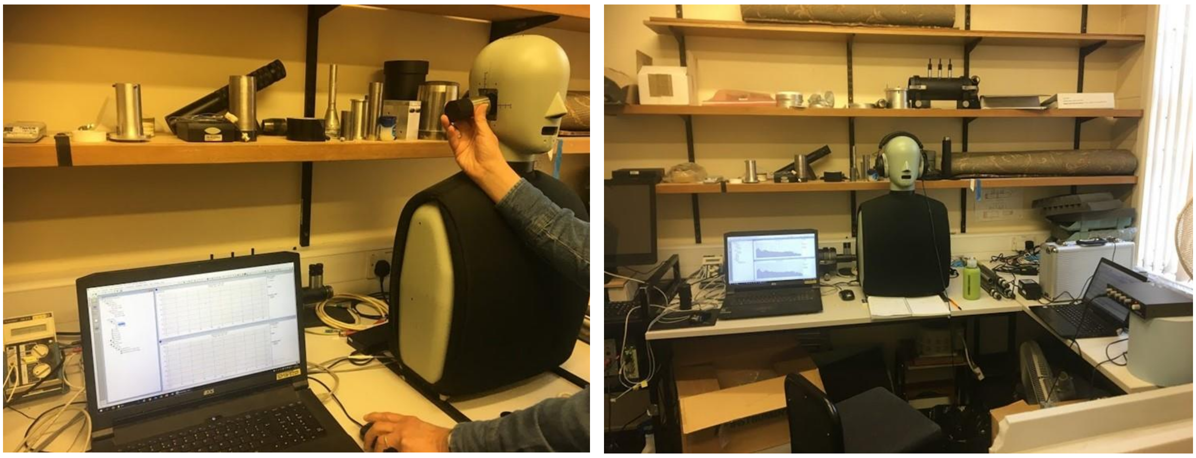


FIGURE 25: HATS INTERNAL MICROPHONE CALIBRATION ON THE LEFT, AND SETUP FOR SAMPLE CALIBRATION ON THE RIGHT.

To align the audio and video to the same direction, the azimuth angle of the audio signal X (front-back) was extracted from the initial recorded clap. This procedure became relevant because audio and video were recorded separately, and direction was not accounted for during field recordings. To acquire the azimuth angle θ Equation 2 (section 2.3.3) was used calculated with a MATLAB script (Appendix three for script). With the azimuth angle θ, the FB360 Spatializer plug-in was used to rotate the audio in the digital audio workstation (DAW). At this point, it was possible to observe simultaneously the video through the Audio 360 Video Player plug-in. The DAW system used was REAPER. Afterwards, the audio was rendered through the DAW as a four-channel audio file.

To certify that the audio alignment in videos were correct, a small test was run using two free audio files. Audio-visual files were edited in a known location, rendered, encoded, and listened to. The audios were a constant drum beat and an ensemble of trumpets selected from the freesound.org website. The investigation was to observe if the signal would stay in the designed location and head-tracking would be corresponded when moving in the VR environment. For example, the drums would be positioned to the right side of the video while the trumpets would be to the left. These video files were rendered and upload to YouTube so the audio locations could be observed if they were in the right places while navigating in the video.

With audio-visual stimuli ready, a fade-in and fade-out of half a second (.15 second) was inserted to samples using Audacity for audio and Lightworks for video. Additionally, a phrase was inserted at the end of the video so participants would continue the experiment. The message was “Please, go back to respond the questionnaire” both in English and in Portuguese at the bottom part and around the 360 videos. Finally, the Audio 360 Encoder encoded the audio and video files to a single file consisting of the monoscopic video and a head-tracked binaural audio for upload to the YouTube platform. These rendered 3D audio videos and other videos related to this experiment are accessible through the link on the footnote[7].

3.4.1.2 Final preparations for launching online

With the uploaded videos, a web-based questionnaire was built in JotForm platform, an online form company. Videos and questionnaires were tested in different browsers and smartphones, to obtain the best possible performance to all participants. Advertisement counted with a short video teaser done by the researcher and different flyers posted in social media, such as Facebook, Instagram, Tweeter, and LinkedIn. Participants were individuals on the mailing list of the Acoustic Research Centre of Salford representing people with connections to the University of Salford, above 18 years old, and recruited over the internet on social networks as listed above. Once people made contact, an email was sent with links and instructions. They participated voluntarily. Recommendations were to use headphones and, when using mobile phone, to turn into landscape for better performance. According to individual online access, participants were orientated differently to access videos, depending if they used IPhones, desktop computers, laptops, or Androids. Additionally, the questionnaire was translated into Portuguese.

The questionnaire began with a consent form. Then, general questions were asked about demographic information (gender, age, nationality, and residency), auditory health (evidence of hearing loss and tinnitus), and digital settings (what audio and video system they used during the experiment). The experimental questions were responded to after watching each

[7] https://youtube.com/playlist?list=PLrHLMWWyWmTchlVVB5MM7s4jmJx54bR4a

video and are presented in Appendix One. Questions were the ISO's PAQs paired into four groups (ISO 12913-2, 2018) and the SAM emotional states (Bradley and Lang, 1994) where each word was accompanied by three synonyms. For the PAQs, the question was phrased as "Please, slide to the word that best describes the sounds you just heard. To the left (-) is NEGATIVE, and to the right (+) is POSITIVE." Scores ranged from -10 to +10 for negative to positive semantic values of terms through a slider. Even though part 2 of the soundscape ISO 12913-2:2018 (ISO 12913-2, 2018) determines that the opposite of pleasant is annoying, we preferred to use the term "unpleasant" to establish a more contrasting taxonomy given that words were in pairs. For the SAM scale, the question was phrased as "Please, slide to the figure that best describes how you FEEL regarding the sounds you just heard." A Likert scale of 5-points where the middle represented neutral and the poles were the extremes for each term. That is, unhappy to happy for valence, relaxed to excited for arousal, and controlled to controlling for dominance. Participants were divided into two groups, to reduce the experimental time for the online experiment: one with the bus stop and Peel Park, and the other with Market Street and Piccadilly Gardens (Figure 26).

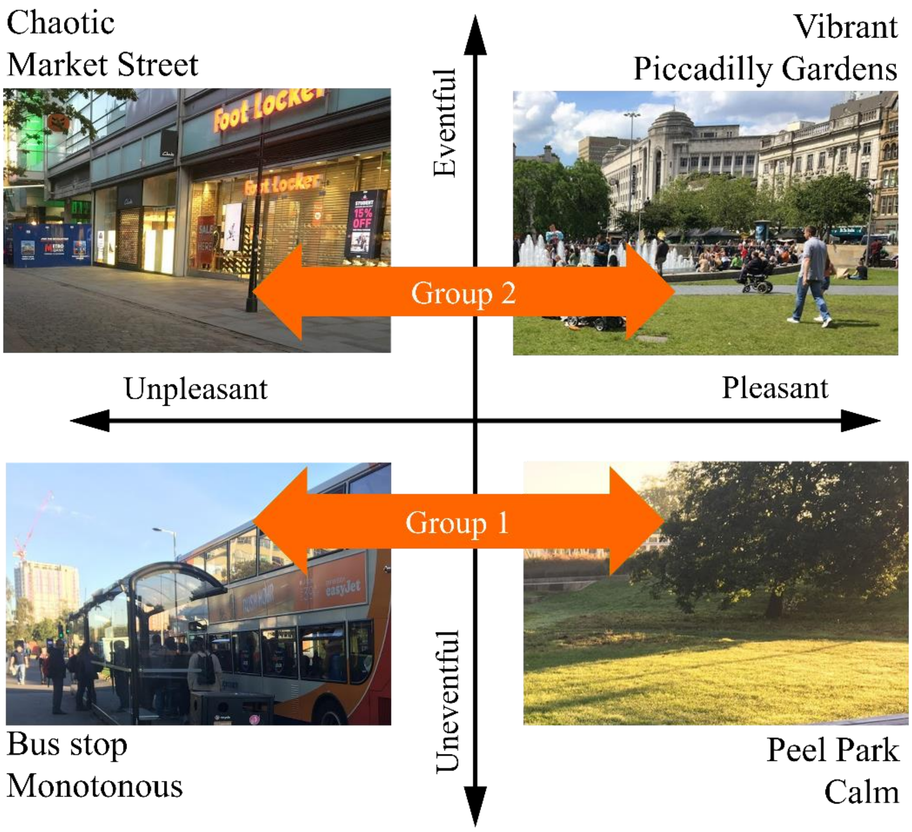


FIGURE 26: THE LOCATIONS PLOTTED OVER THE TWO-DIMENSIONAL SOUNDSCAPE COORDINATES SEPARATED BY GROUPS 1 AND 2.

Given the non-normality of data, all statistical analysis of the self-reports were non-parametric. Results were statistically tested for group differences among groups 1 and 2 for the soundscape attributes and emotional traits responses (dependent variables) between the different locations and population densities (independent variables) through a within subject design using the Friedman's test. Additionally, differences among Brazilian and non-Brazilian participants were observed through a between subject design using the Mann-Whitney U test. All statistical tests were processed in IBM SPSS (SPSS Statistics, 2016).

3.5 Experiment 5: VR & EEG laboratory experiment

Given possible biases of self-report, this experiment pursued a physiological and objective way to observe emotional responses to urban soundscapes in addition to the questionnaire. At the planning stage, the researcher was motivated by colleagues and intrigued with EEG research leading to follow this technique of observing brain activity in an exploratory fashion. Thus, it resulted in a VR and EEG laboratory experiment to investigate urban soundscapes with improvements and adaptations gained from the previous experiments.

Due to COVID, the number of people using public transport reduced during the new 2020 field recordings, becoming difficult to obtain the experimental busy condition that led to the withdrawal of the bus stop as a studied location. Additionally, the medium population density condition was eliminated to reduce the long sessions of the EEG. In short, a total of six conditions were maintained, that being three locations (Piccadilly Gardens, Market Street, and Peel Park) in two population densities (empty and busy). Regarding the self-reports, the ISO's PAQs (ISO 12913-2, 2018) were maintained, and the emotional assessment was tested with the Plutchik's wheel of emotions (Plutchik, 1982).

For this final experiment, the hypotheses were:

- There are differences among the subjective ratings of the ISO's PAQs when experiencing different population densities (empty and busy) in different locations (Plaza, Street, and Park) through an HMD VR reproduction in laboratory environment;
- There are differences in selecting the categories of the Plutchik's wheel of emotions when experiencing different population densities (empty and busy) in different

locations (Plaza, Street, and Park) through an HMD VR reproduction in laboratory environment; and

- There are differences among the power spectrum of alpha brain wave at EEG sensors when experiencing different population densities (empty and busy) in different locations (Plaza, Street, and Park) through an HMD VR reproduction in laboratory environment.

Notice, proposal outline for this experiment has been published in a EEGLab Workshop 2021 as a poster (Carvalho, Davies and Fazenda, 2021a), resulting in an opportunity to discuss the plans for the final experiment with experts in EEG area. A network was created, and future publications are in plan to occur with Dr. Makoto, one of the EEGLab developers (MATLAB plugin for processing EEG data).

3.5.1 Methods

The methods for this experiment evolved from previous experiments with the questionnaires, field recordings, and VR preparations for experimental reproduction. Methods and techniques for the EEG preparation, data collection, and pre-processing data for data analysis were new and are presented in subsection 3.5.1.4 and 3.5.1.5.

3.5.1.1 Field recordings

Locations for field recordings were maintained as initial experiment (session 3.1), however complaints of low resolution of previous video footage with Ricoh Theta camera led to new recordings with a better resolution camera. The Insta 360 Pro2 VR camera was used which records from 4k 30fps to 8k 60fps. It has six lenses which record simultaneously with the option of spatial audio. Pre-recordings procedures are necessary, such as formatting the SD card, testing card speed, and two types of calibrations, stitching and gyro, for adapting the six lenses to the number of movements in site. Both calibrations must be done in site to adapt to scenery.

Equipment used were an Insta 360 Pro2 360° video camera, a sound field microphone ST250 recording at 44.1 kHz sampling rate plugged into an Edirol R44 Recorder, and the sound pressure level meter, type BSWA 308, for the A-weighted equivalent continuous sound pressure ($L_{Aeq,60}$) recording. Procedure for recordings was the same as previously described in session 3.3.2.1 except for equipment location and the new camera. The camera was positioned with a robust tripod that reaches 1.70 m and the microphone placed right below the camera at 1.5 m from the ground as illustrated in figure 27.

(1)

(2)

(3)

FIGURE 27: EQUIPMENT SETUP AT MARKET STREET WITH INSTA 360 PRO2 VR CAMERA (1), SOUND FIELD MICROPHONE ST250 (2), AND EDIROL R44 RECORDER (3).

3.5.1.2 Audio & video editing

Considering that new footage was required to enhance video resolution due to participants suggestions, and the experiment included EEG readings, new audio-visual selections and sample duration were determined. Also, other stimuli characterization was applied.

The first step was to determine the duration of stimuli. Audio sample sizes for EEG experiments vary from 210 milliseconds for noise sensitivity (Kliuchko *et al.*, 2016) to two minutes for music videos (Koelstra *et al.*, 2010). However, due to the many sound sources included in the foreground and background of soundscapes, milliseconds could not be a representative size. Also, minutes is considered too long given EEG scalp reads brain activities in 0.5–130 milliseconds. Moreover, EEG researchers (Julie A. Onton and Johanna Wagner) suggested the original 10 stimuli repeats would be increased to at least 40 because of possible EEG data rejection during data cleaning which diminishes statistical power. These considerations were discussed during the 2021 EEGLab Workshop over the published poster regarding the experimental proposal outline of this experiment (Carvalho, Davies and Fazenda, 2021a). Finally, stimuli duration was established at 8 seconds, supported by another soundscape study using fMIR (Irwin *et al.*, 2011), and desired reduced stimuli exposure in EEG readings.

Next, a visual criterion took place followed by the audio procedure to select the experimental audio-visual stimuli. Some parts of the video were removed, when the researcher appeared, and any other activity that passed closer than two meters to the camera. The later criterion guarantees that future stitching of 360° videos is smooth and do not chop image transition which interferes in visual quality.

The busy conditions were identified as previously (Ballesteros et al., 2014), through counting the number of individuals from a frame. Then, the cleared footage was divided in three equidistant time parts (middle of the first half, middle, and middle of the second half), exported the images, and the number of people was counted for each photo. The most populated frame was selected for the busy condition and became the reference for the medium condition (half the number of people from the busiest scene). The empty condition was the most void possible footage. Videos were stitched in the Insta360 Pro2 software and due to computer limitations rendered to 4K resolution (3840x1920 pixels). From this point forward, all video editing for this experiment were developed in Premiere Pro.

For validating the researcher’s people count, two small surveys with ten persons each were done with the final selection of samples. Participants were asked to estimate how many individuals they believed were in the picture, through an online survey done in Google Forms with an image for each of the nine different conditions. From a group of ten participants, an average was done with the estimated number, then a frequency was calculated from the mean for the ten participants, where the value for the busy condition was considered as 100% while the medium and empty were divided by the mean of the busy condition.

After visual analysis was done, the time synchronisation of the video and audio took place as described in session 3.4.2.2. Next, a descriptive analysis of the sound events, foreground and background, was done of the region so to select fragments rich in soundscape diversity (Liu *et al.*, 2014), *identity* (Siebein, 2013), *character* (Bento Coelho, 2016), *soundmarks*, representative sound signals (Schafer, 1977), while maintaining original number of people and controlling some soundscape factors. For the bird call identification, the BirdNET: The Easiest Way To Identify Birds By Sound online was accessed through the https://birdnet.cornell.edu/ website.

Then, an index for soundscape diversity of selected stimuli was calculated with the Simpson's Diversity Index (SDI) according to the Equation 5, and based on previous work applied to soundscape diversity (Liu *et al.*, 2014).

$$\mathrm{SDI} = 1 - \sum_{i=1}^{S} \left(\frac{n}{N}\right)^2 \qquad (5)$$

where *n* is equal to the total number of perceived occurrences of a specific sound source (*i*), and *N* refers to all sound sources (*S*) in the soundscape sample. The index varies from zero to one with maximum values representing a diverse soundscape.

Afterwards, the audio calibration of audio stimuli and FOA calculus were done as described in section 3.4.2.2, but here the Facebook 360 Spatial Workstation was not used. Instead, the O3A Core Rotation and Visualiser plug-ins within REAPER was used to rotate the audio. With angle and plug-in, it was visually possible to identify where the clap was located.

Also, a white balance was applied to all videos using the white colour from the "Filming in Progress" poster placed over the tripod. Finally, audio-visual files had a fade in and fade out of half a second done in Premiere Pro (cut at 00:15 and 07:15) and videos were exported as media in H.264 format and VR Monoscopic Match Source Ambisonic pre-set in Premier Pro to be edited in Unity 3D later.

Initial VR stimuli preparation in Unity was done as described in section 3.3.2.3. Additionally, given the experiment would have many repeats of the same stimuli due to EEG readings demands, an interval between samples was necessary to determine. From literature, this gap can vary from 5 seconds (Koelstra *et al.*, 2010, 2012), 10 seconds (Juhari, Nagarajan and Yaacob, 2009; Frescura *et al.*, 2021), and 15 seconds (Lin *et al.*, 2010). In these studies, the gap represents around half the time of the stimuli. Considering that the current stimuli was established at 8 seconds, final gap time was chosen to be 5 seconds. Also, most experiments in

EEG collect an initial baseline with a fixation cross in the beginning of the experiment. To follow procedure, a baseline of 2 minutes with a fixing cross was collected in the beginning of the EEG readings.

Moreover, stimuli were randomized, and synchronization of EEG readings with stimuli order reproduction was done. A randomization code was created and inserted in Unity where the number of repeats and gap between stimuli was possible to edit (Appendix Three). For the EEG synchronization, a hardware was installed to the PC that would send stimuli to the VR device that participant used. Once installed, hardware was connected with cable to EEG system. The system marked in real time the EEG data every time the stimuli was projected to participants.

3.5.1.3 Final preparations for experiment

Participants were individuals on the mailing list of the Acoustic Research Centre of Salford (ARC) representing people with connections to the University of Salford, and above 18 years old. They received a compensation of £25 Amazon voucher for 2h30 of experiment. Tests were done inside the student semi-anechoic chamber of the university. Equipment placed inside the chamber were a PC, Laptop, the EEG eego™ sports system from AntNeuro Technologies, a Beyerdynamic DT 1990 Pro headphone plugged to the VIVE HMD system, two small tables, two comfortable chairs, and two supporting stools (Figure 28). Before arriving, an email with a detailed COVID Free protocol was sent (Appendix Four).

FIGURE 28: EQUIPMENT ARRANGEMENT IN THE SEMI-ANECHOIC CHAMBER FOR EXPERIMENT.

The experiment workflow was separated in eight steps as illustrated in figure 29. First, the experiment was presented through information sheet and two posters, one as the above-mentioned workflow and the other containing the research application (Figure 30) outside of the chamber.

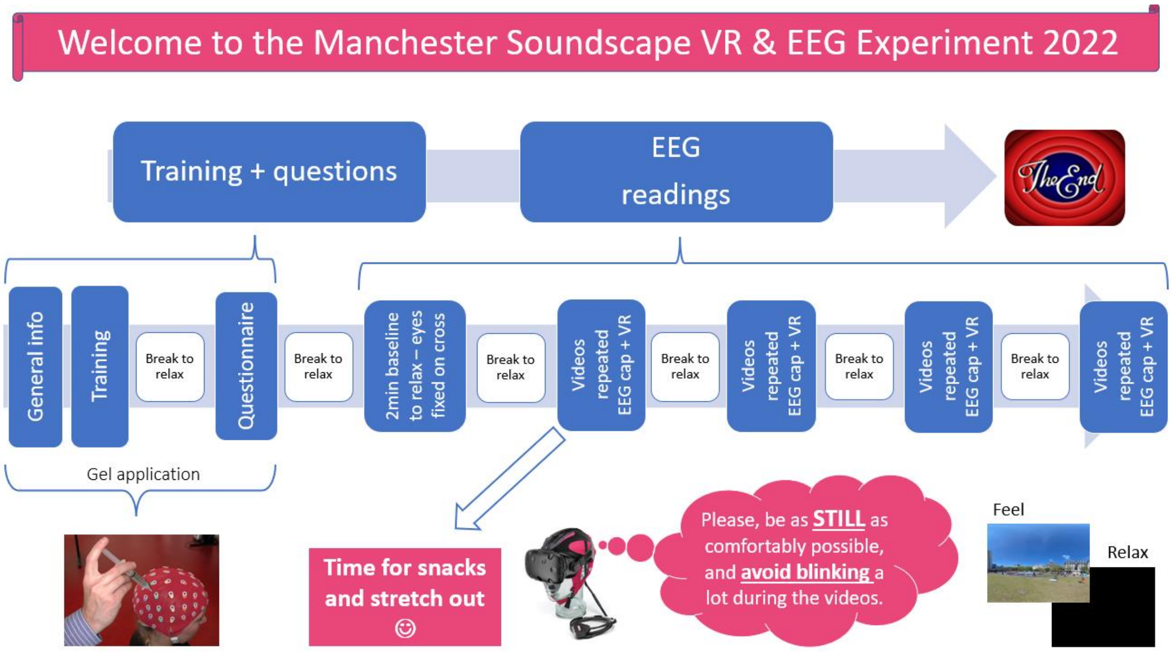


FIGURE 29: POSTER PRESENTED TO PARTICIPANTS OUTSIDE THE CHAMBER BEFORE EXPERIMENT.

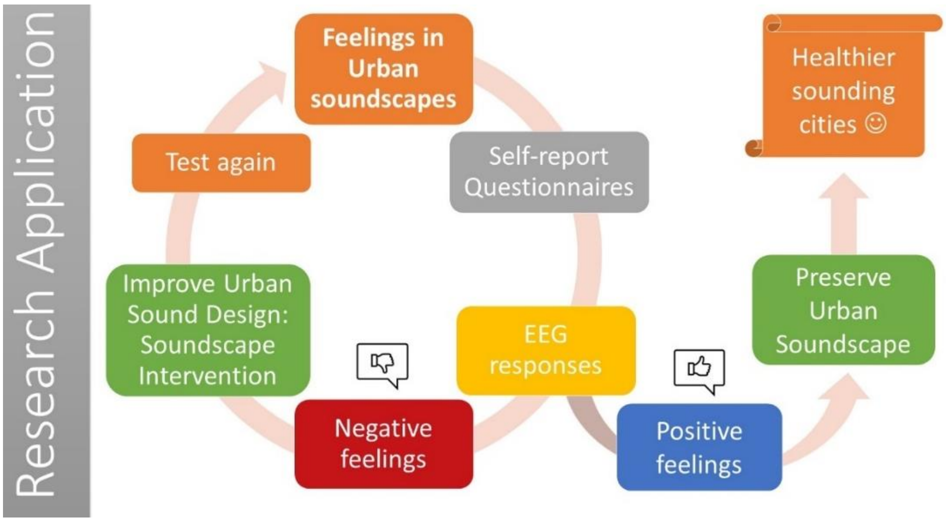


FIGURE 30: POSTER PRESENTED AS RESEARCH APPLICATION TO PARTICIPANTS DURING EXPERIMENT.

Then, researcher measured participant head's diameter so to select the correspondent EEG cap. Once experimental procedure was clarified, participants were invited to enter and sit in the center of the chamber where their head was measured again so to position the cap in the Cz electrode. While they watched the pre-recorded presentation, answered general information questionnaire, and did the training session, researcher applied EEG gel in each 32 electrodes

(Fig. 31a). For training and self-report sessions, participants were asked to watch the audio-visual stimuli in the VR headset (Fig. 31b) as many times as they wished so to answer the subjective questions on the laptop (Fig. 31c).

FIGURE 31: A) GEL APPLICATION OF 32 ELECTRODES ON THE LEFT, B) PARTICIPANT WATCHING VR AUDIO-VISUAL STIMULI IN THE MIDDLE, AND C) PARTICIPANT RESPONDING THE SUBJECTIVE QUESTIONS AT THE LAPTOP ON THE RIGHT.

The questionnaire began with a consent form. The general questions were demographic information (gender, age, and nationality), auditory health (evidence of hearing loss and tinnitus), number of languages spoken, education level, and acoustic or music background (no, a little, moderate, and expert level). The experimental questions were formulated: “To what extent do you think the sound environment you just experienced was... 0 = Not at all, 50 = Neutral, and 100 = Extremely”. The PAQs were presented individually and rated through a slider. The soundscape attributes tested were Pleasant, Calm, Uneventful, Monotonous, Annoying, Chaotic, Eventful, and Vibrant PAQs. Also, they were asked to select an emotion from the 32 emotional options that best represented what they felt regarding the scenario from the Plutchick’s wheel of emotions. Question was phrased as follows: “According to the image, how does the sound environment you just experienced make you feel?” Full experimental self-report is presented in Appendix One.

When EEG gel application was finished, electrode impedance was checked to stay below 10kΩ for the quality of connection between electrode and scalp. Time duration to obtain low values varied among participants from 20 to 40 minutes. With stable values, the EEG recordings began. In accordance with the International 10/20 system, the following 32 EEG channels were acquired: Fp1, Fpz, Fp2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC5, T7, C3, Cz, C4, T8, M1, CP5, CP1, CP2, CP6, M2, P7, P3, Pz, P4, P8, POz, O1, Oz, and O2 (Figure 32). Sampling rate was 500 Hz. To avoid eye and movement artefacts in EEG data, participants were asked to keep "still as comfortably possible" during the stimuli presentation. Data was monitored through *eego* software in a separate tablet. For data acquisition, EEG recording started some seconds before launching the audio-visual stimuli.

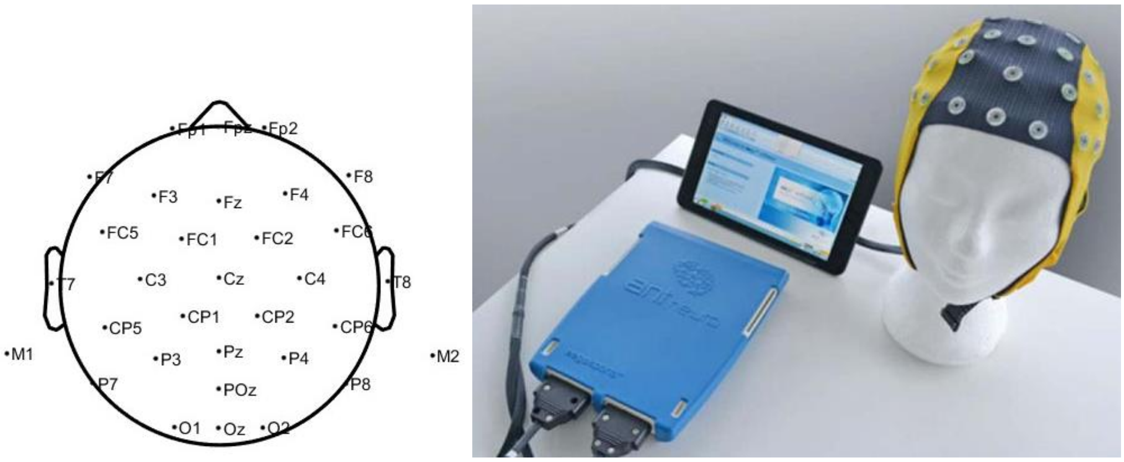


FIGURE 32: THE INTERNATIONAL 10/20 SYSTEM FOR 32 EEG CHANNEL POSITIONS ON THE LEFT, AND THE EEG EEGO™ SPORTS SYSTEM USED IN EXPERIMENT ON THE RIGHT.

The EEG recordings consisted of five runs with the first run of a 2-minute baseline where participants rested while looking into a silent fixation cross using the VR HMD and headphones. The four 10-minutes experimental EEG reading sessions contained eight trials of each condition, that is, each of the six stimuli was presented eight times in each session. Before and during breaks, special care was taken to explain to participants that they should think, as best they could, on the emotion they would feel when immersed in the scenario they were experiencing in the VR set. Additionally, during the 5-seconds blank, they were asked to relax before the next video appeared during the session.

Participants were encouraged to take a break in between sessions where they could take out the HMD, stretch-out, use the toilet, and relax before continuing. Non-caffeinated, simulating substances (chocolate or coca cola), or both, snacks and drinks were offered at this time. They were also asked to turn off mobile phones or leave them outside of the listening room to avoid electromagnetic interference in the experiment.

3.5.1.4 EEG data pre-processing pipeline

Final pre-processing of EEG data was selected after conducting a literature review presented previously at table 5 of section 2.4.1. Majority of steps followed what literature indicated and is illustrated in figure 33. All procedures used the EEGLab plugin for MATLAB.

Initially, data was imported in .CNT extension. Then, signal distortions from the beginning of recording removed manually. Five scripts were developed to automate the 29 steps so to reduce time and possible human error from processing manually. These scripts were done using EEGLab resources and are available at Appendix Three.

Given the use of HMD during the EEG-VR experiment, a strong 50 Hz line noise was accounted for in the EEG data. Tests with different types of filters in EEGLab led to the use of a low-pass filter. First, the traditional CleanLine plug-in was tested, but it did not remove the noise. Then, a short infinite impulse response filter (IIR), called notch filter from 45 to 55Hz was applied, however, this left a flat horizontal line in the spectrum representing absence of information. Next, ZapLine plug-in was implemented, but after its use the data become distorted with strong peaks. Finally, low-pass filter was implemented using 45Hz as the cut off frequency and transition bandwidth of 5Hz. For this reason, it is strongly suggested that researchers using EEG and VR HMD apply a low-pass filter with a cut off frequency slightly below the energy line noise created through the HMD in the EEG data so to clean data.The first script included a high pass filter at 1 Hz as recommended from literature, import of channel location to the 10-20 standardized system with 32 positions, and a low pass filter at 45 Hz using a hamming window type with transition bandwidth at 5 Hz to remove the electronic line noise at 50 Hz.

Next, the second script rejects bad channels and corrects continuous data using the Artifact Subspace Reconstruction (ASR) plug-in, interpolates the removed channels, re-reference channels to common average, and extract epochs from data. It was chosen to correct data when using ASR instead of removing bad data because of the high loss of epochs when using removal option. Additionally, due to the removal of bad channels, a channel interpolation guaranteed that results did not tend to weigh more towards one region than others. The re-reference of channels to average guarantees the charge conservation between channels. And all six epochs were extracted to prepare data. Subsequently, an Independent Component Analysis (ICA) was done to identify and separate the brain components for final analysis. This step was not automated given a new data directory needed to be assigned for the Adaptive Mixture ICA plug-in (AMICA) to run.

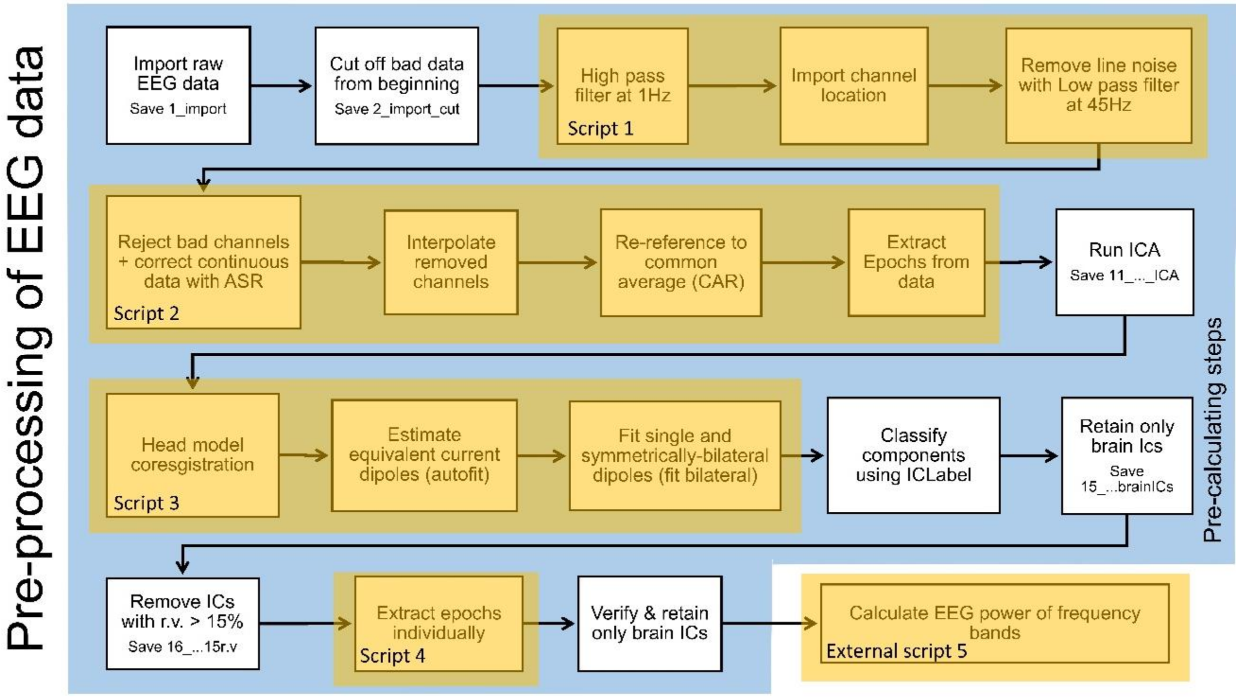


FIGURE 33: FINAL PRE-PROCESSING STEPS OF EEG DATA.

The third script included a head model co-registration, estimate equivalent current dipoles, and fit single and symmetrically bilateral dipoles. Steps were time consuming for the scalp topography generated by the ICA should fit to different models. Bilateral dipoles were estimated so that Independent Components (ICs) could be classified using ICLabel plug-in and brain ICs identified in dataset manually. Then, brain ICs are evaluated by dipoles and those dipoles with residual variance (r.v.) superior to 15% removed, brain ICs verified again, so to finally calculate EEG power of brain frequency bands. Residual variance represents the difference between the ICA scalp topography on which dipole was fitted and the projection from fitted dipole. That is, the higher the difference between the original ICA scalp and theoretical dipole projections, the higher the r.v., thus, being rejected for the projection from fitted dipole was far from original ICA scalp topography.

3.5.1.5 EEG data analysis

Due to natural variability of participants outputs, an initial cluster analysis was applied. The exploratory aspect of cluster analysis indicates that different methods should be tested to compare results and identify optimised result (Kaufmann and Rousseeuw, 1990). Ideally, one would desire to obtain a reduced number of groups so to maintain a representative sample size.

Moreover, given that each electrode has 192 independent reading resulting in 6144 data points, sensors were combined by brain regions as specified in Figure 34 to simplify analysis and data presentation. Then, brain waves were explored per region. Figure 35 illustrates this workflow. Special attention to the higher differences in alpha band power was identified in occipital region for participant 1 in the first session of the experiment.

As initial exploratory analysis demonstrated possible non-normality of data, a cluster analysis was applied over results to achieve a balanced sample size while grouping similar distributions. In addition, the average Silhouette and Chi-Square for goodness of fit test were observed to certify quality of clustered groups.

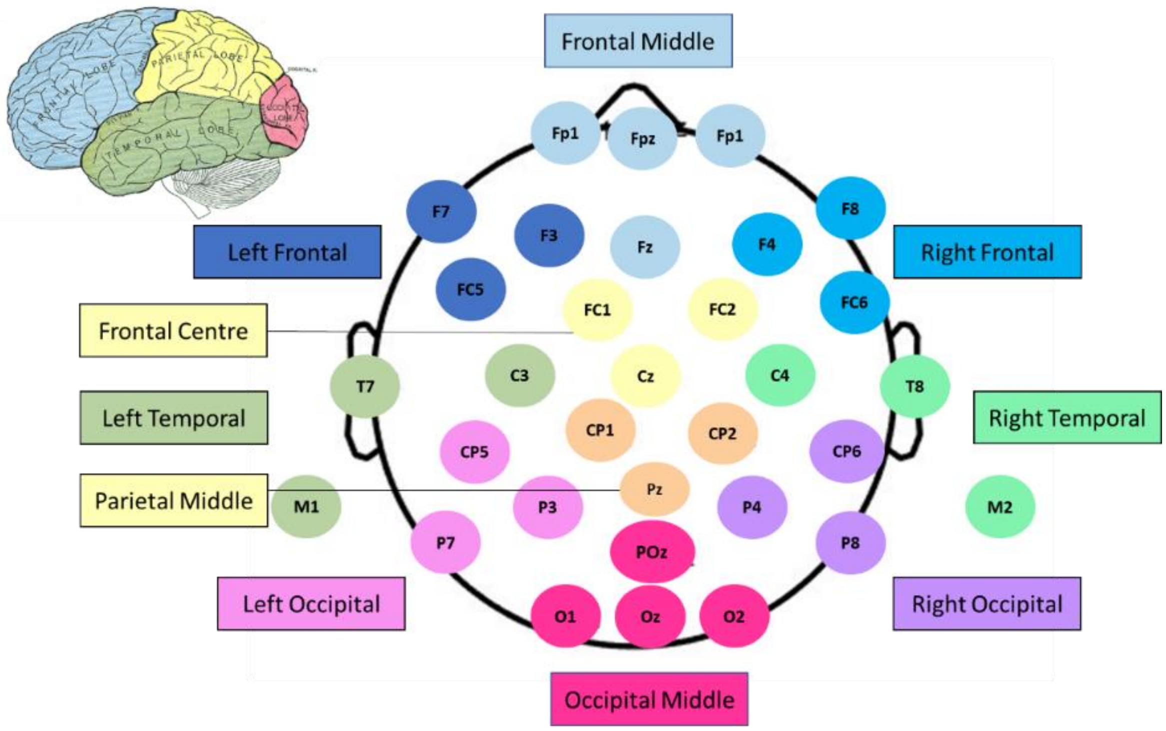


FIGURE 34: TOP RIGHT DEMONSTRATES A GENERAL VIEW OF THE BRAIN. CENTRAL PICTURE SHOWS ALL EEG SENSORS LOCATIONS AND GROUPS CREATED ACCORDING TO BRAIN REGIONS. EACH CIRCLE REPRESENTS THE 32 ELECTRODES, AND EACH COLOUR GROUP ILLUSTRATES THE 10 BRAIN REGIONS.

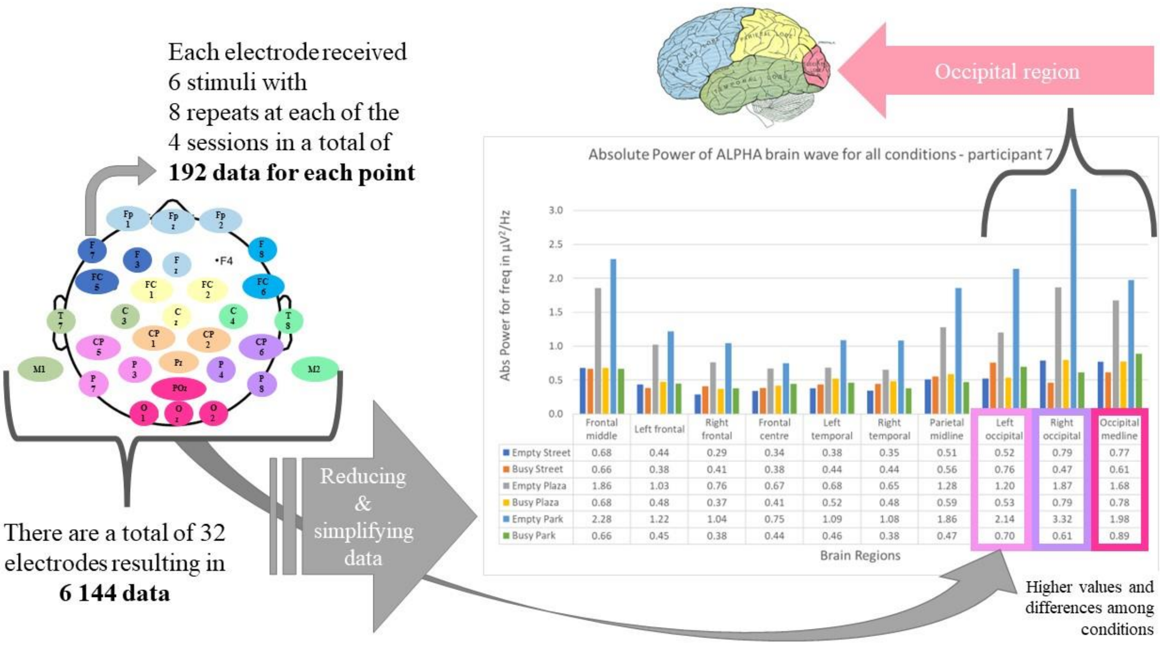


FIGURE 35: EEG DATA ANALYSIS WORKFLOW TO SIMPLIFY ANALYSIS AND DATA PRESENTATION.

While robust statistics applied to EEG data has been suggested through connectivity among sensors, simple ANOVA tests have also been applied to EEG data (Lin et al., 2011; Lee and Hsieh, 2014; Li and Kang, 2019; Shepherd, Lodhia and Hautus, 2019). Therefore, normality test and homogeneity of variances were assessed by Levene's test to continue analysis. Once, assumptions were met, ANOVA test was applied to observe significant effects of studied conditions.

3.5.1.6 Other procedures

Given Plutchik's Emotion Wheel has 32 emotional options, a reduction into 4 or 5 emotional categories was applied before further analysis. The criteria were to unify those emotions positioned close to each other to the most frequent one. For example, when 2 participants chose "joy" and 8 participants chose "serenity", data was merged into the word "serenity". Top selected emotions were plotted over the Plutichik's emotional wheel for each soundscape location and population density with the number of scores over the total number of participants. Then, a Chi-square goodness-of-fit test was conducted on these emotion results to test the null hypothesis for equal proportions among selected categories. That is, if all emotions would have the same frequency across categories.

For the ISO's PAQs, results were observed through suggested data analysis of PD ISO 12913-3:2019 (PD ISO 12913-3, 2019) as described in Equations 6 for Pleasantness (*P*) and 7 for Eventfulness (*E*). Initially, all scores were divided by 20 so to change to the ±5 range suggested in the standard. And results for all locations were scatter plotted into the two-dimensional soundscape axis.

$$P = (p - a) + cos45° * (ca - ch) + cos45° * (v - m) \tag{6}$$

$$E = (e - u) + cos45° * (ch - ca) + cos45° * (v - m) \tag{7}$$

were *a* is annoying, *ca* is calm, *ch* is chaotic, *e* is eventful, *m* is monotonous, *p* is pleasant, *u* is uneventful, and *v* is vibrant rating from initial questionnaire. Also, standard indicates to change the range to ±1 by dividing the coordinates by $4+\sqrt{32}$ (PD ISO 12913-3, 2019).

Psychoacoustic metrics for sound levels, loudness, sharpness, fluctuation strength, tonality, tonality with threshold, and roughness were observed with the final 8-seconds stimuli using the Artemis software. Audio signals were recorded over the experimental setup through the HATS dummy head using the Pulse system. First a signal of 1Hz at 94 dB was recorded through the HATS as reference. Then, all stimuli were reproduced through headphones and recorded through the same system. In Artemis, the reference signal was opened to identify the dB level so to stablish the subtraction or addition necessary to arrive the initial 94 dB. With such number, a new file was opened, and level corrected. From this point, all stimuli were processed correctly given the calibration. Calculous methods were as default from Head Acoustics, Artemis. The representative single value reported followed PD ISO 12913-3:2019 (PD ISO 12913-3, 2019) with the higher value from the left and right metric value for the Sound Levels and the average from left and right metric values for the other psychoacoustic metrics. All psychoacoustic metrics were averaged over time from the original 8-seconds stimuli.

4. CHAPTER FOUR: Results and Discussions

In this chapter, the results of the five experiments are presented and discussed. The experiments are the site survey, the field survey, the VR pilot, the MCR online, and the EEG and VR listening test. The fifth experiment was the major experiment of this thesis and is displayed in section 4.5.

4.1 Experiment 1: Survey to identify study locations

The participants were twenty-three members (67% men and 33% women) of the School of Science, Engineering & Environment, University of Salford, Greater Manchester, UK. They were approached during the period of November and December 2018. The word clouds in Figure 36 represent the places the surveyed public indicated over the PAQ two-dimensional model of the PD ISO 12913-3:2019 (PD ISO 12913-3, 2019). The words increased font size with the number of occurrences within the sample. However, their sizes are not related between quadrant figures. Additionally, the number of repeats is indicated at the lower-bottom-right of each name or soon afterwards.

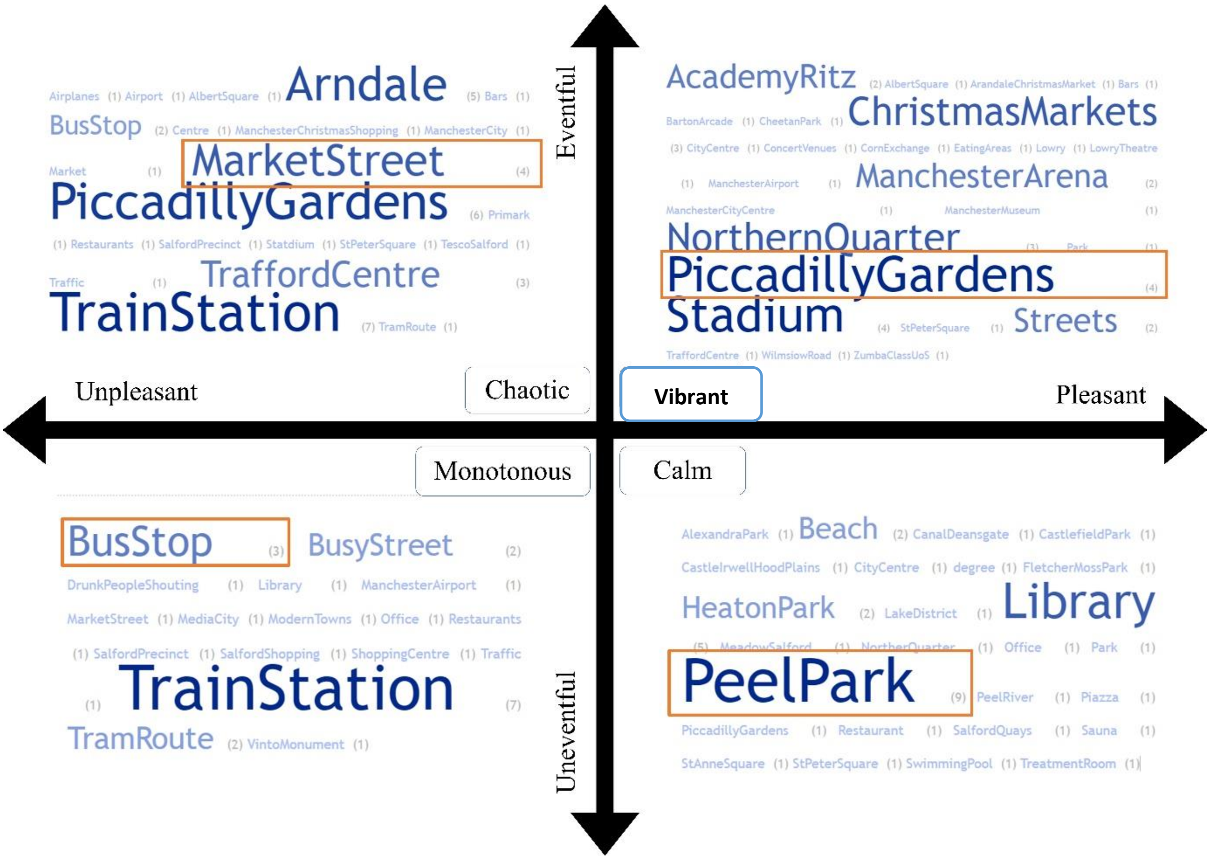


FIGURE 36: RESULTS FROM STRUCTURED SURVEY WITH RESIDENTS TO DETERMINE THE TYPES OF SOUNDSCAPES IN PUBLIC PLACES OF MANCHESTER (UK) REGION.

The final selections are marked by the orange rectangle. They were Piccadilly Gardens (popular city centre plaza) for the Vibrant, Peel Park (park in the University of Salford) for the Calm, a bus stop (common bus stop in front of the University of Salford) for the Monotonous, and Market Street (pedestrian shopping street) for the Chaotic soundscape. Regarding urban mobility, all locations have traditional and sustainable options of transport applied in place or close by. That meaning the streets are equipped for cars, buses, trams, cyclers, wheelchairs, and walking.

Piccadilly Gardens (Figure 37) is the largest public space in central Manchester with 1.49 Ha and various functions of "passive" recreation--activities with no specific function, such as crossing, eating place, children play, place for small and large events (Byass, 2010). It received a new Design between 2001-2002 that included a water fountain, playground, café store, a barrier by Tadao Ando (famous Japanese architect), sitting areas with chairs, grass areas, and trees where people sit on sunny days. Recently, the garden does not have flowers and only 29% of the area has grass. It is surrounded by Piccadilly Street at the north, Mosley Street at the west, Parker Street at the south, and One Piccadilly Gardens building at the east side. A small part of Piccadilly Street is a pedestrian zone with grocery stores and pharmacies on the bordering building which receives a street food market and fair on the weekends. Then, it continues as a traffic street for conventional traffic and buses with restaurants and grocery stores. On Mosley Street, only trams and pedestrians can circulate, and it ends when Market Street starts. Royal Buildings border the street and has a big clothing department store, fast-food places, and a bank on the ground floor. Parker street traffic is for buses and trams only having many buses stops and the Piccadilly Gardens tram station. On the opposite side of the street, there are different commercial units ranging from food places to gambling facilities at the ground floor including the entrance to the City Tower, one of the tallest buildings in Manchester that includes the main radio transmitting station placed on the roof and different commercial office spaces. In addition, through all four borders of Piccadilly Gardens, there are benches, bike racks, and telephone booths.

Peel Park (Figure 38) has 9.40 Ha and is one of the oldest public parks in the world dating from 1846 (Keeling, 2015). Today it integrates with the Peel Park Campus, University of Salford counting with walking paths, many tall and scattered trees, a structured playground, sculptures, a garden with flowerbeds, lots of green area, and benches to sit. The park is surrounded by a Student Accommodation and access to David Lewis Sports Ground at the north; River Irwell with a bridge accessing The Meadow, a public green space, and a housing area at the east; Maxwell Building, and Salford Museum and Art Gallery on the south; and the University House, Clifford Library, and Cockcroft Building at westside. The local population uses the location for "passive" recreation, exercise, and crossing path to other locations.

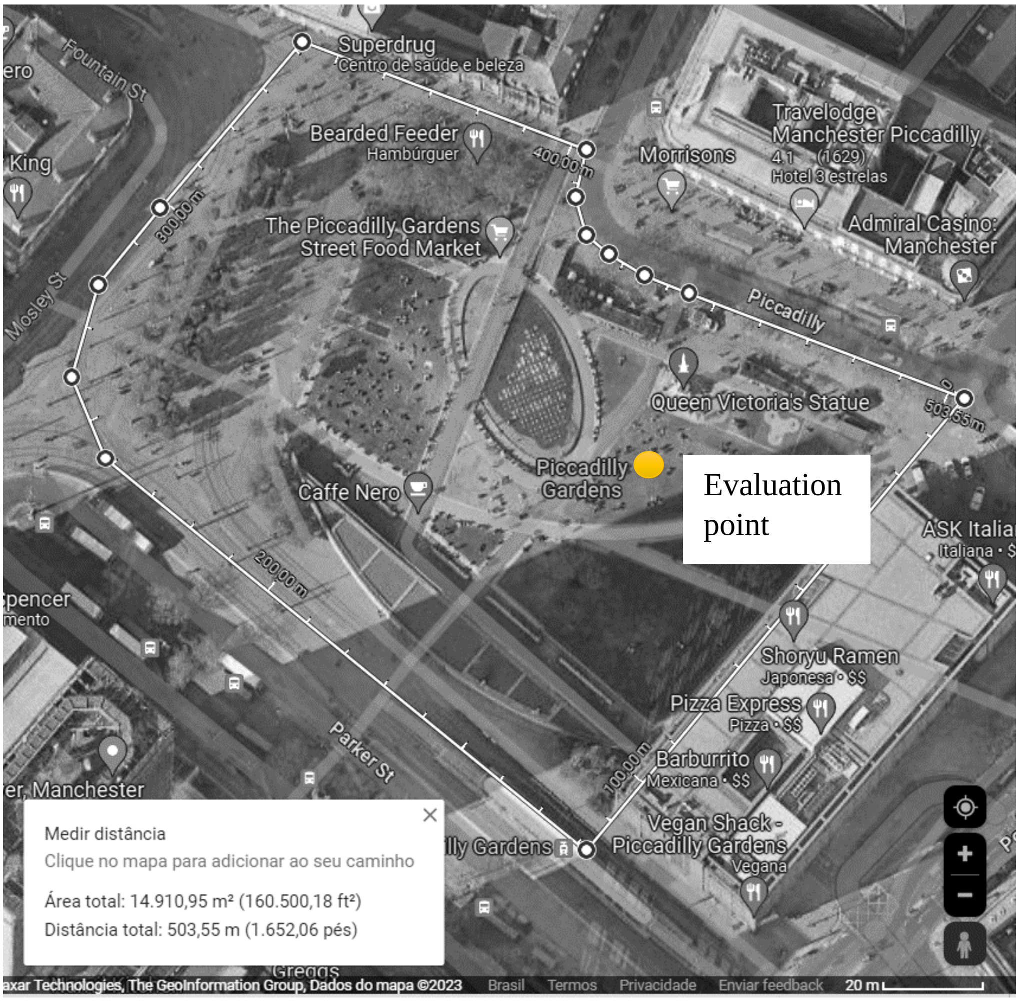


FIGURE 37: MAP OF PICCADILLY GARDENS (ADAPTED FROM GOOGLE MAPS, 2023).

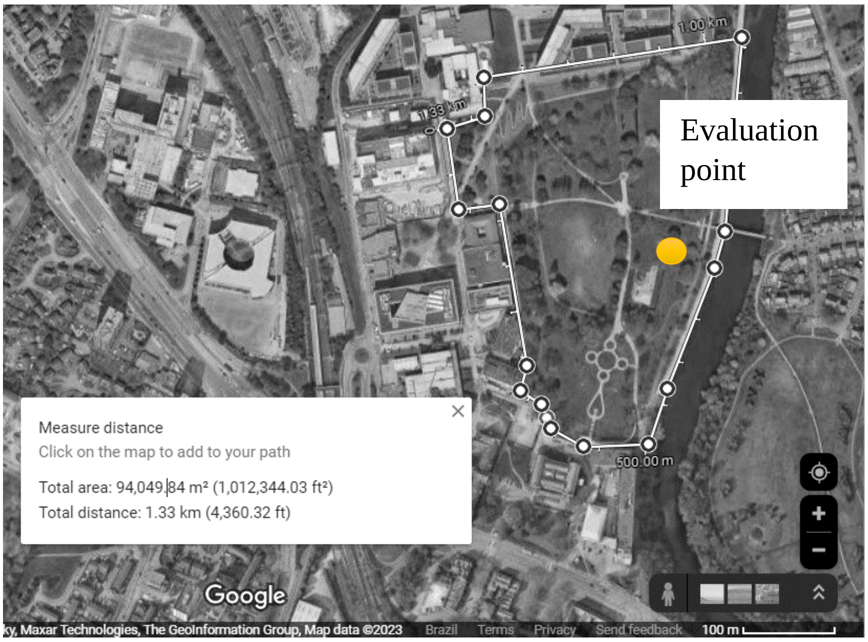


FIGURE 38: MAP OF PEEL PARK (ADAPTED FROM GOOGLE MAPS, 2023).

Market Street (Figure 39) is approximately 370 meters long, with a 280 m pedestrian zone occupying around 0.91 Ha. Exchange Street delimits it on the west until High Street on the east. The pedestrian zone is between High Street and Corporation Street counting with primally commercial activities, such as clothes and shoes stores, banks, grocery stores, street food huts, gyms, bookstores, mobile stores, pharmacies, coffee stores, and three accesses to Manchester Arndale Shopping. When the street gains traffic, commercial activities are more related to beauty products, confectionary, stationary, clothing and footwear, and coffee shops, as well as access to the Royal Exchange building.

The studied bus stop (Figure 40) is located on road A6, also known as Chapel Street at the University of Salford. Behind the bus stop, there are Peel Building in the west, a green area at the north with the Salford Museum and Art Gallery in the far back, and the Maxwell Hall to the east. At the other side of the road, there is another bus stop going towards city centre with Working Class Movement Library at west, the Old Fire Station building where the Salford Institute for Public Policy building lies today at south, and the Albert Bentley Place (memorial park) at east. The studied location has 0.46 Ha with approximately 140 meters distance from reduction to acceleration lane.

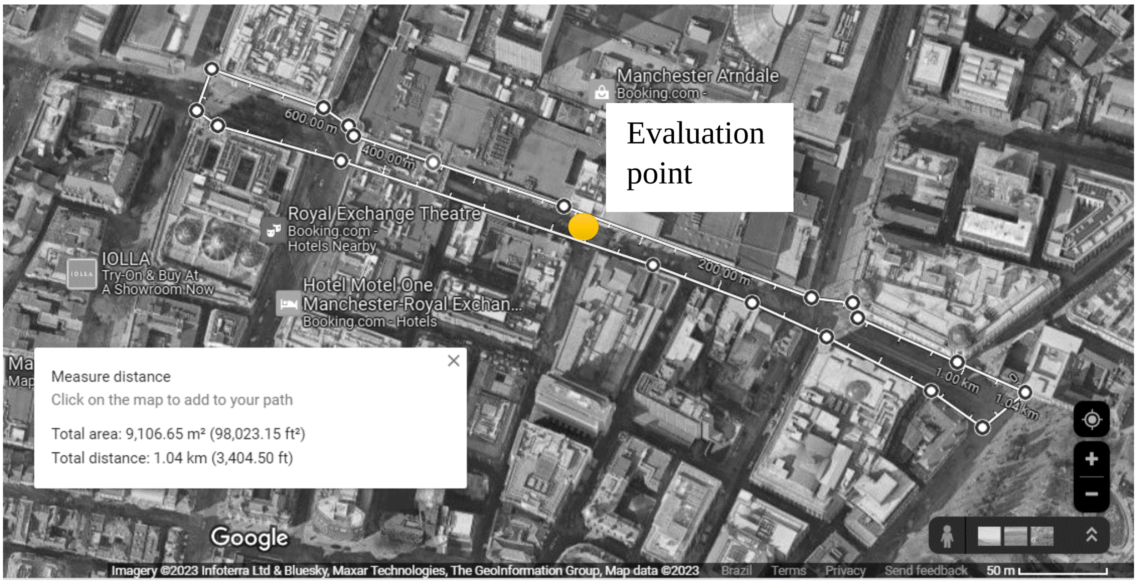


FIGURE 39: MAP OF MARKET STREET (ADAPTED FROM GOOGLE MAPS, 2023).

FIGURE 40: MAP OF BUS STOP (ADAPTED FROM GOOGLE MAPS, 2023).

4.1.1 Discussion

To work with local users brings advantages in achieving the correct selection of studied locations that can result in successful results. Nevertheless, some reasoning led to final selections as described below.

The Train Station appeared the same number of times for Chaotic and Monotonous PAQs. When considered Chaotic, the location was related to traffic noise as screeching of trains and horns in participants answers. For the Monotonous scale, unfortunately, some participants left answers blank with no explanation. Nevertheless, the Train Station appeared in large scale and interestingly related to traffic noise again with one comment indicating the announcements to be boring. When contacting the authorities to obtain permission to proceed recordings at this location, no reply was granted leading to the abandon of location in this study.

Piccadilly Gardens appeared in the Chaotic, Vibrant, and Calm quadrants with respectively six, four, and one vote. Four participants (17% of respondents) claimed it to be Chaotic in peak hours. It is important to notice that one of the streets that surrounds the location has several bus stops and a tram stop. Noise from these public transports contributes to the sonic pollution and can be included as representative of rush hours.

Additionally, human sounds, such as voices and loudspeakers were mentioned as undesirable. When Piccadilly Gardens was indicated as a Vibrant place, participants included details as live music (street busking) and the water fountain in the open question. Another interesting comment was regarding the weather. One respondent mentioned that the garden was considered Vibrant on a “nice warm day”. Important to notice is that sunny days are rare in Manchester and it is considered to be within the rainiest city of Europe (Feldmann, 2008). Intriguing to observe is that whether rated as Chaotic or Vibrant, participants mentioned live music as an element that either bothers or adds to the pleasant sensation. Given the paradox, all recordings avoided recordings of amplified music so to eliminate possible divergence and confusion.

For the selection of the Vibrant location, the first two locations were the Stadium and Piccadilly Gardens. Again, the Stadium demanded formal authorization for recordings which would take time and characterize the location as a non-public place, thus leaving Piccadilly Gardens as representative of this type of site. Once selected, this location could not be repeated eliminating it from the Chaotic category. Next, the most voted location for the Calm soundscape was Peel Park followed by the library. The location was maintained because it had no demand of authorization to record given it has public access and the location is in the Peel Park Campus of the University of Salford. For the Monotonous site, after the Train Station, the next most voted was a bus stop which led to the selection of the University of Salford’s main bus stop. Regarding the Chaotic scale, the most voted after the Train Station were Piccadilly Gardens, Arndale Shopping Centre, and Market Street. The Train Station and Piccadilly were eliminated, one for lack of authorization and the other because it belonged to the Vibrant category. Again, Arndale Shopping Centre had issues with permission for recordings being eliminated which left Market Street to be representative of the Chaotic locations, specifically at rush hour, as on a Saturdays afternoon.

Piccadilly Garden’s 2002 redesign aimed to give Vibrancy to the location (Byass, 2010) which corroborated with current selection as a Vibrant soundscape. On a sunny day, children playing within the projection of the water fountain jets enhances the atmosphere of the plaza into a cheerful and happy scenario which can characterize a Vibrant soundscape with the Pleasant and Eventful sonic events. Meanwhile, Peel Park in previous study was categorized as “excellent” level of perceived tranquillity (Watts, Miah and Pheasant, 2013) which can be correlated to the selection of the location as a Calm place.

From another perspective, for those who have the habit in taking a bus, waiting for it to arrive can be tedious. In undeveloped countries, tardiness on bus arrivals can be up to one hour or more due to traffic jams, and lack of cultural tradition to be on time. In these circumstances, to wait for a bus in a bus stop can be reasonably understood to be considered as a Monotonous soundscape.

Furthermore, Market Street can be a crowded place in Manchester city centre. A large number of people are constantly moving to a point of bumping into each other while they talk, cycle through, perform music, preach religious thoughts, all at the same time. Just the descriptions of these activities can illustrate a busy moment there. Therefore, the location would represent a Chaotic location.

It is relevant to observe that the appearance of the same location in more than one PAQ category indicated other factors within the same site are influencing soundscape perception. Piccadilly Gardens appeared in the Vibrant and Chaotic categories which are both in the high Eventful dimension but changed from the Pleasant to Annoying scale. Meanwhile, the bus stop and the Train Station were present in the Chaotic and Monotonous categories, both in the Annoying axis, but opposites in the Eventful axis. These shifts among soundscape categories led the investigation to also consider population density as a controlled factor. That is, to consider how the number of people in the location might influence how people perceived soundscapes.

4.2 Experiment 2: Soundscape Field questionnaires at Peel Park and Clifford Whitworth Library

Data was collected on the 3rd of May at the library, and in the 5th and 15th of May of 2019 at the park. A total of 30 participants (55% men and 45% women) at the library and 20 participants (60% men and 40% women) at the park answered the questionnaire. The researcher perceived that the park had predominant sounds of nature like birds and people talking, while the library consisted mainly of sounds of people talking softly and typing on computers. The activities in the park consisted of children playing in the playground, people sitting in different green areas, strolling, and exercising, such as running, walking, and cycling. In the library, all floors had people reading, typing, or taking notes. However, the ground and "studying out loud" floors included groups of people talking.

Figures 41 and 42 illustrate the box plots of all results for the soundscape descriptors of Peel Park and library, respectively. Even though the park had fewer participants, the results demonstrated less dispersion than those for the library.

Table 6 presents the Mann-Whitney U results for the group differences among the park and library of the soundscape descriptors. A total of 11 parameters from the 19 descriptors were significantly different at a *p-value* of 0.05 or lower. These descriptors with significant differences had a superior mean rank for the park except for the directional-universal soundscape descriptors.

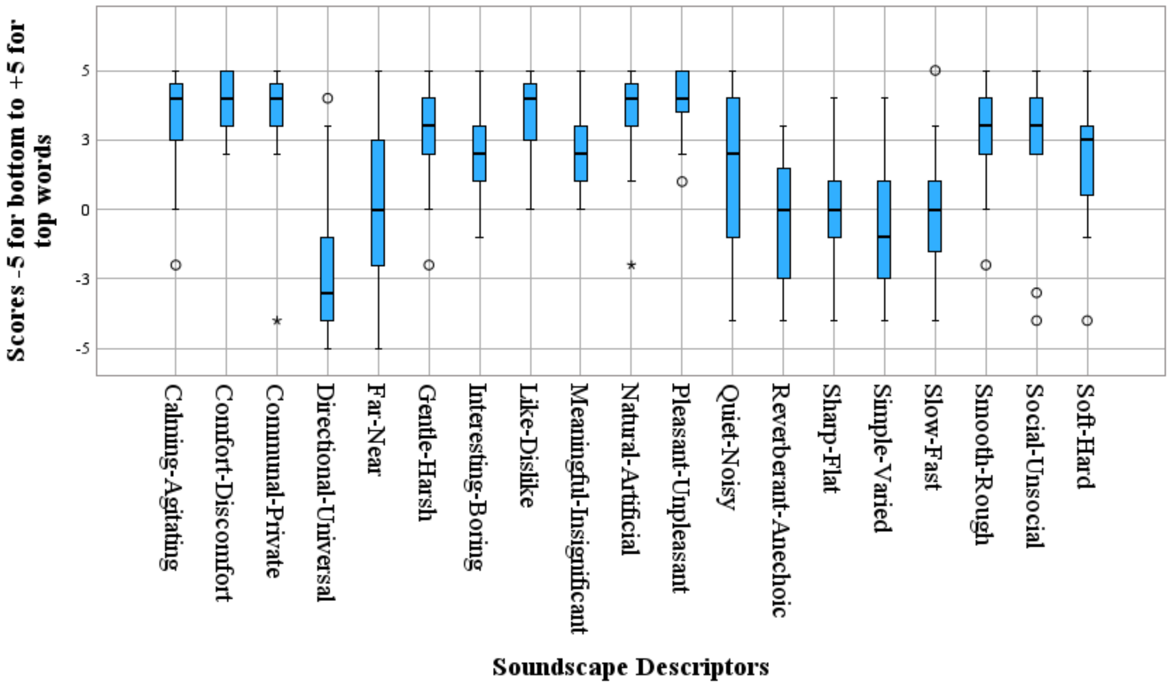


FIGURE 41: SOUNDSCAPE DESCRIPTOR BOXPLOTS OF PEEL PARK WITH 20 PARTICIPANTS. WHERE TOP WHISKER IS THE MAXIMUM VALUE, TOP PART OF THE BOX IS THE THIRD QUARTILE, THE MIDDLE THICK LINE IS THE SECOND QUARTILE (MEDIAN VALUE), THE LOWER PART OF THE BOX IS THE FIRST QUARTILE, THE LOWER WHISKER IS THE MINIMUM VALUE, AND DOTS ARE OUTLIERS.

Figure 43 illustrates the boxplots for the PANAS results of Peel Park and Library. Again, the sample distributions for the library are more scattered than for the park. Table 7 presents the Mann-Whitney U results for the group differences among the park and library of the PANAS emotional states. From the 10 states, only upset, inspired, determined, and active had a significant difference among the park and library.

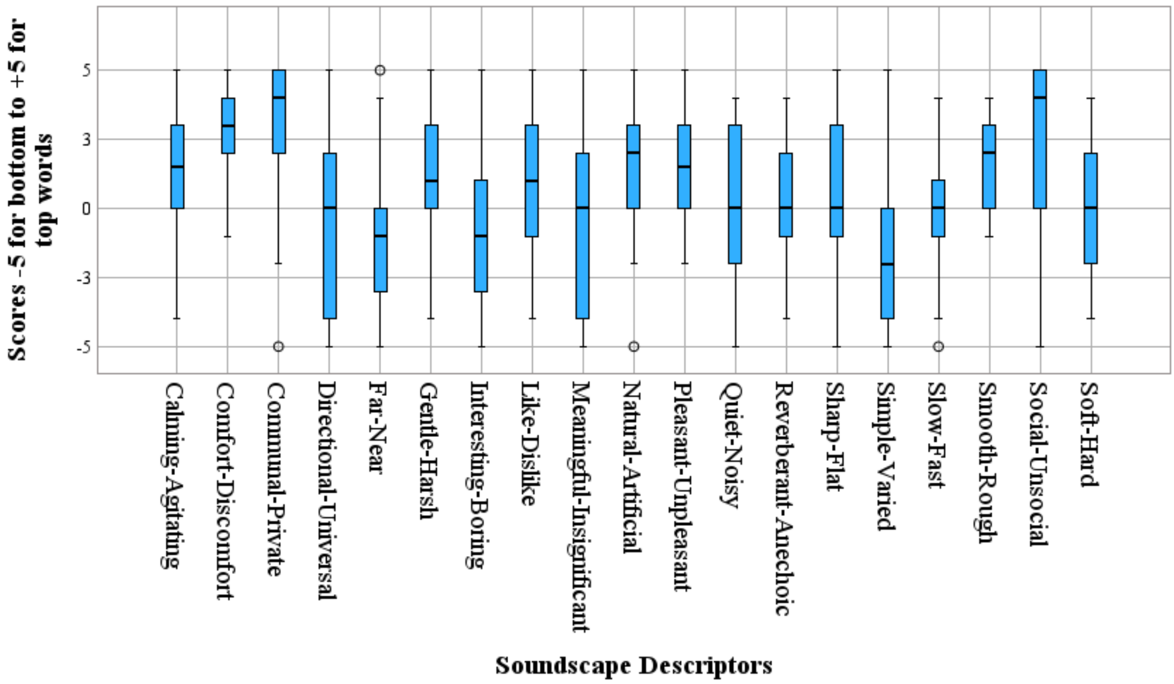


FIGURE 42: SOUNDSCAPE DESCRIPTOR BOXPLOTS OF LIBRARY WITH 30 PARTICIPANTS. WHERE TOP WHISKER IS THE MAXIMUM VALUE, TOP PART OF THE BOX IS THE THIRD QUARTILE, THE MIDDLE THICK LINE IS THE SECOND QUARTILE (MEDIAN VALUE), THE LOWER PART OF THE BOX IS THE FIRST QUARTILE, THE LOWER WHISKER IS THE MINIMUM VALUE, AND DOTS ARE OUTLIERS.

TABLE 6: MANN-WHITNEY U RESULTS FOR SOUNDSCAPE DESCRIPTORS. * FOR SIGNIFICANT DIFFERENCE P<0.05, + FOR P VALUE BELOW 0.001, AND # FOR SUPERIOR MEAN RANK.

Soundscape Descriptors	**Median**		**Mean Rank**		**U**	***p*-value**
	Peel Park	**Library**	**Peel Park**	**Library**		
Comfort/Discomfort	4	3	**31.77#**	21.32	174.5	0.011*
Quiet/Noisy	2	0	29.18	23.05	226.5	0.142
Calming/Agitating	4	1.5	**33.31#**	19.22	111.5	0.001+
Pleasant/Unpleasant	4	1	**35.06#**	17.14	62	0.000+
Smooth/Rough	3.5	2	**33.88#**	17	58	0.000+
Natural/Artificial	4	2	**34.29#**	18.09	89.5	0.000+
Soft/Hard	2.5	0	**29.88#**	19.21	122	0.008*
Like/Dislike	4	1	**33.68#**	19.5	120	0.001+
Slow/Fast	0	0	24.29	24.64	279.5	0.931
Gentle/Harsh	3	1	**32.18#**	20.45	148.5	0.004*
Sharp/Flat	0	0	22.66	25.71	310.5	0.451
Interesting/Boring	2	-1	**34.65#**	19.4	117	0.000+
Simple/Varied	-1	-2	28.5	22.59	220	0.152
Social/Unsocial	3.5	4	26.67	23.2	231	0.397
Reverberant/Anechoic	0	0	22.16	25.25	301	0.44
Communal/Private	4	4	26.08	23.47	245.5	0.514
Far/Near	0	-1	29.1	22.17	208	0.09

Meaningful/Insignificant	2	0	**33.9#**	19.9	132	0.001+
Directional/Universal	-3	0	18.22	**28.27#**	383	0.015*

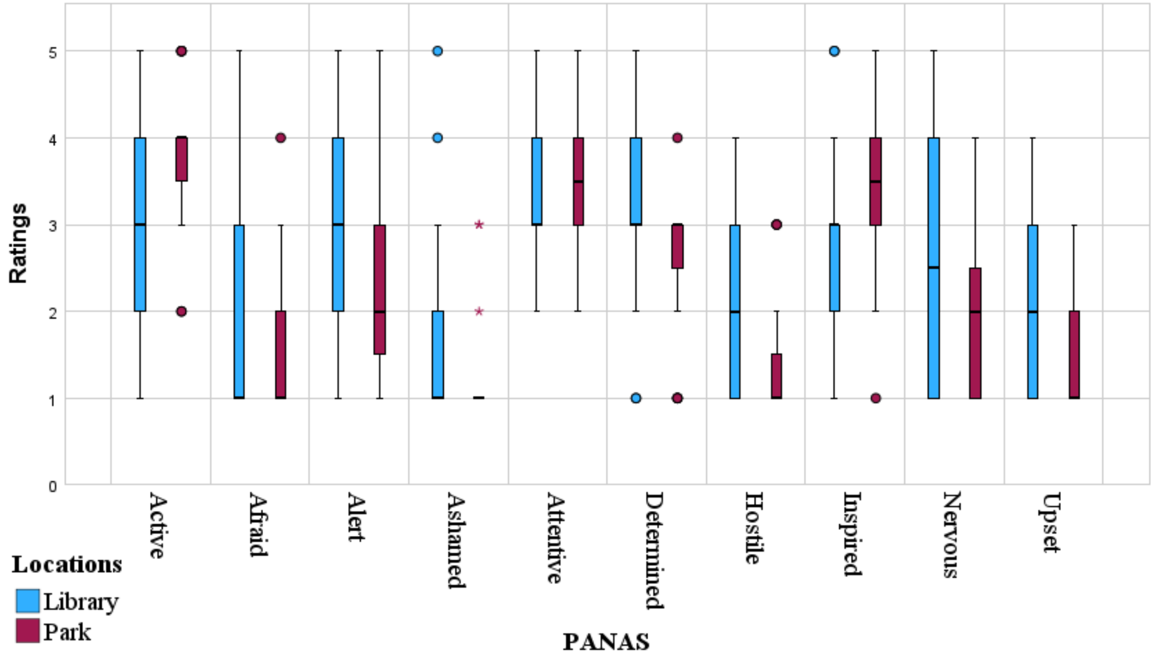


FIGURE 43: PANAS BOXPLOT FOR PEEL PARK AND LIBRARY. NUMERIC SEMANTIC SCALES WITH ONE FOR "NEVER", THREE FOR "NEUTRAL", AND FIVE FOR "ALWAYS". WHERE TOP WHISKER IS THE MAXIMUM VALUE, TOP LINE OF THE BOX IS THE THIRD QUARTILE, THE MIDDLE THICK LINE IS THE SECOND QUARTILE (MEDIAN VALUE), THE LOWER LINE OF THE BOX IS THE FIRST QUARTILE, THE LOWER WHISKER IS THE MINIMUM VALUE, AND OUTER DOTS ARE OUTLIERS.

TABLE 7: STATISTICAL MANN-WHITNEY U RESULTS FOR PANAS. * FOR SIGNIFICANT DIFFERENCE P<0.05, AND # FOR SUPERIOR MEAN RANK.

PANAS	Median		Mean Rank		U	*P*
	Peel Park	Library	Peel Park	Library		
Upset	1	2	20.8	**28.63#**	394	0.039*
Hostile	1	2	21	27.53	361	0.081
Alert	2	3	21.3	28.3	384	0.086
Ashamed	1	1	21.25	26.45	328.5	0.067
Inspired	4	3	**30.89#**	18.75	119	0.002*
Nervous	2	2.5	21.25	28.33	385	0.081
Determined	3	3	18.61	**27.66#**	368.5	0.013*
Attentive	3.5	3	28.75	23.33	235	0.169
Afraid	1	1	21.66	27.12	348.5	0.14
Active	4	3	**30.92#**	20.65	154.5	0.01*

4.2.1 Discussion

Even though the park and library were classified as calm soundscapes, results demonstrated that the park was considered more calming than the library, possibly because of its benefits for stress recovery due to natural sounds (Payne, 2013). Also, the comfort-discomfort scale was found not to influence library ratings like in other library study (Ikhwanuddin *et al.*, 2017), possibly because people visit them with a work-related purpose.

Even though the park had fewer participants, the results demonstrated less dispersion than those for the library on both soundscape descriptors and PANAS responses. This dispersion could be explained by the distinct functions for each floor in the library. Furthermore, the park and library responses were considered significantly different in 10 different soundscape descriptors with superior ratings for the park. Most of the descriptors found here were included in the pleasantness dimension, such as in previous study (Ikhwanuddin *et al.*, 2017).

In contrast, the PANAS questionnaire for emotional traits had weak responses, where from the 10 emotional traits only four feelings demonstrated statistical differences between the park and library analysis. People in the library presented to be more “upset” in the place, possibly related to the academic environment where tension is present while studying for assessment and exams. Also, they may feel more “determined” to develop intellectual tasks in the library than a public place. People also felt more “inspired” and “active” in the park.

Furthermore, even though the questionnaire resumed on one page, several individuals avoided answering the survey because of the number of elements to read. In general, the public in the library was more receptive than in the park resulting in a higher number of respondents. Nevertheless, the experiment was important to test the questions in the survey.

4.3 Experiment 3: VR pilot experiment with Piccadilly Gardens

Recordings made on different days during June 2019 followed two specifications: a sunny moment and three different population densities of Piccadilly Gardens. Estimates of people count from Piccadilly Gardens and Market Street VR stimuli are presented in table 8. Participant three was considered an outlier and taken out of analysis. Final means and standard deviations demonstrated results for medium and busy were practically one double of the other, securing final stimuli were sufficient representative of the medium and busy population densities.

TABLE 8: RESULTS FROM ONLINE SURVEY FOR VALIDATION OF RESEARCHER'S PEOPLE COUNT FROM VIDEO TO DETERMINE MEDIUM AND BUSY CROWD DENSITIES FOR PICCADILLY GARDENS AND MARKET STREET.

Condition	Participants								Mean	SD	Mean no part 3	SD
	1	2	3	4	5	6	7	8				
Medium Piccadilly	35	40	50	30	35	15	30	35	33.8	9.9	31.4	8
Buys Piccadilly	75	60	300	50	70	45	60	75	91.9	84.8	62.1	11.9
Medium Market	80	40	200	60	55	30	50	60	71.9	53.8	53.6	16
Buys Market	160	100	400	100	75	55	80	100	133.8	111.8	95.7	33

The pilot test with eleven participants (36% men and 64% women with average age 28 and standard deviation of 8) in a public academic event took place during the 5th of July of 2019 at University of Salford, Manchester, UK (Carvalho, Davies and Fazenda, 2019).

Figure 44 presents the results in boxplots of the PAQ ratings in the three conditions. Perceptions of medium population density soundscape characterised the scenario as pleasant while in the busy and empty conditions results were not so consistent. Regarding the eventful descriptor, the busy and empty population densities indicated opposite differences in perception--eventful and uneventful respectively (Carvalho, Davies and Fazenda, 2019).

However, an experimental error was identified in the medium density sample, where the audio was not calibrated and louder than the empty and busy scenarios. Therefore, the significance in the pleasant scale of the medium population density result was associated with the disproportional sound level of the sample. This mismanagement was corrected in the next experiments, where all samples were calibrated to reproduce original sound level measured on field (Carvalho, Davies and Fazenda, 2019).

Although respondents in our initial survey (Figure 36 section 4.1) had described Piccadilly Gardens as a Vibrant, Chaotic or Calm soundscape, the outcomes of the soundscape ratings did not confirm the place as such. Instead, the scenario in the empty condition was reported as monotonous. Also, the Plaza in medium and empty conditions were assessed to be calm indicating a low effect of the human presence on this PAQ scale (Carvalho, Davies and Fazenda, 2019).

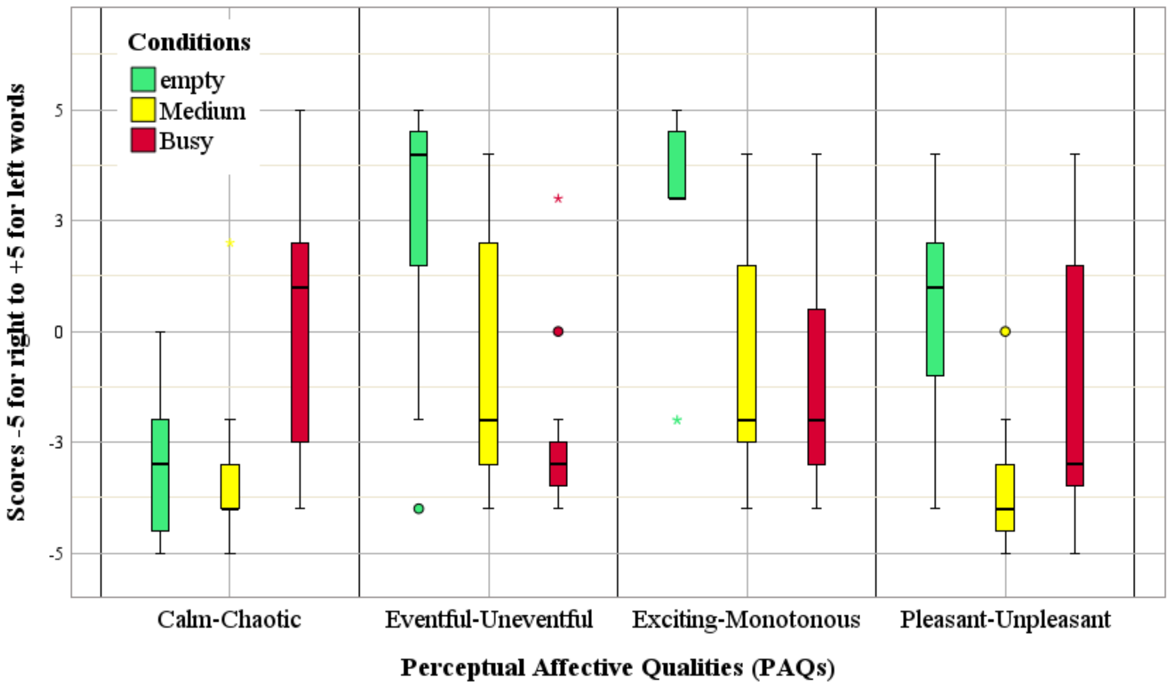


FIGURE 44: BOXPLOT DISTRIBUTIONS FOR PLAZA PAQ SCORES IN BUSY, MEDIUM, AND EMPTY POPULATION DENSITIES. NUMERIC SEMANTIC SCALES WITH -5 FOR RIGHT TO +5 FOR LEFT WORDS. WHERE TOP WHISKER IS THE MAXIMUM VALUE, TOP LINE OF THE BOX IS THE THIRD QUARTILE, THE MIDDLE THICK LINE IS THE SECOND QUARTILE (MEDIAN VALUE), THE LOWER LINE OF THE BOX IS THE FIRST QUARTILE, THE LOWER WHISKER IS THE MINIMUM VALUE, AND OUTER DOTS ARE OUTLIERS.

Table 9 presents the pairwise comparison results in which significant difference due to population density was identified in all PAQ scales. As the population density increased so did the ratings from uneventful-eventful and monotonous-vibrant scales. However, only for the eventful-uneventful PAQs did the effect size have a positive relationship among all conditions while monotonous-vibrant ratings did not have the same effect among medium and busy conditions. Additionally, when the number of people incremented in the plaza scores decreased in the chaotic to calm PAQ with a significant negative effect between empty-busy and medium-busy. In short, population density increase effected positively the eventful and vibrant scales, while negatively the calm scores (Carvalho, Davies and Fazenda, 2019).

Figure 45 illustrates the medians and their ranges in boxplots for the results of the ratings of the PANAS emotional states in the three soundscape conditions. In contrast to the soundscape PAQs, most of the emotion scores show small variation among the three population density conditions. In particular, the results for “upset” and “ashamed” are almost unchanging across the three conditions, and most of the other emotional scale results overlap considerably from one soundscape condition to another (Carvalho, Davies and Fazenda, 2019).

TABLE 9: PAIRWISE COMPARISON RESULTS FOR SOUNDSCAPE PAQS WITH * FOR SIGNIFICANT DIFFERENCE P-VALUE <0.05, AND + FOR SIGNIFICANT EFFECT SIZE WHERE -.3 < R IS A NEGATIVE EFFECT AND R <.3 IS POSITIVE EFFECT IN BOLD.

PAQs	Friedman value		Wilcoxon signed-rank test					
	$\chi^2(2)$	*p*-alue	Empty -Medium		Empty – Busy		Medium - Busy	
			T	*r*	*T*	*r*	*T*	*r*
Pleasant/Unpleasant	7.762	.021*	53.5	**.5673+**	44	.2092	11.5	**-.3503+**
Eventful/Uneventful	12.634	.002*	57	**.4563+**	62	**.5530+**	31	**.3929+**
Vibrant /Monotonous	14.683	.001*	66	**.6287+**	45	**.5714+**	31	.0772
Calm/Chaotic	6.186	.045*	39.5	.1241	7	**-.4951+**	1.5	**-.5665+**

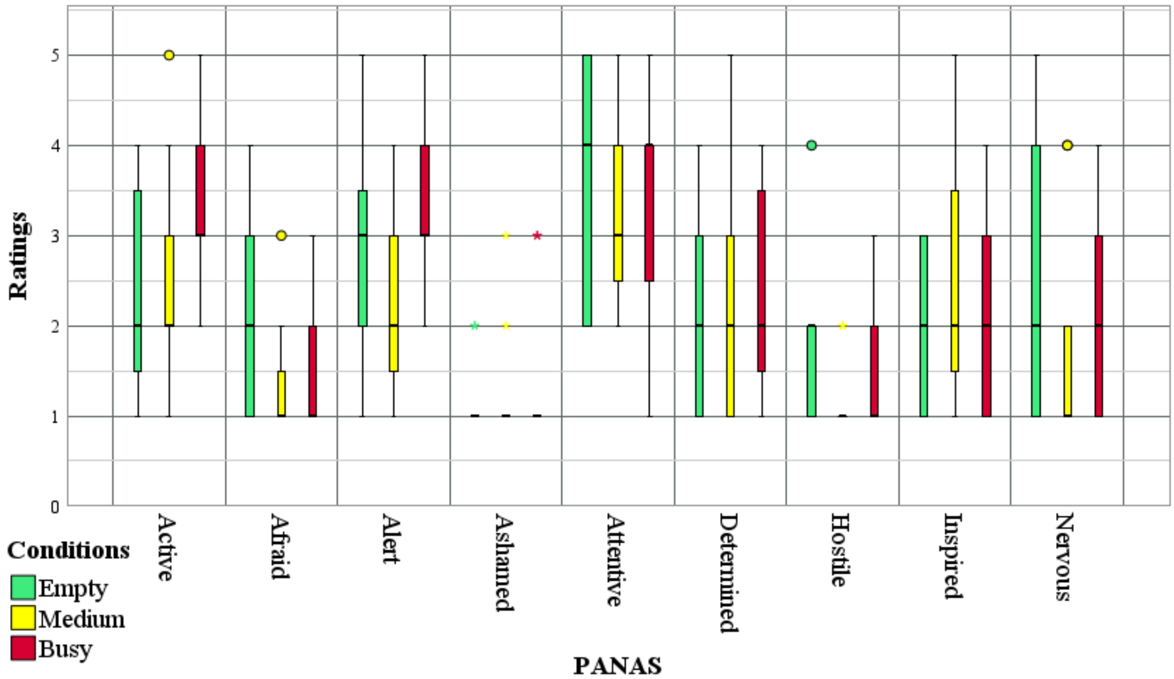


FIGURE 45: BOXPLOT DISTRIBUTIONS FOR PICCADILLY GARDENS PANAS EMOTIONAL RATING FOR EMPTY, MEDIUM, AND BUSY POPULATION DENSITIES. NUMERIC SEMANTIC SCALES WITH ONE FOR "NEVER", THREE FOR "NEUTRAL", AND FIVE FOR "ALWAYS". WHERE TOP WHISKER IS THE MAXIMUM VALUE, TOP LINE OF THE BOX IS THE THIRD QUARTILE, THE MIDDLE THICK LINE IS THE SECOND QUARTILE (MEDIAN VALUE), THE LOWER LINE OF THE BOX IS THE FIRST QUARTILE, THE LOWER WHISKER IS THE MINIMUM VALUE, AND OUTER DOTS ARE OUTLIERS.

Table 10 presents the pairwise comparison results for the PANAS emotional state ratings in the three population density conditions. Only the "active" emotional state had a significant difference among conditions with a positive effect among the empty-busy and medium-busy conditions. That is, people rated more towards always "active" when population density increased (Carvalho, Davies and Fazenda, 2019).

Table 60: Pairwise comparison results for PANAS emotional states with * for significant difference p-value <0.05, and $^{+}$ for significant effect size where -.3 < r is a negative effect and r <.3 is positive effect in bold.

Soundscape descriptors	Friedman value		Wilcoxon signed-rank test					
	$\chi^2(2)$	*p*-value	Empty - Medium		Empty - Busy		Medium - Busy	
			T	*r*	*T*	*r*	*T*	*r*
Upset	1.077	.584	2	-.123	4	-.0806	2	.0953
Hostile	3	.223	3	**-.3554**$^{+}$	14.5	-.1094	3	.2861
Alert	2.513	.285	14	-.2194	28.5	.1534	47.5	**.4435**$^{+}$
Ashamed	3	.223	1	.2132	3	**.3015**$^{+}$	1	.2132
Inspired	1.514	.469	34.5	.1580	20.5	.0765	13.5	-.1379
Nervous	1.867	.393	3.5	-.2411	19	-.0895	21	.2697
Determined	1.238	.538	9	.0878	8.5	.2748	13	.1153
Attentive	1.032	.597	14	-.123	17.5	-.0151	13	.1153
Afraid	3.931	.140	0	**-.4413**$^{+}$	12	-.2793	14	.1740
Active	6.75	.034*	15.5	.0563	26	**.4371**$^{+}$	41.5	**.4972**$^{+}$

4.3.1 Discussion

Although this experiment had limitations related to uncontrolled experimental environment, small sample size, noises interfering experiment, and uncalibrated samples, outcomes were expressive for the soundscape PAQs. Therefore, the experience supported continuation using the ISO's soundscape PAQs to assess human soundscape perception (Carvalho, Davies and Fazenda, 2019).

Results suggested that the increase of population density exerts a significant influence on the uneventful-eventful, monotonous-vibrant, and calm-chaotic PAQs. This indicates that soundscape researchers may need to account for (or at least to measure) this variable in future experiments. This finding was also present in other studies where human sounds indicated eventfulness and the sense of safety (Aletta and Kang, 2018; Bosch *et al.*, 2018). Additionally, the ISO 12913-3 (PD ISO 12913-3, 2019) describes eventful soundscapes as full of human activity (Carvalho, Davies and Fazenda, 2019).

In contrast, results for the PANAS emotional states in the three soundscape conditions were scattered and overlapped. Only the "active" emotional state had a significant effect on the treatment in a positive and increasing trend. Given the lack of expressive outcomes using the PANAS scale, other forms of identifying human emotional states were investigated in the next experiment, such as the Arousal-Valence Space (AVS) model (Russell, 2003) through the Self-Assessment-Manikins (SAM) (Bradley and Lang, 1994), Plutchik's wheel of emotions (Plutchik, 1982) and physiological tests, such as Electroencephalography (EEG) (TSANG *et al.*, 2001).

4.4 Experiment 4: The Manchester Soundscape online experiment (MCR Online)

A total of 17 visits from January to December of 2019 on days with no precipitation were done at Peel Park, Piccadilly Gardens, Market Street, and the bus stop in the three-population density. Market Street in the empty condition was the most problematic to record since it was hardly ever empty. Four trips to this location occurred until it was decided to gather the sample with fewer people: two to three individuals walking by with cars parked on the street. When aligning audio and video stimuli, the azimuth angle was calculated, and results are in table 11. Figure 46 illustrates all final locations with the values for $L_{Aeq,60}$ at the bottom right side of the figure. Sound levels increased with the population density in all scenarios due to human presence (Piccadilly Gardens, Market Street, and Peel Park) and traffic (bus stop). The increment mainly occurred between empty and medium conditions except for the bus stop. In contrast, the dB(A) varied in smaller portions from medium to busy conditions.

TABLE 11: AZIMUTH ANGLES FROM AUDIO SIGNALS FOR ALIGNMENT.

ID	Angle θ
Park Empty	-10,68
Park Medium	-16,8
Park Busy	-1,304
Bus Empty	-71,0591
Bus Medium	59,0348
Bus Busy	37,5055

ID	Angle θ
Plaza Empty	-62,11
Plaza Medium	37,59
Plaza Busy	34,83
Street Empty	-35,84
Street Medium	42,58
Street Busy	-27,37

With stimuli selected and prepared for reproduction, the experiment was launched online from August to November 2020. The 155 participants came from 63 countries, with 75 individuals in Group 1 (Park and the bus stop) and 80 in Group 2 (Plaza and Street). Group 1 consisted of 49% women, 48% males, and 3% who preferred not to say or non-binary aged 21 to 68 years old (38±12). Furthermore, 80% used a computer screen and 20% a smartphone to watch the videos while 76% used a headphone, and 24% external audio to reproduce audio signals during experiment. Regarding hearing health, 89% declared they had no hearing loss and 11% some hearing loss. Meanwhile, 77% mentioned not to have tinnitus, and 23% to have signs of tinnitus (Carvalho, Davies and Fazenda, 2022).

Group 2 included 51% women, 45% males, and 4% who preferred not to say or non-binary with an age range from 21 to 67 (38±11). Additionally, 86% used a computer screen and 2014% a smartphone to watch the videos while 65% used a headphone, and 35% external audio to reproduce audio signals during experiment. Regarding hearing health, 90% declared they had no hearing loss and 10% some hearing loss. Meanwhile, 81% mentioned not to have tinnitus, and 19% to have signs of tinnitus (Carvalho, Davies and Fazenda, 2022).

The results of the Friedman's non-parametric test with pairwise comparisons to observe the differences among population densities are presented in Table 12. All semantic parameters changed with the different number of people in all locations except for the Monotonous to Vibrant PAQs at the bus stop and the dominance scale at the Street. Reported medians across population densities in these conditions were similar: -2 and -1, respectively. The bus stop outcome was monotonous independently of the number of individuals in the scene, corroborating the previous selection of the site as a monotonous place (Session 4.1). From another perspective, the dominance scale consistency independently of the number of individuals at Market Street still needs further investigation if the indifference of the rating demonstrated a lack of understanding of the term or the absence of a sense of safety due to the proximity to people walking by the street (Carvalho, Davies and Fazenda, 2022).

Figure 46: Locations Piccadilly Gardens (a, b, & c), Peel Park (d, e, & f), the bus stop (g, h, & i), and Market Street (j, k, & l) in the three population densities with the one-minute equivalent sound pressure level, $L_{Aeq,60}$, in dB(A) at the conner bottom right of each image.

From the seven tested semantic scales (four PAQs pairs and three SAM emotional states), only six results changed significantly and gradually with the increase of people. They were as follows: Chaotic to Calm PAQs and arousal scale at the Park (Figure 47); Uneventful to Eventful PAQs and Monotonous to Vibrant PAQs at the Plaza (Figure 48); and Uneventful to Eventful PAQs and arousal at the Street (Figure 49) (Carvalho, Davies and Fazenda, 2022).

At the Park, the increased number of people significantly diminishes the perception of calmness towards a perception of chaos (Figure 47a). This concept can be reasonably understandable given that urban parks represent an ecosystem with predominant natural elements, such as different vegetations, types of birds, and small animals. From a perspective of sustainability, these locations need a reduced presence of people to preserve natural urban areas for the local fauna and flora, and to provide possible places for human restoration (Payne, 2013). In addition, when the Park rates as a calm place, this result corroborates with the initial site selection of Peel Park as a calm soundscape indicated in Session 4.1. Also present in the aroused emotional state, a sense of calmness appeared in the absence of people for the empty and medium conditions at the Park (Figure 47b). Likewise, a change in this emotional state was significant with the increase of people on the Street. However, the medians varied from a more neutral score in the empty condition to an excited and alert state in the busy condition (Figure 49b) (Carvalho, Davies and Fazenda, 2022).

The increase in the eventful ratings with the number of people at the Plaza (Figure 48a) and the Street (Figure 49a) corroborates with the description of the Eventful places in part 3 of the soundscape ISO 12913-3 (PD ISO 12913-3, 2019). Furthermore, the shift in the perceived soundscape quality from monotony to vibrancy at the Plaza (Figure 48b) when more individuals are in the scene, confirms the initial site selection representing a vibrant scenario in Manchester (Session 4.1). However, Piccadilly Gardens was considered a vibrant soundscape only when in busy condition (Carvalho, Davies and Fazenda, 2022).

The large number of Brazilian participants led to observe if people would rate differently the conditions in the subjective responses. Sample size was balanced randomly to 37 (Group 1) and 38 (Group 2) participants in each group classified as Brazilians and Other countries. Significant differences among subjective results were observed in 11 semantic scales through the Mann-Whitney U test presented in Table 13 with their medians. Brazilians demonstrated to rate significantly higher the listed semantic scales except on the Monotonous to Vibrant

PAQ for the medium and busy conditions at the Street, and the same PAQ for the medium condition at the bus stop.

TABLE 7: FRIEDMAN'S TEST $X^2(2)$ RESULTS OF THE PAQ SCALES THAT HAD SIGNIFICANT DIFFERENCES WITH THE INCREASE OF POPULATION DENSITY. *SIGNIFICANCE THRESHOLDS FOR PAIRED COMPARISONS HAVE A BONFERRONI CORRECTION.

Location	PAQs	Friedman's test X2(2)	Overall p-value for group differences	p-value* for Pairwise Comparisons		
				Empty vs medium	Empty vs busy	Medium vs busy
Park	Unpleasant to Pleasant	42.625	<0.001	0.000	0.000	0.060
	Uneventful to Eventful	38.835	<0.001	0.000	0.000	0.334
	Mononous to Vibrant	26.867	<0.001	0.013	0.000	0.101
	Chaotic to Calm	58.161	<0.001	0.000	0.000	0.011
	Arousal	54.175	<0.001	0.001	0.000	0.002
	Valence	32.328	<0.001	0.000	0.000	0.662
	Dominance	17.325	<0.001	0.165	0.000	0.165
Bus stop	Unpleasant to Pleasant	70.398	<0.001	0.136	0.000	0.000
	Uneventful to Eventful	15.007	<0.001	0.054	0.001	0.617
	Mononous to Vibrant	0.78	0.677	N/A	N/A	N/A
	Chaotic to Calm	60.596	<0.001	0.181	0.000	0.000
	Arousal	41.595	<0.001	0.000	0.000	1.000
	Valence	48.509	<0.001	0.662	0.000	0.000
	Dominance	23.631	<0.001	0.000	0.000	1.000
Plaza	Unpleasant to Pleasant	47.352	<0.001	1.000	0.000	0.000
	Uneventful to Eventful	80.129	<0.001	0.000	0.000	0.000
	Mononous to Vibrant	61.517	<0.001	0.012	0.000	0.000
	Chaotic to Calm	48.609	<0.001	0.755	0.000	0.000
	Arousal	84.864	<0.001	0.000	0.000	0.089
	Valence	35.668	<0.001	0.158	0.000	0.001
	Dominance	24.087	<0.001	0.013	0.000	0.291
Street	Unpleasant to Pleasant	11.681	0.003	0.537	0.005	0.207
	Uneventful to Eventful	86.457	<0.001	0.000	0.000	0.043
	Mononous to Vibrant	71.456	<0.001	0.000	0.000	0.370
	Chaotic to Calm	28.872	<0.001	0.007	0.000	0.109
	Arousal	35.806	<0.001	0.027	0.000	0.009
	Valence	14.947	<0.001	0.053	0.001	0.707
	Dominance	1.862	0.394	N/A	N/A	N/A

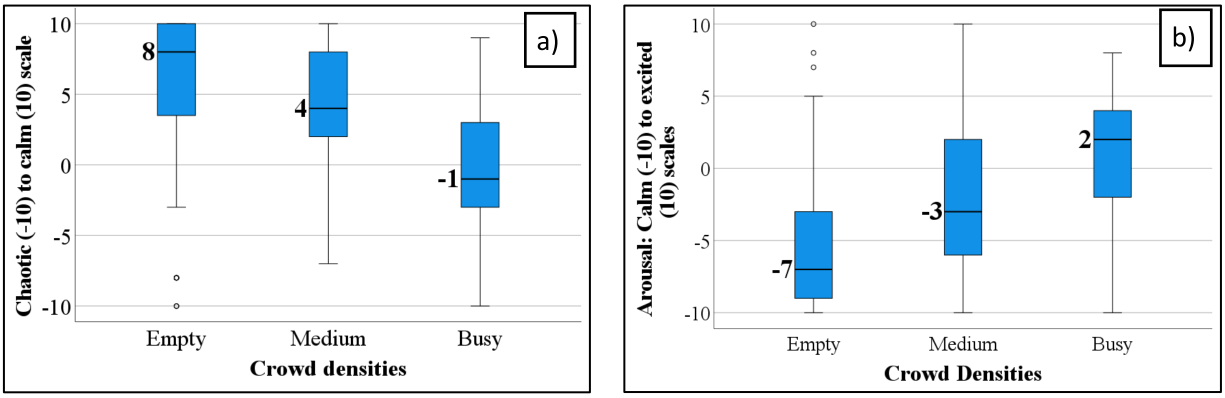


FIGURE 47: BOXPLOTS WITH MEDIANS OF A) CHAOTIC (-10) TO CALM (10) SCALES, AND B) AROUSAL SCALE FROM CALM (-10) TO EXCITED/ALERT (10) AT THE PARK.

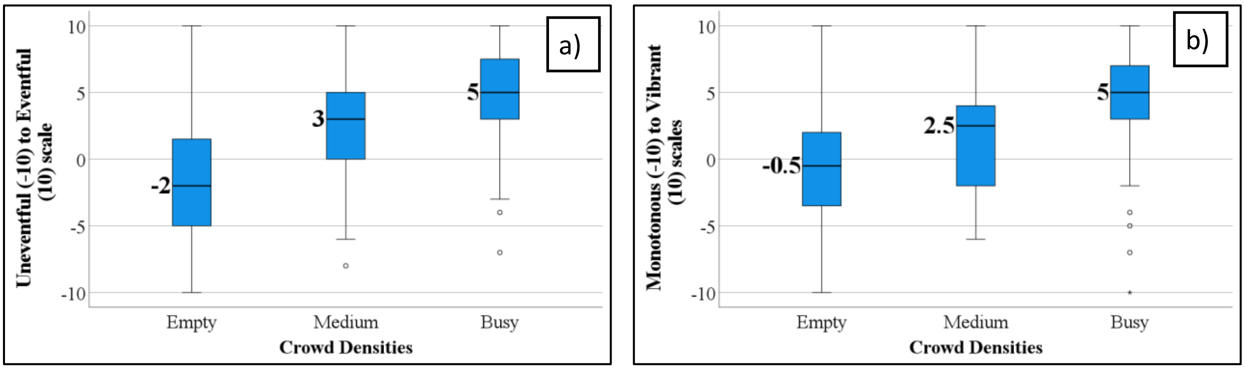


FIGURE 48: BOXPLOTS WITH MEDIANS OF A) UNEVENTFUL (-10) TO EVENTFUL (10) SCALES, AND B) MONOTONOUS (-10) TO VIBRANT (10) SCALES AT THE PLAZA.

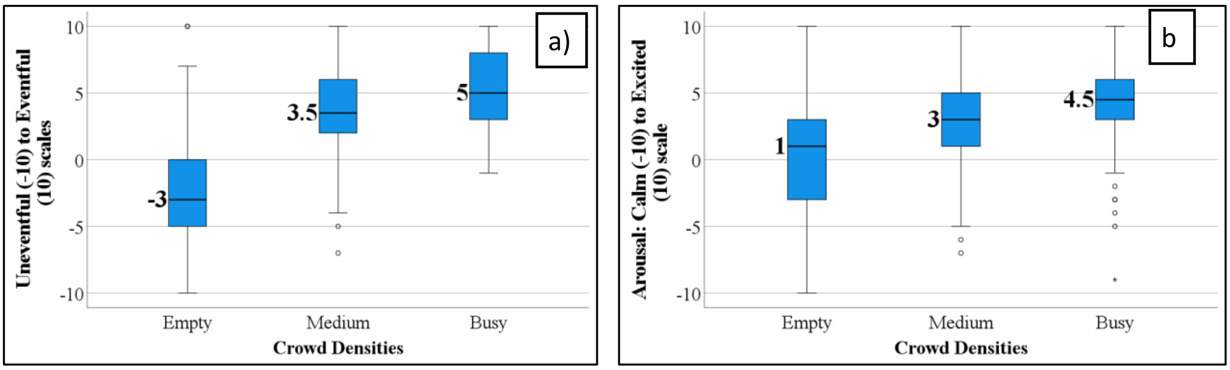


FIGURE 49: BOXPLOTS WITH MEDIANS OF A) UNEVENTFUL (-10) TO EVENTFUL (10) SCALES, AND B) AROUSAL SCALE FROM CALM (-10) TO EXCITED/ALERT (10) AT THE STREET.

TABLE 8: MANN-WHITNEY U TEST RESULTS OF THE SUBJECTIVE RESPONSES THAT HAD SIGNIFICANT DIFFERENCES AMONG BRAZILIANS AND OTHER COUNTRIES.

Location	Density	Semantic scale	Mann-Whitney U test		Medians	
			U	*p*-value	Brazilians	Other countries
Park	empty	Pleasant to Unpleasant	462	0.015	9	6
	empty	Valence	473	0.021	8	5
	medium	Calm to Chaotic	479	0.026	6	4
Bus stop	empty	Eventful to Uneventful	427.5	0.005	2	-2
	medium	Eventful to Uneventful	477	0.024	4	2
	busy	Eventful to Uneventful	452	0.012	5	1
	medium	Vibrant to Monotonous	884	0.030	-4	1
Plaza	busy	Calm to Chaotic	481	0.012	2	-3
Street	empty	Vibrant to Monotonous	490.5	0.016	-4	-6
	medium	Vibrant to Monotonous	944	0.020	2	4
	busy	Vibrant to Monotonous	1051	0.001	2	5
	empty	Eventful to Uneventful	453.5	0.005	-2	-4

4.4.1 Discussion

Running an online soundscape experiment during the pandemic had many challenges, going from digitally implementing with success the stimuli online to giving enough assistance to participants so they could complete it via the web. Benefits can be that the recruitment is not limited to local individuals, there can be a higher number of participants, and experimental completion can be flexible to the schedule of participants. Some downsides are the lack of controlled laboratory conditions, such as constant audio and video reproduction system for all participants, efficient acoustic laboratory settings, and consistent contact between researcher and participant to facilitate the experiment (Carvalho, Davies and Fazenda, 2022).

The main findings were that as population density increased, so did the eventful responses at the Plaza and Street, corroborating the ISO 12913-3 (PD ISO 12913-3, 2019) description of eventful places. Also, the number of people in the scene increased the ratings on the arousal scale at the Park and Street, and the Monotonous to Vibrant PAQ at the Plaza, but decreased the ratings on the Chaotic to Calm PAQs at the Park. Additionally, initial survey to identify the soundscape locations representing the Monotonous, Calm, and Vibrant attributes confirmed by the current results for the bus stop in all population densities, the Park in empty and medium conditions, and the Plaza in the busy condition (Carvalho, Davies and Fazenda, 2022).

Further, Brazilian participants demonstrated different ratings for all PAQs and Valence scales that may be related to cultural differences, unknown European scenarios, and non-validated translations of PAQ words into Portuguese. Many challenges exist in the cross-cultural translation of terms, such as vocabulary, idiomatic, grammatical-syntactic, experimental, and conceptual equivalents (Sechrest, Fay and Zaidi, 1972). These inconsistencies in translations were also encountered in participating countries of the "Soundscape Attribute Translation Project" (SATP) group (Aletta *et al.*, 2020). For instance, there were identified issues in the translated attributes for Eventful (Tarlao *et al.*, 2016; Sudarsono *et al.*, 2021; Mediastika *et al.*, 2022; Papadakis *et al.*, 2022; Antunes *et al.*, 2023), Vibrant (Jeon *et al.*, 2018; Papadakis *et al.*, 2022; Antunes *et al.*, 2023), Uneventful (Antunes *et al.*, 2021, 2022, 2023; Sudarsono *et al.*, 2021; Michalski *et al.*, 2022; Papadakis *et al.*, 2022), Monotonous (Jeon *et al.*, 2018; Antunes *et al.*, 2021, 2022; Michalski *et al.*, 2022; Papadakis *et al.*, 2022), Uneventful (Antunes *et al.*, 2021, 2022; Michalski *et al.*, 2022; Papadakis *et al.*, 2022), Annoying (Jeon *et al.*, 2018; Lam *et al.*, 2022), and Chaotic (Tarlao *et al.*, 2016; Jeon *et al.*, 2018; Sudarsono *et al.*, 2021) attributes.

In specific, the Portuguese group only managed to corroborate the Calm and Pleasant PAQ results from their listening tests with results from the English model (Antunes *et al.*, 2023). For example, authors suggested the Eventful PAQ translation failed to capture the significance of the English word as observed in other studies in Indonesian (Sudarsono *et al.*, 2021), Canadian French (Tarlao *et al.*, 2016), and Greek (Papadakis *et al.*, 2022) languages. Therefore, further investigations with Brazilian participants should continue to translate and validate the PAQ terms within the Portuguese group (Antunes *et al.*, 2023).

From this experiment and publications, new partnerships developed towards the translation of the soundscape attributes to the Portuguese language which resulted in four publications (Antunes *et al.*, 2021, 2022, 2023; Michalski *et al.*, 2022). Additionally, further publications investigated emotional taxonomy (Engel, Carvallho, *et al.*, 2021), memory perceptions (Engel, Carvalho and Davies, 2022), and different methods of assessing soundscapes using VR (in progress).

4.5 Experiment 5: VR & EEG laboratory experiment

A total of nine visits to execute field recordings were done from December 2020 to July 2021 on days with no precipitation forecast in the three different population densities (empty, medium, and busy) at Piccadilly Gardens, Market Street, and Peel Park. With stimuli selected and prepared for reproduction, the experiment with 36 participants took place in the student semi-anechoic chamber of the Acoustic Research Centre from June to August of 2022 at University of Salford, Manchester, UK. They were composed of 64% men and 36% women with average age from XX to XX (32±10) originally from 11 different countries with 47% from the United Kingdom, 17% from India, 6% each from Brazil, Chile, China, and Poland, and 3% each from Ecuador, Egypt, Islamic Republic of Iran, Myanmar, and Pakistan. Furthermore, 75% of them spoke one or two languages, and 25% three or more languages. Their educational level was 86% level 6 or more, and 14% level 4 or 5. Their acoustic or musical background was 64% with little, moderate, or expert experience, and 36% with no experience. Regarding hearing health, 97% declared they had no hearing loss and 3% mild hearing loss. Meanwhile, 83% mentioned not to have tinnitus, and 17% heard infrequently or regularly signs of tinnitus.

4.5.1. Stimuli characteristics

Results for validating the number of people in the selected footage were done through two small surveys during the 17 to 27 of July 2021 presented in Table 14. When the test was done, the medium population density was still considered an experimental stimulus and is considered in this analysis. The first survey demonstrated that the Plaza in the medium population density represented 84% of the busy one. This result led to a second survey with a new extraction of image to achieve better results. Results got to reasonable values with exception to the empty condition for pedestrian Street and Plaza. For the pedestrian Street, the constant occupancy might be because of the high degree of commercial activity of the location. When the stores were closed and there was the presence of day light, construction and maintenance workers, and people going to work were always on scene. For the Plaza, occupancy was reported around 10% in both surveys, which may be related to the lack of refined image resolution described by participants.

When descriptively analysing the footage, each location had a sound signal maintained in all population density that represented a controlled factor (highlighted in grey in Table 14). At the Plaza, sounds from the water fountain were constant with mechanical sounds prevailing when empty. The Street had the “hoot” of the tram always present with mechanical sounds predominant when empty. Meanwhile, the Park had the sound of birds as sustained in all samples and predominant in the empty condition. For the medium and busy conditions, all locations had human sounds as predominant. Results for final SPL and audio angle rotations are presented in table 15.

TABLE 9: RESULTS FROM ONLINE SURVEY FOR VALIDATION OF RESEARCHER'S PEOPLE COUNT FROM IMAGE TO DETERMINE ALL FINAL POPULATION DENSITIES. FIRST SURVEY ON THE TOP AND SECOND SURVEY ON THE BOTTOM.

Condition	FIRST SURVEY											
	Participants										Mean	Frequency
	1	2	3	4	5	6	7	8	9	10		
Empty Park	0	1	0	0	0	0	0	0	0	1	0.2	2%
Medium Park	4	10	6	3	5	3	4	8	4	7	5.4	47%
Busy Park	10	27	5	7	10	12	7	12	6	18	11.4	100%
Empty Plaza	0	1	4	2	6	4	3	10	2	3	3.5	9%
Medium Plaza	26	50	28	13	20	35	38	56	21	35	32.2	84%
Busy Plaza	25	60	25	27	37	45	35	63	30	35	38.2	100%
Empty Street	7	7	5	4	10	4	6	6	1	12	6.2	14%
Medium Street	26	15	22	17	25	12	25	25	26	9	20.2	47%
Busy Street	50	50	47	32	45	45	48	47	34	30	42.8	100%
Condition	SECOND SURVEY											
	Participants										Mean	Frequency
	1	2	3	4	5	6	7	8	9	10		
Empty Park	0	0	0	0	3	0	0	1	0	0	0.4	4%
Medium Park	6	5	4	3	12	2	4	6	9	4	5.5	57%
Busy Park	10	4	10	13	15	6	2	10	14	12	9.6	100%
Empty Plaza	5	3	3	8	10	0	5	10	8	4	5.6	13%
Medium Plaza	20	15	20	15	12	15	10	17	18	15	15.7	37%
Busy Plaza	100	30	40	41	50	19	30	28	37	45	42	100%
Empty Street	10	4	5	11	5	11	5	9	10	6	7.6	17%
Medium Street	20	7	25	28	28	20	15	24	24	20	21.1	47%
Busy Street	100	23	45	51	35	42	15	51	51	39	45.2	100%

Results of Simpson's Diversity Index (SDI), also presents in Table 16, demonstrated different values when combining and separating sound sources individually. That is, when grouping all children's shout by type, the SDI values decreased while outcomes increase when considering each shout as unique. When examining separately, SDI results did not vary with population density as much as when combined by sound type but had values above 0.75 to 0.9. Furthermore, when observing results by source types, SDI values varied more, but not with a tendency to increase or decrease with population density. Exception occurred for the Street where SDI value decreased with the increase of people in the scene. Nevertheless, given initial goal was to select samples rich in soundscape diversity (Liu *et al.*, 2014), *identity*

(Siebein, 2013), *character* (Bento Coelho, 2016), and *soundmarks* (Schafer, 1977), all stimuli had high values of SDI even in empty conditions.

Additionally, final experimental signals used in the psychoacoustic calculus were recorded on the 3rd of August 2022 in the student anechoic chamber of the Acoustic Research Centre of the University of Salford, Manchester, UK. Tables 17 and 18 present results of Sound levels, Loudness, Sharpness, Roughness, Fluctuation Strength, Tonality, and Tonality Threshold metrics, where red cells contain higher single values, and blue cells illustrate the lower single values.

For the Sound Levels, the busy Plaza had the higher values among metrics with exceptions to L_{99} and SPL_{Min} where the busy Street had the superior levels. Meanwhile, the lower sound level parameters were mostly reported in the empty Street with exemptions to the SPL_{Min}, L_{90}, and L_{99} which were measured respectively in the empty Park, empty Street and busy Plaza. Regarding the Loudness metrics, the higher values were for the busy Plaza with exception to N_5/N_{95} that was reported at the busy Park. When observing the lower values of Loudness, the empty Street had the smallest results except for N_5/N_{95} that was identified at the empty Plaza. When examining results for Sharpness, the busy Plaza had the higher values across all metrics. In contrast, the lower values were mostly reported at the busy Park, in addition to other conditions like the empty Plaza, Park, and Street. On the Roughness parameter, the single values were considered low ranging from 0.02 to 0.085 asper. The highest values were observed at 0.18 asper for R_{max} and 0.155 asper for R_1 at the busy Park. Fluctuation strength was also considered to have low values among metrics with the highest values found at the busy Street ranging from 0.12 to 0.14 vacil.

TABLE 10: SPL REGISTERED ON FIELD AND FOA AZIMUTH ANGLE FOR EACH SCENARIO.

Scenario	SPL dB(A)	Angle θ
Park Empty	47.1	22.0
Park Medium	53.9	-16.8
Park Busy	53.9	-25.4
Plaza Empty	64.5	9.6
Plaza Medium	64.5	9.6
Plaza Busy	64.3	14.2
Street Empty	55.1	15.8
Street Medium	61.2	26.2
Street Busy	62.8	41.4

TABLE 11: DESCRIPTIVE AND SDI RESULTS WHERE BOLD WORDS ARE GROUPED SOURCES BY TYPE WITH [A] FOR MECHANIC, [B] FOR TRAFFIC, [C] FOR HUMAN, AND [D] FOR NATURE SOUNDS.

Location	Density	Sound Sources	Number	SDI (combined)
Plaza	Empty	Fountain	Continuous	0.75 (0.38)
		Double beep - high frequency [a]	1	
		Double beep - low frequency [a]	1	
		Continuous machine noise [a]	1	
	Medium	Fountain	Continuous	0.75 (0.68)
		Chat	1	
		Horn [b]	1	
		Traffic [b]	1	
	Busy	Fountain	Continuous	0.90 (0.54)
		Chat [c]	3	
		Kid's shout [c]	3	
		Tram [b]	2	
		Breaks [b]	1	
Street	Empty	**Traffic** [b]	Continuous	0.83 (0.61)
		Tram [b]	1	
		Double snap w/freq. interval [a]	1	
		Chat	1	
		Mechanical noise [a]	1	
		Single snap [a]	1	
	Medium	**Babble** [c]	Continuous	0.88 (0.53)
		Tram	1	
		Chat [c]	4	
		Sharp snap	2	
	Busy	**Babble** [c]	Continuous	0.88 (0.41)
		Tram	1	
		Snap	1	
		Footsteps [c]	5	
Park	Empty	**Bird 1 (Pica Pica)** [d]	1	0.80 (0)
		Bird 2 (Eurasian Wren) [d]	1	
		Bird 3 (Redwing) [d]	1	
		Bird 4 (Eurasian Tree Cree or Jay) [d]	1	
	Medium	Bird (Little Ringed Plover)	1	0.80 (0.64)
		Kid's voice	2	
		Mechanical snap [a]	1	
		Undefined noise [a]	1	
	Busy	Bird (unrecognizable - too noisy)	1	0.88 (0.22)
		Kid's voice [c]	3	
		Kid's shout [c]	1	
		Football kicks [c]	3	

TABLE 12: SOUND LEVELS, LOUDNESS, SHARPNESS, AND ROUGHNESS METRICS FOR SOUNDSCAPE STIMULI WHERE RED CELLS REPRESENT HIGHEST VALUE AND BLUE CELLS LOWEST VALUES WHEN COMPARED ACROSS CONDITIONS.

	Conditions	Plaza Empty	Plaza Busy	Park Empty	Park Busy	Street Empty	StreetBusy
Sound Levels in dB(A)	L	62.87	**67.64**	60.17	62.79	57.34	65.85
	SPL_{Min}	46.8	39.7	39.21	45.36	45.62	**53.51**
	SPL_{Max}	64.69	**76.58**	63.27	69.76	62.09	71.36
	L_1	64.44	**75.58**	63.04	67.55	61.79	70.08
	L_5	63.9	**70.48**	62.49	66.17	59.03	68.32
	L_{10}	63.77	**68.99**	61.98	64.69	58.44	67.67
	L_{50}	62.99	**67.14**	59.98	62.67	57.32	65.56
	L_{90}	62.08	**65.22**	58.21	57.79	63.72	55.54
	L_{95}	57.75	**60.36**	54.22	56.86	50.61	59.61
	L_{99}	48.16	43.4	44.14	46.27	45.97	**53.94**
Loudness in sones	N_5	18.83	**26.78**	16.51	18.63	12.26	21.34
	N_{max}	20.58	**31.36**	18.42	25.86	15.54	29.00
	N_1	19.70	**29.17**	17.72	19.92	14.46	22.57
	N_5	18.83	**26.78**	16.51	18.63	12.26	21.34
	N_{10}	18.53	**26.17**	15.72	18.08	11.93	20.57
	N_{50}	17.35	**23.72**	13.69	15.93	11.01	18.73
	N_{90}	15.94	**20.66**	11.94	11.41	9.49	16.20
	N_{95}	11.06	**14.02**	8.75	9.08	6.01	10.72
	N_{99}	3.91	**4.84**	3.27	3.32	2.39	4.50
	$N_{avg\ arit}$	16.82	**23.01**	13.46	15.09	10.61	18.13
	N_5/N_{95}	1.70	1.91	1.89	**2.05**	2.04	1.99
Sharpness in acum	S	1.695	**1.835**	1.33	1.305	1.305	1.425
	S_{max}	1.91	**3.075**	1.765	1.545	1.6	1.7
	S_1	1.86	**2.855**	1.675	1.515	1.525	1.65
	S_5	1.81	**2.09**	1.59	1.44	1.445	1.59
	S_{10}	1.785	**1.95**	1.505	1.395	1.41	1.55
	S_{50}	1.705	**1.805**	1.315	1.305	1.3	1.425
	S_{90}	1.61	**1.705**	1.2	1.215	1.205	1.305
	S_{95}	1.575	**1.68**	1.17	1.19	1.185	1.27
	S_{99}	1.48	**1.64**	1.13	1.035	1.155	1.215
Roughness in asper	R	0.02	0.02	0.03	0.03	0.02	0.03
	R_{max}	0.04	0.055	0.05	**0.18**	0.045	0.085
	R_1	0.04	0.05	0.045	**0.155**	0.045	0.07
	R_5	0.035	0.035	0.04	0.07	0.035	0.05
	R_{10}	0.03	0.03	0.04	0.04	0.03	0.045
	R_{50}	0.02	0.02	0.03	0.03	0.02	0.03
	R_{90}	0.02	0.02	0.02	0.02	0.02	0.02
	R_{95}	0.015	0.015	0.02	0.02	0.02	0.02
	R_{99}	0.01	0.01	0.01	0.01	0.01	0.02

TABLE 13: FLUCTUATION STRENGTH, TONALITY, AND TONALITY THRESHOLD METRICS FOR SOUNDSCAPE STIMULI WHERE RED CELLS REPRESENT HIGHEST VALUE AND BLUE CELLS LOWEST VALUES WHEN COMPARED ACROSS CONDITIONS.

Conditions		Plaza Empty	Plaza Busy	Park Empty	Park Busy	Street Empty	StreetBusy
Fluctuation Strenght in vacil	F	0.02	0.03	0.03	0.03	0.02	0.04
	F_{max}	0.11	0.11	0.10	0.09	0.10	**0.14**
	F_1	0.11	0.11	0.10	0.09	0.10	**0.14**
	F_5	0.10	0.10	0.09	0.08	0.09	**0.13**
	F_{10}	0.09	0.09	0.08	0.08	0.08	**0.12**
	F_{50}	0.00	0.02	0.03	0.02	0.01	0.02
	F_{90}	0.00	0.01	0.01	0.01	0.00	0.01
	F_{95}	0.00	0.00	0.00	0.00	0.00	0.00
	F_{99}	0.00	0.00	0.00	0.00	0.00	0.00
	9/vacil	0.08	0.09	0.09	0.08	0.08	**0.12**
Tonality in dB	T	0.09	**0.29**	0.14	**0.29**	0.05	0.13
	T_{max}	0.44	**2.14**	0.51	1.82	0.17	0.64
	T_1	0.33	**1.80**	0.47	1.67	0.13	0.50
	T_5	0.21	0.84	0.31	**1.20**	0.08	0.30
	T_{10}	0.15	0.58	0.27	**0.76**	0.06	0.23
	T_{50}	0.03	**0.15**	0.10	0.11	0.02	0.10
	T_{90}	0.00	0.02	0.03	0.02	0.00	0.02
	T_{95}	0.00	0.01	0.02	0.01	0.00	0.02
	T_{99}	0.00	0.00	0.01	0.00	0.00	0.01
	$T_{avg\ arit}$	0.06	**0.25**	0.13	**0.25**	0.02	0.11
Tonality Threshold in tuHMS	T_{NR}	0.00	**10.29**	0.81	0.62	0.00	0.00
	T_{NRmax}	0.00	**10.29**	0.41	0.62	0.00	0.00
	T_{NR1}	0.00	**6.53**	0.00	0.00	0.00	0.00
	T_{NR5}	0.00	**6.53**	0.00	0.00	0.00	0.00
	T_{NR10}	0.00	0.00	0.00	0.00	0.00	0.00
	T_{NR50}	0.00	0.00	0.00	0.00	0.00	0.00
	T_{NR90}	0.00	0.00	0.00	0.00	0.00	0.00
	T_{NR95}	0.00	0.00	0.00	0.00	0.00	0.00
	T_{NR99}	0.00	0.00	0.00	0.00	0.00	0.00
	$T_{NRavg\ arit}$	0.00	**1.93**	0.00	0.00	0.00	0.00
	$T_{NR\ Penality}$	0.00	**5.00**	0.00	0.00	0.00	0.00

When observing Tonality in dB, higher values were scattered among the busy Plaza and Park while the lower values were predominant in the empty Street and Plaza. Finally, the Tonality with threshold demonstrated contrasting values ranging from zero to 10.29 tuJMS with the higher values at the busy Plaza.

4.5.2. Plutchik's wheel of emotions

Results for frequencies are presented in Table 19, and for the Chi-square goodness-of-fit test with the Plutchik's Emotion Wheel results is presented in Table 20. Only the busy Plaza and empty Park had statistically significant proportion in the selected emotions with over half participants perceiving the scenario with "joy" (19 individuals, $\chi^2(3) = 15.778$, $p = 0.001$) and "serenity" (23 participants, $\chi^2(3) = 30.00$, $p < 0.001$) respectively. All other conditions (empty Plaza, busy Park, empty Street, and busy Street) indicated that the selected emotions for the scenes did not have a significant proportion among selected emotions.

4.5.3. ISO's PAQs

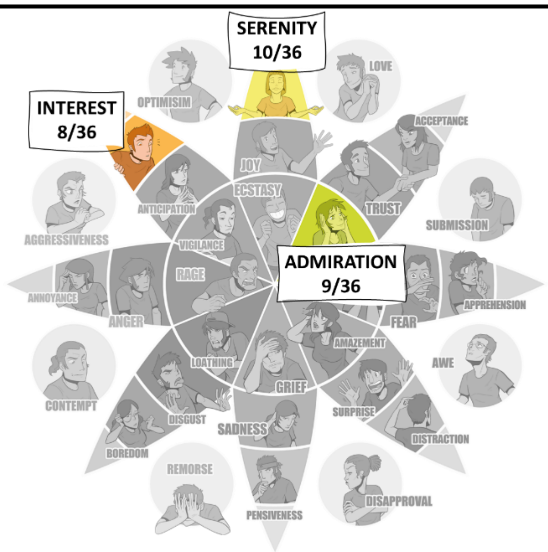
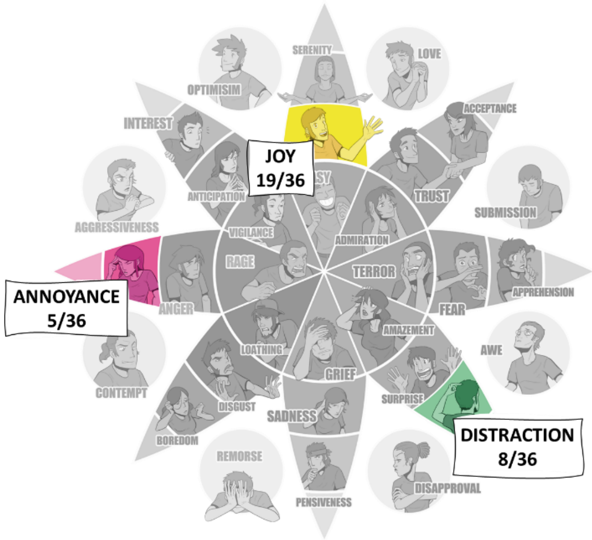
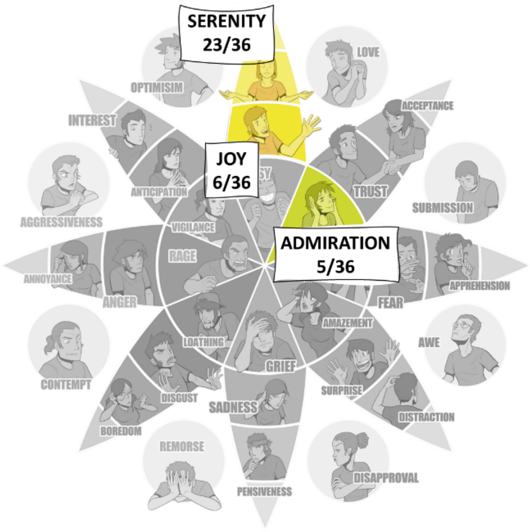
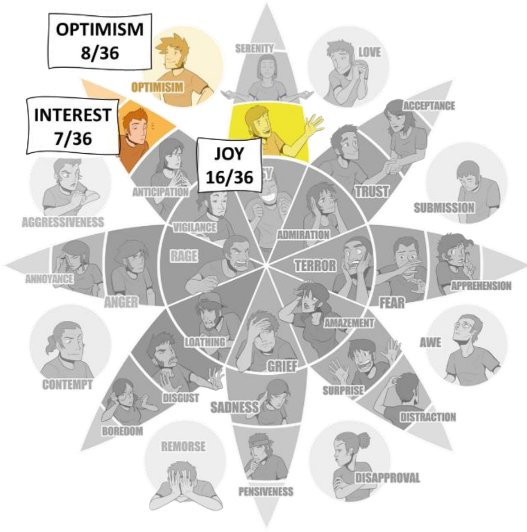
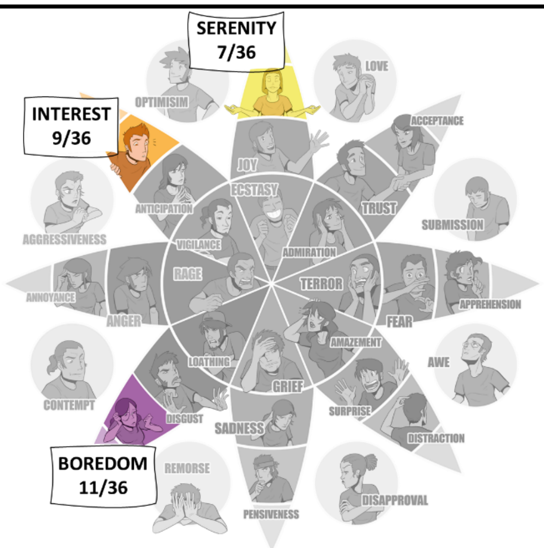
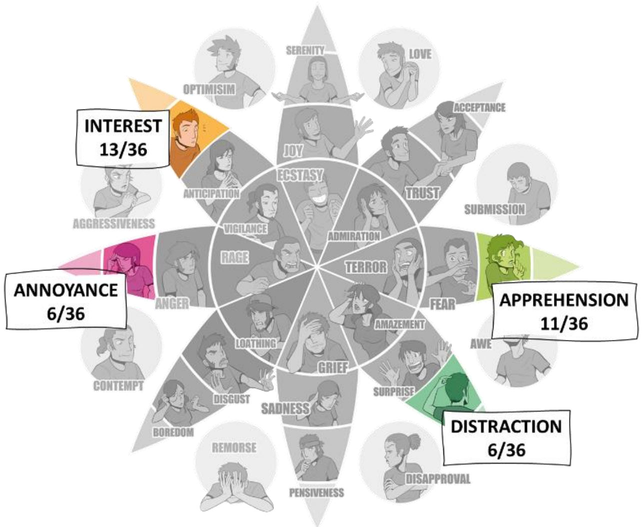
Raw PAQ datasets are presented through boxplots for empty and busy conditions of the Plaza (Figure 50), the Park (Figure 51), and the Street (Figure 52). All PAQs significantly changed with population density. Exceptions were for the Annoying scale for the Park and Street, and the Vibrant scale for the Street indicating participants perceived these locations in the same way independently of the number of people. PAQ ratings increased when locations were busy for the Annoying PAQ at the Plaza and Street, the Chaotic PAQ at the Plaza, the Vibrant PAQ at the Plaza and Park, the Monotonous and Uneventful PAQs at the Street and Park, and the Eventful PAQ at all locations. Meanwhile, Calm and Pleasant scores decreased with the number of people in all locations. Important to report is that even though there was a reduction in pleasantness in busy conditions, the Plaza and Park still had high values for the Pleasant PAQ with respectively 31 and 50 mean scores (range of -100 to 100). That is, these locations can still be considered pleasant when compared to the pedestrian street independently of the number of people in the scene.

TABLE 14: THE CHI-SQUARE GOODNESS-OF-FIT TEST VALUES FOR CHI-SQUARE (χ^2), DEGREES OF FREEDOM (DF), AND THE SIGNIFICANCE LEVEL (ASYMP. SIG.) ARE PLACED BY ROWS, AND LOCATION AND POPULATION DENSITY POSITIONED BY COLUMN.

Parameters	Empty Plaza	Busy Plaza	Empty Park	Busy Park	Empty Street	Busy Street
Chi-square	3.722[a]	15.778[b]	30.0[b]	7.778[b]	5.111[a]	4.222[b]
df	4	3	3	3	4	3
Asymp. Sig.	0.445	0.001	<0.001	0.051	0.276	0.238

[a] The minimum expected cell frequency is 7.2.
[b] The minimum expected cell frequency is 9.

TABLE 15: THE TOP EMOTIONS SELECTED FOR EACH SOUNDSCAPE LOCATION (LINES) AND CROWD DENSITIES (COLUMNS) PLOT OVER PLUTCHIK'S EMOTIONAL WHEEL. THE HIGHLIGHTED BOXES INCLUDE WORDS WITH THE NUMBER OF OCCURRENCES OVER TOTAL PARTICIPANTS.

<table>
<tr><th></th><th>Empty</th><th>Busy</th></tr>
<tr><td>Plaza</td><td>
</td><td>
</td></tr>
<tr><td>Park</td><td>
</td><td>
</td></tr>
<tr><td>Street</td><td>
</td><td>
</td></tr>
</table>

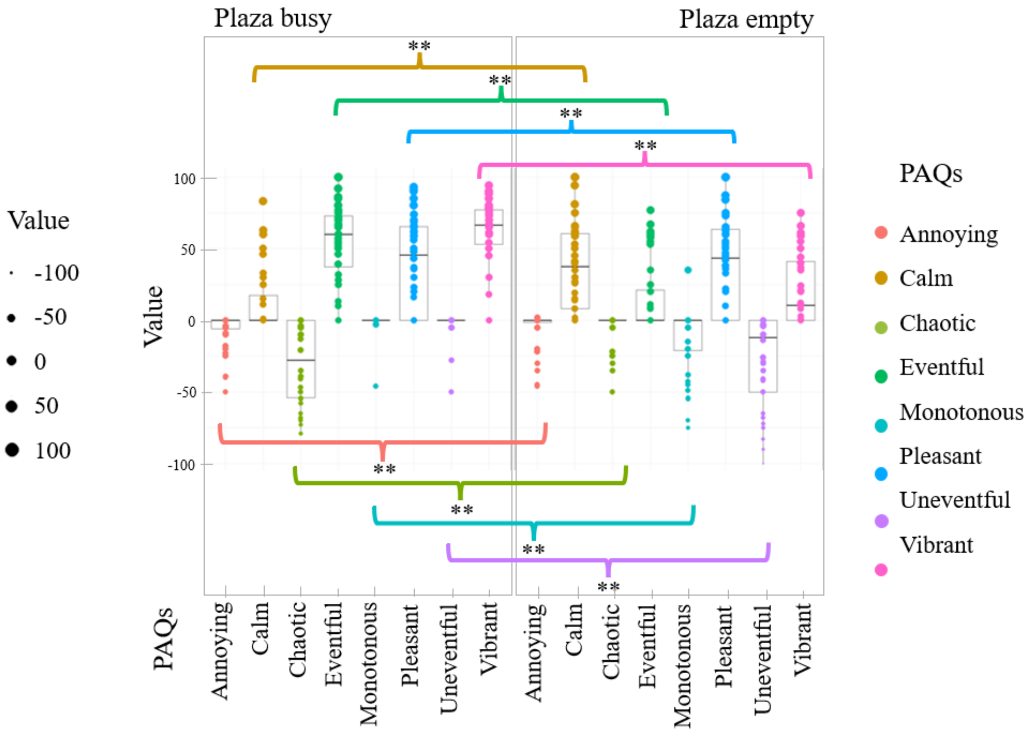


FIGURE 50: PAQS BOXPLOTS FOR EMPTY AND BUSY PLAZA WHERE BRACKETS ILLUSTRATE SIGNIFICANT DIFFERENCES WITH * FOR P-VALUE < 0.05 AND ** FOR P-VALUE < 0.001.

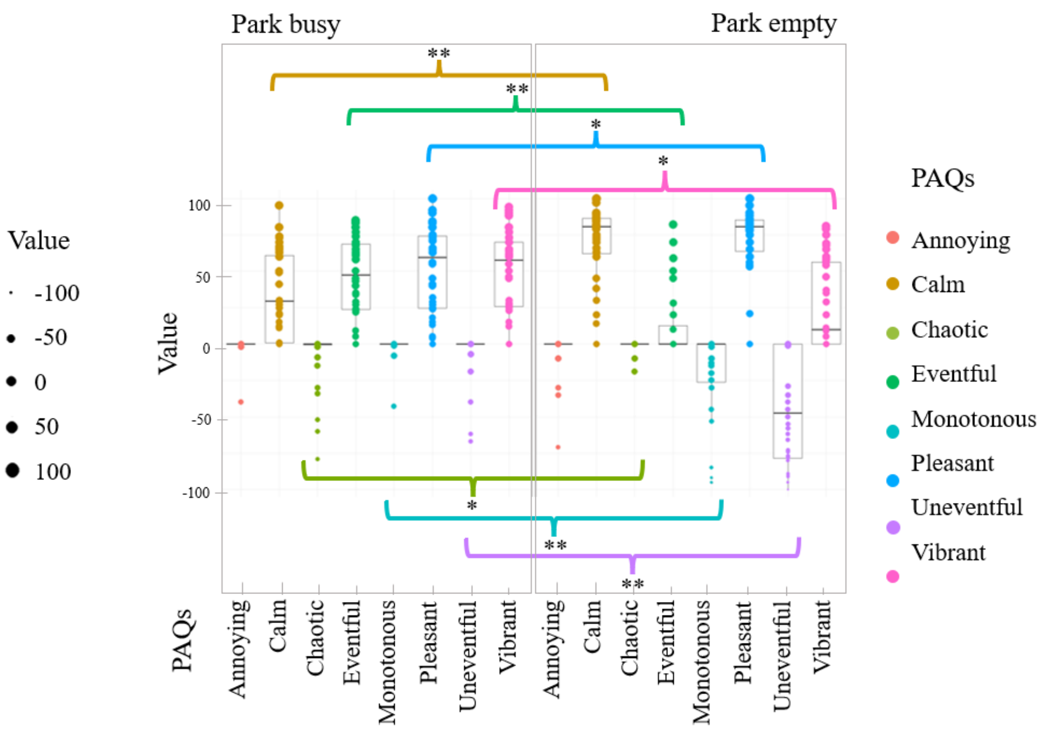


FIGURE 51: PAQS BOXPLOTS FOR EMPTY AND BUSY PARK WHERE BRACKETS ILLUSTRATE SIGNIFICANT DIFFERENCES WITH * FOR P-VALUE < 0.05 AND ** FOR P-VALUE < 0.001.

FIGURE 52: PAQS BOXPLOTS FOR EMPTY AND BUSY STREET WHERE BRACKETS ILLUSTRATE SIGNIFICANT DIFFERENCES WITH * FOR P-VALUE < 0.05 AND ** FOR P-VALUE < 0.001.

Furthermore, PAQs results for same population density were compared among locations separately for empty and busy conditions (Figure 53). In interpreting these results, dissimilarities in PAQ ratings among locations would be expected given they are different sites with distinct urban functions and context. Therefore, observing similar PAQ results becomes relevant in terms of non-significant results. For the Plaza and the Street, both locations reported to be annoying (neutral scores) and pleasant (positive) in both densities, in addition to calm (positive), and chaotic (neutral) when empty. Meanwhile, the Park and Street were considered annoying (neutral) when empty and uneventful (neutral) when busy. Moreover, the Park and Plaza was perceived similarly in the PAQs of Eventful (neutral for empty, and positive for busy), Monotonous (neutral for both), Vibrant (positive for both), Annoying (neutral for empty), Chaotic (neutral for empty), Pleasant (positive for busy) and Uneventful (neutral for busy). In short, the comparison of PAQ results among locations demonstrated that the Park and Street were the most distinct locations while the Park and Plaza shared more similarities.

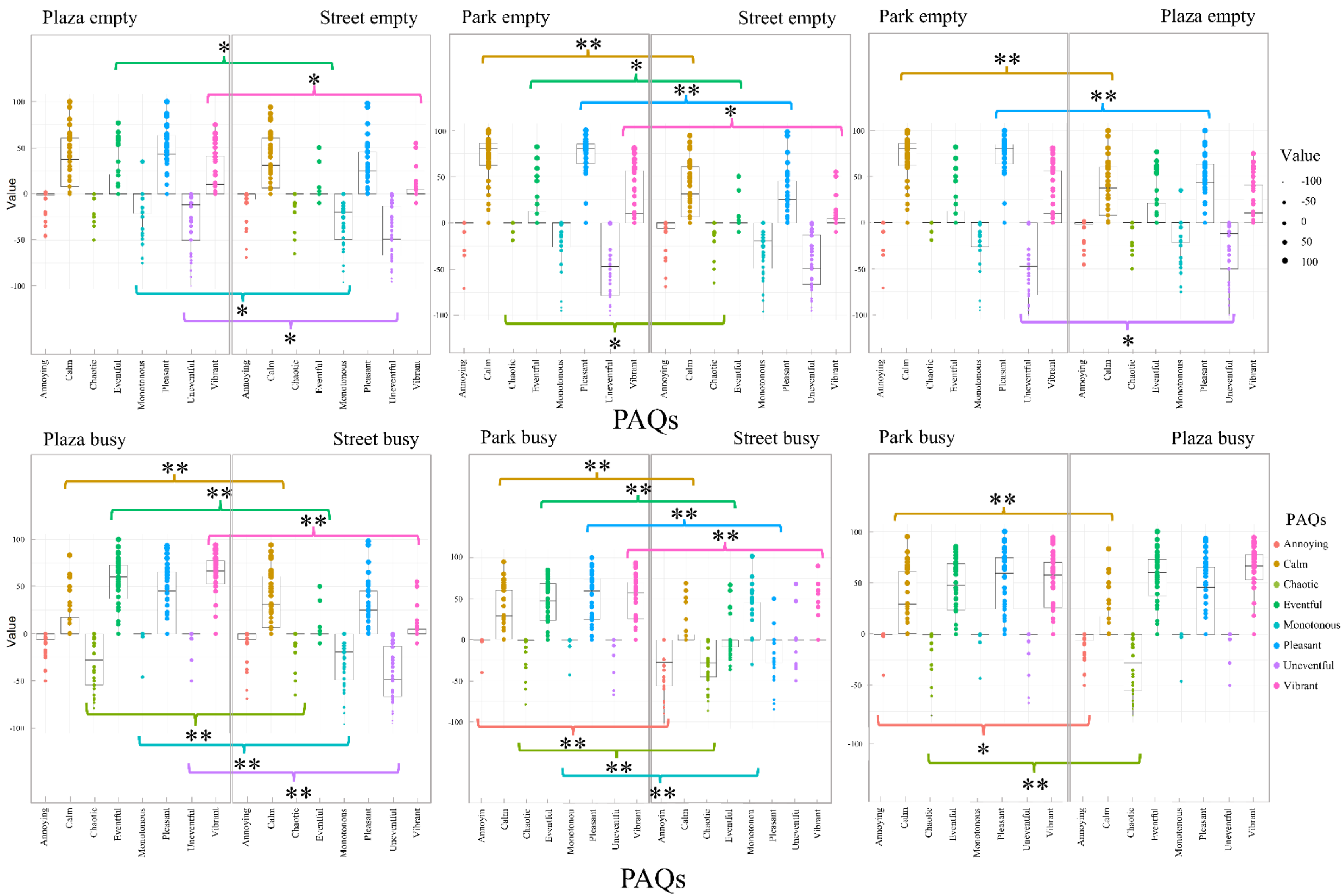


Figure 53: Boxplots comparing differences among locations in the same population density where brackets illustrate significant differences with * for p-value < 0.05 and ** for p-value < 0.001.

Next, the PAQs results were plotted into the two-dimensional model for pleasantness and eventfulness of the PD ISO 12913-3:2019 (PD ISO 12913-3, 2019). First, the original scale was converted from zero (not at all) to 100 (extremely) to the standards strongly agreed (5) to strongly disagree (1). Figure 54 presents a scatterplot all data with confidence ellipses and centroids, and figure 55 illustrates the medians of the ISO-*P* and ISO-*E* results over the standard's two-dimensional model. Ellipses demonstrated tendencies for the Park to be mainly on the pleasant side of the axis while the Plaza and the Street had overlaps on both pleasant and annoying scales. When population densities changed, ellipses shifted from the uneventful (empty) to eventful (busy) scale being the busy Plaza predominantly on the eventful side of the axis.

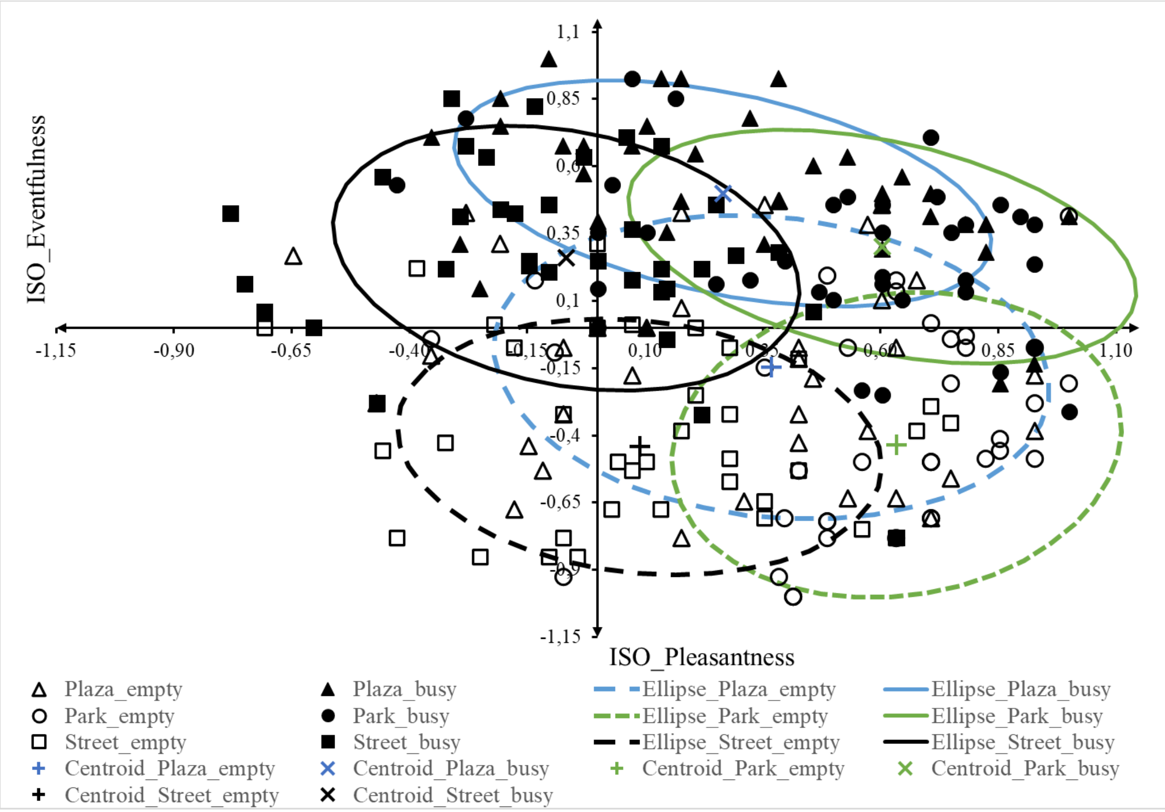


FIGURE 54: SCATTERPLOT OF ISO-*P* AND ISO-*E* FOR EACH SITE AND POPULATION DENSITY OVER THE TWO-DIMENSIONAL MODEL FOR PLEASANTNESS AND EVENTFULNESS WITH EACH PARTICIPANTS SCORES, CONFIDENCE ELLIPSES, AND CENTROIDS.

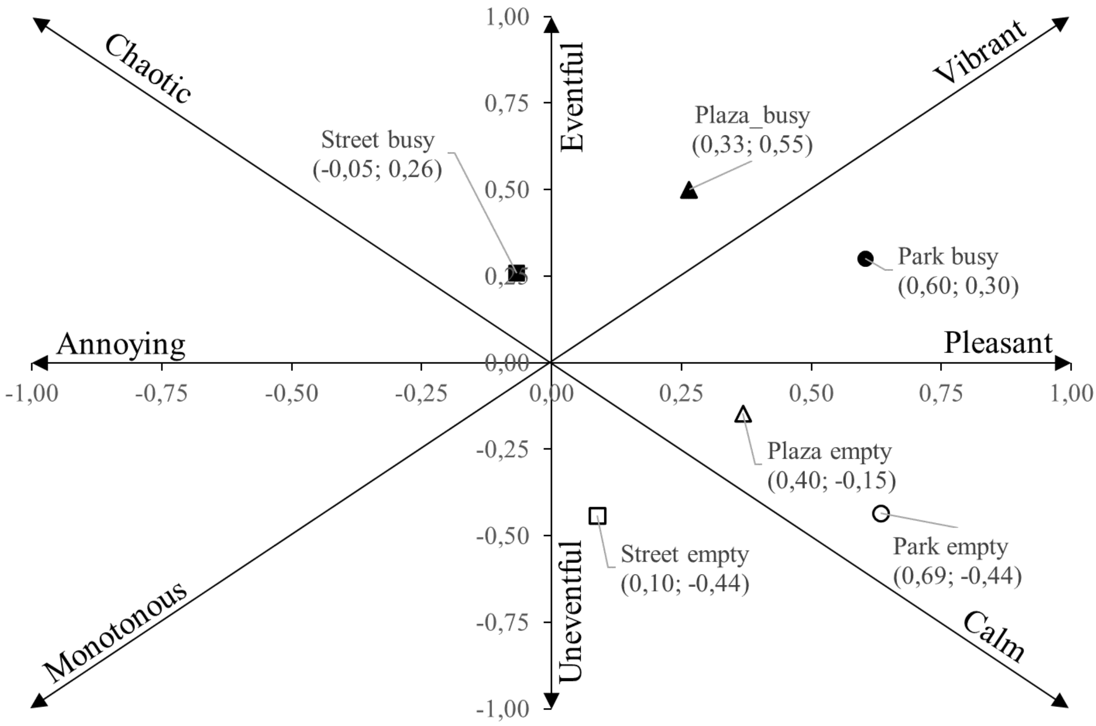


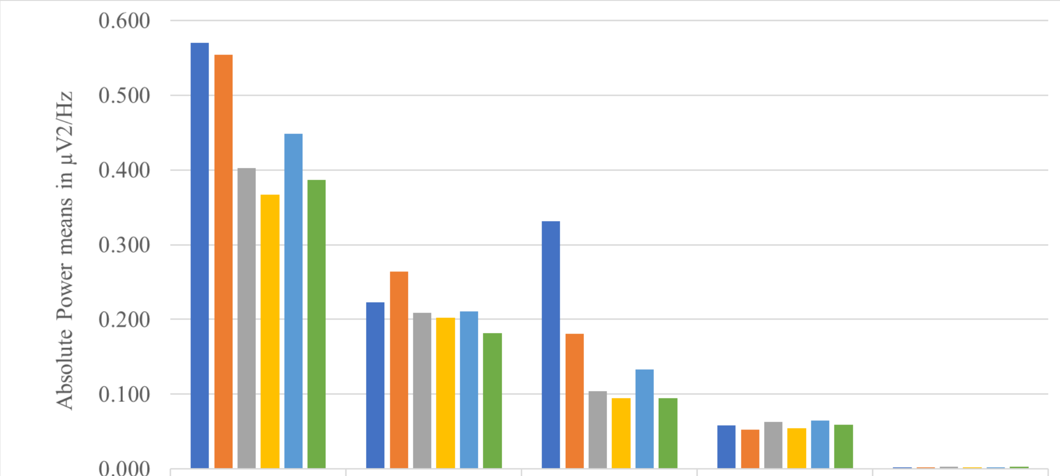
FIGURE 55: ISO-*P* AND ISO-*E* MEDIANS FOR EACH SITE AND POPULATION DENSITY OVER THE TWO-DIMENSIONAL MODEL FOR PLEASANTNESS AND EVENTFULNESS. WHERE ▲ IS BUSY PLAZA, Δ IS EMPTY PLAZA, ● IS BUSY PARK, ○ IS EMPTY PARK, ■ IS BUSY STREET, AND □ EMPTY STREET.

It is interesting to observe that when empty, all locations are placed over the Calm quadrant. Meanwhile, the Plaza and Park are positioned over the Vibrant quadrant when busy. Again, as observed through figure 54 and 55, both the Plaza and Park demonstrate to be perceived as pleasant independently of the number of people in the scene.

4.5.5. EEG readings

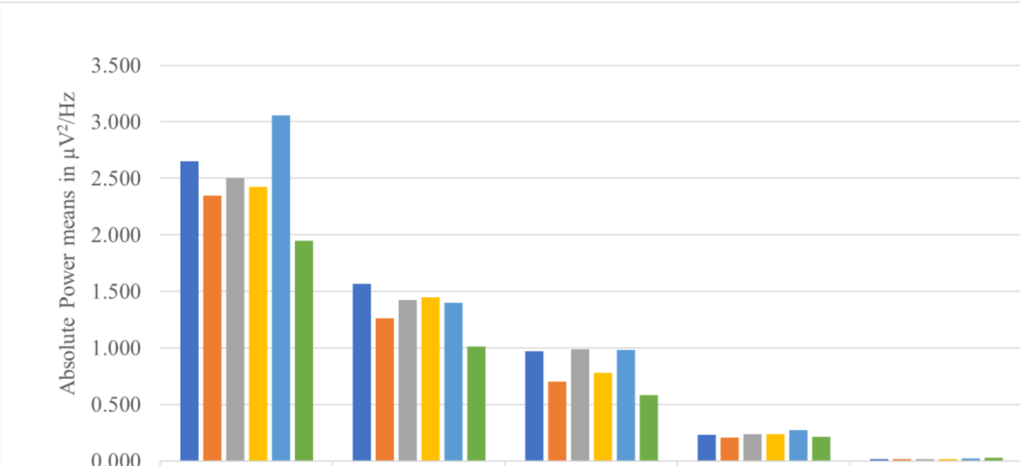
Given experimental duration with 40 stimuli repeats became exhausting for participants, the researcher reduced the experiment to 32 repeats distributed in four sessions of 10 minutes each. Even so, the participant's average stay in the laboratory was of two and half hours. Once sessions were maintained consistent, identical experimental protocol was conducted until the end with 30 participants.

Initially, EEG data analysis was explored through the observation of two participants. Figures 56 and 57 presents the Absolute Power means in $\mu V^2/Hz$ for all sensors and conditions separated by brain waves of participants 1 and 2 of their first session. Important to notice is that Gamma band had small absolute power for both individuals which led to the elimination of it from analysis. In addition, an expressive difference in Absolute Power among participants 1 (Fig. 59 – up to 0.57 µV^2/Hz) and 2 (Fig. 60 – up to 3.05 µV^2/Hz) was observed also leading to observe differences among participants. Nevertheless, a similar increasing tendency when locations were empty was observed in alpha power. This observation led to further investigation towards alpha power.



	Delta (1-4)	Theta (4-8)	Alpha (8-13)	Beta (13-30)	Gamma (30-80)
Street empty	0.570	0.223	0.331	0.058	0.002
Street busy	0.554	0.264	0.181	0.053	0.002
Plaza empty	0.402	0.209	0.104	0.063	0.003
Plaza busy	0.367	0.202	0.094	0.054	0.002
Park empty	0.449	0.211	0.133	0.065	0.002
Park busy	0.387	0.182	0.094	0.059	0.003

FIGURE 56: ABSOLUTE POWER MEANS IN µV^2/HZ FOR ALL SENSORS AND CONDITIONS SEPARATED BY BRAIN WAVES OF PARTICIPANT 1.



	Delta (1-4)	Theta (4-8)	Alpha (8-13)	Beta (13-30)	Gamma (30-80)
Street Empty	2.651	1.565	0.971	0.230	0.017
Street Busy	2.346	1.262	0.698	0.207	0.015
Plaza Empty	2.502	1.420	0.986	0.237	0.017
Plaza Busy	2.422	1.446	0.781	0.237	0.017
Park Empty	3.053	1.398	0.981	0.269	0.020
Park Busy	1.948	1.012	0.579	0.211	0.028

FIGURE 57: ABSOLUTE POWER MEANS IN µV^2/HZ FOR ALL SENSORS AND CONDITIONS SEPARATED BY BRAIN WAVES OF PARTICIPANT 2.

Figure 58 presents the boxplot for alpha power results in μV²/Hz at different brain regions of all conditions and participants in all sessions where outputs are scattered and overlap. Due to this divergence among results, a cluster analysis to group similar responses was conducted. However, when running analysis per condition, clusters demonstrated different groupings for each of the six stimuli which prevented further investigations to compare group differences. Therefore, all conditions were included to run the cluster analysis.

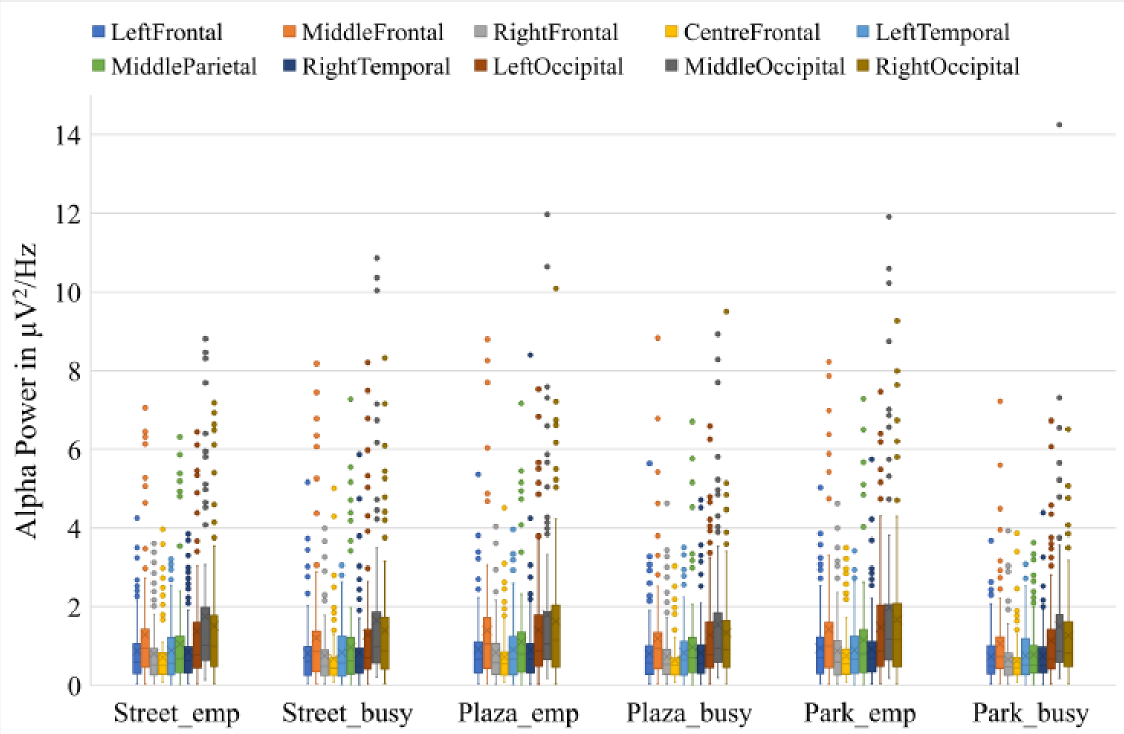


FIGURE 58: BOXPLOT OF ALPHA POWER AT DIFFERENT BRAIN REGIONS IN μV²/HZ FOR ALL PARTICIPANTS AND CONDITIONS.

After running different clustering methods, the Ward's Hierarchical Cluster analysis was applied because results presented a more even distribution of participants among groups. Figure 59 presents the dendrogram with alpha power of ten brain regions in the six conditions for all sessions. Graph demonstrates three groups of 3, 11, and 16 individuals each. Quality of clusters was confirmed through 0.6 average Silhouette, 5.33 ratio size (largest cluster to smallest cluster), and Chi-Square goodness of fit value of 8.6 with *p*-value of 0.014.

Interesting to report is that participants 8, 24 and 29 were always grouped together independently of the type of cluster methods applied. When looking into them, their alpha power was above 3 μV²/Hz with maximum value of 14 μV²/Hz for participant 29. In specific, this participant mentioned experiment was "hard to switch on/off from emotions" when exposed to the different conditions, demanded mental effort, and got “tired in the third session”. Additionally, the person demonstrated to be worried with matters outside the experiment which could represent multi thinking, lack of concentration, or distraction during data collection. This behaviour was considered to compromise the EEG readings because of the non-experimental related thoughts.

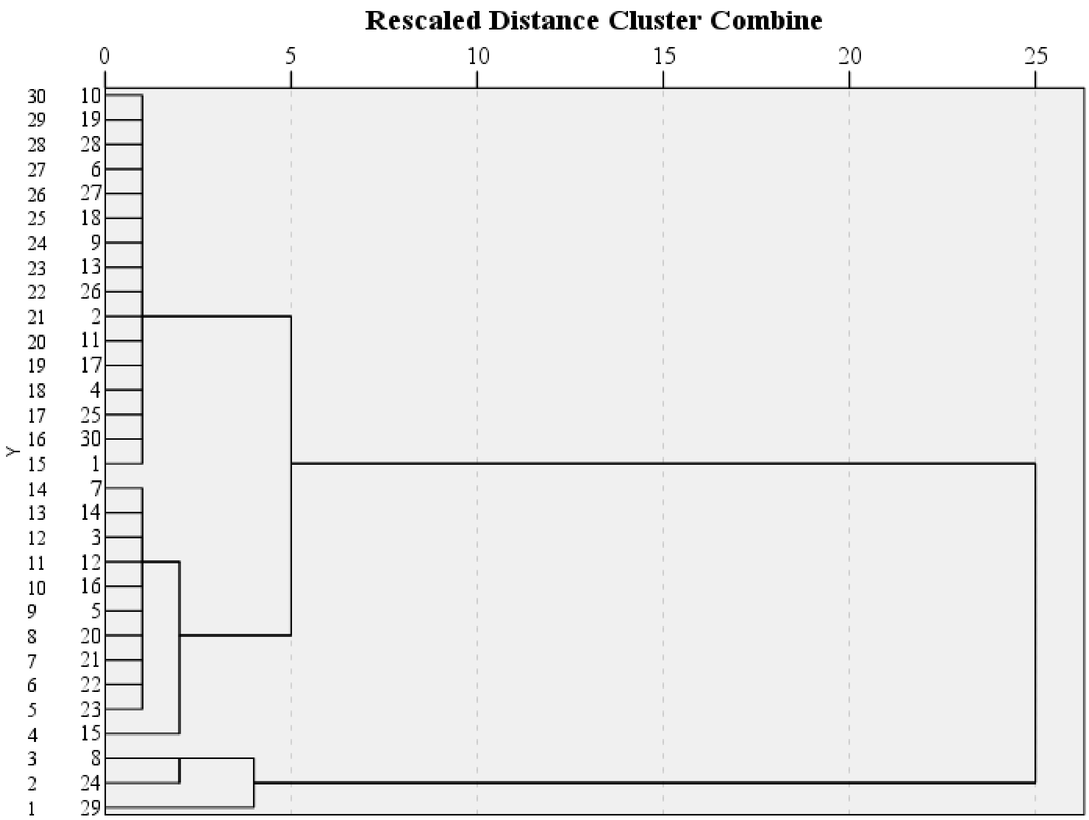


FIGURE 59: WARD’S HIERARCHICAL CLUSTER ANALYSIS DENDROGRAM OF 30 PARTICIPANTS WITH ALPHA POWER RESULTS OF ALL CONDITIONS.

Next, only the groups with 16 (Cluster 1) and 11 participants (Cluster 2) were further investigated. Cluster 1 was composed of 56% men and 44% women with average age 35 (S.D. 11) originally from nine different countries with 44% from the United Kingdom, 13% from India, and 6% each from Brazil, Chile, China, Egypt, Pakistan, Myanmar, and Poland. Furthermore, 69% of them spoke one or two languages, and 31% three or more languages. Their educational level was 81% level 6 or more, and 19% level 4 or 5. Their acoustic or musical background was 50% with little, moderate, or expert experience, and 50% with no experience. Regarding hearing health, all declared they had no hearing loss while 13% mentioned to have tinnitus infrequently.

Meanwhile, cluster 2 was composed of 55% men and 45% women with average age 30 (S.D. 8) originally from five different countries with 45% from the United Kingdom, 27% from India, and 9% each from Chile, Islamic Republic of Iran, and Poland. Furthermore, 73% of them spoke one or two languages, and 27% three or more languages. Their educational level was 91% level 6 or more, and 9% level 4 or 5. Their acoustic or musical background was 73% with little, moderate, or expert experience, and 27% with no experience. Regarding hearing health, all declared they had no hearing loss while 9% mentioned to have tinnitus infrequently.

Table 21 presents the mean values with difference between population density of the EEG Alpha Power for Cluster 1 and 2 in all conditions at the ten brain regions. Difference among empty and busy condition is named Delta value and placed right below results of each location. Superior values of alpha power delta were observed for the Park followed by the Plaza in cluster 2. Meanwhile, the highest values of alpha power delta in cluster 1 appeared for the Park at the occipital regions.

Table 16: Mean and delta values of EEG Alpha Power for Cluster 1 and 2 in all conditions at the ten brain regions.

Cluster	Conditions	Left Frontal	Middle Frontal	Right Frontal	Centre Frontal	Left Temporal	Middle Parietal	Right Temporal	Left Occipital	Middle Occipital	Right Occipital
	Park_empty	0.42	0.62	0.35	0.35	0.35	0.43	0.42	0.59	0.76	0.73
	Park_busy	0.32	0.46	0.28	0.31	0.30	0.32	0.34	0.47	0.63	0.51
	Delta value	0.10	0.16	0.07	0.05	0.05	0.12	0.08	0.12	0.13	0.22
	Street_empty	0.35	0.51	0.29	0.32	0.31	0.36	0.36	0.48	0.70	0.56
1	Street_busy	0.32	0.46	0.28	0.29	0.29	0.32	0.34	0.46	0.63	0.51
	Delta value	0.03	0.05	0.01	0.02	0.02	0.03	0.03	0.02	0.07	0.06
	Plaza_empty	0.38	0.60	0.33	0.33	0.33	0.41	0.39	0.53	0.69	0.62
	Plaza_busy	0.35	0.52	0.30	0.31	0.31	0.37	0.36	0.50	0.62	0.54
	Delta value	0.03	0.08	0.03	0.02	0.01	0.04	0.03	0.03	0.08	0.08
	Park_empty	1.15	1.57	1.03	0.84	1.38	1.34	1.26	1.68	2.13	1.86
	Park_busy	0.95	1.22	0.82	0.69	1.20	1.02	1.07	1.31	1.65	1.57
	Delta value	0.20	0.35	0.21	0.15	0.18	0.32	0.19	0.36	0.48	0.29
	Street_empty	1.10	1.46	1.01	0.81	1.42	1.27	1.22	1.64	1.94	1.73
2	Street_busy	1.01	1.34	0.91	0.75	1.31	1.16	1.22	1.46	1.80	1.66
	Delta value	0.09	0.12	0.09	0.06	0.11	0.11	0.00	0.18	0.14	0.07
	Plaza_empty	1.15	1.56	1.04	0.85	1.45	1.36	1.34	1.66	2.07	1.92
	Plaza_busy	1.02	1.33	0.90	0.73	1.31	1.17	1.21	1.50	1.73	1.60
	Delta value	0.13	0.23	0.15	0.12	0.14	0.19	0.13	0.16	0.33	0.31

An ANOVA test to observe variances among locations, population density, and sessions was run with alpha power results presented in Tables 22 and 23 for clusters 1 and 2 respectively. On tables, top part presents the left, right, middle and centre frontal, and left temporal regions, while the bottom part presents the middle parietal, right temporal, left, middle, and right occipital brain regions. The four sessions were also tested because differences in alpha power were observed, however, lacking a tendency to increase or decrease with time. Possible reasons might be related to the level of engagement from participant, given reports of fatigue at the end, familiarity with experiment task, or other factors.

Cluster 2 outputs demonstrated that eight brain regions had a significant effect with population density (exceptions of the left and right temporal regions), while in cluster 1 only three out of the ten brain regions had this behaviour. Additionally, cluster 1 had significant effect of experimental sessions at the middle occipital brain region. Nevertheless, middle parietal, middle and right occipital regions demonstrated significant effect of population density in alpha power results for both clustered groups.

Interestingly, cluster 2 had more significant results in alpha power than cluster 1. In additional, 10 out of 11 participants in cluster 2 had educational level 6 or above. This behaviour may indicate that people with superior educational level manifest more change in alpha power behaviour across brain regions when exposed to empty locations.

TABLE 17: ANOVA RESULTS FOR CLUSTER 1 WITH FIVE BRAIN REGIONS ON TOP AND FIVE BRAIN REGIONS ON BOTTOM. SIGNIFICANCE *P*-VALUE REPRESENTED IN BOLD AND BY * FOR <.05 AND ** FOR <.001.

Source	df	Left Frontal		MiddleFrontal		RightFrontal		CentreFrontal		LeftTemporal	
		F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Location	2	0.720	0.488	1.085	0.339	0.798	0.451	0.570	0.566	0.739	0.478
Density	1	3.635	0.057	5.145	0.024	3.010	0.084	2.613	0.107	1.328	0.250
Session	3	0.332	0.802	1.709	0.165	0.450	0.717	2.847	0.038	1.814	0.144
Location * Density	2	0.685	0.505	0.631	0.533	0.640	0.528	0.187	0.829	0.250	0.779
Location * Session	6	0.085	0.998	0.217	0.971	0.167	0.985	0.195	0.978	0.028	1.000
Density * Session	3	0.010	0.999	0.002	1.000	0.010	0.999	0.033	0.992	0.116	0.951
Location * Density * Session	6	0.269	0.951	0.164	0.986	0.119	0.994	0.042	1.000	0.062	0.999

Source	df	MiddleParietal		RightTemporal		LeftOccipital		MiddleOccipital		RightOccipital	
		F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Location	2	1.248	0.288	0.683	0.506	1.193	0.305	0.570	0.566	1.091	0.337
Density	1	5.448	**0.020***	3.013	0.083	2.962	0.086	7.942	**0.005****	6.106	**0.014***
Session	3	1.424	0.235	1.349	0.258	1.179	0.318	6.301	**0.0004****	0.276	0.843
Location * Density	2	0.977	0.378	0.480	0.619	0.936	0.393	0.425	0.654	1.131	0.324
Location * Session	6	0.184	0.981	0.059	0.999	0.279	0.947	0.170	0.985	0.040	1.000
Density * Session	3	0.037	0.990	0.077	0.972	0.005	1.000	0.078	0.972	0.095	0.963
Location * Density * Session	6	0.161	0.987	0.141	0.991	0.128	0.993	0.070	0.999	0.164	0.986

TABLE 18: ANOVA RESULTS FOR CLUSTER 2 WITH FIVE BRAIN REGIONS ON TOP AND FIVE BRAIN REGIONS ON BOTTOM. SIGNIFICANCE *P*-VALUES REPRESENTED IN BOLD AND BY * FOR <.05 AND ** FOR <.001.

Source	df	Left Frontal		MiddleFrontal		RightFrontal		CentreFrontal		LeftTemporal	
		F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Location	2	0.084	0.919	0.216	0.806	0.265	0.767	0.126	0.881	0.495	0.610
Density	1	4.569	**0.034***	9.502	**0.002***	8.940	**0.003***	9.314	**0.003***	3.531	0.061
Session	3	1.042	0.375	2.636	**0.0504**	2.372	0.071	0.433	0.729	1.977	0.118
Location * Density	2	0.236	0.790	0.756	0.471	0.459	0.632	0.626	0.535	0.059	0.943
Location * Session	6	0.148	0.989	0.157	0.988	0.184	0.981	0.185	0.981	0.285	0.944
Density * Session	3	0.161	0.922	0.333	0.801	0.188	0.904	0.357	0.784	0.160	0.923
Location * Density * Session	6	0.123	0.994	0.161	0.987	0.156	0.988	0.129	0.993	0.273	0.949

Source	df	MiddleParietal		RightTemporal		LeftOccipital		MiddleOccipital		RightOccipital	
		F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Location	2	0.774	0.462	0.228	0.796	0.304	0.738	0.024	0.976	0.204	0.815
Density	1	13.556	**0.0003****	0.684	0.409	7.163	**0.008***	7.207	**0.008***	7.005	**0.009***
Session	3	0.416	0.742	0.567	0.637	0.312	0.817	1.686	0.171	1.576	0.196
Location * Density	2	1.240	0.291	0.198	0.821	0.545	0.580	0.699	0.498	0.805	0.448
Location * Session	6	0.133	0.992	0.096	0.997	0.085	0.998	0.071	0.999	0.091	0.997
Density * Session	3	0.249	0.862	0.193	0.901	0.074	0.974	0.359	0.782	0.575	0.632
Location * Density * Session	6	0.273	0.949	0.216	0.971	0.102	0.996	0.105	0.996	0.258	0.956

4.5.6. Discussion

Findings from this experiment were: characteristic highlights of the busy Plaza stimuli, clear emotional identification of the empty Park and busy Plaza, effects of population density in the ISO's PAQs, similarities among locations indicated through the ISO's PAQs, and effects of population density on brain activity observed through EEG alpha power. Additionally, some successes of running the experiment are relevant to point out, such as field recordings and ethics approval during COVID, collecting EEG readings from 36 participants, and cleaning the EEG dataset.

Regarding experimental stimuli, the survey to validate number of participants in footage and the soundscape diversity index (SDI) results demonstrated that audio-visual samples were efficiently selected as a diverse sample with a representative sound signal for each location. Nevertheless, effects of auditory masking may have limited the identification of more sound sources from audios due to energetic masking.

Note that the busy Plaza had many children playing on the water fountain representing the high pitch sounds from their screams and sounds of water, also present in the higher values of sound levels, loudness, sharpness, and some metrics of tonality threshold when compared to the other conditions. Even though these high values of psychoacoustic metrics can be considered promising, further investigations would be necessary given results originate from a single stimulus recording per condition.

Considering the Plutchik's wheel of emotions, participants significantly agreed with emotions of "joy" when in the busy Plaza and "serenity" in the empty Park when watching the audio-visual stimuli through the HMD. The concept of these emotions may carry resemblances with the PAQs where joyfulness relates to vibrancy and serenity to calmness. Thus, these results were considered to corroborate with initial identified locations (section 4.1) where Piccadilly Gardens and Peel Park were selected as Vibrant and Calm soundscapes in Manchester. Moreover, other soundwalk study in Manchester centre identified emotions of happiness which supports this finding (Davies *et al.*, 2013).

PAQ results at all studied locations confirm with literature in the Eventful scale (Russell, Ward and Pratt, 1981; PD ISO 12913-3, 2019) when the soundscape attribute increases in busy with human activities. In addition, the presence of people also increased the Vibrant scale at the Plaza and Park as observed in previous study (Aletta and Kang, 2018). In contrast, the Calm and Pleasant PAQs decreased as the number of people increased in all sites. However, the Park and Plaza still had positive PAQ values for pleasantness independently of the population density indicating these locations can still be considered pleasant to participants when busy as reported for crowded soundscapes in Indonesian study (Mediastika *et al.*, 2022). Furthermore, similarities among PAQ ratings and high pleasantness ratings for the Plaza and Park indicate these locations might be considered equally valued among participants. Given urban park soundscapes have proven to contribute to the well-being, this observation might suggest that Plazas should also be included to the urban soundscape repertoire so to contribute to healthier sounding cities.

Variability in EEG results were considered acceptable given differences are also expected between participants (Koelstra *et al.*, 2012), their emotional perception (Barrett, 2017), and uniqueness of their brain (Teplan, 2002). Nevertheless, EEG alpha power results demonstrated a significant effect of population density when data was clustered. Considering alpha brain waves can be induced at the posterior brain regions by relaxation and drowsiness (Teplan, 2002), the increased values of alpha power at occipital regions in empty locations may indicate participants were more relaxed when there were no people in the scene.

From another perspective, the empty Park with bird calls as predominant sound sources had high values of EEG alpha power. This behaviour was also observed in Li, Ba and Kang's study where increased values of α-EEG reactivity was observed for sea and bird sounds when compared to street and traffic sounds (Li and Kang, 2019). Furthermore, a previous study reported that Peel Park was predicted to leave 50% of visitors more relaxed after visiting the location (Watts, Miah and Pheasant, 2013). Thus, results from this experiment might support that the empty Peel Park may represent a location for relaxation given reports of evoked emotions of serenity and high values of alpha power at occipital regions.

Furthermore, the increased values of EEG alpha power and Pleasant PAQ ratings when exposed to empty locations was also observed in Koelstra et al (Koelstra *et al.*, 2012) study. They identified strong correlations among valence ratings and EEG alpha power at occipital regions when participants were exposed to emotion-evoked video clips (Koelstra *et al.*, 2012).

In conclusion, a finding from this experiment that might be relevant was that population density significantly effected PAQ ratings and EEG alpha power of participants, when exposed to different urban soundscapes through HMD. In addition, the busy Plaza and empty Park significantly evoked emotions of joy and serenity on participants. Thereby, one should take into consideration population density when assessing, planning, and designing urban soundscapes. In addition, busy Plazas should also be integrated to the options of urban soundscape interventions along with empty parks.

5. CHAPTER FIVE: Conclusions

The main aim of the thesis was to investigate associations between urban soundscape perception and emotional states in different locations and population densities using VR audio-visual reproduction of real places. Five experiments were used to elaborate the investigation. One to identify locations to be studied, another to test questionnaire and validate the calm scenario, a pilot to test VR audio-visual reproduction for future laboratory experiment, a VR online experiment (MCR 2020) due to COVID, and, finally, an EEG-VR soundscape experiment to test the different locations and population densities in laboratory.

5.1 Findings and discussions

Studied sites were successfully identified in the first experiment given PAQ plots over the two-dimensional model for pleasantness and eventfulness of the EEG-VR experiment confirmed locations. Additionally, the site survey results demonstrated that a location could represent types of soundscapes, as observed with Piccadilly Gardens, train station, and bus stop. Findings suggested the number of people influenced these shifts among categories. For instance, the busy Piccadilly Gardens with children playing in the water fountain was perceived as a Vibrant soundscape in all experiments and declared to evoke “joy” in the last one. Thus, urban Plazas could be considered as a desired tool in urban soundscape design when occupied. This eye-opening result should also be shared with Manchester city planners to preserve the water feature, as recent news declared that changes will happen to the Plaza soon (Byass, 2010; Deloitte LLP, 2016).

Another shift among PAQ quadrants was observed at Peel Park from the Calm to the Vibrant category when people increased in the scene. Important to note that in both busy locations, Park and Plaza, the weather was sunny with children playing. So, the effect of population density may include children playing given that the busy Street had predominantly adults walking by and not playing. These results also suggest that vibrancy may relate to the soundscapes of children playing on sunny days. In these cases, the type of individuals could have added to the liveliness given that Market Street was not rated in such category possibly due to the absence of infants and the many adults passing by. This observation demands more tests to certify if children are an influencing factor in characterizing the Vibrant soundscape. All the same, these findings support the plans to improve Piccadilly Gardens to a vibrant location (Deloitte LLP, 2016).

Specifically related to the subjective results, Piccadilly Gardens demonstrated a significant increase towards the Eventful, Vibrant, and Chaotic PAQs as the sense of activeness (PANAS emotional scale) when population density increased in the third VR pilot experiment. The MCR 2020 experiment revealed a gradual and significant increase in the Eventful and Vibrant PAQ at Piccadilly Gardens, and the Eventful PAQ and arousal emotion scale in Market Street, while the Calm PAQ significantly decreased as did the arousal emotion scale increased at Peel Park with the number of people in the scenario.

In the EEG-VR soundscape experiment, all PAQ results changed with population density except for the Annoying PAQ at the Park and the Vibrant PAQ at the Street. The Eventful PAQ increased in all locations for the busy conditions as expected and indicated by the ISO 12913-3 (PD ISO 12913-3, 2019). When observing PAQ scores among sites, the Park and Street had significantly different results, and the Park and Plaza had similarities. This finding reinforces that Plazas should be considered as a soundscape design tool, just as parks already are.

For the eventful PAQ, these results corroborate with ISO 12913-3 (PD ISO 12913-3, 2019), where eventful places are described as busy in human activities. Aletta and Kang (Aletta and Kang, 2018) also identified significant correlations between vibrancy and eventfulness scores. Thus, this study supports and fits in the context of the soundscape research area when busy locations indicate vibrant and eventful perceptions of soundscapes.

In MCR 2020, Brazilian participants rated differently on 12 of the 28 semantic scales with higher values in nine of these ratings. In particular, the valence scale was significantly higher than individuals from other countries in the empty park indicating possible cultural differences among participants. As observed by the sociologist Oliveira, Brazilians may have the "complex of pooch", originating from the historic racial and social segregation of the Lusophone colonizers who maintained a Eurocentric sociocultural standard (de Oliveira Jr, 2019). Thus, local Brazilian culture tends to be undervalued while people are fascinated with the European style of cultural hegemony (de Oliveira Jr, 2019) which may justify the higher ratings among subjective scales observed in current findings. Nevertheless, broader, and more robust investigations must verify such observations.

Differences among ratings of the PAQs from English to different languages have also been observed in the Soundscape Attributes Translation Project – SATP (Aletta *et al.*, 2020). Some researchers suggest possible cultural differences between the English model and other translated models, such as the French (Tarlao *et al.*, 2016), Indonesian (Sudarsono *et al.*, 2021), and Portuguese groups (Antunes *et al.*, 2023). These diversions indicate the need for further investigations on the taxonomic translations, and how other factors may influence the soundscape perception, such as cultural background.

Initial findings of population density significantly altering EEG alpha power when exposed to the empty Park and Plaza may suggest that participants were relaxed and calm, given that EEG data may demonstrate how agitated or calm the mind is (Cochrane *et al.*, 2021). Furthermore, these empty spaces evoked “serenity” in Plutchik’s emotion wheel which can be associated with states of calmness. Note that these locations also had predominant sounds of nature. At the empty Peel Park, three types of bird calls were present as foreground sounds. In Piccadilly Gardens, the water fountain stood out from the background sound. Meanwhile, the empty pedestrian street, Market Street, had mechanical sounds as predominant and did not have high EEG alpha power as did the park and plaza.

Current findings indicating high values of alpha power in empty places with natural sounds can be considered to go in line with other nature and EEG-related studies (Li, Xie and Woodward, 2021; Li *et al.*, 2022; Jeon, Jo and Lee, 2023). However, these studies had differences with this thesis results, such as Li, Xie, and Woodward experiment was an in situ experiment (Li, Xie and Woodward, 2021), Li et al. investigated only water features (Li *et al.*, 2022), and Jeon, Jo, and Lee used a stress task (Jeon, Jo and Lee, 2023). Yet, authors pointed out that alpha parameters increased when in environments with sounds of nature, suggesting an increase in states of relaxation (Li *et al.*, 2022; Jeon, Jo and Lee, 2023), possible stress recovery (Jeon, Jo and Lee, 2023), and mental restoration (Li, Xie and Woodward, 2021; Jeon, Jo and Lee, 2023).

Furthermore, diverse studies (Teplan, 2002; Sharma and Singh, 2015; Li, Xie and Woodward, 2021; Li *et al.*, 2022; Jeon, Jo and Lee, 2023) indicate that a high alpha rhythm represents moments of calmness. Li et al. demonstrated that water sounds showed higher values of relative alpha power and alpha-beta ratio when compared to traffic noise and confirmed that water sounds increased mental relaxation (Li *et al.*, 2022). Li, Xie, and Woodward declared that alpha frequency bands can represent restorative states observed to be more pronounced in locations with bird calls than in traffic noise environments (Li, Xie and Woodward, 2021). Thus, current EEG alpha power findings at Peel Park (bird calls) and Piccadilly Gardens (water fountain) go in line with other works, such as Li et al. for water (Li *et al.*, 2022), and Li, Xie, and Woodward for bird call sounds (Li, Xie and Woodward, 2021), but are not identical to cited studies.

Additionally, the finding of high alpha power in occipital regions has been observed in relaxed states in Sharma's study (Sharma and Singh, 2015) and stated to occur in the posterior parts of the brain by Teplan (Teplan, 2002). However, visual cues are also processed in this area, indicating that the results of higher alpha power values in the occipital regions require caution as a statement due to the possibility that the activation comes from the visual stimuli from the VR HMD and not necessarily from the soundscape audio-visual stimuli.

Another interesting finding was that participants from EEG cluster 2 were predominantly highly educated individuals, and eight out of 10 brain regions had significant differences in population density conditions, whilst cluster 1 had only three regions significantly different. This result may indicate an effect of educational level on EEG responses of participants with higher education demonstrating more consensus in brain activity than those with lower education level. One could say that this sampled population represents part of the Western, Educated, Industrialized, Rich, and Democratic (WEIRD) group, revealing an elite population from Manchester.

In 2008, the WEIRD population was a majority sample of 96% in the top psychology journals while representing only 12% of the world's population (Arnett, 2008). Henrich, Heine, and Norenzayan suggest four scientific conducts to improve psychology studies regarding such limitations (Henrich, Heine and Norenzayan, 2010). First, they indicate that enough scientific evidence specific to the subject's background must support generalisations. Second, the scientific community and grating agencies should recognise research with diverse subjects and inconvenient comparisons. Third, granting agencies should prioritize cross-disciplinary and cross-cultural research. And fourth, comparisons among different populations should test findings (Henrich, Heine and Norenzayan, 2010). From this perspective, even though the ‘education level’ effect was a promising finding, further investigations should include and compare results with other parts of the world's population. Specifically, similar experiments could occur to compare to the current executed EEG-VR experiment with Brazilians to observe possible cultural differences.

From the VR perspective, several realistic spaces VR soundscape studies have grown (Maffei *et al.*, 2016b; Sun, De Coensel, *et al.*, 2019; Tarlao, Steele and Guastavino, 2022). However, investigations of different population densities as contextual factors have not been investigated and may support multiple evaluations. In field experiments, only one site is assessed at a time before participants move to another, resulting in longer experimental sessions, making it difficult to rate distant sites, and demanding more visits to observe the population density. In addition, perceptual responses to soundscapes in real space VR are more common than emotional responses, which first reinforce the ISO’s PAQs and later suggest new affective models in evaluations of urban soundscapes.

Another relevant contribution of this thesis was to implement real VR reproductions of different sites and population densities, together with EEG readings, while immersed in virtual environments. Such an approach was considered to complement the self-reported perceptual and emotional responses to soundscapes. VR has become a promising tool in assessing environmental sounds, and EEG use in soundscape studies has slowly increased, however not always combined with VR reproduction. An exception can be made to Jeon, Jo, and Lee’s work (Jeon, Jo and Lee, 2023), although with differences in experimental goals where they aimed to observe restoration states after a stress-related task, and, here, participants thought about feelings when immersed in the VR soundscape. Thus, the current use of both methods represents a reasonably recent contribution to soundscape research.

In Jeon, Jo, and Lee work, recording methods were very similar (Jeon, Jo and Lee, 2023). However, the experimental design differed from the current thesis in sample size and characteristics, stimuli and duration, observed parameters, and especially the EEG experimental task. Participants in Jeong's study were 60 Seul University students with mild depression, stress or anxiety levels equally divided among males and females, while here 30 participants with different educational levels were observed with no control of their mental state and gender. Stimuli used by authors were not the same given streets and roads with automobiles were present in their urban scenarios, and there was the use of natural waterfronts (Jeon, Jo and Lee, 2023). The green areas may relate to the current thesis, but not directly, given that none of their sites were an urban park or plaza. Predominant sound sources in the urban environments included human sounds related to the busy conditions in the studied areas of this thesis. Meanwhile, birdsongs were predominant in the green areas of Jeong's study, also observed in the empty Peel Park. Stimuli's duration was 3 minutes for them and 8 seconds here. Subjective responses collected by Jeong were broader and could be related to some of the ISO's PAQs used in this thesis. Physiological metrics were heart rate variability and EEG ratio determined as alpha divided by low and high beta EEG rhythms. These parameters differ from current work given statistical analysis, up to now, was done only by observing alpha power.

The major difference between the current thesis and Jeon's work (Jeon, Jo and Lee, 2023) is that they observed states of restoration after an artificially induced stress (mental arithmetic stress task), and here the participants thought about what they felt when immersed in the different audio-visual stimuli. Nevertheless, their increase of alpha ratio in predominant natural soundscapes is similar to current thesis findings, where empty sites with predominant bird calls and water features demonstrated higher alpha power than in the highly occupied studied sites. Furthermore, Jeon, Jo, and Lee (Jeon, Jo and Lee, 2023) and this current author consider findings relevant to support urban planning and design in enhancing existing or new urban areas into better-sounding cities using green areas and water features to bring birds and create pleasant sounds of water.

All mentioned findings from the current thesis are in line with questions raised in interviews conducted by Aletta and Xiaou (Aletta and Xiao, 2018) to identify priorities and challenges in soundscape research. The "Relationships between soundscape and behaviour" topic was associated with the different population densities in urban soundscapes observations in participants' subjective responses and EEG alpha power. Moreover, the number of people on site could serve as a concept to consider when assessing, planning, and designing urban soundscapes embracing the theme of the "Academia-Practice gap". Meanwhile, the VR reproductions and EEG findings support the "Technology for soundscapes" theme that interviewees declared relevant for soundscape research (Aletta and Xiao, 2018). Therefore, current findings reflect what the urban soundscape community is looking for.

5.2 Future work

The next steps are to investigate EEG results with neuroscience experts, to continue enhancing the PAQs translation to the Portuguese language, and to reproduce EEG-VR soundscape experiments in Brazil. However, other ideas are to observe if there is an optimised number of people to evoke well-being, validate if the sounds of children playing are associated with Vibrant soundscapes, and observe the relations of memory with soundscape perception, among others.

Regarding high EEG results at occipital regions, further analyses shall test if these results are due to the processing of visual cues in the posterior part of the brain. For instance, Li, Xie, and Woodward's work demonstrated that audio-only stimuli had higher alpha values than audio-visual conditions (Li, Xie and Woodward, 2021). Thus, new investigations controlling the audio and visual stimuli should observe if alpha increases in occipital regions are related to the soundscapes, the visual cues, or both.

These are only some thoughts resulting from this thesis. Nevertheless, the architectural, urbanist, musician, and art debutant within the researcher may wander towards other borders of creativity and interdisciplinary work.

APPENDIX ONE: Questionnaires

Stage 1 – Survey to identify studied locations.

QUESTIONNAIRE

Project: Soundscape effects on emotional states and behaviour.

Stage: Identifying places with sounds that represent different emotional states.

Think about the times when sounds in public spaces have contributed to your sense of **EXCITEMENT.** Are there places in Manchester that represent them? Could you name them?

Think about the times when sounds in public spaces have contributed to your sense of **CALM.** Are there places in Manchester that represent them? Could you name them?

Think about the times when sounds in public spaces has contributed to your sense of **CHAOTIC.** Are there places in Manchester that represent them? Could you name them?

Think about the times when sounds in public spaces has contributed to your sense of **MONOTONOUS**. Are there places in Manchester that represent them? Could you name them?

Stage 2 - Soundscape Field questionnaires

Acoustics Research Group

University of Salford MANCHESTER

Ethics Approval: Research Instrument – Questionnaires - Version 2
Project Title: Connections between Soundscape, Behaviour, and Emotional States.
Stage: Field questionnaire.

1. Perceived affective quality:

For each of the scales below, please evaluate the current sound environment (click on only one response per scale):

	5	4	3	2	1	0	1	2	3	4	5	
Comfort												Discomfort
Quiet												Noisy
Calming												Agitating
Pleasant												Unpleasant
Smooth												Rough
Natural												Artificial
Hard												Soft
Like												Dislike
Fast												Slow
Gentle												Harsh
Sharp												Flat
Boring												Interesting
Varied												Simple
Social												Unsocial
Reverberant												Anechoic
Communal												Private
Far												Near
Meaningful												Insignificant
Directional												Universal

2. Analysis for emotional states - feelings:

Thinking about the current sound environment you are experiencing, to what extent do you generally feel:

	Never 1	2	Neutral 3	4	Always 5
Upset					
Hostile					
Alert					
Ashamed					
Inspired					
Nervous					
Determined					
Attentive					
Afraid					
Active					

Stage 3 – Virtual Reality Pilot test questionnaire

Acoustics Research Group

University of Salford MANCHESTER

Ethics Approval: Research Instrument – Questionnaires - Version 2
Project Title: Connections between Soundscape, Behaviour, and Emotional States.
Stage: Pilot at IMMERSE event.

ID ☐

Condition ☐

1. Perceived affective quality:

For each of the scales below, **please evaluate the sound environment** you have experienced (click on only one response per scale):

	5	4	3	2	1	0	1	2	3	4	5	
Pleasant												Unpleasant
Eventful												Uneventful
Exciting												Monotonous
Calm												Chaotic

2. Analysis for emotional states - feelings:

Thinking about the current sound environment you are experiencing, **to what extent do you generally feel**:

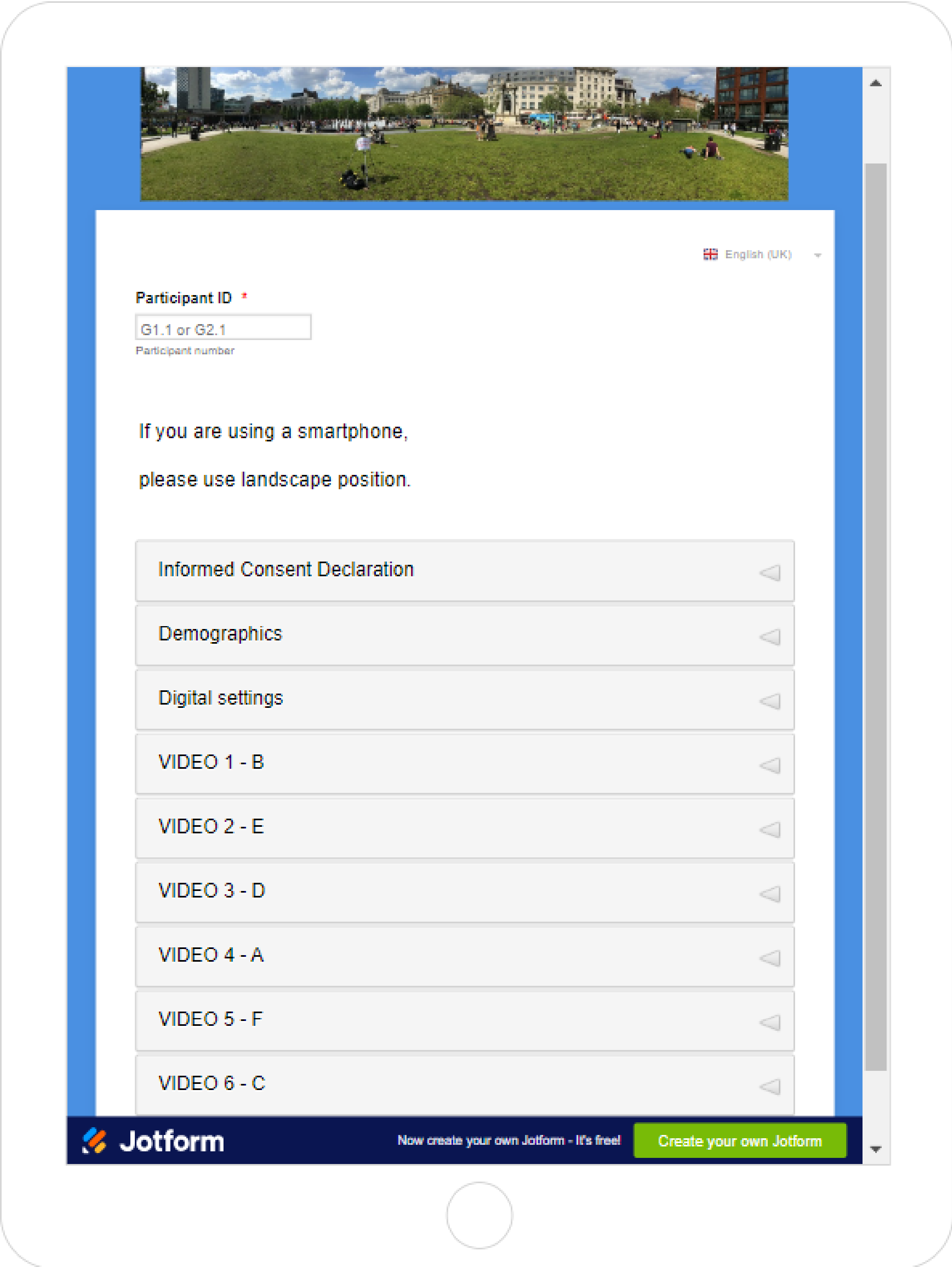
	Never 1	2	3	4	Always 5
Upset					
Hostile					
Alert					
Ashamed					
Inspired					
Nervous					
Determined					
Attentive					
Afraid					
Active					

Please leave any comments, thoughts, or feedback about the experiment. This feedback will be anonymous as all data collected. It helps us understand any problems that participants had, or what worked well, so that we can improve our studies.

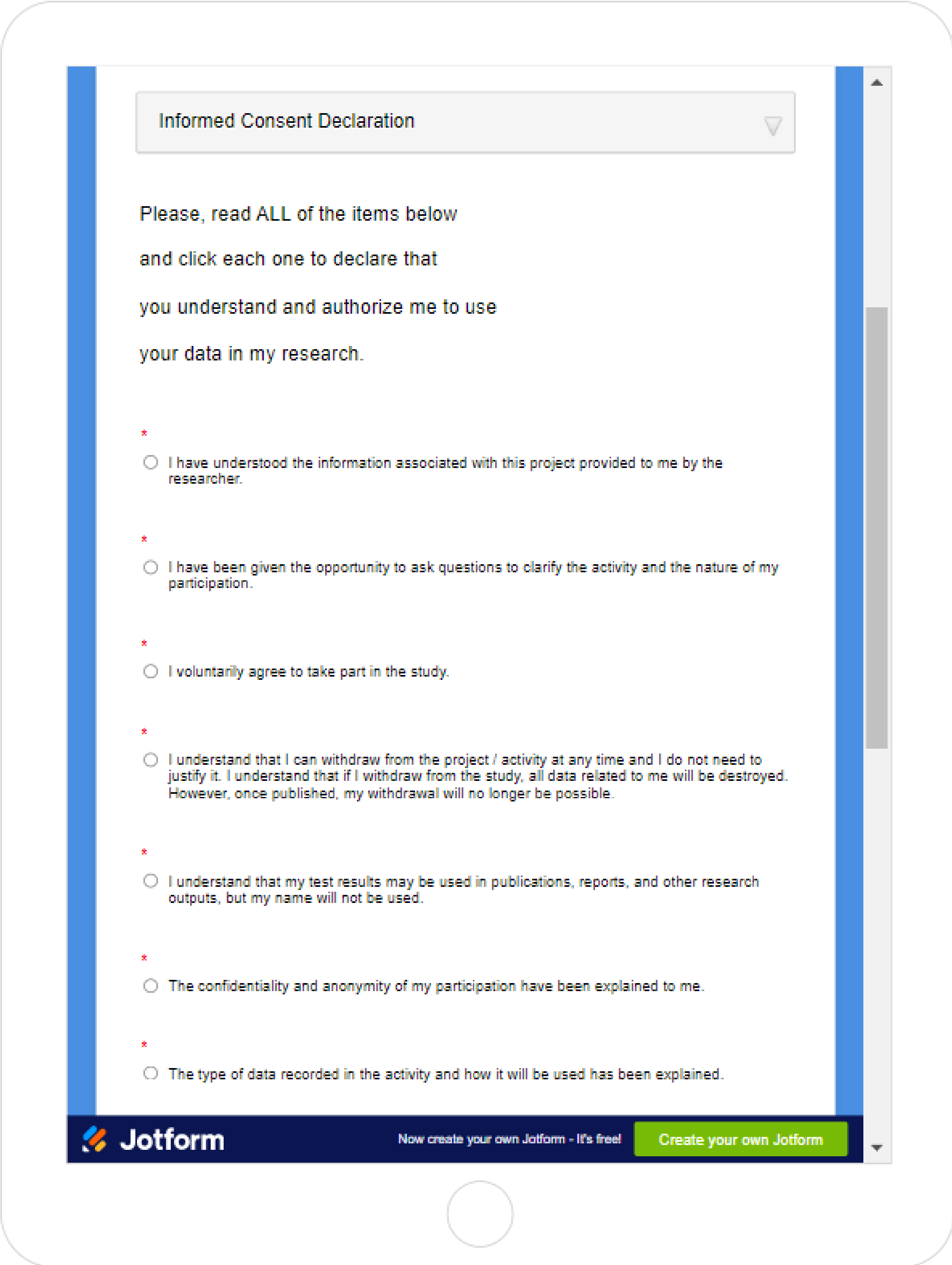
You might consider the duration of the session comfortable, were stimuli (soundscapes) too long or short, and any other ideas you may have.

Stage 4 – The Manchester Soundscape online experiment questionnaire

General view of the questionnaire displayed through a tablet.



Informed Consent Declaration displayed through a tablet.



Informed Consent Declaration

Please, read ALL of the items below

and click each one to declare that

you understand and authorize me to use

your data in my research.

*

○ I have understood the information associated with this project provided to me by the researcher.

*

○ I have been given the opportunity to ask questions to clarify the activity and the nature of my participation.

*

○ I voluntarily agree to take part in the study.

*

○ I understand that I can withdraw from the project / activity at any time and I do not need to justify it. I understand that if I withdraw from the study, all data related to me will be destroyed. However, once published, my withdrawal will no longer be possible.

*

○ I understand that my test results may be used in publications, reports, and other research outputs, but my name will not be used.

*

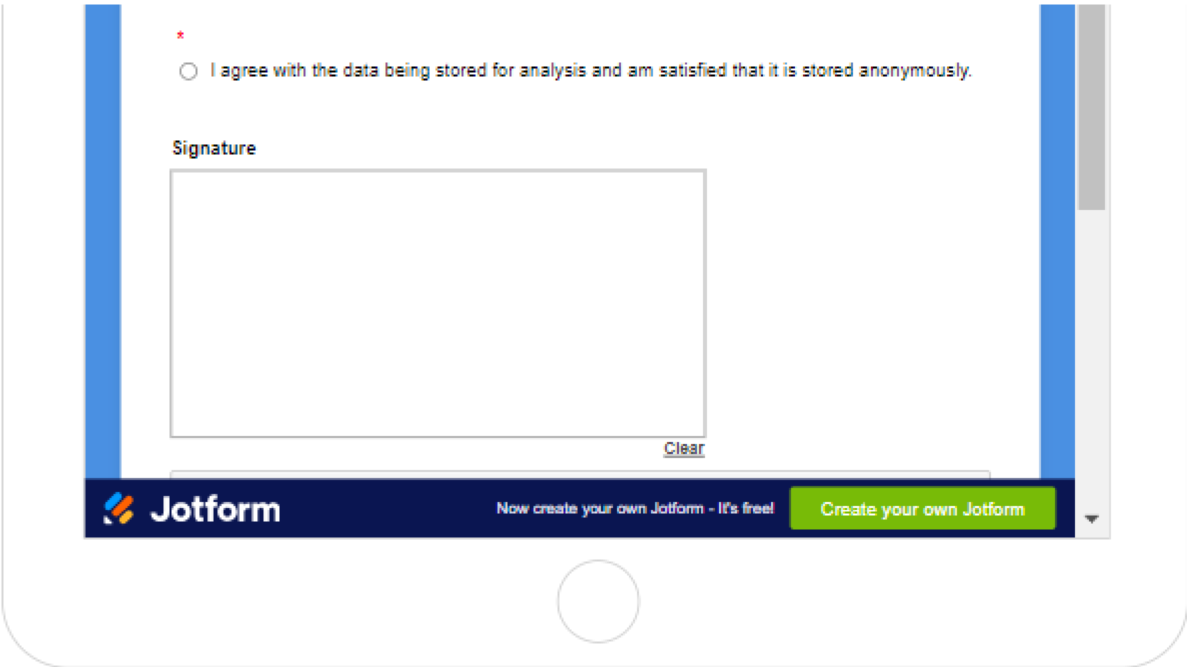
○ The confidentiality and anonymity of my participation have been explained to me.

*

○ The type of data recorded in the activity and how it will be used has been explained.

Jotform Now create your own Jotform - It's free! Create your own Jotform

Informed Consent Declaration displayed through a tablet (continuation).



*

I agree with the data being stored for analysis and am satisfied that it is stored anonymously.

Signature

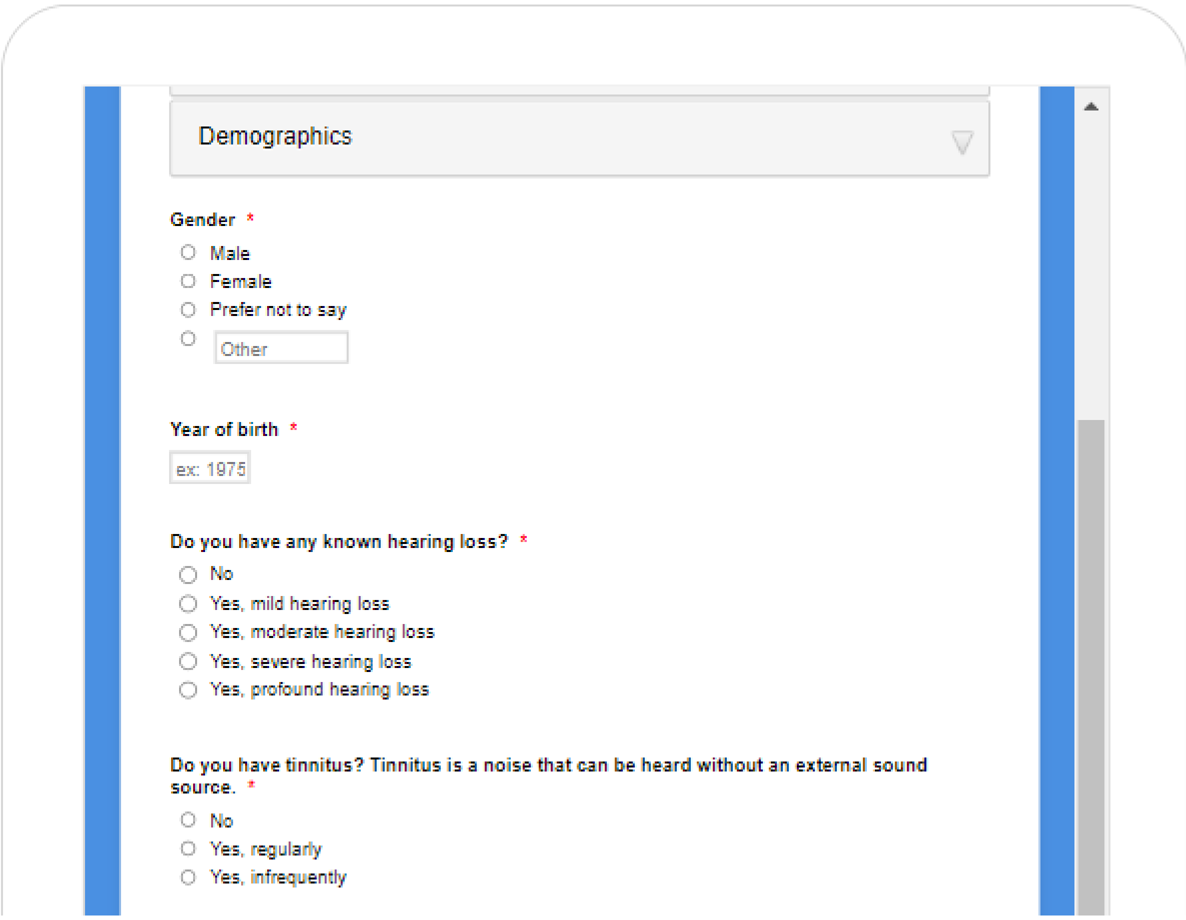
Clear

Jotform

Now create your own Jotform - It's free!

Create your own Jotform

Demographic information displayed through a tablet.



Demographics

Gender *

- Male
- Female
- Prefer not to say
- Other

Year of birth *

ex: 1975

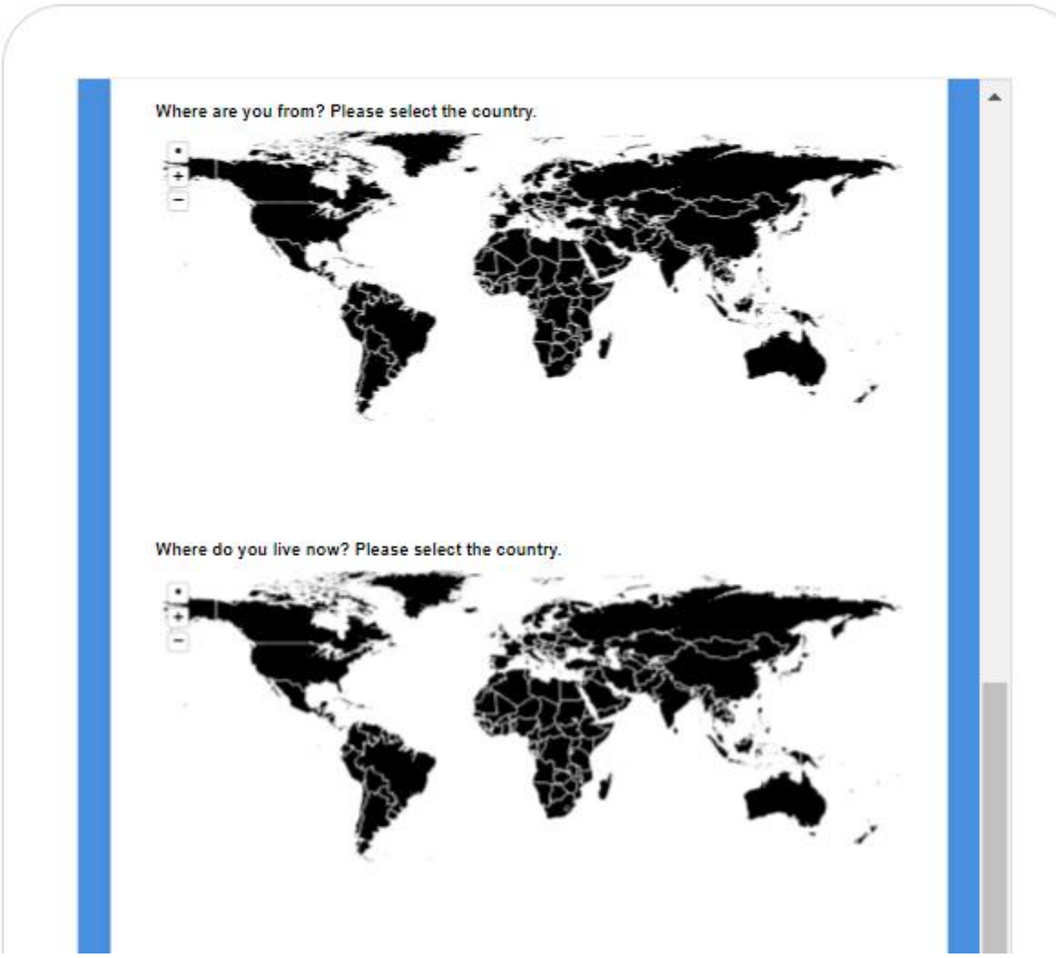
Do you have any known hearing loss? *

- No
- Yes, mild hearing loss
- Yes, moderate hearing loss
- Yes, severe hearing loss
- Yes, profound hearing loss

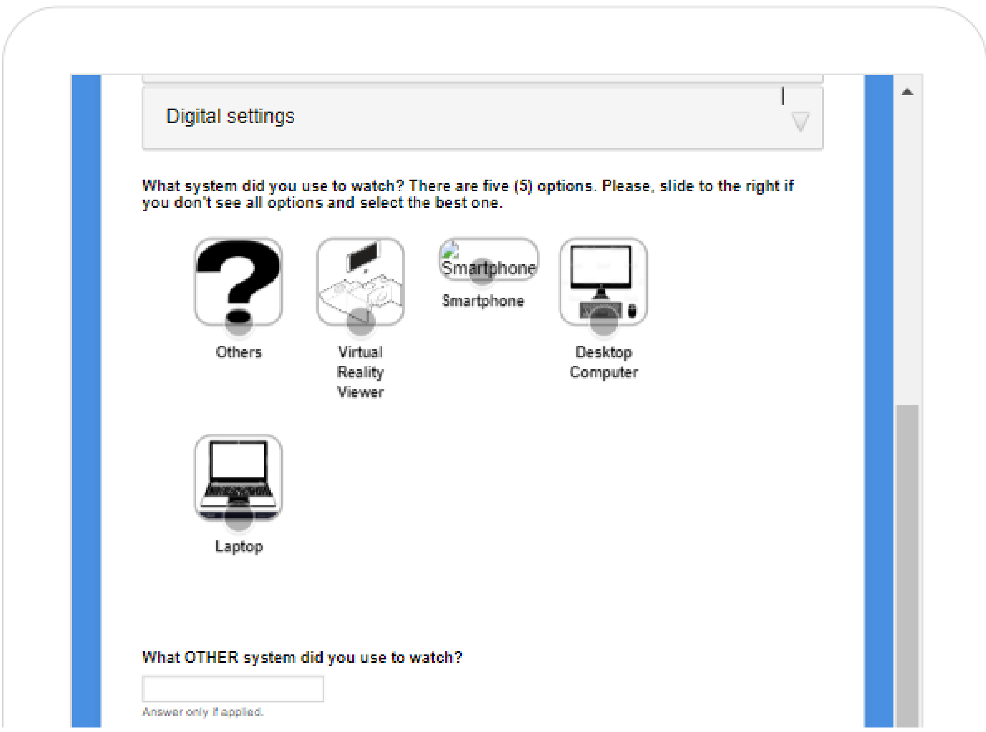
Do you have tinnitus? Tinnitus is a noise that can be heard without an external sound source. *

- No
- Yes, regularly
- Yes, infrequently

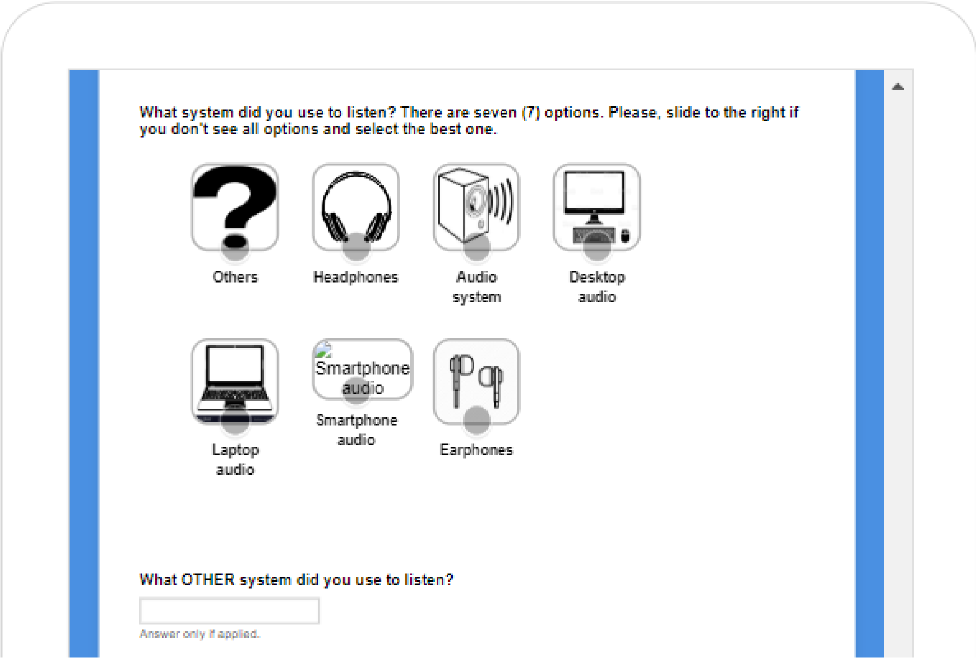
Demographic information displayed through a tablet (continuation).



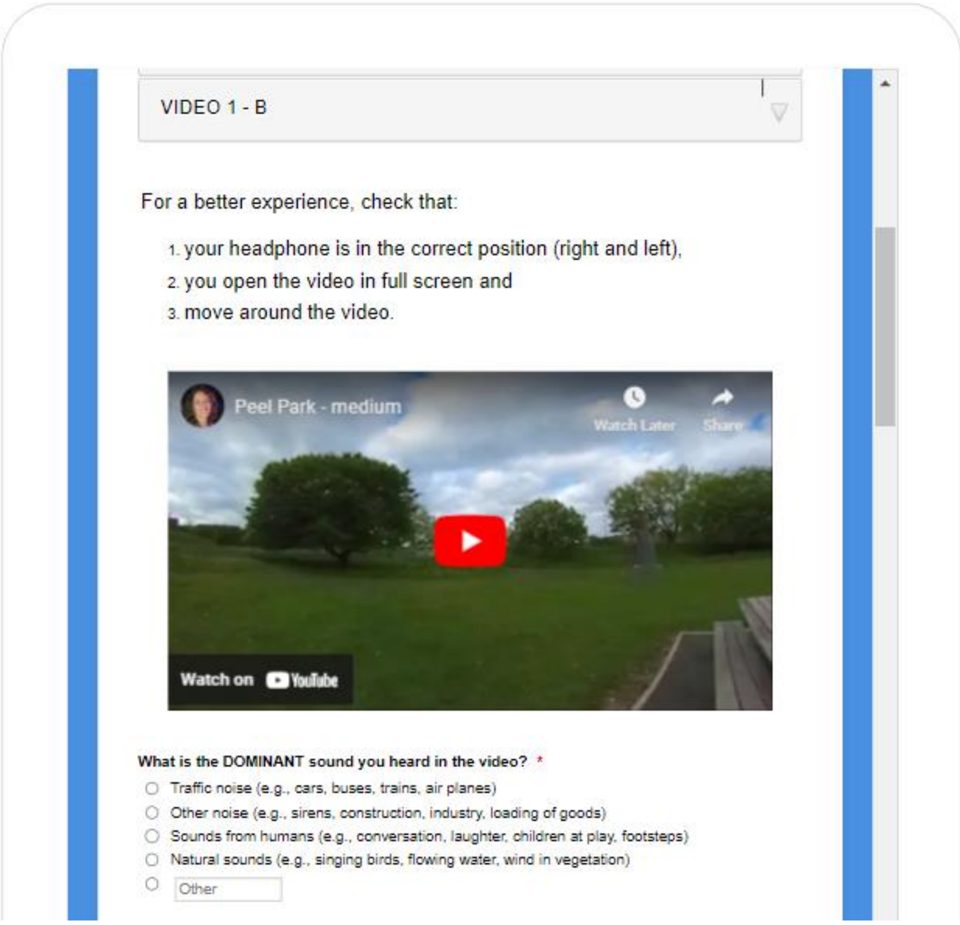
Digital settings displayed through a tablet.



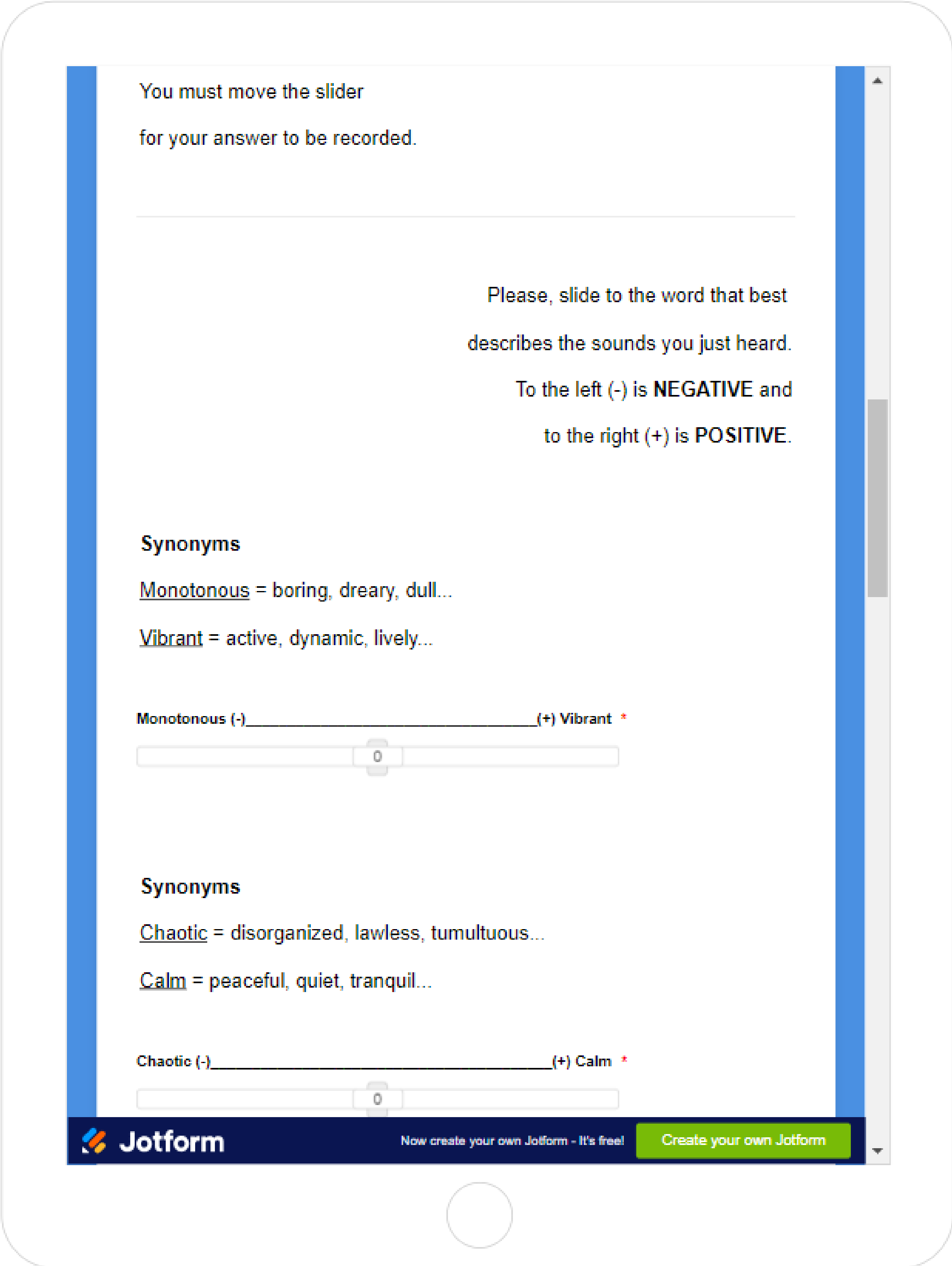
Digital settings displayed through a tablet (continuation).



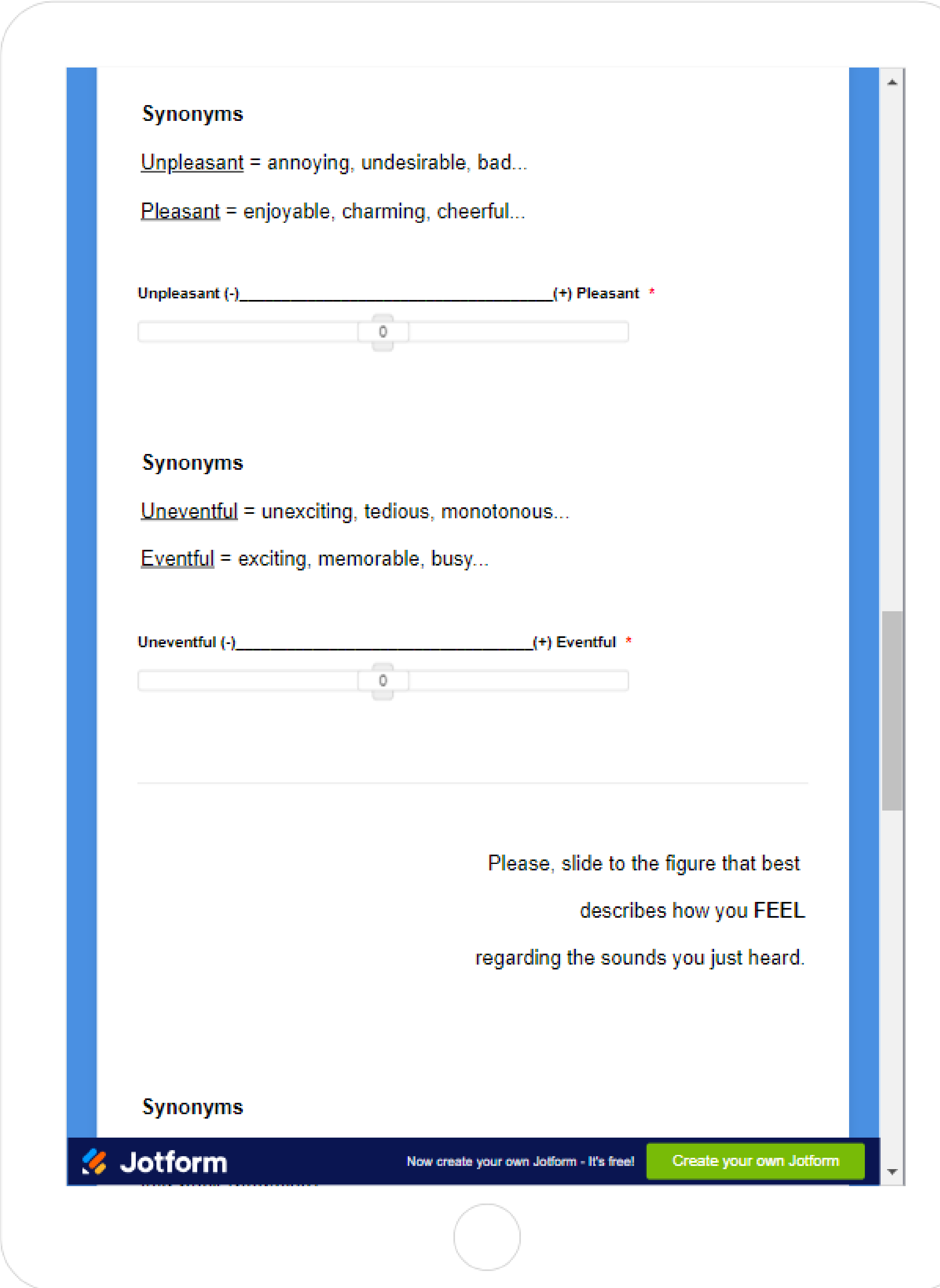
Experiment question displayed through a tablet.



Experiment question displayed through a tablet (continuation).



Experiment question displayed through a tablet (continuation).



Synonyms

Unpleasant = annoying, undesirable, bad...

Pleasant = enjoyable, charming, cheerful...

Unpleasant (-)________________________________(+) Pleasant *

0

Synonyms

Uneventful = unexciting, tedious, monotonous...

Eventful = exciting, memorable, busy...

Uneventful (-)______________________________(+) Eventful *

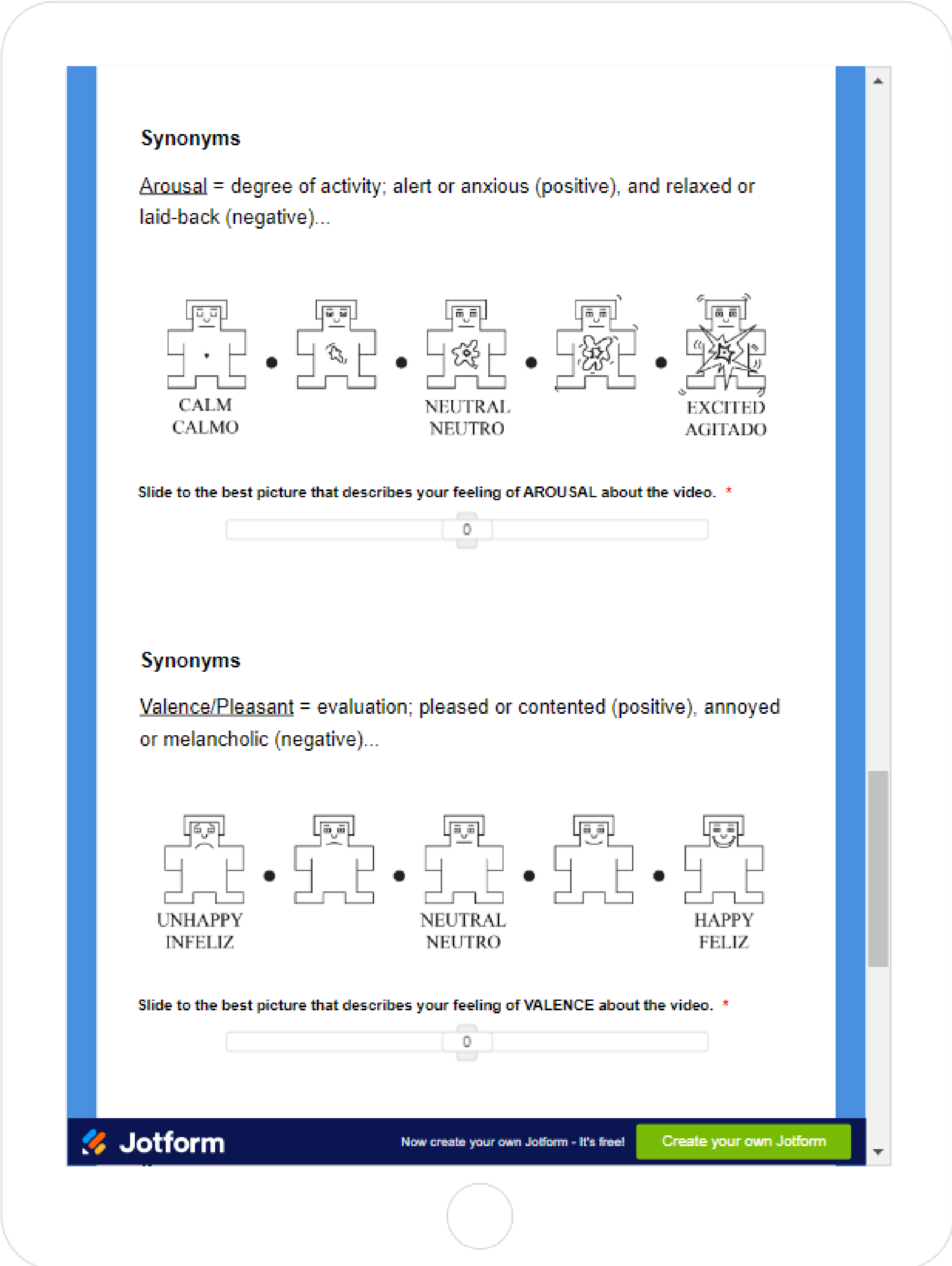
0

Please, slide to the figure that best describes how you **FEEL** regarding the sounds you just heard.

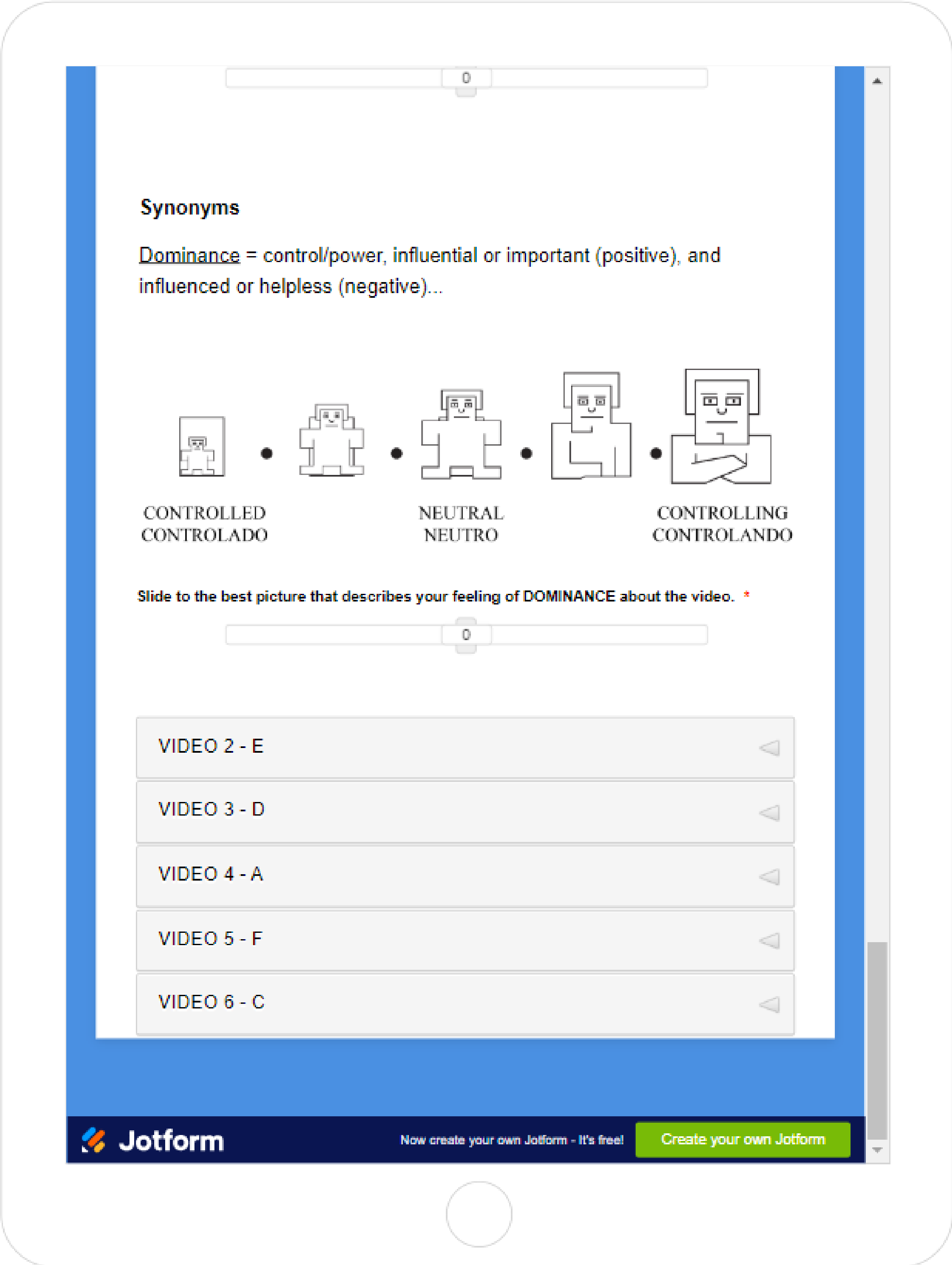
Synonyms

Jotform Now create your own Jotform - It's free! Create your own Jotform

Experiment question displayed through a tablet (continuation).



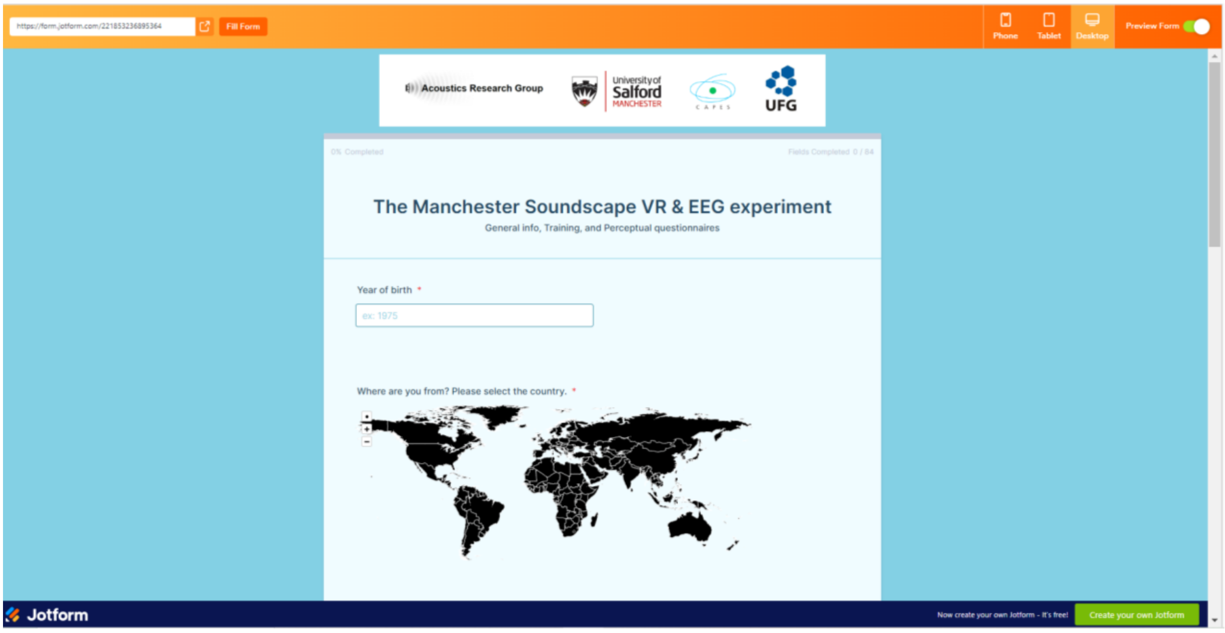
Experiment question displayed through a tablet (continuation).

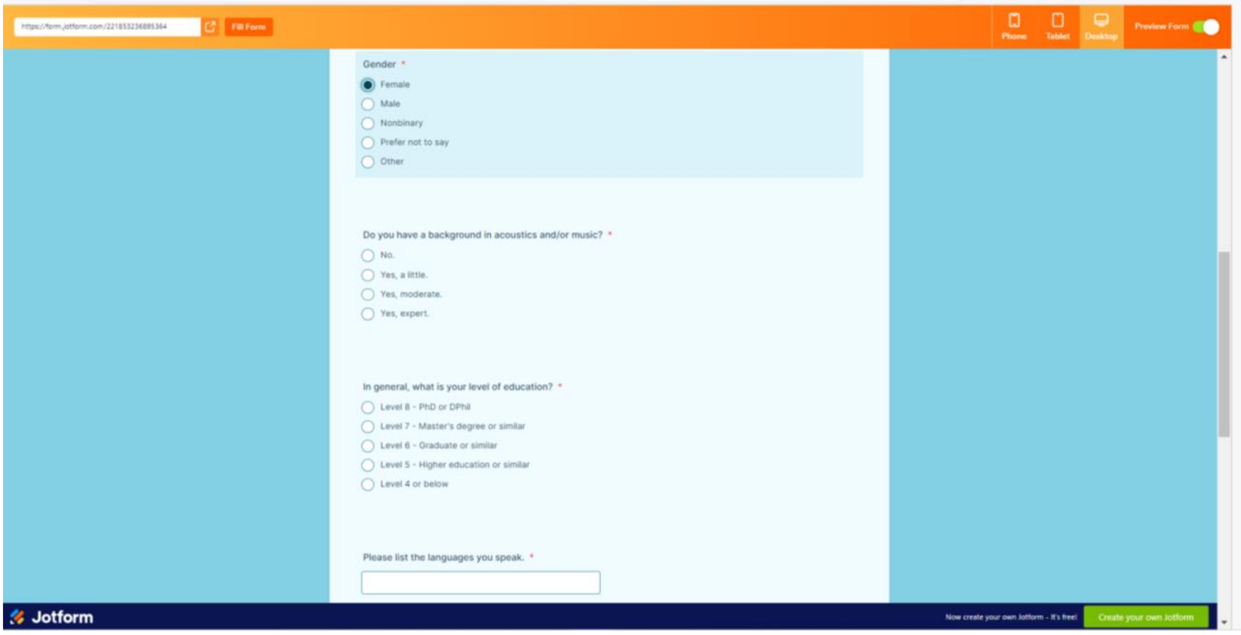


Each of the six videos had the same questions in random order.

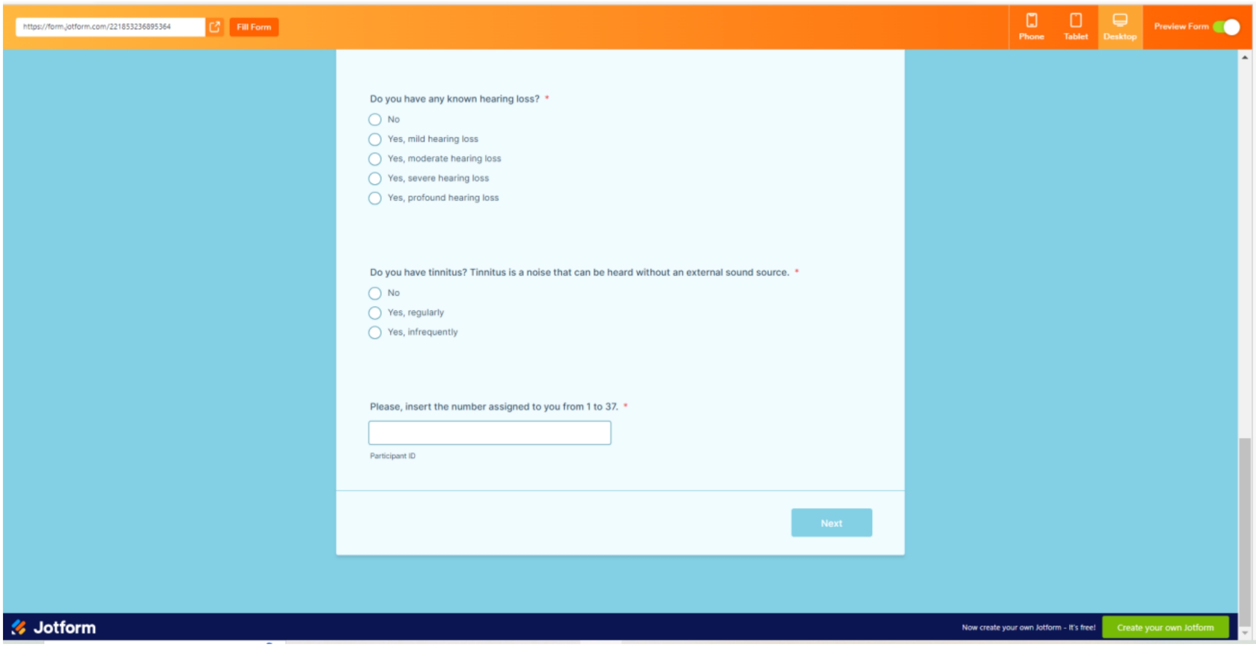
Stage 5 – VR & EEG Laboratory Experiment questionnaire

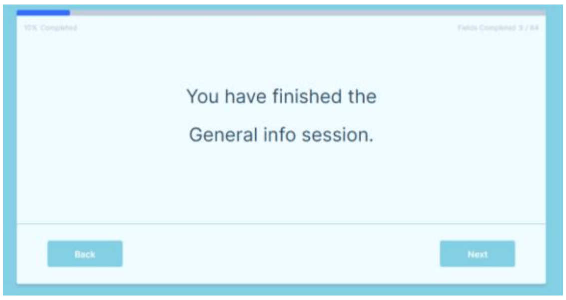
General information displayed through Laptop.

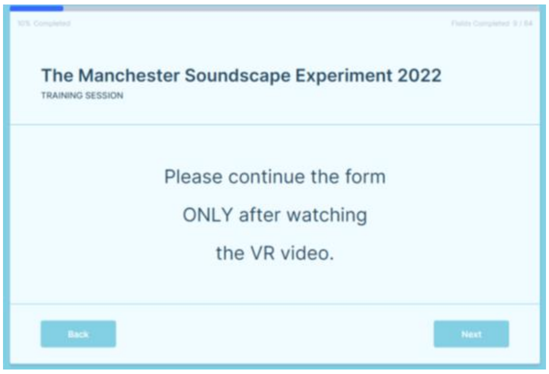




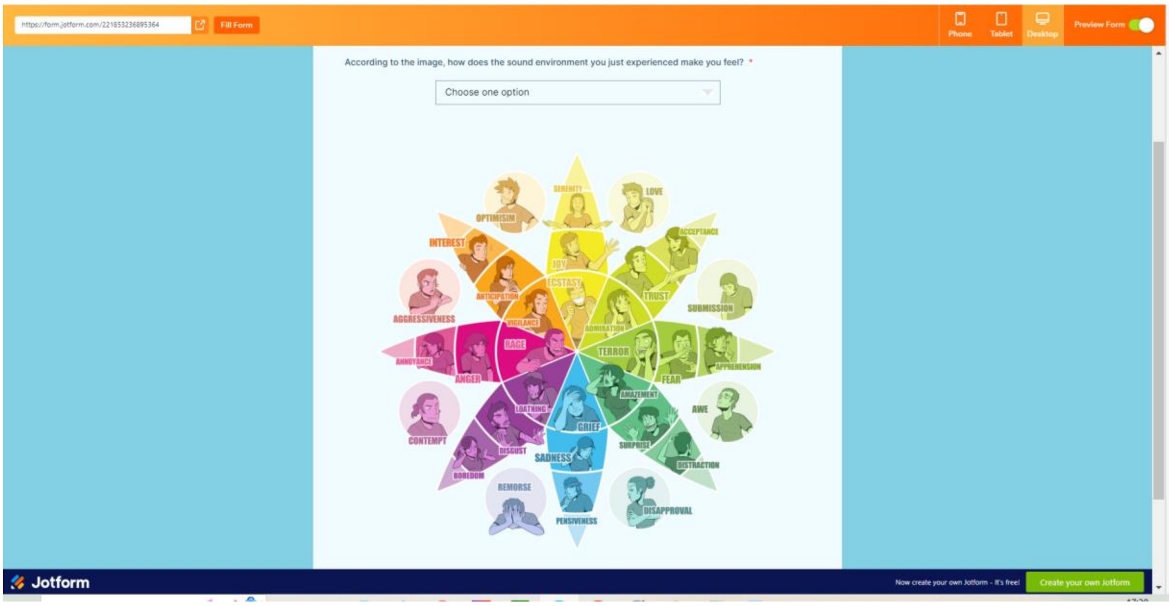
General information displayed through Laptop (continuation).



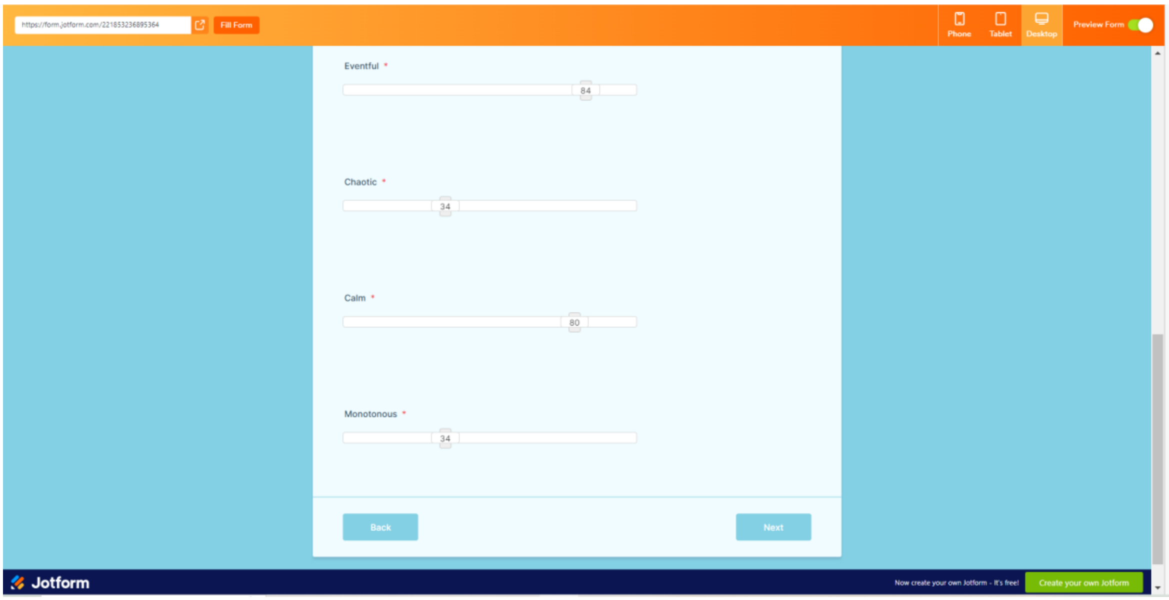


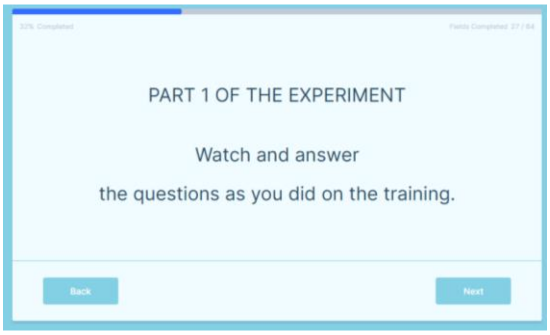


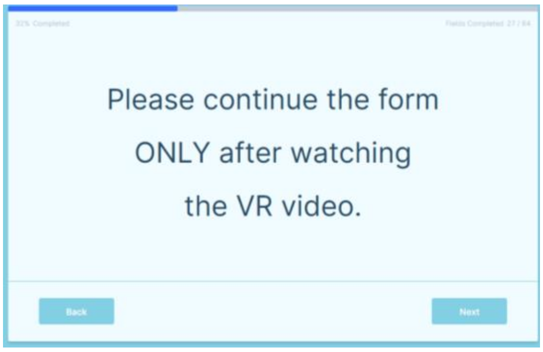
Experiment question for training session displayed through a laptop.



Experiment question for training session displayed through a laptop (continuation).

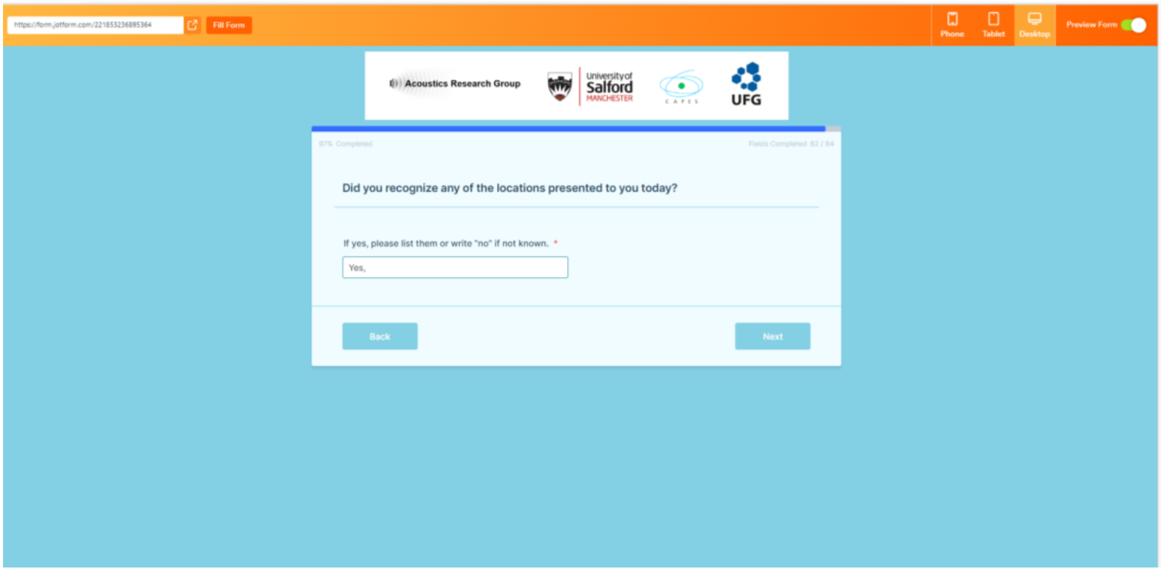


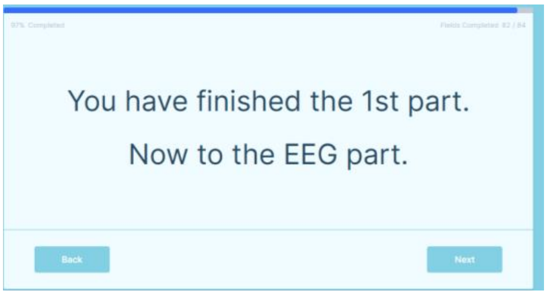




Each of the six videos had the same questions from training session in random order.

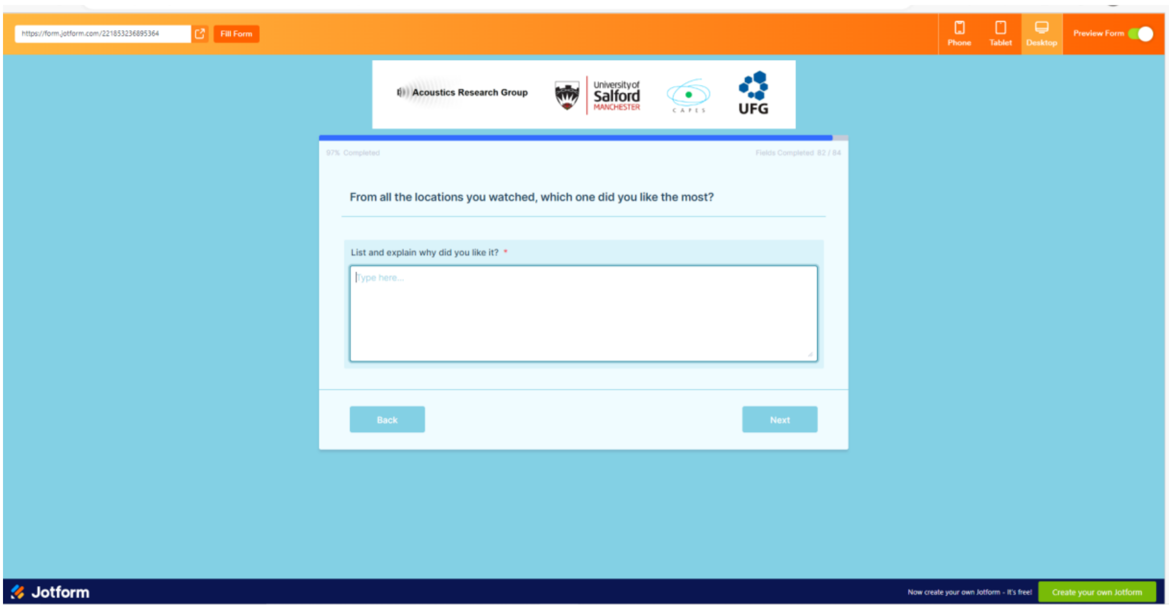
Open questions displayed through a laptop.



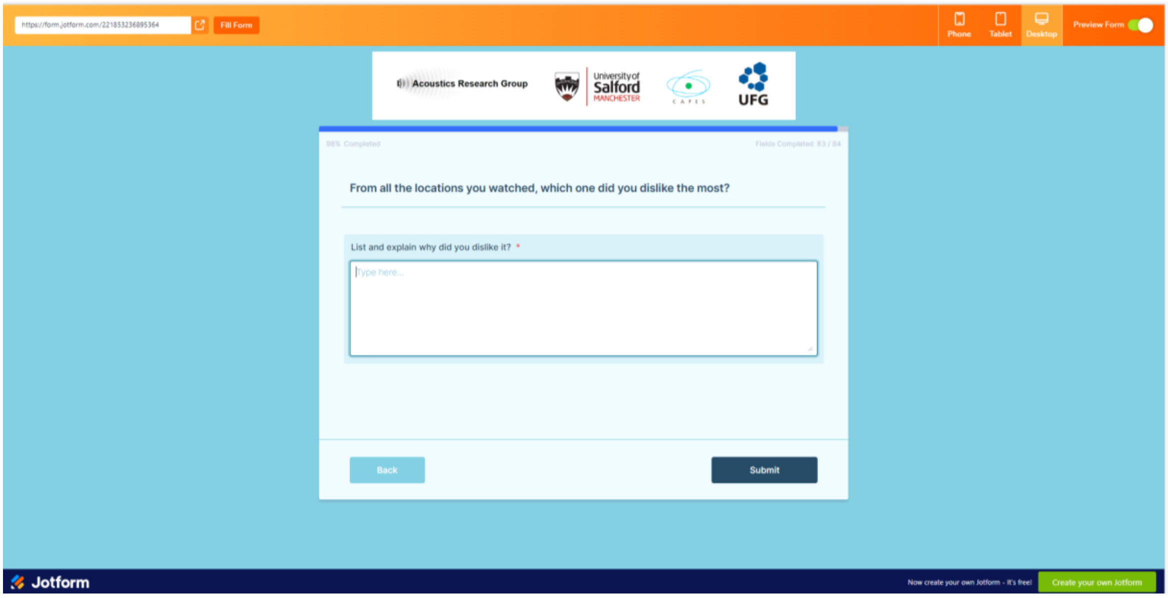


Completion of the questionnaire was interrupted to perform an EEG experiment.

Final open questions displayed through a laptop.



Final open questions displayed through a laptop (continuation).



APPENDIX TWO: Checklist for field recording

CHECK LIST FOR SOUNDSCAPE FIELD RECORDINGS

Equipment	**Check**	**Equipment**	**Check**
1. Sound field microphone ST250		15. Headphone	
2. Wind shield		16. Posters "Filming…"	
3. Mic amplifier		17. Tape	
4. 3 cables		18. Logbook	
5. Mic holder		19. Scissors	
6. ZOOM H6 Handy Recorder		20. Fly repellent	
7. Ricoh Theta camera*		21. Umbrella	
8. Ricoh cable*		22. Questionnaires	
9. SLM BSWA 308 – class 1		23. Pens	
10. Floor microphone stand		24. Clipboard	
11. Tripod for camera for 1.2m		*for initial recordings	
12. 2 C+ batteries spare			
13. 8 AA batteries spare			
14. Notebook charged			

ATTENTION = Fully charge all equipment + empty camera and audio memory card.

PROCEDURE FOR SOUNDSCAPE FIELD RECORDINGS

Procedure	Check
1. Calibrate SPL meter at a quiet place	
2. Chose a place where people will not trip on equip	
3. Position equip: 1.2-1.5m camera + mic on floor strait below	
4. Mic cables = certify WYXZ signals = + all appear on recorder	
5. Recorder (switch to -20dB PAD) and mic amplifier inside the bag	
6. Record L_{Aeq} for 1 minute at mic position	
7. Pulverise for bugs if necessary	
8. Test the audio settings (if quiet, increase gain – if noisy, reduce gain)	
9. Check on notebook for audio consistence (gain and WYXZ)	
10. Initiate the (1st) audio and (2nd) camera recordings	
11. Clap in front of the camera for future synchronisation	
12. Step out of sight of the camera or stay camouflaged	
13. Register date, time, and main sound events on logbook	
14. Leave recording for approximately 12 to 15 minutes	
15. Turn off camera	
16. Turn off audio	
17. Register the end of recording	
18. Take pictures of equipment in position and scenario	
19. Dismount if it is the last place of recording or unplug the mic and camera from stands to transport to next location.	

APPENDIX THREE: Scripts

Identifying clap time for audio and video synchronization

MATLAB script

```
clear %closes all and clears command window
%save all files on the same folder as script
%change filename for each sample location
%[x,fs]=audioread('filename.wav') for reading the audio file
[x,fs]=audioread('clap_audio.wav');
%assign channels 1=W or single audio from preview file
a=x(:, 1);
%[maxA, idx] = max(a) for identifying the maxA (amplitude of the 1st peak)
% and idx (moment in frequency rate)
[maxA, idx] = max(a)
%divide the idx by the recorded sampling rate idx = 48kHz
clap_time = idx/48000
```

Azimuth angle for audio and video alignment

MATLAB script

```
clear %closes all and clears command window
[x,fs]=audioread('ambi_Picc_busy.wav');%change filename for each sample location
a=x(:, 1);%assign channels 1=W/ 2=X/ 3=Y
b=x(:, 2);
c=x(:, 3);
[maxA, idx] = max(a)
%value of X - positive value=front / negative value=back
b(idx)
%value of Y - positive value=left / negative value=right
c(idx)
%value of angle to be corrected
Y=(atan((c(idx))/(b(idx))))*180/pi
```

EEGLab scripts

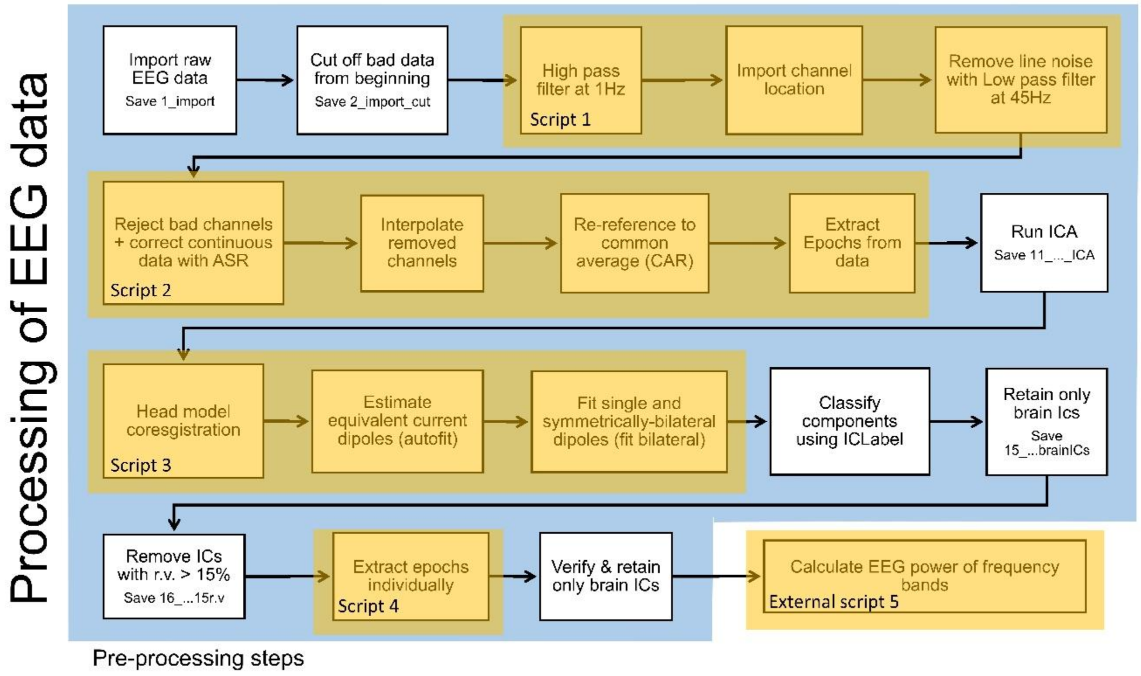


Figure with workflow for the pre-processing of EEG data. More details on section 3.5.2.3.

- **Script 1 with steps according to Figure above**.

Title: 1_eeglabhist_1Hz_chanLoc_45Hz

```
% EEGLAB history file generated on the 29-Jan-2023
% ------------------------------------------------
[ALLEEG EEG CURRENTSET ALLCOM] = eeglab;
pop_editoptions( 'option_savetwofiles', 0);
EEG = pop_loadset('filename','2_import_cut.set','filepath','C:↙
\\0_ML\\0_Maria\\Part_run');
[ALLEEG, EEG, CURRENTSET] = eeg_store( ALLEEG, EEG, 0 );
EEG = pop_eegfiltnew(EEG, 'locutoff',1,'plotfreqz',1);
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 1,'savenew','C:↙
\\0_ML\\0_Maria\\Part_run\\3_import_cut_1Hz.set','gui','off');
EEG = eeg_checkset( EEG );
EEG=pop_chanedit(EEG, 'lookup','C:↙
\\Users\\luiza\\Documents\\Packages\\eeglab_current\\eeglab2022.↙
0\\plugins\\dipfit\\standard_BEM\\elec\\standard_1005.elc','eval','chans =↙
pop_chancenter( chans, [],[]);');
[ALLEEG EEG] = eeg_store(ALLEEG, EEG, CURRENTSET);
EEG = pop_firws(EEG, 'fcutoff', 45, 'ftype', 'lowpass', 'wtype', 'hamming', 'forder',↙
330, 'minphase', 0, 'usefftfilt', 0, 'plotfresp', 0, 'causal', 0);
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 2,'savenew','C:↙
\\0_ML\\0_Maria\\Part_run\\4_import_cut_1Hz_chanLoc_45Hz.set','gui','off');
eeglab redraw;
```

- **Script 2 with steps according to Figure above.**

Title: 2_eeglabhist_ASR_interPol_+CPz_reRef_-CPz_epoched

```
% EEGLAB history file generated on the 29-Jan-2023
% ------------------------------------------------
[ALLEEG EEG CURRENTSET ALLCOM] = eeglab;
EEG = pop_loadset('filename','4_import_cut_1Hz_chanLoc_45Hz.set','filepath','C:↙
\\0_ML\\0_Maria\\Part_run');
[ALLEEG, EEG, CURRENTSET] = eeg_store( ALLEEG, EEG, 0 );
EEG = eeg_checkset( EEG );
EEG = pop_clean_rawdata(EEG, 'FlatlineCriterion',5,'ChannelCriterion',↙
0.8,'LineNoiseCriterion',4,'Highpass','off','BurstCriterion',8,'WindowCriterion',↙
0.25,'BurstRejection','off','Distance','Euclidian','WindowCriterionTolerances',[-Inf↙
7] );
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 1,'savenew','C:↙
\\0_ML\\0_Maria\\Part_run\\5_import_cut_1Hz_chanLoc_45Hz_ASR.set','gui','off');
EEG = eeg_checkset( EEG );
EEG = pop_interp(EEG, ALLEEG(1).chanlocs, 'spherical');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 2,'savenew','C:↙
\\0_ML\\0_Maria\\Part_run\\6_import_cut_1Hz_chanLoc_45Hz_ASR_interPol.↙
set','gui','off');
EEG = eeg_checkset( EEG );
EEG=pop_chanedit(EEG, 'append',32,'changefield',{33,'labels','CPz'},'lookup','C:↙
\\Users\\luiza\\Documents\\Packages\\eeglab_current\\eeglab2022.↙
0\\plugins\\dipfit\\standard_BEM\\elec\\standard_1005.elc','setref',{'33','CPz'});
[ALLEEG EEG] = eeg_store(ALLEEG, EEG, CURRENTSET);
EEG = eeg_checkset( EEG );
EEG = pop_saveset( EEG, 'filename','7_import_cut_1Hz_chanLoc_45Hz_ASR_interPol_CPz.↙
set','filepath','C:\\0_ML\\0_Maria\\Part_run\\');
[ALLEEG EEG] = eeg_store(ALLEEG, EEG, CURRENTSET);
EEG = eeg_checkset( EEG );
EEG = pop_reref( EEG, []);
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 3,'savenew','C:↙
\\0_ML\\0_Maria\\Part_run\\8_import_cut_1Hz_chanLoc_45Hz_ASR_interPol_CPz_reRef.↙
set','gui','off');
EEG = eeg_checkset( EEG );
EEG=pop_chanedit(EEG, 'delete',33);
[ALLEEG EEG] = eeg_store(ALLEEG, EEG, CURRENTSET);
EEG = eeg_checkset( EEG );


EEG = pop_saveset( EEG,↙
'filename','9_import_cut_1Hz_chanLoc_45Hz_ASR_interPol_CPz_reRef_-CPz.↙
set','filepath','C:\\0_ML\\0_Maria\\Part_run\\');
[ALLEEG EEG] = eeg_store(ALLEEG, EEG, CURRENTSET);
EEG = eeg_checkset( EEG );
EEG = pop_epoch( EEG, {  '1'  '2'  '3'  '4'  '5'  '6'  }, [0  8], 'newname', 'EEProbe↙
continuous data epochs', 'epochinfo', 'yes');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 4,'savenew','C:↙
\\0_ML\\0_Maria\\Part_run\\10_import_cut_1Hz_chanLoc_45Hz_ASR_interPol_CPz_reRef_-↙
CPz_epoched.set','gui','off');
EEG = eeg_checkset( EEG );
eeglab redraw;
```

- **Script 3 with steps according to Figure above.**

Title: 3_eeglabhist_DIPFIT_headModel_autofit_2fit

```
% EEGLAB history file generated on the 29-Jan-2023
% ------------------------------------------------
[ALLEEG EEG CURRENTSET ALLCOM] = eeglab;
EEG = pop_loadset('filename','11_import_cut_1Hz_chanLoc_45Hz_ASR_interPol_CPz_reRef_-↙
CPz_epoched_ICA.set','filepath','C:\\0_ML\\0_Maria\\Part_run\\');
[ALLEEG, EEG, CURRENTSET] = eeg_store( ALLEEG, EEG, 0 );
EEG = eeg_checkset( EEG );
EEG = pop_dipfit_settings( EEG, 'hdmfile','C:↙
\\Users\\luiza\\Documents\\Packages\\eeglab_current\\eeglab2022.↙
0\\plugins\\dipfit\\standard_BEM\\standard_vol.mat','coordformat','MNI','mrifile','C:↙
\\Users\\luiza\\Documents\\Packages\\eeglab_current\\eeglab2022.↙
0\\plugins\\dipfit\\standard_BEM\\standard_mri.mat','chanfile','C:↙
\\Users\\luiza\\Documents\\Packages\\eeglab_current\\eeglab2022.↙
0\\plugins\\dipfit\\standard_BEM\\elec\\standard_1005.elc','coord_transform',[0 0 0 0↙
0 -1.5708 1 1 1] ,'chansel',[1:32] );
[ALLEEG EEG] = eeg_store(ALLEEG, EEG, CURRENTSET);
EEG = pop_saveset( EEG,↙
'filename','12_import_cut_1Hz_chanLoc_45Hz_ASR_interPol_CPz_reRef_-↙
CPz_epoched_ICA_HeadModel.set','filepath','C:\\0_ML\\0_Maria\\Part_run\\');
[ALLEEG EEG] = eeg_store(ALLEEG, EEG, CURRENTSET);
EEG = pop_multifit(EEG, [1:30] ,'threshold',100,'plotopt',{'normlen','on'});
[ALLEEG EEG] = eeg_store(ALLEEG, EEG, CURRENTSET);
EEG = pop_saveset( EEG,↙
'filename','13_import_cut_1Hz_chanLoc_45Hz_ASR_interPol_CPz_reRef_-↙
CPz_epoched_ICA_HeadModel_autofit.set','filepath','C:\\0_ML\\0_Maria\\Part_run\\');
[ALLEEG EEG] = eeg_store(ALLEEG, EEG, CURRENTSET);
EEG = fitTwoDipoles(EEG, 'LRR', 35);
eeglab('redraw');
EEG = pop_saveset( EEG,↙
'filename','14_import_cut_1Hz_chanLoc_45Hz_ASR_interPol_CPz_reRef_-↙
CPz_epoched_ICA_HeadModel_autofit_2fit.set','filepath','C:↙
\\0_ML\\0_Maria\\Part_run\\');
[ALLEEG EEG] = eeg_store(ALLEEG, EEG, CURRENTSET);
eeglab redraw;
```

- **Script 4 with steps according to Figure above.**

Title: 4_eeglabhist_epoch_extraction

```
% EEGLAB history file generated on the 29-Jan-2023
% ------------------------------------------------
[ALLEEG EEG CURRENTSET ALLCOM] = eeglab;
EEG = pop_loadset('filename','16_import_cut_1Hz_chanLoc_45Hz_ASR_interPol_CPz_reRef_-↙
CPz_epoched_ICA_HeadModel_autofit_2fit_brainICs_15r.v.set','filepath','C:↙
\\0_ML\\0_Maria\\Part_run\\');
```

```
[ALLEEG, EEG, CURRENTSET] = eeg_store( ALLEEG, EEG, 0 );
EEG = pop_epoch( EEG, {  '1'  }, [0  8], 'newname', 'EEProbe continuous data epochs
pruned with ICA pruned with ICA epochs', 'epochinfo', 'yes');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 1,'savenew','C:
\\0_ML\\0_Maria\\Part_run\\epoch1.set','gui','off');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 2,'retrieve',1,'study',0);
EEG = pop_epoch( EEG, {  '2'  }, [0  8], 'newname', 'EEProbe continuous data epochs
pruned with ICA pruned with ICA epochs', 'epochinfo', 'yes');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 1,'savenew','C:
\\0_ML\\0_Maria\\Part_run\\epoch2.set','gui','off');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 3,'retrieve',1,'study',0);
EEG = pop_epoch( EEG, {  '3'  }, [0  8], 'newname', 'EEProbe continuous data epochs
pruned with ICA pruned with ICA epochs', 'epochinfo', 'yes');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 1,'savenew','C:
\\0_ML\\0_Maria\\Part_run\\epoch3.set','gui','off');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 4,'retrieve',1,'study',0);
EEG = pop_epoch( EEG, {  '4'  }, [0  8], 'newname', 'EEProbe continuous data epochs
pruned with ICA pruned with ICA epochs', 'epochinfo', 'yes');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 1,'savenew','C:
\\0_ML\\0_Maria\\Part_run\\epoch4.set','gui','off');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 5,'retrieve',1,'study',0);
EEG = pop_epoch( EEG, {  '5'  }, [0  8], 'newname', 'EEProbe continuous data epochs
pruned with ICA pruned with ICA epochs', 'epochinfo', 'yes');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 1,'savenew','C:
\\0_ML\\0_Maria\\Part_run\\epoch5.set','gui','off');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 6,'retrieve',1,'study',0);
EEG = pop_epoch( EEG, {  '6'  }, [0  8], 'newname', 'EEProbe continuous data epochs
pruned with ICA pruned with ICA epochs', 'epochinfo', 'yes');
[ALLEEG EEG CURRENTSET] = pop_newset(ALLEEG, EEG, 1,'savenew','C:
\\0_ML\\0_Maria\\Part_run\\epoch6.set','gui','off');
eeglab redraw;
```

- **Script 5 with steps according to Figure above.**

Title: powerS

The presentation of this code is illustrative so to demonstrate it's structure.

```
% This example Matlab code shows how to compute power spectrum of epoched data,
channel 1
 [spectra,freqs] = spectopo(EEG.data(1,:,:), 0, EEG.srate);

 % Set the following frequency bands: delta=1-4, theta=4-8, alpha=8-13, beta=13-30,
gamma=30-80.
 deltaIdx1 = find(freqs>1 & freqs<4);
 thetaIdx1 = find(freqs>4 & freqs<8);
 alphaIdx1 = find(freqs>8 & freqs<13);
 betaIdx1  = find(freqs>13 & freqs<30);
```

```
% Compute absolute power.
deltaPower1 = mean(10.^(spectra(deltaIdx1)/10));
thetaPower1 = mean(10.^(spectra(thetaIdx1)/10));
alphaPower1 = mean(10.^(spectra(alphaIdx1)/10));
betaPower1  = mean(10.^(spectra(betaIdx1)/10));

% This example Matlab code shows how to compute power spectrum of epoched data, ↙
channel 2.
[spectra,freqs] = spectopo(EEG.data(2,:,:), 0, EEG.srate);

% Set the following frequency bands: delta=1-4, theta=4-8, alpha=8-13, beta=13-30, ↙
gamma=30-80.

deltaIdx2 = find(freqs>1 & freqs<4);
thetaIdx2 = find(freqs>4 & freqs<8);
```

[… code repeats for each of the 32 channels]

```
% Delegate channel locations
sensor_1 = 1
sensor_2 = 2
sensor_3 = 3
sensor_4 = 4
sensor_5 = 5
sensor_6 = 6
sensor_7 = 7
sensor_8 = 8
sensor_9 = 9
sensor_10 = 10
sensor_11 = 11
sensor_12 = 12
sensor_13 = 13
sensor_14 = 14
sensor_15 = 15
sensor_16 = 16
sensor_17 = 17
sensor_18 = 18
sensor_19 = 19
sensor_20 = 20
sensor_21 = 21
sensor_22 = 22
sensor_23 = 23
sensor_24 = 24
sensor_25 = 25
sensor_26 = 26
sensor_27 = 27
sensor_28 = 28
sensor_29 = 29
sensor_30 = 30
sensor_31 = 31
sensor_32 = 32

chanLocations = [sensor_1; sensor_2; sensor_3; sensor_4; sensor_5; sensor_6; ↙
sensor_7; sensor_8; sensor_9; sensor_10; sensor_11; sensor_12; sensor_13; sensor_14; ↙
sensor_15; sensor_16; sensor_17; sensor_18; sensor_19; sensor_20; sensor_21; ↙
sensor_22; sensor_23; sensor_24; sensor_25; sensor_26; sensor_27; sensor_28; ↙
sensor_29; sensor_30; sensor_31; sensor_32];

deltaP = [deltaPower1; deltaPower2; deltaPower3; deltaPower4; deltaPower5; ↙
deltaPower6; deltaPower7; deltaPower8; deltaPower9; deltaPower10; deltaPower11; ↙
deltaPower12; deltaPower13; deltaPower14; deltaPower15; deltaPower16; deltaPower17; ↙
deltaPower18; deltaPower19; deltaPower20; deltaPower21; deltaPower22; deltaPower23; ↙
deltaPower24; deltaPower25; deltaPower26; deltaPower27; deltaPower28; deltaPower29; ↙
deltaPower30; deltaPower31; deltaPower32];

thetaP = [thetaPower1; thetaPower2; thetaPower3; thetaPower4; thetaPower5; ↙
thetaPower6; thetaPower7; thetaPower8; thetaPower9; thetaPower10; thetaPower11; ↙
thetaPower12; thetaPower13; thetaPower14; thetaPower15; thetaPower16; thetaPower17; ↙
thetaPower18; thetaPower19; thetaPower20; thetaPower21; thetaPower22; thetaPower23; ↙
thetaPower24; thetaPower25; thetaPower26; thetaPower27; thetaPower28; thetaPower29; ↙
thetaPower30; thetaPower31; thetaPower32];

alphaP = [alphaPower1; alphaPower2; alphaPower3; alphaPower4; alphaPower5; ↙
alphaPower6; alphaPower7; alphaPower8; alphaPower9; alphaPower10; alphaPower11; ↙
alphaPower12; alphaPower13; alphaPower14; alphaPower15; alphaPower16; alphaPower17; ↙
alphaPower18; alphaPower19; alphaPower20; alphaPower21; alphaPower22; alphaPower23; ↙
alphaPower24; alphaPower25; alphaPower26; alphaPower27; alphaPower28; alphaPower29; ↙
alphaPower30; alphaPower31; alphaPower32];
```

```
betaP = [betaPower1; betaPower2; betaPower3; betaPower4; betaPower5; betaPower6; ↙
betaPower7; betaPower8; betaPower9; betaPower10; betaPower11; betaPower12; ↙


betaPower13; betaPower14; betaPower15; betaPower16; betaPower17; betaPower18; ↙
betaPower19; betaPower20; betaPower21; betaPower22; betaPower23; betaPower24; ↙
betaPower25; betaPower26; betaPower27; betaPower28; betaPower29; betaPower30; ↙
betaPower31; betaPower32];

cond_chan = table (chanLocations,deltaP,thetaP,alphaP,betaP)

filename = 'allChan_partXX_sessionXX_epocXX.xlsx';

writetable(cond_chan,filename,'Sheet',1,'Range','A1')
```

APPENDIX FOUR: EEG laboratory procedures

REVIEW_Procedure for placing EEG caps

The procedure for setting up the EEG system on participant was as follows:

- measure head of participant to position electrodes according to the international 10-20 system;
- EEG Cap, Size M (51-56 cm head circumference)
- EEG Cap, Size S (47-51 cm head circumference)
- Measure the distance from Nasion to Inion centrally over the head with a measuring tape. Clean for head and back of the ears with alcohol wipes. Then put on the cap and place Cz half-way. Make sure the cap is left-right symmetric.
- connect cap and amplifier to notebook (password = neuro);
- open *eego* software on notebook;
- >Acquire>Montage Setup:10/20 common average – rest leave as default
- select predefined montage (default from previous research – still in development from the present research);
- create new subject with name or number code;
- select impedance setup to "10 impedance values";
- insert gel in cap electrodes starting from central ones (Fpz, GND, Fz, Cz, Pz, CPz, Pz, POz, and Oz) and continue until all electrodes become green on "impedance" screen. This procedure took 30 to 45 minutes; and
- start recording.

EEG system began collecting data before the stimuli started and once sample finished acquisition was stopped. Then, initial montage was selected to visualise and export data by selecting "Review recorded data on finalized".

Press next

Select – "Export recordings"

Select "Neuroscan" type of file to export

Gel application:

- Once you put the gel, give some time to soak in – suggested time 5-10min – that was when I let participants watch introductory video and do training session.
- When applying gel, hold electrode, lift, apply small amount, and push down to scalp gently.
- Improve impedance with 1) twisting the electrode, 2) pressing down gently in the hole with stick in all directions while holding the electrode at all times, 3) draw circle in electrode with stick while holding electrode, the bigger circle the better.
- Never pull electrode up;
- Must avoid air between electrode and scalp.
- For more tips, watch (101) Tips and Tricks for qEEG Setup - Part 1 - YouTube

Electrode impedance increases with time. High impedance results in bad data. Avoid long experiment duration and maintain the room cool and dry.

Too much gel creates bridges avoid it.

After the break, twiddle the electrodes and review impedance to put it to a lower level.

COVID free protocol

<u>EXPERIMENTAL PROCEDURES FOR COVID-19 SAFETY</u>

(experimental moment/COVID protocol)

Developed by Maria Luiza de U. Carvalho & Bill Davies, July 2021.

Outside the laboratory:

- **For your transport**, consider the best method of transport for you to get to campus. **Wash or sanitise your hands** before and after travelling. Ensure you maintain **social distancing** and wear a **face covering** throughout your journey if travelling on public transport.
- **Before the experiment**, you will be asked to complete the University's personal risk assessment process, about your vaccination status (preferably be vaccinated at least once) and to take the COVID lateral flow test within 24 hours prior to the experiment and present proof when arriving at the lab. You will be asked to download and enable the NHS Covid-19 app on your phone. The researcher (I) will clarify all questions related to the experiment remotely to **reduce your time in the laboratory**.

In the laboratory with social distancing:

- **Upon arrival**,
    - Please **wear your face covering** and contact me so I can escort you in the building. Once inside, follow **approved walkways** and allow enough time to move around the campus. The walkways and building usage routes have been developed with **social distancing** in mind and therefore it is important to **stay within the routes** and walkways outlined.
    - Use the **hand sanitiser** provided at the entrance of the building on entry and exit.
    - You will be **asked if there are any presence of symptoms** related to the COVID-19 (cough, runny nose, sore throat, loss of taste or olfactory sense) and **potential risk exposure** in the past 2 weeks to COVID infection (close contact with a suspected or confirmed case of COVID-19). If all negative, I will give you a new face mask (Type IIR) to use and you will attend the lab.

- **At all times**, I will wear a **mask**, a **gown, gloves, face shield** and **sanitize hands** before having any contact with you. Additionally, a social **distance of 2 m** will be maintained between us.

In the laboratory near you:

- Any **procedure close to you**, during the placement and application of the gel will be done from **behind** or **beside you**, avoiding face-to-face positioning. In addition to the internal ventilation system, the room will have its **doors kept open for extra ventilation** as much as possible when the experiment is not in progress, closing only when necessary (when the experiment is in progress).
- For the **first part of the experiment**, you will **place the virtual reality (VR) device and the headphones** on your head. **First, only you** will carefully adjust the VR and the headphones on your head to a comfortable position. **Then, only I** will make sure that the device is in the correct position from **behind** or **beside you**, avoiding face-to-face positioning.
- Hands should be sanitised **before the start** of the experiment and **at the end** of the experiment. **Hand sanitiser** will be available in the room.

In the laboratory with social distancing:

- To **start the experiment**, **I will step away** and start with a training session followed by the different scenes through the VR headset so that you can answer the survey using a laptop placed in front of you after each video.
- Before the **second part of the experiment**, **only you** will carefully remove the VR headset and headphones when I request it.

In the laboratory near you:

- Before **placing the EEG cap**, I will measure your head to select the correct size of the EEG cap and will **clean** your **forehead** and **mastoids** with **alcohol wipes** to improve skin contact.
- When **placing the EEG cap**, **only I** will place and adjust the cap, connect, and configure the EEG cap on the amplifier and tablet from **behind** or **beside you**, avoiding face-to-face positioning.

- At this point, I will start **applying the gel** to each of the electrodes on the EEG cap (there are 32 units) with a **disposable syringe and needle**. This procedure is done until all EEG sensors are activated.
- When **placing the VR device for baseline recording**, **only I** will place and adjust the VR device from **behind** or **beside you**, avoiding face-to-face positioning.

In the laboratory with social distancing:

- To **start the EEG experiment**, **I will step away** and begin recording a baseline while you use the EEG cap and VR device. Before I start the EEG recording, you will be asked to **remove the mask** to avoid possible hypercapnia and EEG data contamination.
- To **continue the experiment**, **I will step away** and start a new recording. Before I start the EEG recording, you will be asked to **remove the mask** to avoid possible hypercapnia and EEG data contamination.
- **During the experiment**, there will be short breaks when you can have a snack and move around before the next session. You must bring any snack yourself. Suitable snacks include fruit, cookies, water, non-caffeinated and non-alcoholic drinks. You must use a **hand sanitiser before** and **after** the snack.

In the laboratory near you:

- **At the end of the session**, you will **put your mask on again** and I will remove the EEG cap carefully from **behind** or **beside you**, avoiding face-to-face positioning. You should clean the excess gel left on your head by yourself and dispose tissues in delegated bin. Also, use a **hand sanitiser** after cleaning your head.

In the laboratory with social distancing:

- **Between sessions**, the laboratory room, surfaces, furniture, and EEG materials used by you will be **disinfected** or **disposed of**. In addition to the internal ventilation system, the room will have its doors kept open for **extra ventilation** whenever possible.

HYGIENE PROCEDURES – FOR INTERNAL USE

- **For the researcher**

The researcher will use a surgical mask, wash hands frequently, use a disposable gown, gloves, face shield, and do a COVID test twice a week.

Steps for putting on Personal Protective Equipment (PPE): Wash hands, put on apron, mask, face shield, and gloves.

Steps for taking off PPE (don't touch outside of PPE): remove gloves, clean hands, remove apron, remove face shield, clean hands, remove mask outside testing room, clean glasses when worn, and wash hands.

- **For the participant**

The participant will be asked about their risk group (avoiding high risk groups) and vaccination status (preferably be vaccinated at least once) as well as to take the COVID lateral flow test within 24 hours prior to the experiment and present proof when arriving at the lab. On their arrival, they will be asked for the presence of symptoms related to the COVID-19 (cough, runny nose, sore throat, loss of taste or olfactory sense) and the potential risk exposure in the past 2 weeks to COVID infection (close contact with a suspected or confirmed case of COVID-19) (Campanella *et al.*, 2021). If all negative, the participant will be given a new face mask (Type IIR) to always use and will attend the lab.

For the experiment, participant will touch sanitised surfaces, such as VR device, headphones and EEG cap for adjustments and data collection. Hands should be sanitised before the start of the experiment and at the end of the experiment. Hand sanitiser will be available in the room.

Furthermore, the participant must always use a mask (only removes before EEG recordings to avoid data contamination when the researcher asked for and is distant), sanitize hands when arriving and leaving the lab, and sign a consent form. All surfaces will be sanitised after participant leaves.

- **Procedure/materials**

After each session, the syringe and needle used to apply the gel on the EEG electrodes will be disposed of.

The EEG cap will be washed with light warm water to remove all gel residue. Then it will be soaked for 15 minutes in a small amount of liquid detergent, then soaked in clean water until there is no residue on the cap. Initially, it will be left to dry overnight, and the final drying will be done with a hairdryer in a light cool flow.

The virtual reality head mounted device VIVE will have a disposable paper cover where the device touches the face over the eyes and the joystick to be cleaned with antiviral cleaner and surface wiping paper (electrical approach).

The headphone will have a disposable cover where the device touches the ears of the participant and will be cleaned with antiviral cleaner and surface wiping paper (electrical approach).

Other surfaces and furniture used by the participant will be sanitized with antiviral cleaner and surface wiping paper.

- **Procedure/location**

During experiment, in addition to the internal ventilation system, room will be ventilated as much as possible when experiment not in progress e.g. door propped open and closed only when absolutely necessary (when experiment is in progress). After each session, the room will have its doors kept open for extra ventilated for at least 10 minutes or every 4 hours.

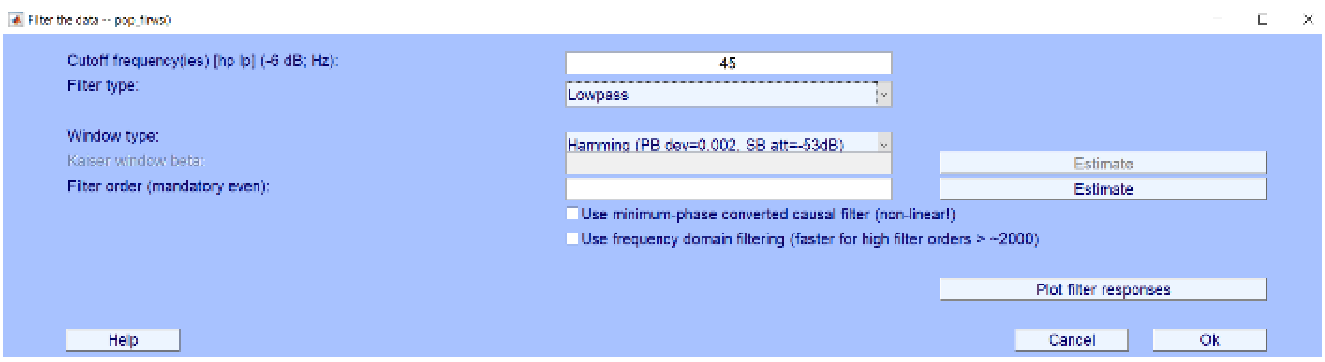
- **Materials/consumables**

70% ethanol wipes for cleaning forehead and mastoids / antiviral cleaner / wiping paper for surfaces / surgical masks / syringes / aprons / gloves / washable face shield / liquid detergent / EEG electrode gel / hairdryer for EEG caps / virtual reality disposal paper covers / headphone disposal covers / cotton tips for electrode activation / facial tissues for removing EEG gel

APPENDIX FIVE: EEGLab step-by-step commands

EEGLab commands for pre-processing pipeline

1. Import data – attention to titles of files and folders
    a. File > Import data > Using EEGLab functions & plugins > From ANT.EEProbe.CNT file
2. Plot (scroll) and remove big artefacts from data. For example, in my data, the beginning of each reading has lots of distortion, so, I removed it before beginning pre-processing.
3. High pass filter data at 1Hz (reason remove slow, possible large amplitude, drift)
    a. Tools > Filter data > Basic FIR filter (new, default) – change "Lower edge of the frequency pass band (Hz)" to 0.5 Hz video (remove what is below 0.5Hz for ICA – but for ERP too high 0.1Hz better) / to 1 Hz – tested it was better results
    b. Makoto – tick "Plot frequency response" – the rest default – transition bandwidth of 0.25 to 0.75Hz – press ok
    c. Save with new name
4. Import channel information
    a. Edit > Channel locations > click on "Look up locs" > choose "use MNI coordinate file for BEM dipfit model" – press ok – click "Opt. head center" (top right corner) – press ok
5. Low pass filter of data before 50Hz
    a. Tools > Filter the data>Windowed sinc FIR filter – "FIR filters […] do not distort wave phases" (Teplan, 2002) p.9



    b. "Cutoff frequency" at 45Hz and "Filter type" at Lowpass

c. Click in the Estimate window for “Filter order” > put 5 as transition bandwidth

d. Click ok here and next

e. Save with new name

6. Remove bad channels and Correct continuous data with ASR – don’t save data so you can interpolate removed channels (time consuming)

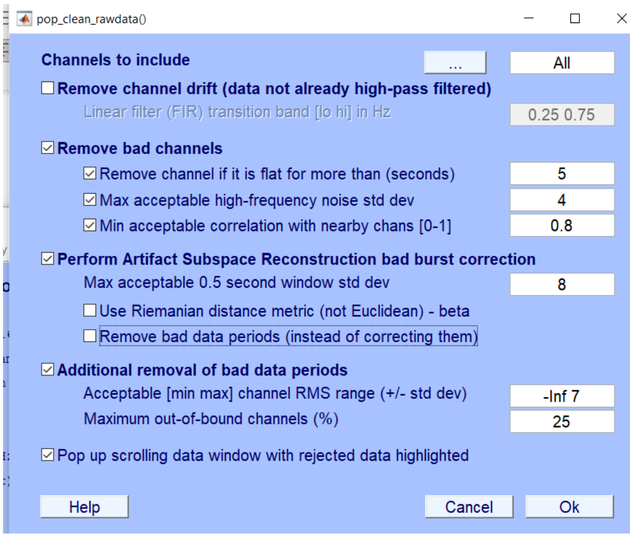
   i. Tools > Reject data using clean Rawdata and ASR

   ii. tick Remove bad channels > tick Min acceptable correlation with nearby chans [0 -1] = 0.8

   iii. tick Perform ASR > Max acceptable 0.5 sec window std dev = 8

   iv. untick “Remove bad data periods…

   v. the rest leave as default



7. Interpolate removed channels

    a. Tools > Interpolate electrodes – select " use all channels form other dataset" choose previous index file
    b. Save with new name
8. Re-reference data to average
    a. Add zero filled channel before re-reference to average
    b. Edit > Channel locations – go to last channel and press ">>" bottom – click "Append chan." To create the new channel > "Label" with the new name ex. FCz > press "Look up locs" > select "use MNI coordinate file for BEM dipfit model" – click ok – press "Set reference" channel indices "33" reference "FCz" – click ok
    c. Reference should appear at the last position – press ok
    d. Tools > Re-reference the data – tick Compute average reference
    e. After Re-referencing, remove extra channel
    f. Save data
9. Epoch data (only when there are a lot of epochs – if not, e.g., for baseline, invert procedure, run AMICA first then extract epoch later)
    a. Tools > Extract epochs – select ALL events (1 2 3 4 5 6) – set limits (0 8) – baseline removal – use default – ok
    b. Don't remove baseline
    c. Save file
10. Run ICA – save data (time consuming) 10 min sessions = 10 min processing
    a. Tools > Run AMICA
11. Head model co-registration and Estimate equivalent current dipoles (time consuming)
    a. Tools > Source localization using DIPFIT > Head model and settings – default "… MNI"
    b. Tools > Source localization using DIPFIT > Component dipole autofit (course fit, fine fit, & plot) – default - use Field Trip plugin (time consuming)
12. Search for, and estimate symmetrically constrained bilateral dipoles
    a. Tools > Fit bilateral dipoles – install "Fit Two Dipole…" - default
13. Plot ICAs
    a. Tools> Classify components using ICLabel > Label components
    b. Maintain all brain ICs
14. Remove non-brain ICs from data
    a. Tools > Remove components from data

15. Generate dipoles for rejection
    a. Tools > Source localization using DIPFIT > Component dipoles plot – default
    b. Identify ICs with r.v. >15% and remove
    c. Tools > Remove components from data
16. Extract epochs
    a. Tools > Extract epochs
17. Run script for power spectrum

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