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Towards a Human-Centered Approach for the Multisensory Design of Urban Park

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Summary

The thesis is an interdisciplinary investigation on urban parks as a space of multisensory human perception and immersive experience. Regardless of the methodology distinction between architecture and neuroscience, the thesis also attempts to provide an empirically plausible cognitive-behavioral framework and its relation with the built environment that best explains the human experience of urban parks. And based on this framework, empirical experiments are preceded to assess the validity of this model through advanced simulation technology and real-time neural measurements.

Nowadays, more and more temporary landscape architects and ecology designers realize the crucial role of urban parks in modern urban settings. Urban parks provide a precious natural environment for city residents' well-being within the urban habitat. Improving the quality of these public spaces in cities is of utmost importance. From the landscape architects' perspectives, urban parks are in various forms, places and categories. If we want to use scientific methods to investigate them, we need to take multiple perspectives, from design concepts to human perception. In order to do so, an alternative way of understanding and designing the urban environment in multi-level (physical/behavioral/mental) and multi-modal (vision/sound/smell/...) should be explored. This thesis attempts to synthesize the multisensory characteristics of urban parks through Immersive Virtual Reality (IVR) technology as a full-stimuli simulation interface and real-time measuring of human perception with embedded eye-tracking systems and brain activity devices. Also, the cognition framework introduced by neuroscience provides a meaningful explanation of the dynamics between human experience and urban park settings, which can help landscape architecture utilize sensory design elements and address new strategies for urban park design for human wellbeing and safety.

To sum it up, the thesis could be taken as (1) an attempt of how building physics and landscape research may go beyond traditional methods and provide more insights for urban park designers, (2) a cross-platform exploration of interactive experience that provides a meaningful explanation of spatial characteristics in urban parks and (3) a framework about the human-centred design of urban park considering human experience on a sensory-level.

Candidato/a
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Abstract

Urban parks, often associated with green urban spaces, have increasing importance in city developments due to the population expansion and urbanism process. Past efforts from researchers and designers in architecture and landscape fields are mainly focused on exploring the nature of landscape environments and the effects on human life over space and time. Regardless of the nature of sensory interaction and inter-sensory coherence in human perception, its implementation in urban design practices has been scarce, and the progress of multi-sensory research has been relatively slow. To provide a better understanding of the urban environment through the senses towards the improvement and enrichment of public spaces, this thesis aims at the process of multisensory human perception while interacting with spatial configuration and physical characteristics in urban park environments. First, a configurable and repeatable audio-visual system is built to simulate the spatial configurations and audio-visual characteristics of an existing urban park environment through Immersive Virtual Reality (IVR) technology and 3D spatial audio system. Then, real-time measurements and ex-post questionnaire evaluations are both combined to get deeper insights into the cognitive process and behavioral effects of multisensory human perception. Finally, general conclusions are explained for the process of multisensory perception, and their effects on mental health and social safety of human wellbeing, while they are in urban parks and different design strategies that can engage humans in the built environments are recommended. These study findings will help generate evidence-based guidelines for building physics, landscape studies and urbanism practices for improving safety and health of human wellbeing while preserving the preferred physical properties of urban landscape.

Content

PART I INTRODUCTION AND LITERATURE REVIEW

CHAPTER 1: INTRODUCTION

1.1 Background

The design and implementation of urban parks have been developed along with the history of cities and urbanization. In 1843, architect Joseph Paxton designed Birkenhead Park, considered the first urban park in the world for public use, financed with public funds in Liverpool, England (see Figure 1) (Taylor, 1995). The role of urban parks, as part of the green space, in urban city development has been repeatedly addressed and discussed across different institutes and privates like governments, policymakers, researchers and designers. The benefits of urban parks in city construction and development include climate change, biodiversity, air cleaning, ecological efficiency, noise protection, disaster protection, tourism etc. Emphasis on different aspects of those benefits, different countries and cities' gernments have published different laws and policies referring to their spatial planning.

Figure 1 - First Public Park - Birkenhead Park, United Kingdom

The research concept and content of urban parks also involved a variety of domains. Based on the 3248 items of bibliometric results from Web of Science database, the scientific reports with the topics about "urban park" and its synonyms have been greatly increased since 1970s (see Figure 2). The sources of those articles are mainly from the journal Urban Forestry & Urban Greening, Landscape and Urban Planning, and Internal Journal of Environmental Research and Public Health. The urban park characteristics involved in those researches and applications are complex. For example, urban park planning could be implemented across different spatial scales, from the garden city (Howard, 1965) strategy for the whole city planning to the pocket park recreation for unused city corners (see Figure 3) (Peschardt and Stigsdotter, 2014; Hussein et al., 2022). The small-size urban parks, named pocket parks, mini-parks, vest-pocket parks, and neighborhood parks, replace vacant building lots or unused space that skipped through the real-estate interest with little landscape patches. The birth of the pocket parks concept in the US in 1987 can be accredited to the urban reformer Jacob Riis which was the Secretary of the Small Parks Committee (Hamdy and Plaku, 2021).

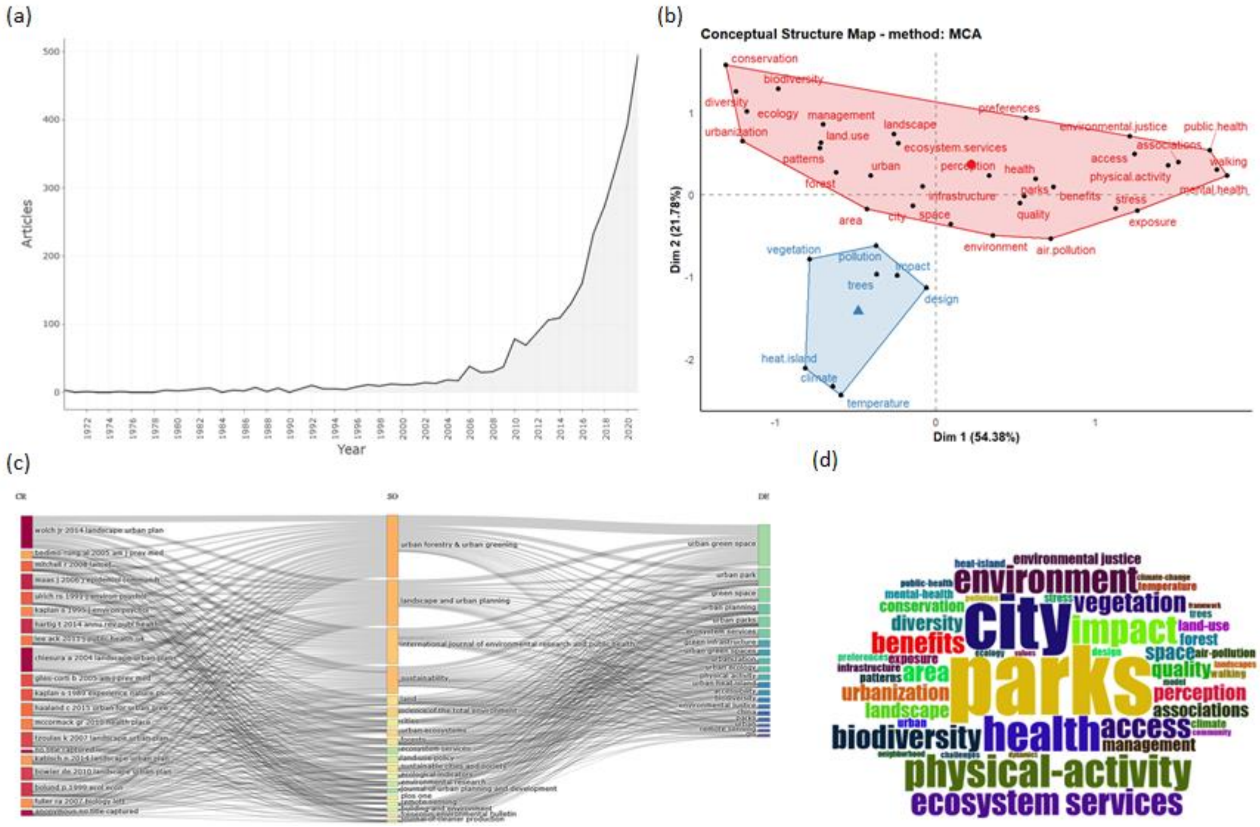


Figure 2 - Systematic review analysis of urban park studies: (a) annual scientific production of "urban park" studies; (b) conceptual structural map of the keywords from urban park studies; (c) references-sources-topics three field plot in urban parks researches.

Figure 3 - From city to corner: Gardens by the Bay, Singapore (a) and Ferry Street Pocket Park, Hong Kong (b)

From the multiple correspondence analysis of the keywords from the bibliometric data, the research paths of urban park studies could be divided into two big sub-topics. While the land planning and assessments of urban parks could be based on the macro level of city policy, the design and implementation of urban parks cannot ignore the consideration of their effects on human well-being from the micro level aspects. It has been well recognized that urban parks have a relevant impact on citizens' health through three main aspects: mitigation from harm, instoration for activity, and restoration of mind (see Figure 4) (Browning et al., 2022).

Figure 4 - The functions of urban parks on human mental health

The characteristics of urban parks affect the multisensory perception of the visitors and evoke different mental states and physical activities for them and yield those benefits to them. And the physical activities also improved the visitors' mental state and health. The WHO European Centre for Environment and Health conducted a systematic review on the types and characteristics of green spaces concerning a broad set of mental health aspects (Europe, 2021). The key findings from the reports can be summarized as follows: most green space types yielded positive effects on short-term influences like affect, stress relief restorative outcomes, and severity of mental disorders and long-term mental health outcomes, including overall mental health, quality of life and subjective well-being. Dense vegetation and shrublands were the most preferred green space type, with no adverse effects on mental health. Neutral or negative reported outcomes are also reckoned in the cross-sectional and longitudinal studies. The comparison between different green space types yielded mixed results, indicating that there is not one single green space type or characteristic that appears best. Characteristics of green spaces and their combinations should be drawn more attention to their effects on mental health.

1.2 The Challenge of Current Approach: Bridging the Design and Assessment of Urban Park

While the merits of urban parks have been well-recognized, the applications of urban park design have been full of variability and dynamics due to the complicated spatial-temporal properties of the urban green spaces and their surrounding environments (Menconi et al., 2021b, 2021a). Several challenges exist behind the discrepancies between the design practice and the empirical evaluation of urban parks. While more principles and approaches (Thammasat University et al., 2021; Wang and Foley, 2021; Woo and Choi, 2022; Zou and Wang, 2021) have been developed into the design process for the urban park with visual characteristics covering park features, conditions, access, aesthetics, safety to policy (Bedimo-Rung et al., 2005), few tools are created and employed for other sense or multi senses resources. Since R. Murray Schafer (Schafer, 1977, 1993) introduced the concept of soundscape in 1977, focusing attention on the perception of the surrounding sound environment, this concept has been mentioned in several research (Raimbault and Dubois, 2005; Zhang and Kang, 2007; Kang and Zhang, 2010; Davies et al., 2013; Brooks et al., 2014; Maffei et al., 2015; Lugten et al., 2018; Hong et al., 2020b; Sztubecka et al., 2020; Van Renterghem et al., 2020; Zhao et al., 2020; Gale et al., 2021; Levenhagen et al., 2021; Jiang, 2022; Lu et al., 2022; Kang, 2023). And similar frameworks like smellscape (He et al., 2022; Song and Wu, 2022) and even sensescape (Ross, 2004; Chourmouziadou and Sakantamis, 2015) are also beginning to address the design and planning aspects of urban spaces for their multidimensional and multisensory contents. But more work is still needed to develop more reliable design methods for the multisensory experiences in urban parks. Similar to the design of urban parks, the assessment of urban park derived from the landscape assessment (Mücher et al., 2010) are also unidimensional and hysteretic embedded with semantic context, making it hard to reflect the outcomes of various features and structure from urban park design. Those challenges are compelling designers and researchers to clarify the key definitions and orientations for the design practice and outcome evaluations of urban parks, to identify trade-offs and synergies between the multidimensional inputs and mental-behavioral outcomes and to develop more frameworks to extend the understanding of the effects of design types and elements in urban park environments across temporal and spatial scales grounded in science-practice interactions.

1.3 The Proposal and Research Aim: Integrating Human-Centered Design Approach with Multisensory Perception of Urban Park

The evidence-based design (EBD) is the concept that occupational practices and design decisions should be based on scientific evidence, originated from the field of medicine in 1992 (Reynolds, 2008). After being referenced by the practice of health care facilities designing (Zimring et al., 2013), this method has been applied to more architecture and landscape fields (Battisto and Franqui, 2013; Brown and Corry, 2020). Started from the intention for mental-health promotion of urban park, the practice of EBD in urban parks is naturally adopted (Graça et al., 2022; Lafrenz, 2022; Veitch et al., 2020).

Although the EBD approach continues to be used positively in designing urban parks or other landscapes, lacking rigorous methods of evaluating strategies and integrating outcomes hinders further developments. The human-centred principle provides a problem-solving framework to develop technologically effective solutions for evidence-based designing (Wells and Stiefel, 2018). Multidisciplinary techniques related to real-time measuring of psycho-behavioral factors are necessary to utilise the qualitative and quantitative analysis from human-centred approaches. Multisensory perception, derived from psychology and neuroscience, is trying to address the question of how different senses interact and what their outcomes are (Soto-Faraco et al., 2019; Spence, 2020). This research harnesses the current advances in Immersive Virtual Reality (IVR) technology and wearable neuro-behavioral sensing technology to conduct multisensory inputs in urban park environments and collect the human psychological-behavioral responses to their interaction with the environment as a means to drive evidence-based design of urban parks.

1.4 Research Aim and Objectives

The goal of this work is to use an integrated methodological framework of urban parks with multiple sensory inputs, and multi-modal outputs to investigate the general effects of urban park elements and their combinations on human mental health and responses.

Objective 1: investigate the effects of visual and auditory elements with their spatial-temporal settings in urban parks on human multisensory perception.

Objective 2: compare different methodologies and technologies for measuring human perception and behaviors in urban parks with different visual and auditory aspects.

Objective 3: explore the general framework of integrating different design and assessment tools to conduct urban park design with applicable and reproducible outcomes.

1.5 Research Design and Approach

An iterative design and human-centred approach were used to achieve the research aims (see Figure 5). First, different types of urban parks referring to several visual and auditory elements and their combinations were investigated for urban park design. And different experimental methods and platforms were constructed to accomplish the experiences of urban park environment and physical settings for urban park assessments. Moreover, objective measurements, including brain signals and ocular behaviors combined with subjective feedback, were used to extend and makes deeper the understanding of the outcomes of urban park perception and drive the process of the evidence-based design of urban parks.

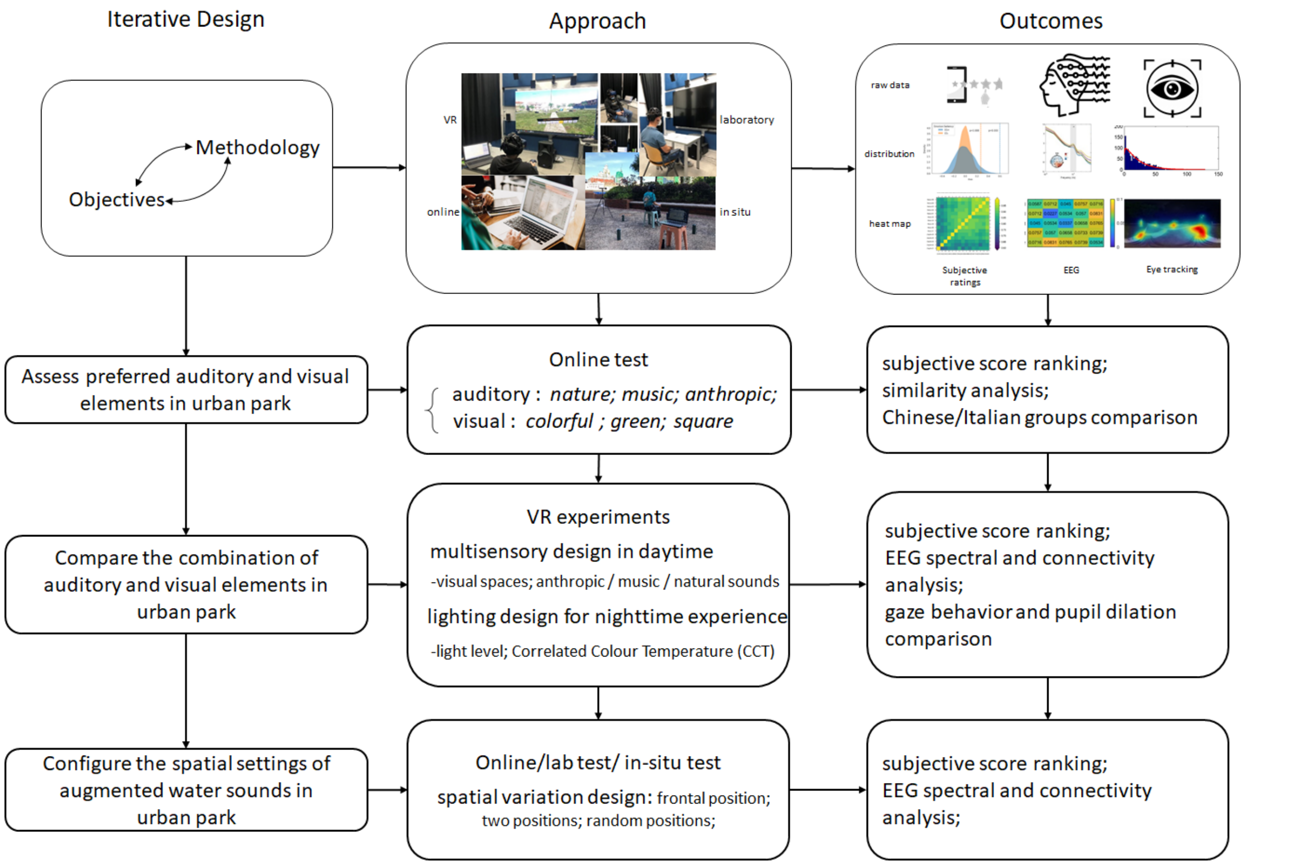


Figure 5 - Research design flow chart of the thesis

1.6 Research Significance

This research will extend the methodologies for the research-driven and evidence-based design of urban parks enabling urban planners and municipal decision-makers to evaluate and foster more environmental settings for human health and well-being. Therefore, citizens will be more likely to benefit from the promoted environments based on human-centred principles.

1.7 Organization of the Thesis

The thesis consists of four parts and nine chapters.

Part I is a background introduction (Chapter 1) and literature review (Chapter 2) on the research topics of urban parks and the current approaches for urban park design and assessments.

Part II describes the methodology of the conducted research, covering the research framework (Chapter 3), experiment design, data collection and analysis method (Chapter 4) used in all the studies for the thesis. Chapter 3 introduces the research framework combining the designer's and the user's views in the thesis. Around this framework, Chapter 4 summarizes the methodology related to the research type/platform for experiment design and environment presentation and brain-behavioral measurements for objective and subjective evaluations.

Part III presents four main studies related to the multifaceted aspects of multisensory design and perception of the urban park environment. Chapter 5 uses the audio and image materials with online research method to assess the subjective feelings about urban parks' different auditory and visual elements. Chapter 6 presents the neural and subjective effects of the combinations of visual and auditory elements in a virtual urban park accomplished by immersive virtual reality technology. Subjective scores and brain signals from viewers were collected to analyse the effects of multisensory inputs of urban parks. Chapter 7 studies the gaze behaviors and perceived qualities of different lighting settings in urban parks. Chapter 8 describes the efforts on the spatial configuration of augmented water sound playback for urban park improvement.

Part IV (Chapter 9) concludes the main findings from the studies and contributions to knowledge, practice, and impact, with a discussion of the limitations of those studies and the directions of future works.

CHAPTER 2: LITERATURE REVIEW

2.1 Theories of the Health Benefits of Urban Parks

As most theoretical and practical research categorized for the health promotion effect of urban parks across three aspects: mental health, physical health, and social health (see Table 1) (Wang et al., 2020; Cohen et al., 2022), the benefits from those aspects also vary from long-term to short-term effects.

Table 1 - Health benefits of urban park (combining results from Wang et al., 2020 and Cohen et al., 2022)

Category	Benefits
Physical health	increase physical activity engagements; promote self-perceived general physical health, reduce the risk of cardiovascular and diabetes, reduce the incidence rate of respiratory diseases, reduce the risk of cancer, improve infant birth weight, reduce the risk of overweight or obesity.
Mental health	promote general mental health, increase self-reported happiness, reduce mental health service use, increase productivity, reduce antisocial behavior, regulate mood, improve anxiety and depression symptoms, improve cognitive ability, improve attention deficit disorder symptoms, reduce pain, and relieve stress.
Social health	improve social cohesion, increase the sense of belonging, reduce crime rate, improve community satisfaction, enhance social security, and promote overall social health.

The earlier theory that tried to explain the effects on health and well-being from natural and green environments is the Biophilia-hypothesis (Kellert and Wilson, 1993; Ulrich, 1993; Wilson, 2021). Wilson described the hypothesis as a human "innate tendency to focus on life and lifelike process" in his book Biophilia in 1984. According to this hypothesis, our modern brain must have inherited from human species history as subsistence hunters, gathers and farmers, then attuned to extracting, processing and evaluating information from the natural environment during the evolutionary process(Gullone, 2000). The more mature theories, including Stress Reduction Theory (SRT), Attention Restoration Theory (ART), and Supportive Environment Theory (SET), have often been referenced for explaining the health benefits of urban parks and related natural settings (see Table 2). The Stress Reduction Theory focuses on restoring individuals from psychophysiological stress. It suggests that autonomic and affective responses, influenced by evolutionary traits, are crucial in how people respond to different environments. Responses of approach or avoidance depend on the interpretation and valuation of environmental perceptions in relation to survival and well-being. Favorable environments, such as urban parks and green spaces, are believed to trigger stress-reducing responses while threatening or adverse conditions induce stress. Generally, urban environments and stimuli are considered more stressful and less restorative compared to natural settings(Bergman and Appleton, 1978; Orians, 1986; Ulrich, 1986; Ulrich et al., 1991; Falk and Balling, 2010; Mercado-Doménech et al., 2017). The Attention Restoration Theory complements SRT by focusing on restoring attention capacities. It distinguishes between two types of attention: directed attention and fascination. Directed attention can become fatigued due to the demands of modern life and excessive stimulation. Restorative environments like green spaces are proposed to provide a sense of being away from the everyday environment, a coherent and uninterrupted space, opportunities for fascination, and compatibility with individual needs. By allowing directed attention to rest, these environments aid in restoring attention capacities, enhancing cognitive functioning, and promoting well-being (Heft, 1988; Kaplan and Kaplan, 1989; Kaplan, 1995; Hartig et al., 1997b; Berto, 2005; Cosco, 2006; Kaplan and Berman, 2010; Zamani and Moore, 2014). The Supportive Environment Theory takes an ecological approach to explain the salutogenic influence of green or natural environments. It emphasizes the embodied relations between individuals and their environment, including the affordances for aesthetic qualities and perceived sensory dimensions. SET recognizes that individuals' experiences of the environment are shaped by their needs, characteristics, social factors, and physical conditions. Designing supportive environments based on SET involves creating spaces that enhance well-being and health outcomes. This theory contributes to understanding how the broader socio-material context influences the perception and utilization of green spaces and natural environments in people's daily lives (Grahn and Stigsdotter, 2010; Stoltz and Grahn, 2021).

Table 2 - Main Theories of the Health Benefits of Urban Parks

Main theories	Key definitions	Description	Application
Stress Reduction Theory (SRT)	psychophysiological stress	Autonomic and affective responses, influenced by evolutionary traits, determine our reactions to different environments. Natural environmental conditions trigger stress-reducing responses, while adverse conditions induce stress.	Designing environments for stress reduction
Attention Restoration Theory (ART)	attention capacities; mental fatigue	Dividing restorative environments into four dimensions: being away, coherence, fascination, and compatibility for assessing restoration of attention capacities;	Designing environments for attention restoration; Enhancing cognitive abilities and human well-being; Promoting mental health;
Supportive Environment Theory (SET)	ecological health	Considers embodied relations with the environment, including affordances for aesthetic qualities and perceived sensory dimensions (PSDs).	Designing supportive environments; Enhancing human well-being and health; Creating therapeutic landscapes and healing gardens;

2.2 Designing Urban Park Characteristics

From the landscape planners' perspectives, the design of an urban park is about shaping the three-dimensional spaces of natural landscapes in the urban environment. It is often a result of intentional design decisions made to achieve certain goals. Physical, biological and social elements and relationships are constantly in flux within urban parks. Most designers seek to identify and promote these inherent processes by relating site conditions and landscape processes to reveal and make these complex and dynamic relationships productive. Based on earlier studies of urban scenic quality and park safety perception, Schroeder & Anderson (1984) summarized 29 physical features related to landscape characteristics in urban parks to evaluate the extent by park designers or managers (see Table 3) (Schroeder and Anderson, 1984). Ayala-Azcárraga et al. (2019) evaluated perceived characteristics of green spaces and environmental components of urban parks as public urban green spaces from nine parks in México City, relating them to the well-being of their visitors. They found a close relationship between patterns of visitor use and urban parks components such as distance, tree abundance, safeness, playground qualities and cleanliness. Eighteen variables were integrated into three components of urban parks, including spatial component (Size, Distance, Accessibility), infrastructure/services component (Walking trails, Illumination, Graffiti, Exercise equipment, Playground equipment, Cleanliness, Seats, Safety), and environmental component (Abundance of trees, Height of trees, Greenness of landscape, Birds song, Biodiversity, Naturalness degree, Noxious fauna) (Ayala-Azcárraga et al., 2019).

Table 3 - The physical features of park from (Schroeder and Anderson, 1984)

Metrics	Feature	Metrics	Feature
Percent of photo image covered by feature (%)	woody vegetation	prominence of feature in scene	maintenance problems
	grass		people
	water		streets
	athletic fields		windows
	park structures		picnic facilities
	nonpark structures		playground equipment
	parking lots		shrubs
Distance seen into site	average view distance		features outside of park
	lowest view distance		park facilities
Tree Quality	tree density		cars
	tree distribution		benches
			fence
			topographic variation

The perceived qualities can also reveal the characteristics of the urban parks. Based on the Human-Centered approach of urban park design and planning, concepts have been developed from the aesthetic aspects of urban parks, termed perceived sensory dimensions (PSDs), accounting for basic human needs in relation to green spaces (Stoltz, 2020). This framework was built from factorial analyses in several studies asking people about their primary needs, motivations and wanted experiences in relation to visits to urban green spaces and natural areas (Adevi and Grahn, 2012; Grahn and Stigsdotter, 2010). Based on people's reported needs about such environments in their daily lives, Grahn and Stigsdotter (2010) interpret and term them as follows: 1) Nature; fascination with the natural world; 2) Culture; cultivation and traces of human efforts; 3) Prospect; views, vistas, and stays; 4) Social; people, movement, and social interactions; 5) Space; a sense of a coherent world in itself; 6) Rich in species; a large variety of plants and animals; 7) Refuge; a protected and safe place; and 8) Serene; peace and freedom from disturbances, The PSDs are summarized in Table 4. PSD framework does not offer detailed suggestions at the level of physical implementation. Instead of, each quality needs to be implemented and operationalized in different ways depending on context and purpose. This could be seen as a weakness of the framework from both a scientific point of view and from the perspective of an environmental designer looking for quick and tangible solutions. However, the framework's top-down and universal approach might also contribute to a lack of resolution and explanatory power about more specific health and well-being outcomes (Stoltz, 2020).

Table 4 - Perceived sensory dimensions of urban parks.

PSDs	The environment affords experiences associated with
Nature	Fascinating, wild nature, developed on its own terms
Culture	Human cultivation, historical heritage, the passage of time
Prospect	Open areas, sceneries, views, and vistas
Social	Social interactions and activities
Space	A spacious whole, a cohesive world in itself
Rich in species	A diversity of species of plants and animals
Refuge	Private hideaways, safe shelters
Serene	Peace and rest, free from disturbances, sounds of nature

Other perspectives for urban park characteristics could be based on the differences in physical activities and functions supported by urban parks. McCormack et al. reviewed the characteristics of urban parks associated with park use and physical activity. The characteristics are divided into five categories: features; conditions; access; aesthetics; safety. The features include a variety of spaces (paths, walk/bike tracks, play equipment, amenities, barbeques), user-friendly signage, pet infrastructure, Age-suitable facilities (kid recreation place, elder-friendly equipment), natural environment (trees, water features, sand or pebbles). The conditions refer to the integrity, cleanliness, space and infrastructures maintenance. The access means the proximity to home or the walking distance of park from home. The aesthetics concerns noise, cleanliness, vegetation maintenance, plants, grass, greenery, natural sounds, colorfulness, fresh air, flowers, and lighting. The safety aspects focused on surrounding roads and traffic, lighting, fencing, crime, law-enforcement, homeless, presence of teenagers (McCormack et al., 2010), etc. Furthermore, urban parks could be characterized by their functions. Markevych et al. (2017) summarized characteristics of the natural settings of green spaces on human health and well-being through three main complementary pathways; 1) mitigation ("reduction of harm", e.g. reducing exposure to environmental stressors like air pollution, noise and heat, etc.), 2) restoration ("restoring capacities", e.g. attention restoration, physiological stress recovery, etc.), and 3) instoration ("building capacities", e.g. encouraging physical activity, facilitating social cohesion, etc.) (Markevych et al., 2017).

In general, urban parks are in various forms, places and categories. Understanding how biological and physical systems are structured and functioning is critical to practice the ecological design of urban parks. The investigation of these contents asks for multifaceted and multiscale perspectives, from design concepts to human perception, across spatial and temporal scales.

2.3 Urban Park Perception and Assessment

Objective and subjective approaches are developed and intersected to reveal this multi-faceted interrelationship between urban park landscape and individuals. From the objective side, urban park landscape evaluation examines how different landscape characteristics influence people's perceptions and judgement. Researchers and designers have built several models to evaluate the effects of numerous physical and topological features of landscape settings on human being (Bishop and Hulse, 1994; Buhyoff and Riesenman, 1979; Dearden, 1980). Examples include landform elements (Crofts, 1975), landscape patterns or themes (Hammitt et al., 1994; Linton, 1968), landscape character (Crofts, 1975), landscape qualities (Palmer, 1983), dimensions (Propst, 1979) and landscape preference predictors (Brush and Shafer, 1975; Hammitt et al., 1994).

As for urban park landscape perception assessment, the early criteria are typically scenic beauty or preference (Parsons and Daniel, 2002). Rachel et al. (1989) provide that the preference matrix specifies two basic human needs that influence landscape preferences: the need for exploration and understanding. Varying from different interpretation levels, four concepts, including coherence, complexity, legibility, and mystery, are assigned to preference judgement (Jagt et al., 2014; Memari and Pazhouhanfar, 2017; Karakas and Yildiz, 2020). As the field has matured over the years, multiple theories and conceptual frameworks of landscape preference have been proposed (see Table 5). These range from adaptations of classical theories of aesthetics (Lothian, 1999) to ecological (Thorne and Huang, 1991; Gobster, 1999), bio-evolutionary (Balling and Falk, 1982; Appleton, 1996), and psychological (Daniel and Boster, 1976; Bourassa, 1988; Kaplan and Kaplan, 1989; Ulrich, 1986) perspectives on landscape preference. While some of this work has been limited in scope, a few frameworks, such as that developed by Kaplan and Kaplan (Kaplan and Kaplan, 1989), have received extensive attention and been extended beyond issues of environmental preference to address broader issues of human well-being (Kaplan, 1995), landscape design and management (Kaplan et al., 1998), and environmental action (Kaplan and Basu, 2015). Ode et al. (2008) advanced a framework called VisuLands for researchers to evaluate visual indicators for capturing landscape visual character through tracing back nine concepts based on aesthetic theories (Ode et al., 2008; Ode and Miller, 2011).

Table 5 - Nine concept of visual character and their theory background (from Ode et al. 2008 (Ode et al., 2008))

Concept	Theory	References
Complexity	Biophilia	Kellert & Wilson (1993)
Coherence	Information Processing Theory	Kaplan & Kaplan (1982,1989)
Disturbance	Biophilia	Kellert & Wilson (1993)
Stewardship	Aesthetic of Care	Nassauer (1995)
Imageability	Spirit of Place/genius Loci/vividness	Lynch (1960); Litton (1972); Bell (1999);
	Topophilia	Tuan (1974)
Visual Scale	Prospect-refuge Theory	Appleton (1975)
	Information Processing Theory	Kaplan & Kaplan (1982, 1989)
Naturalness	Restorative Landscapes	Kaplan & Kaplan (1989); Ulrich (1979,1984)
	Biophilia hypothesis	Kellert & Wilson (1993)
Historicity	Topophilia	Tuan (1974)
	Landscape heritage/	Lowenthal (1979, 1985);
	Historic landscape	Fairclough et al. (1999)
Ephemera	Restorative landscapes	Kaplan & Kaplan (1989); Ulrich (1979, 1984)

These efforts to bridge objective features of landscape and subjective perception together always meet some difficulties, including scalability and validity, because of the interplay between the objective features, the ambiguity and interrelationship of semantic representations, and the uncertainty (variation) of decision criteria in semantic judgement. To discuss the troubles caused by multisensory interactions, semantic ambiguity and contextual complexity for landscape perception, the process and representation of landscape perception itself need more multi-sensory information and multi-stage analysis to be investigated. Considering as an objective procedure for process simplicity and presentation veracity based on structural information theory (SIT) in the perception field (Leeuwenberg and Van der Helm, 2013), the tasks of studying landscape perception of urban parks or other green spaces should include investigating the grouped and organized process of multisensory information and describing the representation of landscape structure information simultaneously. It should be separated from landscape understanding, the goals of which include landscape recognition, visual search, navigation, action, and landscape aesthetics judgment, which is followed by landscape understanding and influenced by memories, knowledge, and social factors. In this thesis, we constrain the investigation contents in a multisensory perception of urban parks rather than a landscape understanding of urban parks, more specifically saying that cognitive/attentional process, perceived restorativeness and emotional response caused by the perception of different urban park environments are the main focuses.

2.4 Multisensory Perception and Methodology Based on Human-Centered Principle

Human perception is intrinsically multisensory proceeded. The full range of perceptual functions includes visual, sonic, olfactory and tactile effects of various landscapes and their interplay effects (Franco et al., 2017; Park et al., 2009; Wang, 2020). The investigation of auditory environments referring to soundscape research has a closer relation to visual perception. Similar to visual scenes having both so-called 'dorsal' and 'ventral' pathways to process visual information, acoustic stimuli around the auditory scenes with spatial-temporal regularities are processed in parallel hierarchical pathways specialized for the extraction of spatial ('where is the sound?') and non-spatial ('what is the sound?') information of auditory scenes (Bizley and Cohen, 2013). The effect of audio-visual effect of landscape perception has been investigated by several studies (Carles et al., 1992; Cassidy, 2013; Pheasant et al., 2010; Iachini et al., 2012; Ruotolo et al., 2013; Maffei et al., 2013; Liu et al., 2013; Lee et al., 2014; Ren and Kang, 2015; Renterghem and Botteldooren, 2016; Chau et al., 2018; Chung et al., 2019). While even fewer studies also explored the olfactory "landscape" (Jiang et al., 2016). Others have studied the combination of light and temperature (Chinazzo et al., 2017; HYGGE and KNEZ, 2001). The demand for research on smells and other sensory perceptions is likely to increase (Gobster et al., 2019).

Although the importance of multisensory perception is well-presented, understanding how different sensory inputs fit together in the perceptual mind of humans in various spatial scenarios still poses a serious challenge to researchers and designers (Soto-Faraco et al., 2019). Some frameworks and methodologies have been developed to overcome those difficulties. Developed by environmental psychologists, the Environment-Behaviour Research (EBR) methods (Wapner et al., 2000) provide insights into the interaction between people and their physical surroundings, their individual experiences and the design quality of public space. Following rapid growth over three decades, EBR was criticized by scholars such as Rapoport for adopting a humanistic "anti-science" biased attitude and not establishing further links with fields other than those it began with when there was a clear potential for the involvement of fields such as Cognitive Sciences, Neuroscience and Brain Science, Integrative Biology, Evolutionary Science, Genetics, Sociobiology, Artificial Intelligence and more computational approaches (Javaheri, 2018). Another way, named Participatory Design, puts human factors into the research focus to conceptualize urban environment analysis. This approach links all stakeholders (e.g. employees, researchers, customers, citizens) together in an attempt to improve human well-being, user satisfaction, accessibility and sustainability (Panagoulia, 2017). Human Centered Design (HCD) provides the framework to integrate all those methods involved and aims at mitigating adverse outcomes and promoting positive and healthy outcomes for human wellbeing in multisensory environments (Panagoulia, 2017; Chokhachian et al., 2017; Chen et al., 2020a; Melles et al., 2021). From the side of environment inputs, the display of urban park design should be reproducible and controllable. This requires cross-modal recording and reproduction techniques. Immersive Virtual Reality (IVR) provides an innovative way to accomplish the later requirements(Caputo et al., 2018; Li et al., 2022). The measurements of humans' psychological and behavioral outcomes from urban parks must also be considered. Post-hoc assessments like semantic reports could meet certain limits. To use this approach for the investigation of multisensory perception and its outcomes in urban parks, cross-modal data providing multi-stage of this process are necessary(Zeisel, 2006). Developed with the innovation techniques of Human-Computer Interaction (HCI), neural-cognitive approaches have been well-accepted to decode user experience and emotion for production promoting (Zheng et al., 2014; Scharinger et al., 2020; Zhu and Lv, 2023).

2.5 Summary and Research Gaps

The main conclusions of the systematic reviews indicate the following points:

1) Urban park brings positive effects and associations for human health and wellbeing.
2) Various types and elements of urban parks increase the difficulty of urban planning and design.
3) Urban park assessment evolves objective descriptions and subjective evaluations.
4) Multisensory perception and the Human-Centred Principle should be considered during the urban park design and assessment procedure.

Several gaps in the research on urban green space and human perception exist.

1) Lacking theoretical frameworks and clear objectives with general methods makes heterogeneous outcomes, which makes the conclusion hard to verify and use. A bunch of reviews, including systematic ones, have indicated that the diversity of purposes and methods makes drawing solid conclusions difficult (Bowler et al., 2010; Bratman, Hamilton & Daily, 2012; Hartig et al. 2014; van den Berg et al., 2015; Gascon et al., 2016; Frumkin et al., 2017; Houlden et al., 2018; Tillmann, Clark & Gilliland, 2018; Twohig Bennett & Jones, 2018; Moens et al., 2019). More homogeneous and iterative research designs are necessary for validations and generalizations.
2) More and a deeper understanding of the various mental and physical outcomes brought by urban park characteristics and types is needed. More dimensional comparisons not only about the research objects but also on the user characteristics across spatial-temporal scales should also be considered.
3) The synergistic or antagonistic effects related to integrating green space and blue space from the environment inputs, along with integrating multiple sense from the user outputs, are valuable for the research. More discussion about investigating the complex relationship between green space and blue space and the associated beneficial effects on mental health are necessary for urban space designing and planning practice.

PART II TOWARD HUMAN-CENTERED PRINCIPLE OF URBAN PARK DESIGN

CHAPTER 3: RESEARCH FRAMEWORK

3.1 The Research Framework for Human-Centered Design in Urban Park

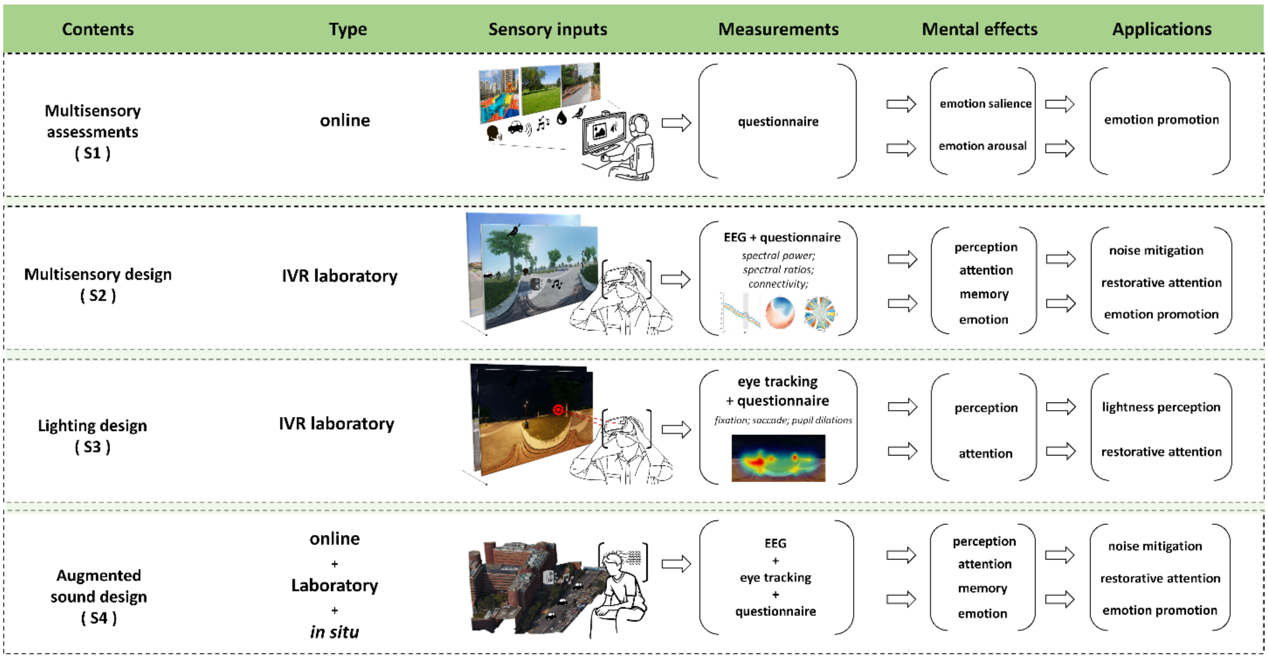


Figure 6 - Theoretical framework of EEG and eye tracking research for multisensory perception in urban parks inspired by HCI applications.

Inspired by EEG and eye-tracking applications in HCI and related fields, as mentioned in the literature review chapter, cross-modal and cross-platform studies are conducted in this thesis to reveal the potential of a Human-Centered approach in urban park design research and encourage HCD-related practices in these spaces (Figure 6). The thesis also aims to balance rigorous experimental control and ecological generalization to ensure the validity of the research findings of those studies. The detailed technical aspects of the methodology will be discussed in the following chapter.

CHAPTER 4: RESEARCH METHODOLOGY

4.1 Introduction

To unveil the complex relationship between urban parks and human perception, a wholescale methodology and techniques across from information obtainment in the "objective" world (urban parks) to the knowledge of the "subjective" world (human being) should be employed towards a Human-Centered approach. Different recordings and measurements are required to analyse the physical characteristics of urban parks based on a multisensory perspective. And the ways for reproduction and simulation of those recordings and measurements, including 2D display, 3D display (laboratory-based real field/VR-based) and real field to experiencers, are needed for various research purposes. Meanwhile, human mental responses and physical behaviors are also necessary for measuring the outcomes of different urban park settings presented by different platforms. Psycho-physiological measurements include neuro-imaging techniques like Electroencephalogram (EEG), Magnetoencephalography (MEG), functional Magnetic Resonance Imaging (fMRI) and physiological techniques such as Electrodermal activity (EDA), Electromyography (EMG), heart rate, blood pressure, respiration etc. And human behaviors measurements are frequently used, including semantical reports, eye and body movements.

The wide range involved in the methodology poses a big challenge for us. Fortunately, newly developed theories and methods in neuroscience have allowed us to improve and deepen our knowledge of human experience in the built environment and address this challenge. Karakas and Yildiz (2020) systematically examined the developing and emerging concepts at the intersection of neuroscience and architecture. They discussed these concepts as a means of deeply understanding the influence of the built environment on human experience, responses to the environment based on approaches from neuroscience, and their potential for providing further directions for future research (Karakas and Yildiz, 2020).

4.2 The Physical Recording and Virtual Reproduction of Urban Park

4.2.1 Applying Visual Recording and Reproduction Techniques

Photographs are used to record and document the geographic environment and landscape photography's early history (Mattison, 1984). Since then, photographic-based methods have repeatedly been applied to urban space planning and development. Most common way to use photographs and videos recorded from 2D cameras in urban park research is related to objective evaluations, aesthetic judgements and preferences, as previously mentioned (Jahani and Saffariha, 2020; Ode et al., 2008; Parsons and Daniel, 2002). Photographs are not only used as materials for urban park analysis. They can also be used as measurement tools for human behavior observations. William H. (Holly) Whyte laid the groundwork for using observations and film photographs to study human behavior in urban settings. From his book *The Social Life of Small Urban Spaces* (1980) they addressed the power of observation and bottom-up place design (see Figure 7) (Whyte, 1980).

Figure 7 - William H. Whyte and His photo graphics of Urban Spaces

Due to the limitations of viewport and perspective for subjective assessments, more advanced techniques like stereoscopic cameras and panoramic cameras for physical recording have become popular in recent years, along with the developments of digital technology applications in photography. Those cameras provide fixed-position views of 3D spaces. For position-free multi-viewing in 3D spaces, 3D models of the spaces and surrounding environments with spatial information are needed. Researchers and designers are using more metric cameras combined with geo-information of 3D spaces for a broader range of physical measurements and accurate 3D reconstruction in urban spaces nowadays (see Figure 8, Figure 9).

Another technical route for 3D recordings and measurements combines multiple images to recover those visual-spatial information with the photogrammetry technique. Photogrammetry deals with the relationship between physical lights in the world and the digital signals from the sensors, simulate the colors and lightness of corresponding pixels in the images capturing from the real field space, to render virtual scene for 3D representation including lights, surface geometry and material information.

Figure 8 - Advanced cameras for physical recording and metrics in 3D space

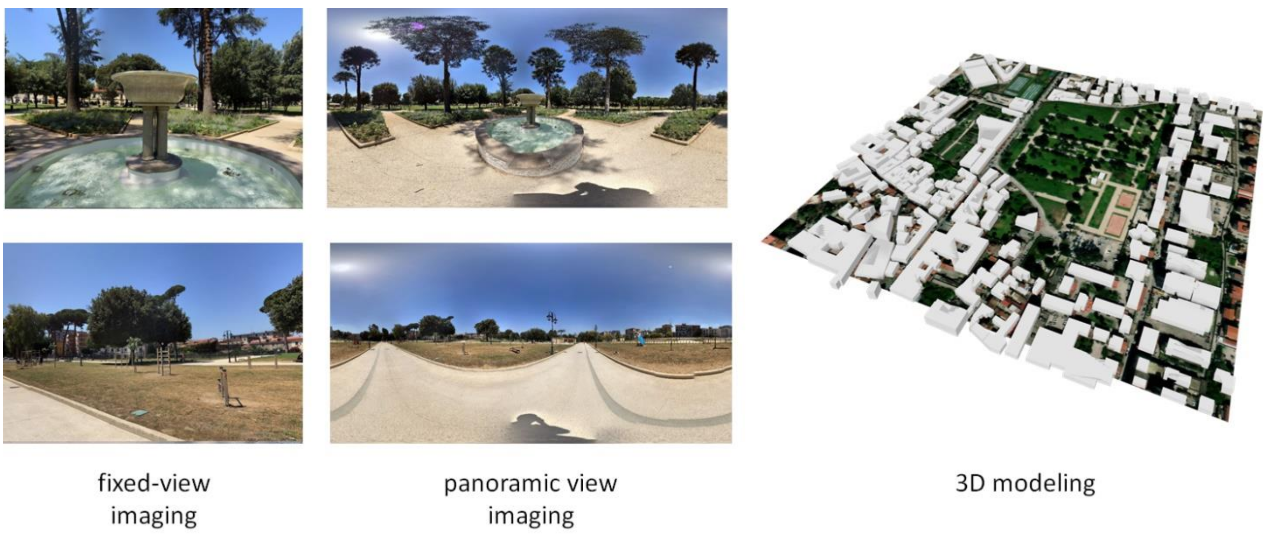


Figure 9 image recordings and 3D modelling in Parco Pozzi related to our studies in the thesis

To investigate the effects of visual elements and their spatial attributes of an urban park on human perception, displaying these images, videos, and 3d model to viewers for subjective assessment are well-accepted (Gao et al., 2022; Mambretti et al., 2004; Yu et al., 2020). To achieve those goals, stereoscopic displays or 3D glasses are required (see Figure 10). Head-mounted displays (HMDs) are the most commonly used stereoscopic displays, or called 3D displays. A head-mounted display (HMD) is a display device worn on the head or as part of a helmet, which has a small display optic in front of one (monocular HMD) or each eye (binocular HMD). HTC Vive Pro 2, Oculus Rift S, HP Reverb G2 are the frequently used products of HMD devices. The VR HMD we used for all the VR studies in the thesis is HTC VIVE Pro Eye, which is a high-quality HMD with dual OLED panel displays of 1440 x 1600 per eye and a built-in eye tracker per eye.

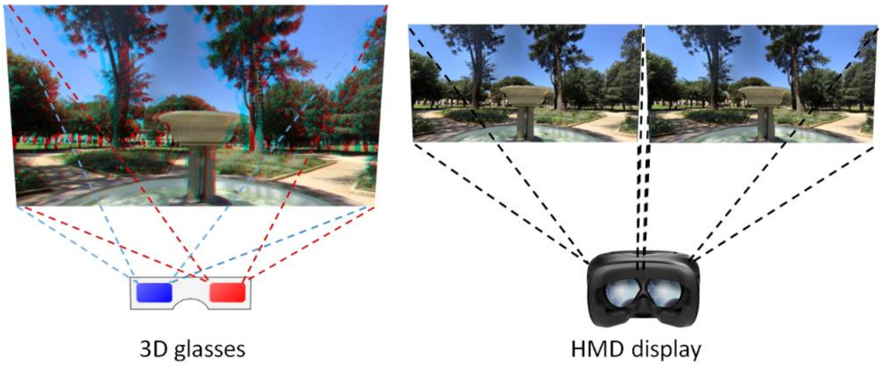


Figure 10 - 3D display methods of visualizing real scenes in urban park

Figure 11 - Ccommonly used HMD products for academic research.

4.2.2 Applying Acoustical Recording and Reproduction Techniques

Acoustical recording and reproduction have similar distinguishes like 2D/3D recordings and ambisonics reproduction/binaural renderings. With the increase of well-accepted soundscape approach in acoustics, the applications of spatial audio techniques are widely used. Hong et al. (2017) and Zhang et al. (2017) both conducted a comprehensive review of spatial audio recording and reproduction (see Table 6, Table 7). All those techniques have been deployed into different platforms to achieve specific purposes in different studies in the thesis.

Table 6 spatial audio recording techniques adapted from (Hong et al., 2017)

Recording techniques	Strengths	Weaknesses	Used in our studies
stereo and surround recording	Legacy recording methods; Widely adopted in industry; Direct playback over loudspeaker system	Does not capture 3D sound field (usually only covers 1D or 2D); Not suitable for direct playback over headphones; Does not support head movements.	online test (S1) / *in situ* test (S4)
microphone arrays	Ability to forus on specific sounds in different sound fields; Support head movements;	Requires a large number of microphones for good performance; Requires sophisticated	

		signal processing to obtain desired sound from the recording.	
ambisonics	Records 3D sound field with only 4 microphones; good mathematical foundations for recording and playback; efficient rendering for interactive applications; Rapidly increasing popularity in industry;	Not suitable for non-diegetic sound like music; Better performance requires higher order ambisonics; Absence of international standards.	laboratory test (S4)
binaural recording	Closest to human hearing; Direct playback over headphones.	Specialized equipment needed, e.g., ear simulators or wearable binaural microphones; Lack of support for head movements; Non-personalized rendering (e.g., dummy head recordings).	IVR test (S2)

Table 7 spatial audio reproduction techniques adapted from (Zhang et al., 2017)

Reproduction Type	Reproduction techniques	Number of channels	Strengths	Weaknesses	Used in our studies
Physical reconstruction	stereo	two	Legacy reproduction method; widely adopted in industry	Poor spatial effect; The sound phantom image is always created at sweet spot	online test (S1)
	multichannel	Three or more	Better spaciousness of 360˚ audio as compared to stereo setups; well adopted by industry	Large numbers of channels and speaker systems are needed for spatial realism; Unable to achieve accurate 360˚ degree phantom images	*in situ* test (S4)
	Ambisonic	$(N+1)^2$ for N^{th} Ambisonic	Used with any speaker arrangement; core technology in not patented and free to use.	Listener movement can cause artefacts in sound; Complicated setup; Not popular in industry	
	Wave Field Synthesis	More than 100 usually	The sweet spot covers the entire listening area; The virtual sound sources independent of the listener's position	High-frequency sounds beyond aliasing frequency are not well reproduced; Large number of speakers needed.	
	Object Based Audio	Generally disposed on three	Use the principles of WFS.	Less accurate than WFS.	laboratory test (S4)

		height levels (from 10 and 30)	The sweet spot covers almost the entire listening area. The virtual sound sources are independent of the listener's position.	High-frequency sounds beyond aliasing frequency are not well reproduced;	
Perceptual reconstruction	binaural	two	Enables creation of virtual source in 3D space with two channels; Lower equipment cost as compared to other solutions	It is only suitable for a single user; Individualized HRTFs needed to avoid front back confusion and in-head localization	IVR test (S2)
	transaural	Two or four	Enhances spaciousness and realism of audio with a limited number of speakers; Accurate rendering of spatial images using fewer loudspeakers	Requires effective crosstalk cancellation; It is only suitable for single user	

To assess the physical properties and mental effects of different sound objects in various scenarios, researchers have tried to record those sound objects across various spaces and time scales. Typical sound objects in urban parks, including traffic noise, human voices, bird songs, water fountain sounds and so on, could be found in different standardized audio databases for research purposes (Piczak, 2015; Mesaros et al., 2016; Salamon et al., 2017; Mitchell, Andrew et al., 2021). The International Affective Digitized Sounds (IADS) and its extended version (IADS-E) (Yang et al., 2018) are some examples of them, consist of 935 digitally recorded natural sounds common in daily life, such as babies crying, typing, footsteps, background music, and sound effects and evaluated for their emotional responses. We have adopted this database for presenting the audio objects in our online test (S1) for urban park audios assessments.

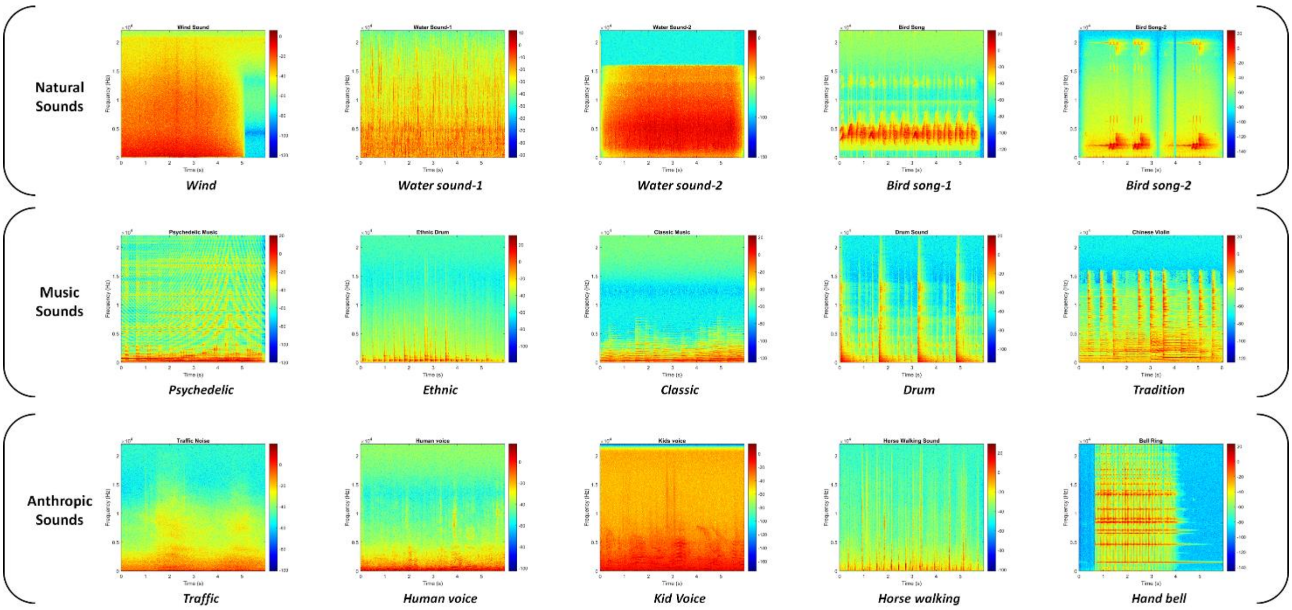


Figure 12 - The audio materials collected from standardized database for assessment study (S1)

To obtain spatial fidelity and perceptual accuracy of the acoustic environment with multiple auditory objects in an urban park, spatial sound recordings were deployed and reproduced by spatial audio systems with a loudspeaker array for laboratory-based perception study in the thesis (see Figure 13). The technique used for spatial sound reproduction is object-based audio. It derives from the principles of Wave Field Synthesis (WFS) (Xie, 2022), the spatial audio rendering technique characterized by creating virtual acoustic environments. It produces artificial wavefronts synthesized by a large number of individually driven loudspeakers. Such wavefronts seem to originate from a virtual starting point, the virtual source or notional source. Contrary to traditional spatialization techniques such as stereo or surround sound, the localization of virtual sources in WFS and OBA does not depend on or change the listener's position (see Figure 14).

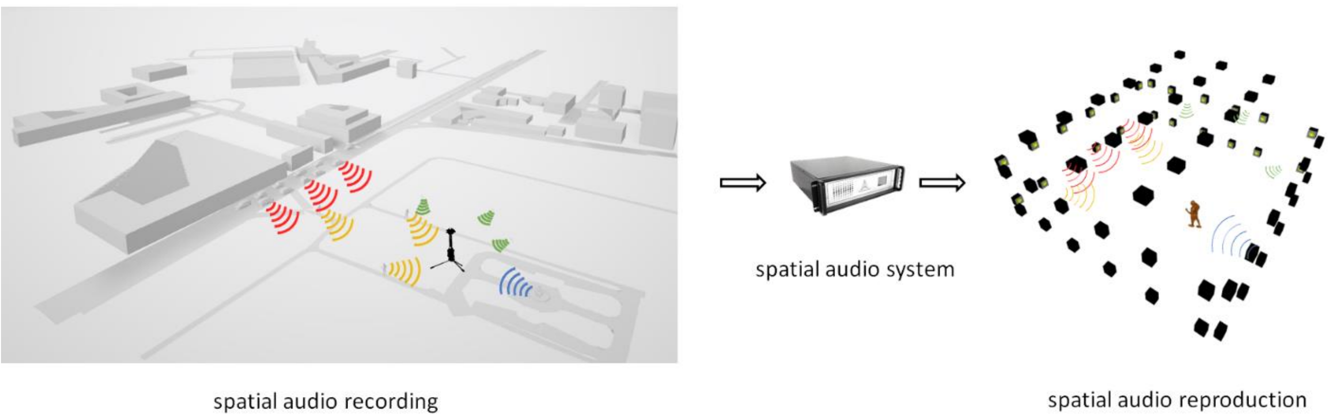


Figure 13 - The spatial audio recording in urban parks (3D model from Parco Pozzi) and the 3D immersive audio reproduction system with loudspeaker arrangements (different colors indicated different sound sources: red color for traffic noise, yellow for human activity, green for bird songs, blue for water fountain).

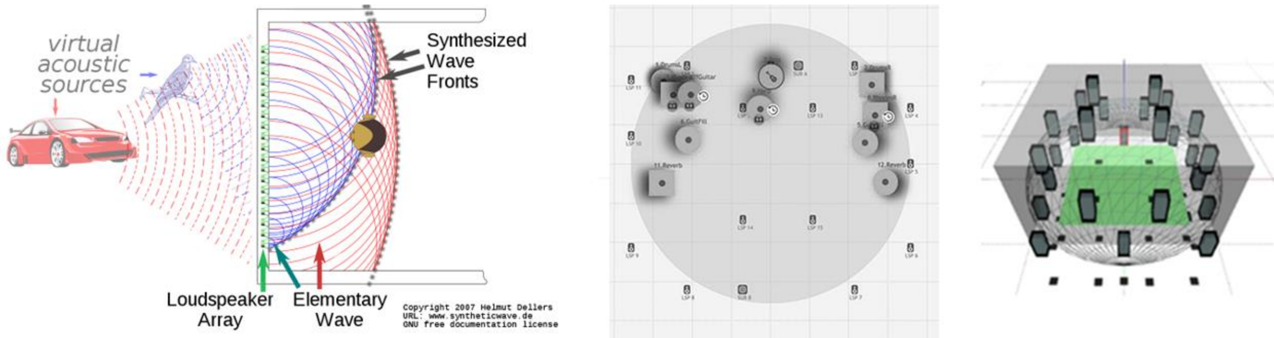


Figure 14 - The illustration of Wave Field Synthesis principle and of the spatial audio system configurations used in our laboratory studies.

When it comes to outdoor soundscape design, such as in the urban park, augmented sounds produced by loudspeakers array are likely impossible. Multichannel surround sound production technique is an alternative method. (Xie, 2022) This method has already been applied to home theatre creation in the interior design field (see Figure 15). Because of the mature Bluetooth speaker products, deploying multichannel surround sounds into outdoor environments like urban parks for augmented sound design became much easier to implement. To study augmented sound design *in situ,* we applied four SONY SRS-XB23 Bluetooth speakers to produce surrounding water sound for traffic noise masking in an existing campus park (see Figure 15). Knowledge of digital signal processing is required to control those speakers for real-time playback (see Figure 16). To play multiple soundtracks with the flexibility of external signal synchronization, we used a python library called PYO to program all the playback of audio sources with external management for experiment control. Pyo is a Python module written in C to help digital signal processing script creation. It provides a complete set of classes to build audio software, compose algorithmic music or explore audio processing with a simple, mature and powerful programming language.

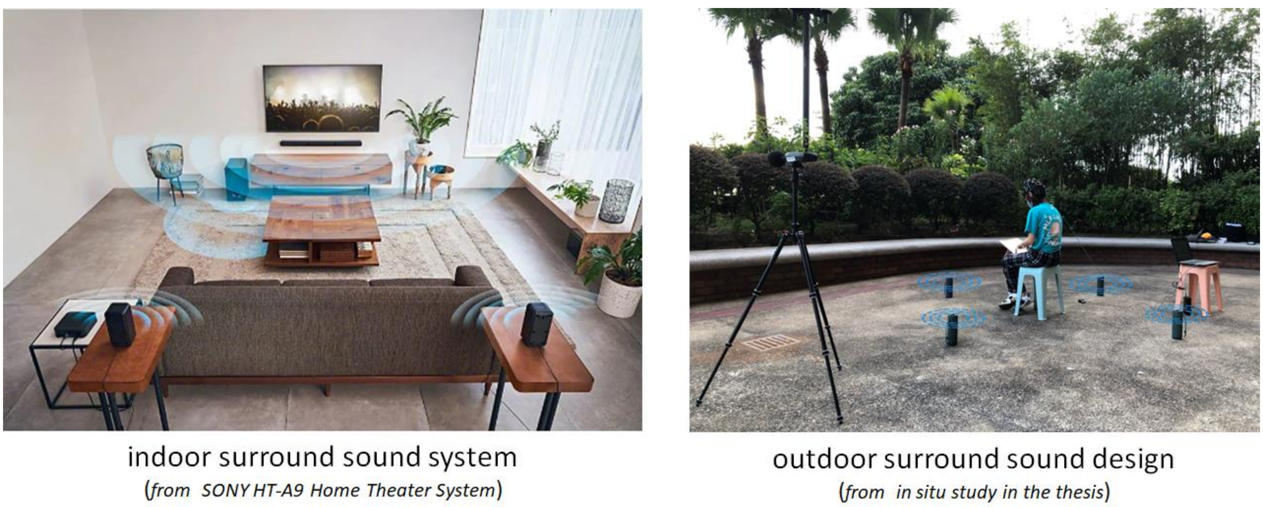


Figure 15 - Using Bluetooth speakers for surround sound playbacks in indoor environment and outdoor environments.

Figure 16 - Available standalone software and language-based libraries for real-time audio programming

Binaural audio techniques are used for 3D immersive auditory experience creation and multisensory integration promotion for IVR-based experiments. Bosman et al. (2023) reviewed the latest progress in audio reproduction techniques and studies in virtual reality (Bosman et al., 2023). In our multisensory IVR study (S2), Oculus Spatializer SDK was used for the binaural reproduction of traffic noise, natural sounds, music etc., in the created virtual urban park. The rendering techniques are illustrated as follows (Figure 17).

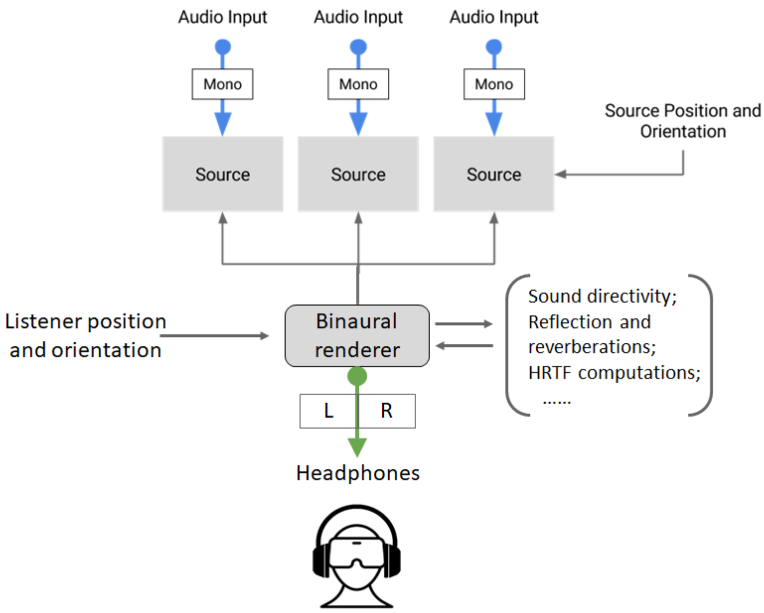


Figure 17 - Spatial audio technique for binaural reproduction in virtual reality applications

To reproduce real or simulated environments or to set the correct signal-to-noise ratios between water sounds and road traffic noise, all the auditory stimuli' sound levels (SPLs or Leq,A) were measured or calibrated, at the listener positions. To this aim, a head and torso simulator, Cortex Mk-2, and a Sound Level Meter (SLM), B&K 2270 (Brüel & Kjær, Virum, Denmark) were used.

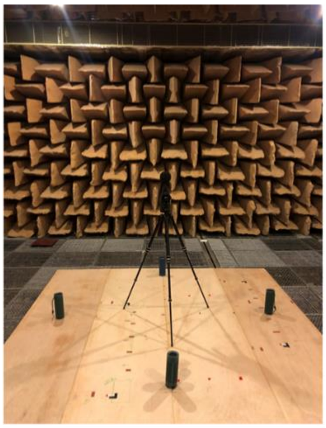


Figure 18 - Binaural recording for calibration in the SENS-i Lab and sound level measurement produced by the Bluetooth loudspeakers in the anechoic chamber from PolyU

4.3 Experiment Platform Development

4.3.1 Online Platform

Image and audio recorded from urban parks and other outdoor environments have been the conventional materials for online research of landscape perception and assessments.

Conventional online questionnaire platforms such as Google Form and Qualtrics don't meet online research requirements for repetition and randomization (see Table 8). To meet these requirements, SurveyJS library was chosen for publishing online experiments, and the data were saved to a personal server for data protection. The online questionnaires used in the research developed by us could be accessed through those links (http://braincoder.io/urban_park/cn/; http://braincoder.io/spatial_sound/en/; http://braincoder.io/spatial_sound/in_situ/). The style and appearance design of the questionnaire referenced the PsyToolkit's outputs.

Table 8 - Different platforms for online questionnaire and research

Platform	Overview
JISC Online Surveys	Questionnaire-style surveys including audio-visuals; GDPR compliant; GUI interface; license needed.
jsPsych	a JavaScript framework for creating behavioral experiments with mouse and eye tracking; programming flexibility; open source;
Psychtoolbox	Build experiments and analyse data using the MATLAB programming language and LabMaestro Pack&Go simulator; programming flexibility; license needed.
PsychoJS	A JavaScript library that creates online experiments from the PsychoPy Builder; programming flexibility; open-source project;

PsyToolkit	Surveys and experiments, including audio-visuals, response time, participant feedback, randomisation and counterbalancing; free for use;
Qualtrics	Surveys and experiments including recording first/last/all participant clicks, loop and merge, and custom coding of response options; GUI interface;
SurveyJS	A JavaScript library supports dynamic, data-driven, multi-language survey forms and run them in personal web applications using a variety of front-end technologies; programming flexibility; open source; strong developer support;

4.3.2 Laboratory Platform

All laboratory experiments from the thesis were conducted in the SENS-i Lab. Despite most research labs always providing very professional settings of specific purposes, SENS-i Lab in the Department of Architecture and Industrial Design at the University of Campania "Luigi Vanvitelli" is a human-centred, multi-physical and multi-purpose laboratory for creating, developing, prototyping, and human interaction with physical and virtual products and systems. The key aspect of SENS-i Lab is creating a holistic experience through the multi-stimulation of different sensory channels and an ecological interaction with the experimental environment. The lab could prepare and carry out, in vivo or in virtual, subjective tests where the human experience of urban/rural or industrial environments, architectures and products, meanwhile measure psychophysiological and behavioural reactions from the participants during those tests. The lighting and temperature are fully controlled by the user console (see Figure 19).

For 3D immersive-sound experience with object-based controlled, Astro Spatial Audio spatial sound system is running in the lab with Martin Audio loudspeaker array. The system used Spatial Sound Wave (SSW) technology, developed by the Fraunhofer Institute for Digital Media Technology IDMT, with the intelligence and power of the SARA II Premium Rendering Engine to bring a sophisticated spatial sound platform to the sound engineer. SARA II calculates the position of each audio object around in the 3D performance space relative to the loudspeaker framework in real-time and in an extremely high resolution. As a result, the engineer can now create immersive experiences by mixing the objects and their characteristics (including their spatial position, their level in the mix, their diffuseness etc), rather than worrying about individual channels. Astro Spatial Audio provides the key features to unlock the full creative potential of an audio experience.

Figure 19 the lighting and loudspeaker layout of SENS-i Lab

4.3.3 Virtual Reality Platform

While all perceptual objects in urban parks mostly have recognizable visual and auditory properties, simulating and manipulating them in virtual environments with psychical-based rules are critical for immersive experiences. Virtual reality (VR) and augmented reality (AR) systems should be employed to accomplish those effects. Virtual Reality (VR) technology brings a new way for environment simulation and presentation for architecture and environment study for its ability to provide multisensory three-dimensional (3D) environments with manageable objects. Virtual reality displays can be divided into two general categories, each with two sub-categories. The first category is stationary displays, including projection-based systems and monitor-based systems. The second is portable displays, categorized as head-based and hand-held systems (Majernik, 2013). Before the 3D display in those systems, a 3D simulation environment is necessary to process these computer-based graphical outputs. Multiple game engines are good at dealing with these processes, such as Unreal Engine (UE), Unity, CryEngine, Torque3D etc. Zhang et al. reviewed the state-of-the-art in VR applications for the built environment to reveal the research trends and challenges for future research. Five future directions were proposed: user-centered adaptive design, attention-driven virtual reality information system, construction training systems incorporating human factors, occupant-centered facility management, and industry adoption (Zhang et al., 2020). Following the 3D scene creation flowchart (Figure 20), we used Unreal Engine 4.2 to present and control the audio-visual properties of virtual urban park with extra plugins for mental and behavioral measurements (like interactive questionnaire, head motion tracking, and eye tracking) in the multisensory experiment (S2) and lighting experiment (S3). The final product of the virtual park is illustrated as follows (Figure 21).

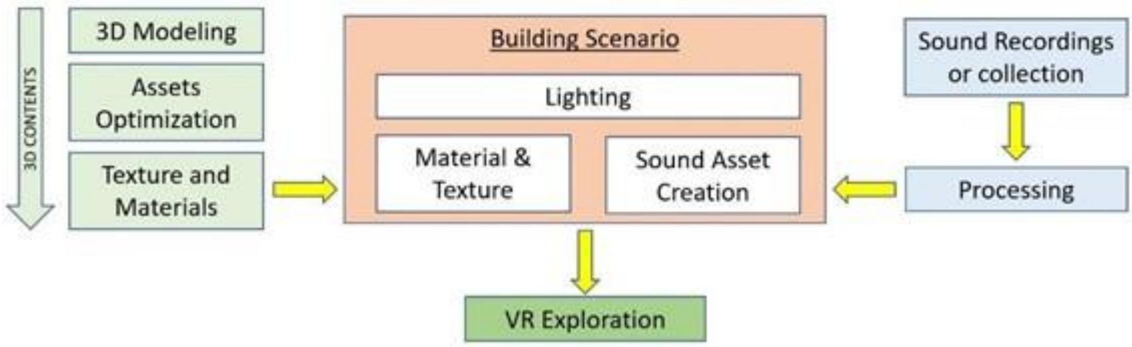


Figure 20 flowchart of virtual 3D scene creation with multisensory inputs

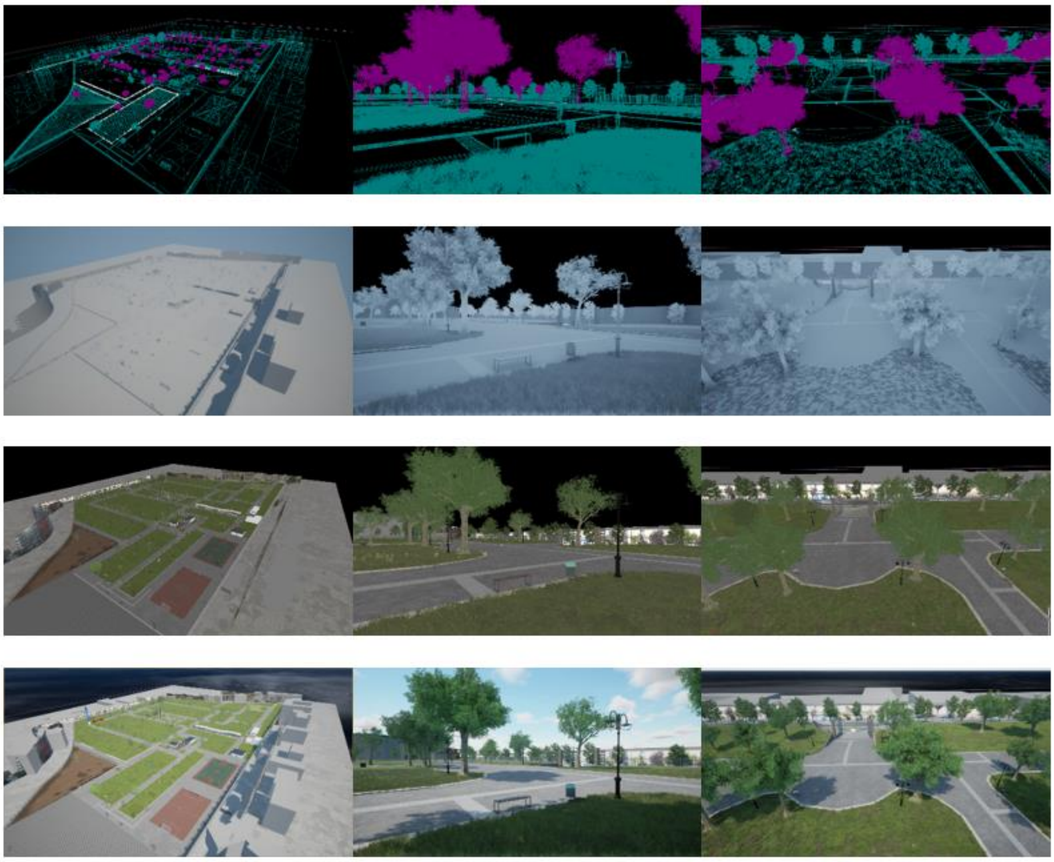


Figure 21 - The created virtual urban park for the multisensory experiment (S2) and lighting experiment (S3) (based on the existing park Parco Pozzi, Aversa).

Several studies on urban park design use virtual reality technology to simulate the perceived environment. The psychological restoration, perceived qualities, and aesthetic preferences are most investigated in those virtual urban environments. However, the influence of the acoustical factors is barely mentioned (see detailed information in Table 9) (van Leeuwen et al., 2018).

Table 9 - Literatue reveiws of VR studies in urban park designs

study	Research contents	Main findings
van Leeuwen et al. (2018) (van Leeuwen et al., 2018)	Used virtual reality (VR) for the participatory design of a public park.	VR increased engagement and created vivid memories of design results.
Gao et al. (2019) (Gao et al., 2019)	Explored psychophysiological restoration and recreational preference in different urban spaces using VR.	Negative mood varied significantly among the environments, with closed green spaces having the worst effect; Blue space and partly closed green space received higher recreational preference ratings; Positive correlation between preferences and improvement in positive mood.

Sacchelli & Favaro (2019) (Sacchelli and Favaro, 2019)	Integrated Geographic Information System, VR, and psychoacoustic measurements for perception of landscape and soundscape in urban forests park.	Logistics and tree variables influenced visual perception; Natural and human-related sounds were perceived along with visual inputs.
Jo & Jeon (2020) (Jo and Jeon, 2020)	Investigated effects of human behavioral characteristics on soundscapes perception in urban parks using multisensory VR experiment.	Sounds made by other people decreased perceived tranquility and increased dynamic experience; Presence or absence of people primarily determined park preferences.
Tabrizian et al. (2020) (Tabrizian et al., 2020)	Developed an integrative approach to measure and model viewscapes characteristics in a city park using lidar-based models and VR.	Strong correlations between viewscape metrics and perceived openness, naturalness, and landscape complexity.
Evensen et al. (2021) (Evensen et al., 2021)	Combined field and VR experiments to evaluate perceived safety in green spaces with different hedge settings.	Cutting down hedges improved perceived prospect and safety, particularly for females.
Jo & Jeon (2021) (Jo and Jeon, 2021)	Used audio-visual stimuli and VR to assess environmental perception in urban parks.	Water-related elements increased perceived pleasantness, while greenery-related elements affected eventfulness; Higher satisfaction with water and greenery elements compared to traffic-related elements.
Masullo et al. (2021) (Masullo et al., 2021b)	Investigated the effects of audio-visual installations in urban parks using immersive VR simulation.	Evocative installations had similar positive effects to traditional installations; Restoration effects increased with larger and enveloping installations
Pei (2021) (Pei, 2021)	Discussed green urban garden landscape design and user experience strengthening using VR technology and embedded network.	The advancement of electronic information technology and the emergence of virtual reality in garden landscape design have brought innovative possibilities for designers. It reduces working time and allows designers to fully express their creativity by visualizing their ideas.
Zhang & Dai (2021) (Zhang and Dai, 2021)	Used VR scenarios to study the effects of lighting on visitor light comfort in urban park pedestrian spaces	Colour temperature influenced subjective light comfort significantly, with warm light preferred; Average horizontal illuminance affected physiological fatigue measured by EEG.
Zhu et al. (2021) (Zhu et al., 2021)	Designed a VR experiment to evaluate human response to residential green space scenes.	Scenes with a Visible Green Index (VGI) of 60-80% and three-layer vegetation structure were most comfortable for the brain; Two-layer vegetation structure with VGI above 80% had the most weakening effect.
Chen et al. (2022) (Chen	Used VR and physiological/psychological data to evaluate satisfaction in urban green spaces.	Single-layer grassland had the highest visual interest, while compound layer of tree-shrub-grass woodland had the strongest comfort;

et al., 2022b)		Subjective satisfaction scores decreased from tree-shrub-grass woodland to single-layer grassland to tree-grass woodland to single-layer woodland.
Fan (2022) (Fan, 2022)	Explored computer simulations for forecasting landscape aesthetic assessment and ranking factors in urban park design.	
Huang et al. (2022) (Huang et al., 2022)	Studied the aging-appropriate design of urban comprehensive parks using computer virtual simulation.	Explored layout, type, distribution, and construction of design schemes to enhance interaction between buildings and users.
Jaalama et al. (2022) (Jaalama et al., 2022)	Examined the feasibility of 3D geovisualization-based urban audit in VR for assessing perceived quality of an urban park.	Perception of tangible elements was similar between VR and *in situ*, but perception of vegetation and surroundings was weaker in VR.
Luo et al. (2022) (Luo et al., 2022)	Created a VR simulation of people sitting in a pavilion to evaluate preferences and mental restoration in Tokyo's pavilions.	VR viewing effectively promoted mental restoration; Prospect and serene dimensions significantly affected preferences, while species richness and serene dimensions related to restoration.
Puyana-Romero et al. (2022) (Puyana-Romero et al., 2022)	Studied the effects of helicopter noise on soundscape perception and landscape quality in an urban park using VR.	Helicopter noise had negative effects on perceived soundscape and landscape quality; Sharpness explained most of the variance in subjective variables.

4.4 Psychophysiological and Psychological Measurements

4.4.1 Psychological Questionnaire

Various semantic scales were developed to measure the human responses and mental health associated to audio-visual environments. Starting with unimodal assessment, two principles are most used for urban parks assessments on the visual dimension, the psychophysical and psychological model (Serrano Giné et al., 2021). The psychophysical model tries to build the relationship between physical elements in the landscape and the preferences of the average observer. The psychological model focuses on the observer's cognitive, affective and evaluative rating based on their experiences. The psychological scales are the most concerning in our studies since they provide the potential for cross-modal generalization. The perceived safety(Mahrous et al., 2018; Zhou et al., 2022), perceived beauty (Zhou et al., 2022), place attachment (Bazrafshan et al., 2023), perceived restorativeness (Szkopiecka et al., 2023), emotional response scale (Qiao et al., 2021), etc. were built by the later model. According to ART, the Perceived Restorativeness Scale (PRS) is a widely used 16-item scale comprising the four main components of Restorative Environments (Hartig et al., 1997b, 1997a). As for acoustical environment assessment, most used items can be sourced from the circumplex model of the Swedish Soundscape-Quality Protocol (SSQP), characterizing the perceived quality from eight items, including pleasant, chaotic, vibrant, uneventful, calm, annoying, eventful, and monotonous (Axelsson et al., 2009, 2012). The Perceived Restorativeness Soundscape Scale (PRSS) (Payne, 2013) is also quite used for assessing the psychological restoration effects of soundscapes based on the Attention Restoration Theory (ART) (Kaplan and Kaplan, 1989; Kaplan, 1995). Masullo et al. developed and compared two different questionnaires focused on assessing the emotional salience of environmental stimuli. The first questionnaire was built from the circumplex model of soundscape perception, whereas the second was constructed from the perceived emotional dimension (Masullo et al., 2021a). Similar items for affective quality assessment of urban parks were used in Jo and Joen (2021) 's urban park audio-visual interaction study (Jo and Jeon, 2021). Emotional salience consist of emotional valence and emotion arousal. Emotional arousal could enhance the spatial attention orienting (Max et al., 2015), body excute control (McConnell and Shore, 2011), physical activity intention (Kok and Broekens, 2008; Schmidt et al., 2009; Maher et al., 2019). Thus we can use this indicator for implying the urban functions on physical activity instoration. The questionnaires used in all the research in this thesis were all based on the work of Masullo et al (Masullo et al., 2021a).

4.4.2 Eye Tracking measurements

The idea of eye movement tracing could be traced back to the reading research at the end of 19th century (Uniwersytet Warszawski and Płużyczka, 2018). Until now, the eye-tracking technology still occupies an important method for studies in the linguistics field. And the fixations/saccades discrimination was first observed from L.É. Javal's reading experiment. The first eye tracker was considered as the work from E. Huey (Huey, 1908). And the first non-invasive eye tracker was created in 1901 by R. Dodge and T.S. Cline. This eye tracker use light reflects from the surface of the cornea and falls through an optical system onto a moving photosensitive photographic plate, thus leaving a record of the eye movement on that plate. A similar mechanism has been applied for the most recently portable and wearable eye trackers, using a video camera instead to extract eye rotation from the corneal reflection and the pupil position, which brings the eye tracking technology can be applied to a much wider field, including advertisement and marketing(Wedel and Pieters, 2017), industrial design(Park, 2016), learning and training(Rosch and Vogel-Walcutt, 2013) as well as the tradition research field like psychology and linguistics(Conklin et al., 2018). The eye-tracking research pipe is illustrated in Figure 22.

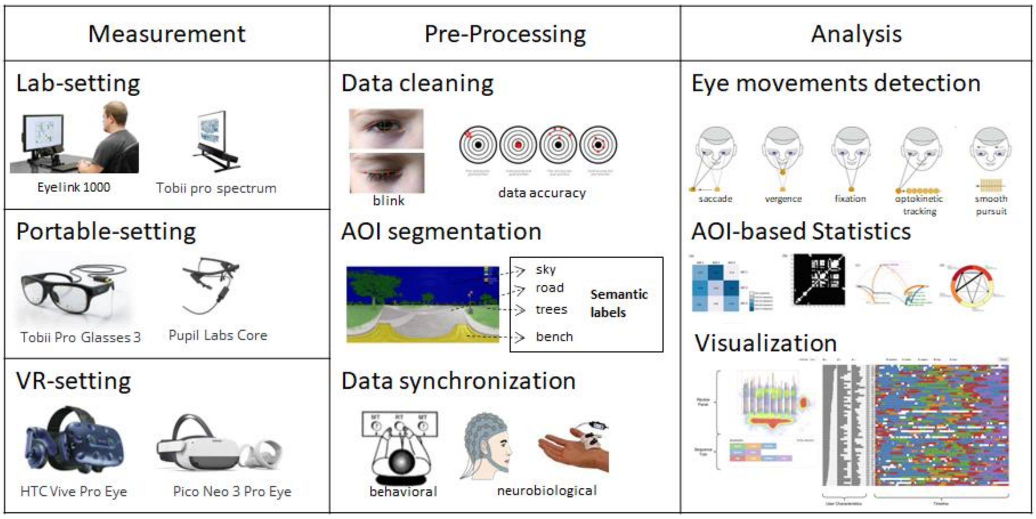


Figure 22 the eye tracking research pipeline

As related techniques are developing, the number of eye-tracking research referring to landscape perception are increasing, and new paradigms are emerging. Those data are deployed for measurements of attraction of external stimuli and performance of cognitive tasks across different scenarios like laboratory, *in situ*, or virtual reality environments (see Table 10, Table 11). Various aspects of the environmental perception can be explored, including the categories of the environments, the environment elements and the cognitive effects of those environments through oculomotor behavior provided by eye tracking data (see Table 12).

Table 10 - The metrics and indexes of eye tracking

Metrical Goals	Mental Properties	Measure Index (Area of Interest Based)
Measures of Attraction	noticeability	number of fixations prior to first fixation time to first fixation
	interest	number of fixations total dwell time percentage of time
	emotional arousal	pupil diameter
Measures of Performance	mental workload	pupil diameter
	cognitive processing	average fixation duration
	target recognizability	time from first fixation on target-to-target selection

Table 11 - The comparision of features and metrics of different category of research

Research Scenarios	Research Features	Typical Metrics	Related Literatures
Photograph-based	merits: easy to conduct experiments; easy to interpret the results; defects: truncated experience behaviors; result lack of ecological validity;	number of fixations; total dwell time; fixation durations;	Brush, 1981; Nordh & hägerhäll, 2009; Huang & Lin ,2019;
in situ field	merits: highly ecological validity; suitable for exploration researches; defects: hard for comparison researches; difficult to analysis and explain data;	spatial gaze distribution; number of fixations; fixation durations; percentage of first fixation on aoi;	Foulsham et al., 2011; Cottet et al., 2018;
Immersive virtual reality	merits: highly ecological validity;	fixation density map (distribution and entropy);	Anderson & Bischof ,2019;

	highly controlled settings for empirical validity; defects: complicated experiment settings; lacking of analysis techniques;		Haskins et al.,2020;

Table 12 - The different paradigms and metrics used in literatures

Research Aims	Research Contents	Typical Gaze Metrics	Related Literatures
Cognitive-based	Kaplan's attention restoration theory ; prospect-refuge theory	number of fixations; total dwell time; fixation durations;	Kaplan, 1975; Kaplan & Kaplan, 1989; Kaplan, Kaplan, & Wendt, 1972; Nordh et al., 2010, 2013; Lee, Lei, Wu, Hou, & Tzeng, 2015;
Element-based	color; pasture; water; …	number of fixations; fixation durations; average dwell time; time to first fixation;	Jacob & Karn, 2003; Arriaza et al., 2004; de Val, Atauri, & de Lucio, 2006; Potocka, 2013; Ode Sang et al., 2014; Ode et al.,2016; Huang and Lin (2019)
Category-based	openness; heterogeneity; urbanization; …	total dwell duration; fixation durations; total scan path; scan length; focus map;	Dupont et al., 2014; Kim et al., 2013; Dupont et al., 2014; Dupont et al., 2016a, 2016b;

Table 13 multisensory behaviours and eye tracking measures

Perceptual Integration	Perceptual Phenomenon	Eye Gaze behaviors	Related Literatures
Sensory & motor interaction	Visual motion aftereffects	visual saccades (direction; frequency; etc.); nystagmus;	Paulsen & Ewertsen, 1966; Rolfs et al., 2005; Valsecchi & Turatto, 2009; Kerzel et al., 2010; Yuval-Greenberg & Deouell, 2011; Zou et al., 2012; Lusk & Mitchel, 2016; Król, 2018
Auditory & spatial localization	ventriloquist effect	fixation (positions; durations); saccades;	Razavi et al., 2007; Pavani et al., 2008; Van Grootel & Van Opstal, 2009; Pages & Groh, 2013; Maddox et al., 2014
Audio-visual integration	McGurk effect	smooth pursuits; fixation (positions; durations); pupil reactivity;	Xiao et al., 2007; Ren & Kang, 2015; Braga et al., 2016; Liu et al., 2019

Moreover, several multisensory phenomena were revealed by the pattern of gaze behaviours, such as visual motion aftereffects, ventriloquist effect, and McGurk effect, which means that eye gaze behaviours can provide the perceived contents and their relationship for investigation of the process and presentation of landscape perception in a multisensory view (see Table 13). In a multisensory landscape environment, vision and hearing both interacts through the "what" and "where" pathways in a temporal-spatial context to form a sense/perception of the place. Combined with a fully stimuli-controlled environment such as Immersive Virtual Reality, gaze behaviours give us not only the information of visual inputs but also real-time and interactive feedback of humans in landscape. It is helpful for researchers to understand the mechanism of human perception in complex contexts and the designers to manage landscape settings for human well-being.

4.4.3 EEG measurements

Electroencephalography (EEG) measures the electrical activity in the brain, which offers a powerful mean for understanding neural activity and psychology phenomena when participants are interacting with the external environment and people or changing internal state. The discovery of EEG could owe to the German psychiatrist Hans Berger, who recorded the first human EEG in 1924 and then recognized it as a new neurologic and psychiatric diagnostic tool in 1929 (Reaves et al., 2021; Tudor et al., 2005). Until now, EEG has been prominently used in the psychology and neuroscience field for its direct measurements of neural activity and high temporal resolution. Meanwhile, the benefits of EEG data are becoming noticeable from other research fields and applications, such as emotion recognition (Dadebayev et al., 2022; Houssein et al., 2022) used in marketing (Pei and Li, 2021) and user experience designing (Deja and Cabredo, 2018; Van Camp et al., 2019), learning feedback for software engineering (Sethi et al., 2018; Zaki and Islam, 2021).

The most commonly used setup for EEG recording is a laboratory-based setup. The external amplifiers are used for higher data quality and more channel recording. The accompanying electrodes usually used are so-called “wet” electrodes, which use a ring structure to hold up conductive gel to increase the conductivity between the electrode and the scalp skin. The drawbacks of these setups are time-consuming and limited application scenarios. With the development of wearable sensing technologies, more portable set-ups for broader applications are becoming realistic. Those systems use embedded amplifiers with wireless connection to limit the size of the recorder, and the electrodes are replaced with metal-made pin-grid structures touching with the scalp skin for conductivity. The drawbacks of these systems are lower data quality and less channels for data collection.

Since the EEG signal is easily interfered by electrical and magnetic noise from the external environment and devices like computers and physiological activity from human such as vasoconstriction and eye movement, the pre-processing of EEG data is always required. Three methods are commonly used, including filtering, re-referencing, and artefact removal. Although there is no standardized procedure for the pre-processing pipeline, much automatic and reproducible algorithms have been accomplished (Bigdely-Shamlo et al., 2015; Gabard-Durnam et al., 2018; Jas et al., 2018; Maria and J, 2022).

After the data cleaning, the EEG signals can be analyzed from different domains to reveal the level and changes of mental state and response to external environments. The widely used paradigm for EEG studies is Event Related Potentials (ERPs), which reveal the temporal changes in the amplitude of the brain response to specific sensory, cognition, or motor event(Luck, 2014). Other event-related paradigms are called Event-related desynchronization/synchronization (ERD/ERS), which extend the analysis from amplitude to frequency and phase of the brain signals. For time-lasting information, EEG was primarily applied to sleep state classification. Later researchers examined its potential on monitoring the conscious state, and more frequency bands and periodic components are recognized as indicators for mental state classification and abnormal state diagnosis. The third analysis method, functional connectivity analysis, originated from the discovery of functional magnetic resonance imaging (fMRI) studies. Functional connectivity is defined as the temporal coincidence of spatially distant neurophysiological events (see Figure 23).

Using EEG to evaluate a built environment's mental effect has become increasingly valuable (see Table 14). Norwood et al. (2019) reviewed the impact of different environments on brain activity and associated mood response. Twenty-six studies with laboratory design or naturalistic design were summarized. They found that natural environments were associated with low-frequency brainwaves and lower brain activity in frontal areas, indicating comfortable and subjectively restorative feelings. Oppositely the urban environments induced brain responses associated with negative affect demonstrated in an overactive amygdala region.

Furthermore, urban conditions were related to the posterior cingulate cortex. The later was associated with top-down processing/effortful attention. More sensory accumulation effects are observed from the more realistic experiments with more sensory settings. Bower et al. (2019) systematically reviewed the impact of built environment design on emotion measured by neurophysiological indicators and subjective descriptors. Only seven studies are selected from the selection criteria. This paper has tried to raise attention to real-time evaluating the emotional effect of built environment exposure rather than post occupancy evaluations(Bower et al., 2019). Karakas & Yildiz (2020) explored the intersection between neuroscience and architecture in theoretical and methodological approaches by examining the existing literature systematically and interpreting the influence of built environment on human experience based on neuroscience approaches (Karakas and Yildiz, 2020). Shemesh et al. (2021) summarized the existing studies based on the intersection of neuroscience and architecture and examined the measurements of emotional reactions to geometrical manipulations within virtual architectural space by using EEG, Galvanic Skin Response (GSR) and eye-tracking. The findings suggested the geometrical criteria influenced the user's emotional state (Shemesh et al., 2021).

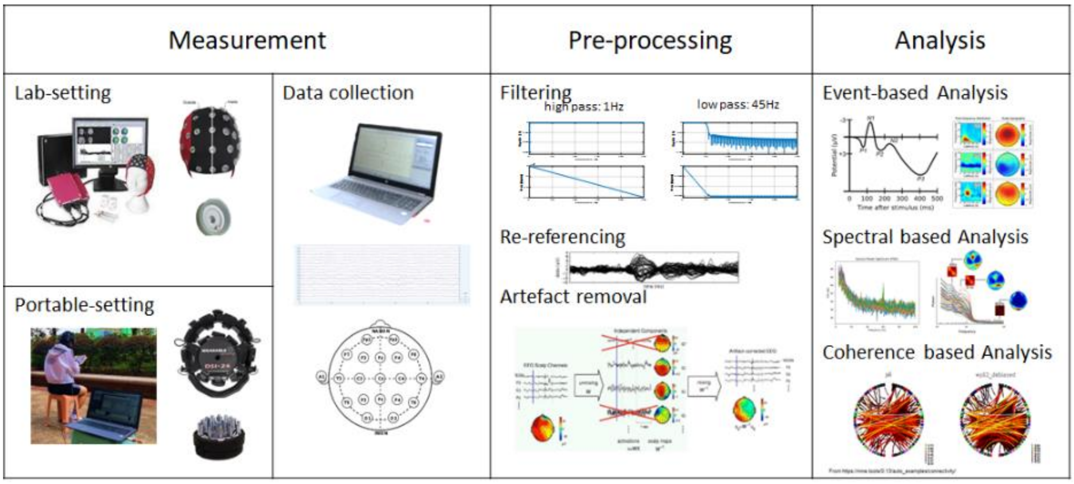


Figure 23 - The pipeline for EEG research.

Table 14 - Outcomes extracted from the experimental articles of built environment and neuroscience interdisciplinary from (Karakas and Yildiz, 2020) and (Shemesh et al., 2021)

Human experience	Built environment features	Measurement techniques	References
Restorative and stress reduction effects of environments. Well-being, stress.	Natural environment and built environment without nature, building-integrated vegetation, stimulus in interior spaces (vegetation, music, and visual features), bed positions, and orientations.	fMRI, EEG, VR, EDA, HRV, questionnaire, self-report, and post-test measurements.	Martínez-Soto et al. (2013); Hekmatmanesh et al. (2019); Higuera-Trujillo et al. (2020).
Aesthetic judgment/appreciation.	Arrangements of furniture, windows, and doors, visual complexity, architectural decorum, typicality, and ambiances of interior spaces.	EEG (BEMicro, EBNeuro wth EEGLAB), VR, aesthetic judgment tasks, and rankings.	Murcia et al. (2019); Vannucci, Gori, and Kojima (2014); *Vecchiato et al. (2015).
Pleasure, familiarity, novelty, comfort, and pleasantness.		*3D Virtual CAVE using 3DS Max 2011.	
Pedestrian experience, navigation, and wayfinding. Mediation, attention, anxiety,	Urban characteristics of a place (edges, patterns, shapes, and narrative), urban spaces and forms	EEG, VR, GIS, GPS, body sensors, self-report, and video recording.	Li et al. (2016); Erkan (2018).

displeasure, pleasant and unpleasant, directional behaviour, familiarity, and fear.	(building shapes, textures, isovist parameters, visual entropy, visual fractals), physical characteristics of routes, and ceiling height.		
Visual engagement, visual attention, and imageability. Visual attention, avoidance behaviour, conscious and unconscious attention.	Spatial characteristics of urban streets (street edges, ground, sky, existence of people and objects, and adjacent realms), characteristics of civic monuments (front facades).	EEG (EASYCAP with EEGLAB toolbox, Emotive), VR Eye tracker, MoBI, video recording, questionnaire, self-report, and scorecards. *3D Virtual HTC-Vive (head mounted) Unity Game software.	Simpson et al. (2019); Sussman and Ward (2019); *Banaei et al. (2017); Hollander et al. (2019).
Aesthetic processing. Efficiency, beauty, safety, pleasantness, and interest assessment.	Comparing rectilinear and curvilinear interior spaces. Architectural space geometry (square, round, sharp, and curvy).	2D image in fMRI Signa Excite HD. 3D Virtual CAVE VizTech XL software, EEG (Emotive-EPOC).	Vartanian et al. (2013), Vartanian et al. (2015), Shemesh, Bar, and Grobman (2015); Shemesh et al. (2017).
Phenomenological experiences, experiential intensity, positive/negative user experience, multisensory experience, and natural experience of architectural spaces. Relaxation, excitement, engagement, stress, focus, interest, attention, appreciation, peace, beauty, connectedness, anxiety, pleasure, motivation, pleasant, and frustration.	Characteristics of religious spaces, mosques, and spirituality of the built environment, ordinary and contemplative architectures, presence and size of windows, spatial alignment, contours of objects, natural daylight, exposure to nature, density, height of ceiling, flexibility in isolation/socialization, openness of space, colour, artificial lighting, visual cue and landmark, shape layout, texture material, ease of access, and symmetry/ asymmetry, design features of interior spaces as levels of luminance, colour of the surfaces, openness in space, natural daylight, and visual cues.	fMRI, EEG, VR, EDA, HRV, questionnaire, self-report, post-test measurements, crowdsourcing, and semantic differential scale.	Vijayan and Embi (2019); Bermúdez (2017); Ergan, Shi, and Yu (2018, 2019); Higuera-Trujillo et al. (2020).
Presence levels with stereoscopic vision.	Residential spaces, and a 'work' office.	3D Virtual CAVE-like (Stereoscopic), questionnaire.	Rodríguez Ortega, Rey Solaz, and Alca*niz Raya (2011).*
Stress and tension.	Materiality and texture.	Autonomic nervous activity (pulse rate, blood pressure and regional cerebral blood flow). Questionnaire. A Physical room.	Tsunetsugu, Miyazaki, and Sato (2005); Zhang, Lian, and Wu (2017).
Engagement and excitement (Betta waves)	Compare the Urban vs. natural environment.	EEG and Interviews.	Tilley et al. (2017).

Levels of frustrations (upper Theta range).			
Brain activity.	Navigation in different urban roots.	EEG.	Karandinou and Turner (2018).
Comfort.	Walking within two different neighbourhoods; residential vs. business.	EEG.	Hollander and Foster (2016).
Arousal levels, anxiety excitement.	Walking on two different trails; park vs. commercial.	EEG.	Banaei et al. (2015).
Excitement. meditation state, engagement.	Comparing green park, urban shopping areas and commercially crowded spaces.	EEG.	Aspinall et al. (2015).
Relaxation and calm awareness (Alpha waves).	The impact of spiritual buildings on the human brain.	EEG.	Essawy, Kamel, and Elsawy (2014).
Right cingulate gyrus and left precuneus were activation.	Comparing urban, mountain, forest, and water environments.	fMRI and Questionnaires.	Tang et al. (2017).

Only a few research studies have measured the EEG signals in urban parks for different study purposes. The objects of those studies covered urban park types (Aspinall et al., 2015; Deng et al., 2020; Gao et al., 2019; Li et al., 2021a; Lin et al., 2020; Neale et al., 2017; Olszewska-Guizzo et al., 2022; Qi et al., 2022; Tilley et al., 2017), landscape elements(Deng et al., 2020; Yang et al., 2011; Zhang and Dai, 2021) to structure configurations(Zhu et al., 2021), and the investigated factors included mental effects such as emotion(Aspinall et al., 2015; Lin et al., 2020; Neale et al., 2017; Olszewska-Guizzo et al., 2022; Yang et al., 2011), fatigue(Zhang and Dai, 2021), restorativeness(Deng et al., 2020; Gao et al., 2019; Li et al., 2021a; Qi et al., 2022) with physical activities(Aspinall et al., 2015; Lin et al., 2020; Neale et al., 2017; Tilley et al., 2017). The methodology of those research is very limited, mainly focused on the spectral power analysis based on brain oscillation characteristics. In the studies (S2, S4) of the thesis, we used the EEG spectral analysis of each brain region to detect the concrete state of brain functions, especially the alpha band activity in each region since it indicates the relaxation state of the brain region, which could help us understand the mental effects of perceptual elements in urban parks (see Figure 24 and Table 15).

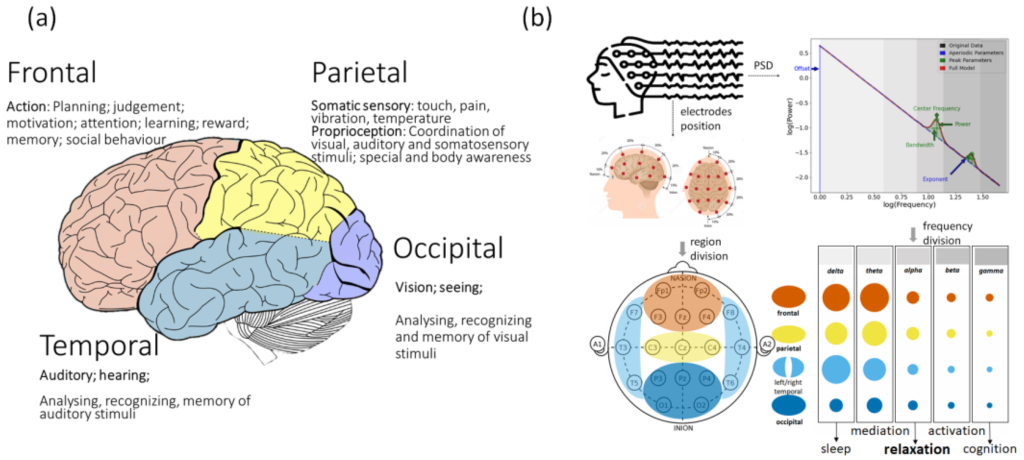


Figure 24 - the function descriptions of brain regions (a) and the EEG spectral analysis of brain regions (b)

Table 15 - EEG oscillation classification and functions (base state means a steady and population state with only spontaneous brain activities; response changes mean brain oscillation activities changes induced or evoked by external events)

Brain Oscillations	Functions Description
Delta band (1–4 Hz)	Base state: sleep; unawareness; deep-unconsciousness Response changes: gating mechanism of excitability of neuronal network for sensory inputs;
Theta band (4–8 Hz)	Base state: drowsiness; unconsciousness; mediative state; Response changes: working memory maintenance; error processing;
Alpha band (8–13 Hz)	Base state: wakeful rest; eye-closed; Response changes: decrease of neuronal activity; cognition inhibition;
Beta band (13–30 Hz)	Base state: normal wakeful consciousness; concentration; Response changes: sensorimotor processing; high-level cognitive process; decision-making;
Gamma band (>30 Hz)	Base state: cognition dysfunctions; mental disorders such as Alzheimer's disease and schizophrenia; Response changes: sensory perception integrating; active neuronal processing of information

To gain deeper insights about the mental process of human perception in urban parks, the connectivity of EEG activity in different frequency bands and brain regions was treated as another focus in our researches. Through EEG connectivity observation, the dynamical changes of intra-region and inter-regions could be used for revealing the process of cognition like perception (Keil and Senkowski, 2018; Wang et al., 2019), attention (Francisco-Vicencio et al., 2022), and emotion (Zhou et al., 2023). In the studies (S2/S4) in the thesis, referenced with the works on auditory attention in multiple spearkers scenarios from language field (Szalárdy et al., 2019; Tóth et al., 2019), we adopted this methodology to interpret the fundamental mental processes induced by the mask sounds in noisy environments regarding acoustic comfort, health, and well-being to enable policymakers and designers to extrapolate solid results (see Figure 25).

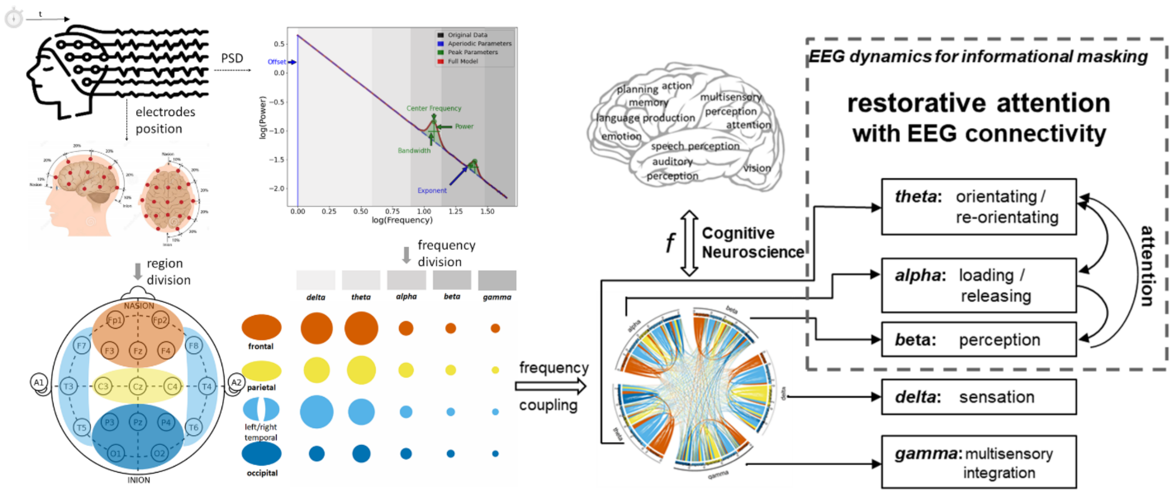


Figure 25 - EEG connectivity methodology for informational masking and restorative attention.

4.5 Summary

In this chapter, we discussed the technical aspects of accomplishing all of the studies in the thesis and summarized state-of-the-art applications in the urban design field. Integrating audio-visual objects into real-virtual urban park environments could help us conduct high ecological validity studies, and combining psychophysiological and psychological measurements could produce more comparable results and reach more solid conclusions for practical applications. We have striven to reveal the application potentials of all the techniques mentioned by different studies will be mentioned in upcoming chapters. Of course, managing all the details in those techniques into different platforms for those studies posed us a big challenge, more developed and integrated devices and tools are strongly called for promoting our studies and also overcoming the limitations of those studies in the thesis.

PART III MULTISENSORY DESIGN AND PERCEPTION IN URBAN PARK

CHAPTER 5: TOWARD NATURE-BASED DESIGN IN URBAN PARK: PERCEPTUAL SIMILARITY ANALYSIS ACROSS MULTIPLE SENSORY MATERIALS AND MULTI GROUPS

5.1 Using Images and Audios for Urban Park Characteristics Assessment

Based on the spatial characteristics of urban parks, different color schemes could be observed from different subareas. For example, trees and vegetation are the more dominant features in most areas in urban parks, especially for resting areas. Activity areas recognized by playground and furniture are more colorful than other areas. And the pavements designed for visitors to transfer between different zones are usually marked as grey color with rigid geometry features. Different strategies employed in different areas could improve the visitors' subjective experience and induce corresponding mental states and physical activities to optimize urban parks' mental and physical effects on human well-being. Rapuano et al. (2022) presented three different types of urban parks (Green Parks/Colorful Parks/Square) through 15 images to investigate their emotional influences on viewers. They found that Green Parks positively affected participants' mood more than Colorful Parks and Squares. And Colorful Parks were more energizing and alleviated sadness compared to Squares, while Green Parks were more calming rather than energizing. The results indicating different types of urban parks can positively affect different aspects of emotion, from relaxation in green spaces to recharging in colorful spaces (Rapuano et al., 2022).

Various auditory stimuli derived from the vibration of physical elements like water, birds, and people in urban park, providing temporal information for perceptual grouping and later high-level cognition. Clark and Stankey (1979) suggested the type of sounds would influence the quality of the spaces depending on the consistency with the spatial settings (Clark and Stankey, 1979). Carles, et al. (1999) revealed that different areas have different sensitivity of acoustical stimuli in urban green spaces. The sensitivity of the vegetated areas were more than the built setting areas. And the sensitivity could be increased by the interaction of the availability of different sounds in the environment. Moreover, they found that individual preferences of sounds inclined more towards to natural sound rather than man-made sounds (Carles et al., 1999). Yang and Kang (2005) highlighted the differences between perceived acoustic comfort and the subjective evaluation of the sound level of the soundscape in open public spaces (Yang and Kang, 2005). Yu and Kang (2010) categorized sound preferences into natural, human, mechanical, and instrumental sounds (Yu and Kang, 2010). Cain et al. (2013) divided the heard sounds in open space into four categories-aircraft, environmental sound, music sound, vehicles and other artificial sound through multi-dimensional evaluation, suggesting the emotional responses of the sounds could be represented in a 2D perceptual space (Cain et al., 2013). Shahhosseini et al. (2014) used Nominal Group technique to conduct a literature review of the non-visual elements (sound/smell/touch) as influential factors on human perception and aesthetic experience in small urban parks. They summarized four kinds of sounds, including human sound (like children playing and human voice), mechanical sound (road traffic mostly), instrumental sound (music, bells etc.), natural sound (such as birdsong, water) were mostly referred in literature and could be named as subscales for sound stimuli in urban park environments (Shahhosseini et al., 2014). More recently, researchers have investigated the role of those auditory stimuli in restorative processes. Among them, natural sound like water, bird and music were the most explored. Benfield et al. (2014) found that exposure to nature sounds showed a greater mood recovery than anthropogenic sound stimuli (voices or motorized vehicles) (Benfield et al., 2014). Ratcliffe et al. (2016) explored the perceived restorative potential (PRB) of 50 bird sounds along with different pictures. Results showed that high PRP rates of bird sounds were associated with pictures of green spaces, spring and summer, daytime, and active behaviour in the environment(Ratcliffe et al., 2016). Moreover, water sounds reduce the loudness of road traffic noise and increase the overall pleasantness(Coensel et al., 2011; Galbrun and Calarco, 2014). However, sea and water stream sounds were generally preferable to fountains and waterfalls (Jeon et al., 2012).

This part of the research aimed to reveal the perceptual dimensions of visual features and auditory elements in an urban park and examined the consistency between visual and auditory sensory modals for perception evaluations. And the culture differences have also been explored to generalise the research results.

5.2 Material Selections and Questionnaire Design

5.2.1 Material Selections

The images of urban parks were selected from Internet, most from the well-known architect design project sharing website https: www.archdaily.com. Three categories of urban parks are defined as green parks (prevalence of green and blue colours with less complicated spatial forms), square parks (prevalence of grey and neutral colours with more spatial forms) and colorful parks (prevalence of multi-coloured grounds, red-coloured bridges and children's carousels), each consisted of five images. All images were formatted as PNG with 600x600 pixels (see Figure 26 for the image list). Related acoustical elements from those three type of parks were selected as: natural sounds, music, and anthropic sounds. Each category consisted of five audio formatted as wav file. Natural sound audios included birds singing, water flowing and wind blowing. Music sounds extracted from different types of music related to urban parks with Italian or Chinese contexts, such as classic Piano music and Chinese violin. And the Anthropic sounds consisted of daily life sounds like traffic noise, and background chattering. Each sound lasted 6 seconds. Some of the sounds included in the materials were chosen directly from the IADS-E database, other were recorded from real parks in Italy (see Figure 26 for the audio list). All the sounds were calibrated. They have the A-weighted sound pressure level from 55 to 65 dB(A) and the 5th percentile of loudness from 12 to 13.7 sones.

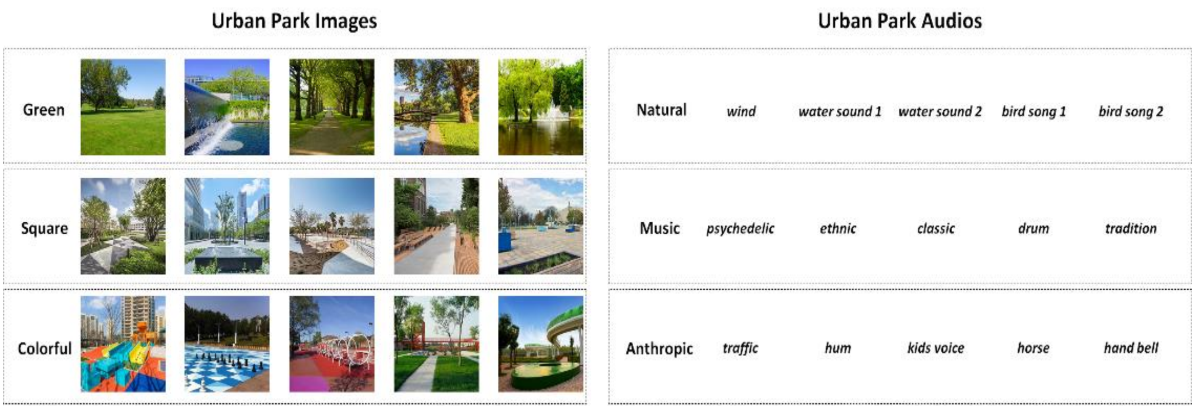


Figure 26 - The selected images of different urban park types and related audios from three categories

5.2.2 Questionnaire Design

Based on previous studies, a 12-items questionnaire was used to assess visual and auditory stimuli. The questionnaire was divided into two parts. Part A focused on how the image/audio is affectively assessed (e.g. pleasant, calm), and part B measured how it makes people feel (e.g. happy, sad, energetic). Part A was built starting from the circumplex model of soundscape perception, whereas part B was created by focusing on the emotional dimension of sounds. Each item is rated on a 9-point Likert scale, from 1= Not at all to 9= Extremely. The validation of the questionnaire was administered to two different groups of participants with sound materials (Masullo et al., 2021a). Principal component analysis and reliability analysis showed that part B could capture more reliably and clearly the

Positive and Negative dimensions of the sound than part A. The implications of these results are discussed in light of recent indications about the need to assess in a clear, reliable and straightforward way the impact of the sound environment on humans. See Appendix A for detailed information on the questionnaires (see Appendix A.).

All the audio/image materials with questionnaires were programmed by the online research PsyToolkit with randomized presentations. For audio playback volume control, a male speech record was used at the beginning of the test to allow the participants to calibrate the playback level of the sound dataset, asking them to adjust the volume until the male voice sounded loud as a normal speech of a talker at about 1 m in a quiet room.

5.2.3 Test Procedure

Eighty participants from both Chinese and Italian groups were invited via e-mail to take part in the test. After receiving information about the study and providing informed consent, participants were asked to fill out the Positive and Negative Affect Schedule (PANAS). Then the two experimental blocks (Images/Audios) were presented in a counterbalanced order across participants. Each block consisted of 15 stimuli randomly presented. Participants were asked to evaluate each stimulus using the questionnaire (for Chinese group, a Chinese translated version of the questionnaire was prepared). Furthermore, participants were also administered Ishihara's test for color blindness to control possible colors perception deficits. The PANAS scale was administered to exclude participants with excessive emotional reactions. Each experimental session lasted approximately 30 minutes.

5.3 Similarity Analysis and Results

5.3.1 The Questionnaire Dimensions in Images and Audio Assessments

The questionnaire items were reduced into two dimensions based on the results of Principal Coordinate Analysis (PCoA). PCoA was conducted through the cosine similarity matrix of all item-pairs in the questionnaire, both on image and audio assessment results (see Figure 27, Figure 28). The two components of emotional salience were shown clearly. The positive component of emotional salience (ES+) included Calm, Happy, Attractive, Pleasant, Stimulating, Energetic items, meanwhile the negative component (ES-) was consisted of Weak, Sad, Unattractive, Unpleasant, Boring, Nervous items. The two components were consistently existed in image assessments and audio assessments. The emotion arousal (EA) reflected by the sum of nervous-boring pair and energetic-calm pair (EA=(nervous-boring)+ (energetic-calm)) were also computed.

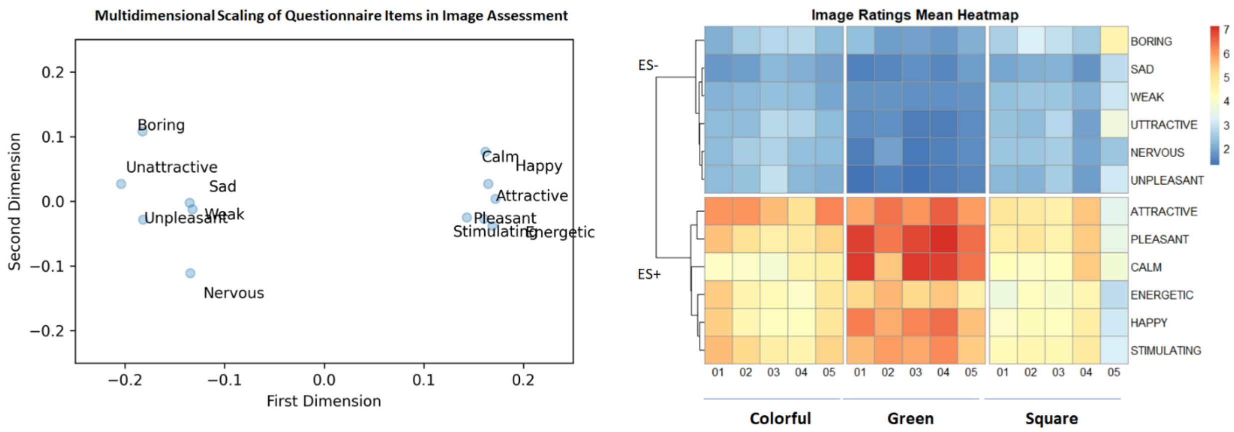


Figure 27 the questionnaire dimensions of image assessments of urban park

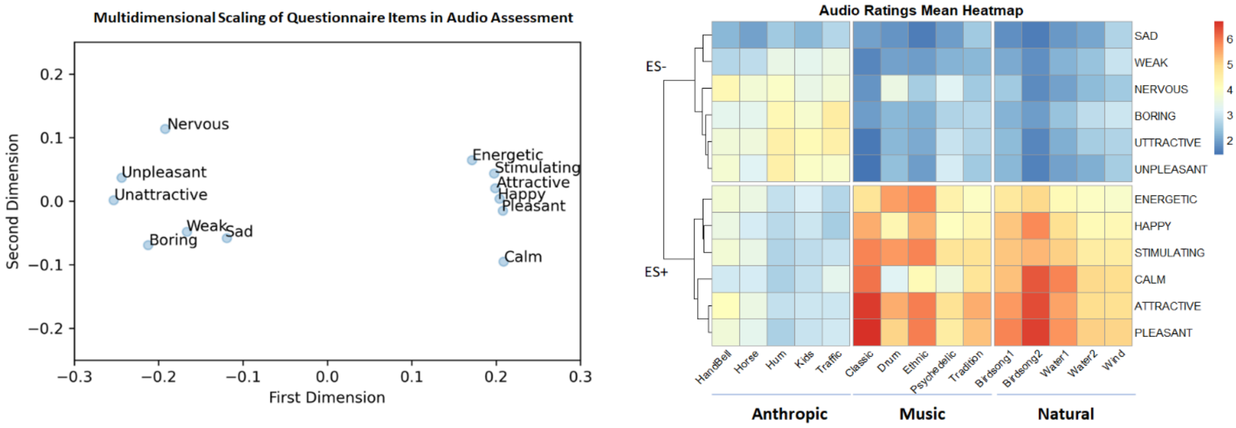


Figure 28 the questionnaire dimensions of audio assessments of urban park.

5.3.2 The Similarity Analysis of Images and Audio Assessments in Two Dimensions of Emotional Feelings

For different urban park images, through the Permutational Multivariate Analysis of Variance (PERMANOVA) in distance matrices by using the adonis function in the R library *Vegan*, the category effects were found significantly in both ES+ (F=3.6174, p<0.001) and ES- (F=3.7838, p<0.001). For the positive and negative components (reversed for comparison consistency) of emotional salience, the differences between different categories were consistent. Green park images were significantly greater than Colorful park images (ES+: t=-2.3621, p=0.024; ES-: t=-2.1943, p=0.039). The later images were greater than Square park images (ES+: t=1.6324, p=0.054; ES-: t=1.4594, p=0.039). Naturally, the Green park images were greater than Square park images significantly (ES+: t=1.9381, p=0.009; ES-: t=2.2181, p=0.003). The differences of emotional arousal (EA) were also significant (F=3.8250, p=0.006). But after the Bonferroni correct for the post-hoc multiple comparisons t-test between each condition, the differences between each other were not significant ($t_{Colorful-Green}$= 2.4285, p=0.060; $t_{Colorful-Square}$= 1.9130, p=0.075; $t_{Green-Square}$= 1.3327, p=0.264) (see Figure 29).

The category effects were also found significantly in both ES+ (F=3.5483, p<0.001) and ES-(F=9.6131, p<0.001) for audio materials. For the positive and negative components (reversely computed) of emotional salience, the differences between different categories were consistent. Anthropic sounds were worse than Music sounds (ES+: t=1.7784, p=0.006; ES-: t=3.2991, p=0.027). The later sounds were worse than Natural sounds (ES+: t=1.9593, p=0.027; ES-: t=1.5035, p=0.090). Naturally, the Anthropic sounds were worse than Natural significantly (ES+: t=1.9536, p=0.009; ES-: t=3.7287, p=0.015). The emotional arousal (EA) differences were insignificant (F=2.0663, p=0.064). The post-hoc multiple comparisons between each condition indicated the difference between Anthropic and Natural sounds was significant ($t_{Anthropic-Music}$= 0.8646, p=1.000; $t_{Music-Natural}$= 1.6417, p=0.294; $t_{Anthropic-Natural}$= 1.8190, p=0.015).

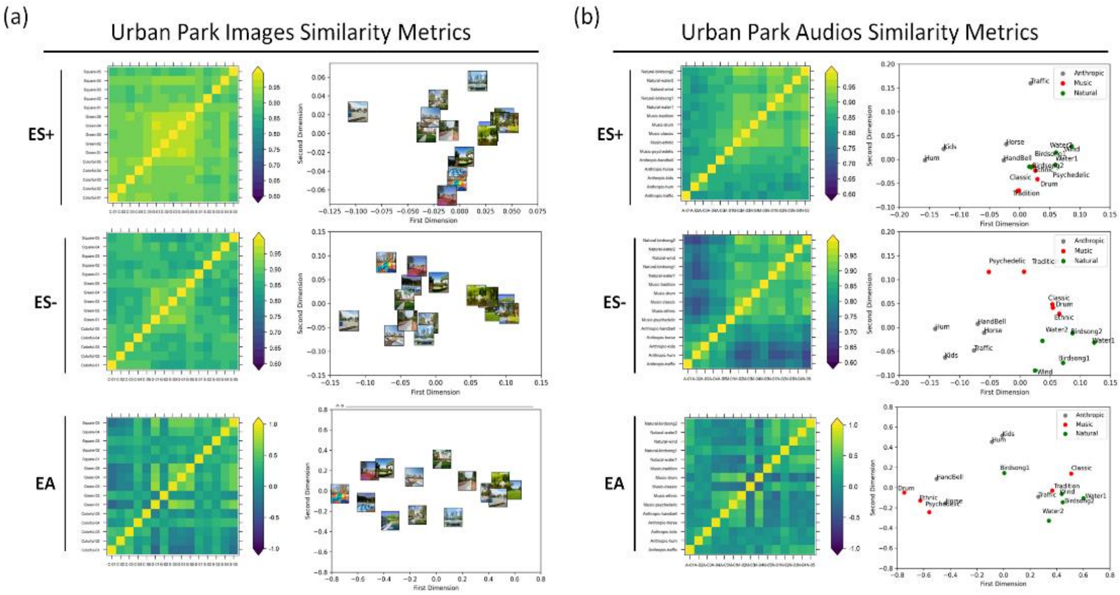


Figure 29 the similarity heatmaps and PCoA plots of urban park images and audios in ES+/- and EA components

5.3.3 The Correlation Analysis of Images and Audio Assessments between Chinese and Italian Groups

Using Mantel Test for similarity correlation analysis from the R library *Vegan*, the correlation of the Chinese group and Italian group was significant in ES+ (r=0.667, p<0.001) but not in ES- (r=0.078, p=0.522) for different categories of urban park images. The correlations of ES+ and ES- were both significant in the Chinese group (r=0.506, p<0.001) and the Italian group (r=0.296, p=0.033). And the correlations of EA were not significant in Chinese and Italian groups (r=-0.029, p=0.571). As for the urban park audio materials, the correlations of Chinese and Italian group were significant both in ES+ (r=0.597, p<0.001) and ES- (r=0.269, p=0.008). The correlations of ES+ and ES- are significant both in Chinese group (r=0.458, p<0.001) and Italian group (r=0.444, p<0.001). And the correlations of EA were not significant in Chinese and Italian groups (r=-0.030, p=0.555).

5.4 Discussion and Summary

The perceived emotional dimensions of visual and auditory stimuli in urban parks were consistent. Both the differences in emotional salience and emotional arousal were founded across different sensory inputs of urban parks revealed by images and audios. Green parks brought more positive emotion salience than Colorful parks, the later were felt better than Square parks, indicating the more natural settings, more restorative effects could be brought by those green spaces. Meanwhile, the Colorful parks evoked more activation of emotion arousal than Square parks and Natural parks, showing the colorful design could help urban park to achieve more instoration effects for physical activity. Another important finding referred to the culture generalization of those emotional dimensions. Only the positive component of emotional salience showed cross-culture consistency for different types of urban parks. For the negative component of emotional salience and emotional arousal, no correlation between different culture groups. For the auditory inputs in urban parks, both components of emotional salience were cross-culture consistent despite of emotional arousal. Those cultural differences could suggest more variations of the human perception on the negative elements of urban parks, which reminds urban park designers and managers that more difficulties exist for controlling negative factors than promoting positive ones, and different positive elements are also needed to be trade-off for diverse function designs.

CHAPTER 6: THE DESIGNING AND PERCEPTION OF THE MULTISENSORY SETTINGS IN URBAN PARK THROUGH VIRTUAL REALITY TECHNOLOGY AND NEURO-PSYCHOLOGICAL MEASUREMENT

6.1 Exploring the Effects of Multisensory Perception of Urban Parks on Human Well-being

While various physical inputs and factors of urban parks have been explored for their mental effects on visitors separately, as mentioned in the previous chapter, their interaction and integration effects are rarely investigated. Clark and Stankey (1979) suggested the type of sounds would influence the quality of the spaces depending on the consistency with the spatial settings (Clark and Stankey, 1979). Carles, et al. (1999) revealed that different areas have different sensitivity of acoustic stimuli in urban green spaces. The sensitivity of the vegetated areas was more than the built setting areas. And the sensitivity could be increased by the interaction of the availability of different sounds in the environment. Moreover, they found that individual preferences of sounds inclined more towards natural than man-made sounds (Carles et al., 1999). Rummukainen et al. (2014) used a spherical screen and spatial audio system to reproduce 19 natural scenes for multisensory categorization. They decoded the perceptual attributes of human attention to natural scenes and showed the amount of movement, perceived noisiness, and eventfulness of the scene were the most important perceptual attributes in naturalistically reproduced real-world urban environments (Rummukainen et al., 2014). Hedblom et al. (2019) using a multisensory virtual experiment to investigate the physiological effects of different sensory qualities of urban green spaces including visual settings (urban/forest/park), olfactory (nature/urban odours) and auditory (bird songs/noise) stimuli. They found that the park and forest provided significant stress reduction. Olfactory and auditory factors were correlated to pleasantness ratings of the environments with physiological stress reduction but no relationship between visual stimuli and those assessments (Hedblom et al., 2019). Zhang et al. (2019) used the multisensory perspective to examine the relationship between different sensory inputs and the restorative quality of the urban park space through the survey of two hundred and fifty park users of Tianhe Park in Guangzhou, China. The results demonstrated that visual and auditory sensation were both linked with mental restoration directly and indirectly, while tactile sensation only influenced mental restoration indirectly. The mediation effects of health-related behaviors and emotional feelings between three sensations and mental restoration were also founded (Zhang et al., 2019b). Shahhoseini et al. (2023) also found human and natural sounds with related smells influenced visitors' visual preference in small urban parks through textual and photo questionnaires with structural equations model and regression models (Shahhoseini et al., 2023).

Due to the complicated interplay effects of cross-modal inputs to human experience in urban parks, semantical reports will not be enough because of their nonlinear properties and they are susceptible to personal factors like previous experience, personal traits and social influences. Therefore, more work are still needed to provide clear and reliable models and frameworks to capture the nature of multisensory perception in urban parks from human well-being perspectives. An old psychology school once used the word "Gestalt" to capture the essence of perception. Although the perception principle they developed lacks strong theoretical coherence and over-generalized problem, it inspired contemporary cognitive science and perceptual psychology. Until today some researchers are still working on using Gestalt-based principles for designing practice, especially for multisensory display (Chang and Nesbitt, 2006). But understanding how all those sensory components fit together in the perceptual mind of visitors in urban parks still poses a serious challenge (Bordier et al., 2013; Cavallina et al., 2018; Nardo et al., 2016; Soto-Faraco et al., 2019; Shahhoseini et al., 2023). Moreover, not only for multisensory perception alone, their effects on human cognition involving attention, memory(Duarte et al., 2023; Quak et al., 2015; Van De Ven et al., 2023), emotion(Pecher and Zeelenberg, 2022) and more should also not be ignored to achieve better experience for visitors in urban parks. Evidence show bottom-up mechanisms induced by multisensory interactions can automatically capture attention, and top-down attention can facilitate the integration of multisensory inputs and lead to a spread of attention across sensory modalities(McDonald et al., 2001; Talsma et al., 2010; Koelewijn et al., 2010; Lunn et al., 2019). Through those mechanisms, designers could manage positive factors in urban parks to capture the eyes of visitor and then create attentional restorative experience(Bentley et al., 2023). There is also some evidence indicating that the emotional value of the environment is coded by valence-coded sensory projection with decentralized process, meaning that, even in the early stage, the signals from nonvisual sensory systems also help inform the experiencer's emotional state (Kryklywy et al., 2020).

With the development of portable and wearable sensing techniques, neural and behavioral measurements became available until recent years. More cognitive psychology and neuroscience studies are emerging to provide deeper insights on those mechanisms, inspiring designers and managers to develop more creative strategies for promoting human well-being (Spence, 2020). Based on the neurocognitive approach, the process of multisensory integration and perception supporting the bottom-up nature of multisensory interactions, such as the pip-and-pop effect and auditory enhancement by vision, were observed ((Maddox et al., 2015; Van der Burg et al., 2008)). Electroencephalogram (EEG) is a widely adopted technique advantaging from non-invasive and direct measures of neuronal activity (Teplan, 2002). Various studies have investigated the neural effects of real-field natural or built environments with their soundscape qualities on the human mind and mental health through EEG measurements (Aspinall et al., 2015; Choi et al., 2015; Guan et al., 2020; Kim et al., 2020; Neale et al., 2020). Those studies have tried to connect the positive effect of natural elements with the patterns of the alpha band, which was considered a neural indicator of relaxation and comfort state. However, rather than changes in the alpha band, changes from the theta (Guan et al., 2020), beta (Choi et al., 2015; Olszewska-Guizzo et al., 2018; Kim et al., 2020; Neale et al., 2020) and gamma-band (Kim et al., 2020) were observed, which were inconsistent with image-based studies (Chang and Chen, 2005; Chiang et al., 2017; Grassini et al., 2019). Moreover, the ratios of different frequency bands were also investigated for detecting concrete mental states, including stress, emotion, mental fatigue, cognitive workload etc.(Ismail and Karwowski, 2020). Few cases, however, have referred to blue spaces or acoustical aspects among those in-situ neural-psychological investigations of natural environments. Li et al. compared the soundscape components and EEG reactions in typical mountainous urban parks. The results showed that the relative power of the alpha band was more evident at the birdsong-dominant site than at the traffic-noise-dominant site, under both the audio-only and audio-visual conditions. Besides, more restorative EEG reactions were found within the audio stimuli than within the audio-visual stimuli (Li et al., 2021a). And Koivisto et al. found stronger activity in the lower alpha band in the nature sound scenario than in the industry ones (Koivisto et al., 2022). Moreover, the ratios of different frequency bands were also investigated for detecting concrete mental state, including stress, emotion, mental fatigue, cognitive workload etc. (Ismail and Karwowski, 2020). It is worth mentioning that the complexity of the multisensory perception caused by the interplay of unimodal sensation inputs makes the neurophysiological results hard to interpret. More comparable studies and multi-modal methodology are urgently needed to build more solid ground-truth about neurocognitive dynamics of multisensory perception, then further inferences and predictions to real world applications could be practical.

6.2 Urban Park Modeling with Multisensory Settings and Neural-Psychological Assessment

6.2.1 Experiment Design

The study investigated how the combinations of visual and acoustic elements interact with each other and affect the perception and experience of urban parks. Four different scenarios of urban parks were built referenced on the existing park named Parco Pozzi at Aversa city in Italy. Keeping the pedestrian space the same behind the resting position, viewers could experience four visual settings. The first two are square character settings and the others two are green settings. The first square extends from the pedestrian space with a gray color scheme (*Gray* square), and the second square is set as colorful arrangements with playground and furniture (*Colorful*

Square). The first green space with fitness equipment is designed for the continuum from activity to resting space (*Green-x* space). The second green space equips with a water fountain for purely resting design (*Green* space) (see Figure 30). Each visual scenario was combined with five different sound conditions including *human voice*, *bird song*, *piano music*, *water sound*, and empty sound, all mixed with spatialized road traffic noise (RTN) as background sound, to investigate which combination resulted the most enjoyable and could

Figure 30 the four types of urban park spaces based on the virtual Parco Pozzi.

better mitigate the traffic sound of the surrounding area.

6.2.2 3D modeling of urban parks

The 3D models of virtual urban parks were created mainly through two modelling methods: CAD and polygonal modelling. The first type of modelling was used to create the main volumes of the park (perimeter walls, avenues, delimitation of green areas and surrounding facades). Polygonal modelling was used to create specific assets to be included in the virtual scenario (streetlamps, benches, fountains, rides, fitness equipment, etc.). After several inspections of the park and the acquisition of the reference measurements and the objects to be modelled, the software "Google Sketchup" was used to create the meshes and, from here, exported in fbx format in 3d Studio Max for their preparation for Unreal Engine 4. This preparation can be mainly divided into two phases: flipping the normal of the meshes exported from Sketchup and the creation of two mapping channels (i.e., "UV sets"), the first one dedicated to texture distribution on the 3d object, the second is used by Unreal for the calculation of diffused lighting and the generation of shadows (i.e., “light baking”). Once these prerequisites were satisfied for each individual mesh, they were exported to Unreal for scene composition. Once the scene was assembled, the lighting was simulated. The actors used for this purpose are "Directional Light" for direct light and "Skylight" for diffused lighting simulations. Both actors are set in dynamic mode, so they proceed to the generation of lights and shadows in real-time. They are managed by a "blueprint" capable of simulating, as needed, different lighting conditions for the different hours of the day and in combination with multiple weather conditions (clear, light rain, rain, storm, snow, storm).

The visual objects imported into Unreal engine for scene modeling were taken both from the libraries made available by Unreal (Megascans) for the composition of the green areas of the park, and created specifically for the different assets present in the scene. The former was created as “BlendMaterials” of grass and clay textures. Through the Unreal tools ("Vertex painting") it is possible to define which part of a single mesh will be covered by one or the other and the falloff between the two. This technique was useful for simulating, for example, the thinning of the lawn in the green areas most used by park visitors, especially in those where physical exercise is practised or where there are attractions for children. Furthermore, specific blueprints made it possible to create a material that simulates small puddles, trickles of water and snow on the mesh, in case you choose to use an atmospheric scenario of rain or snow. The materials applied to the other assets (benches, fountains, streetlamps, etc.) were created through the manipulation of textures in Photoshop from the photos taken during the inspections. The creation of the materials followed the "PBR" (Physical Based Rendering) workflow for a photorealistic simulation of the behavior of light on metallic and dielectric surfaces. Different types of vegetation (grass and flowers) have been downloaded from Unreal libraries (Megascans) and assembled in Unreal's internal "Foliage tool", which allows you to distribute the selected meshes (vegetation in this case) evenly over a surface. To avoid repetition effects, parameters of distribution density and scale range of the meshes have been defined in order to create a convincing variation of the vegetation. Using the same tool, the individual trees and flower beds were manually placed into the park. The dynamic effect only concerned the traffic simulation. For the simulation of vehicular traffic, a predetermined route was first created with the "SplineMesh" tool inside Unreal. Subsequently, the 3d models of some cars were inserted into the scene and instructed to follow the path within a certain time frame (see Figure 31).

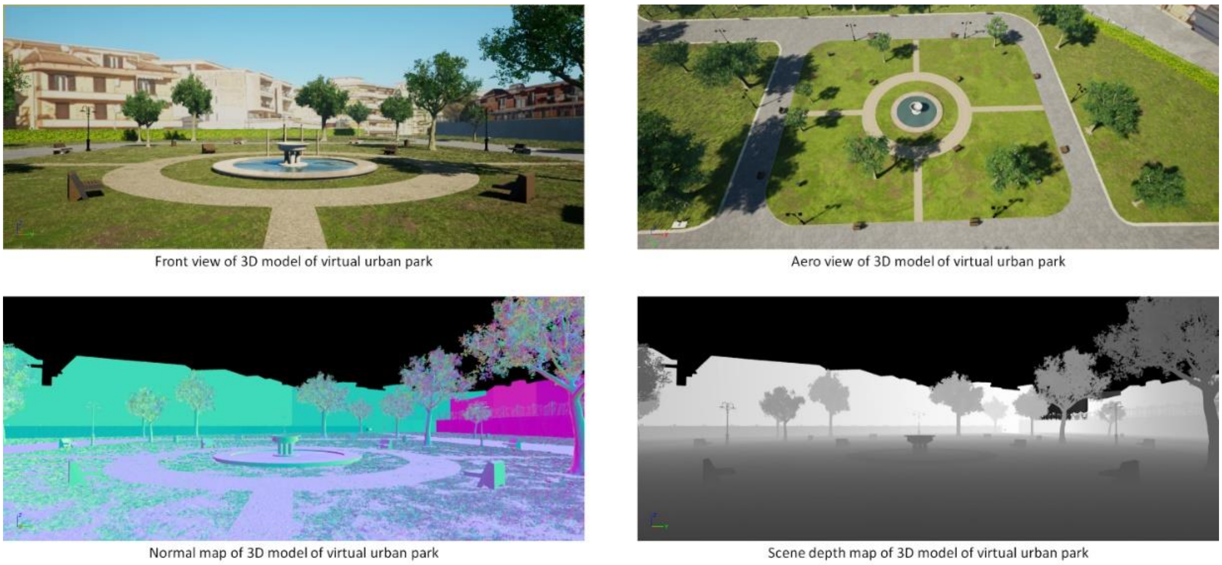


Figure 31 - Different illustrations of the 3D model of virtual green urban park

The sounds were recorded purposely regarding vehicular traffic and natural sounds (e.g. birds chirping, water, etc.). All the sounds of the scenes were calibrated with the MK2 Cortex Manikin and calibrated at 45 dBA (35 dBA for vehicular traffic). The same has been implemented within Unreal through the Sound Cue assets, allowing the precise positioning of the sound sources of interest and their sound propagation. Namely, sounds (both environmental and traffic) were placed in front of the participant.

6.2.3 Experiment Procedure

Thirty participants gave informed consent and were instructed to sit in the center of the test room to be immersed in virtual multisensory environments. Before the formal experiment, the subject filled out the interoceptive awareness (MAIA), mood (PANAS) and noise sensitivity (WNSS) questionnaires. With a comfort sitting position, participants were asked to ear the HTC Vive Pro Eye, DSI-

24 EEG headset and a pair of headphones. After passing the impedance check of EEG electrodes, subject would sit and free-view the virtual scenario for one minute then answer the interactive questionnaire (see Figure 32). The questionnaire included 6 items to assess how Pleasant, Attractive and Stimulating each audio-visual scenario was and how much each made them feel Calm, Happy and Energetic for participants (negative items are excluded for time-saving since the positive items and negative items have clear linear relationships based on the results of previous questionnaire analysis) (see Appendix A.). The saliency of stimuli questionnaire was implemented in an interactive version so that participants could respond while remaining immersed in the virtual scenario. Once the subject finished the questionnaire, next scenario would continue to present after a randomly 30-second to 1-minute blank screen buffering time.

During the whole process, the brain data of each subject were continuously recorded by DSI-24 wireless EEG headset with 20 dry electrodes signals referenced to Pz electrode at locations corresponding to the 10-20 International system. The light and temperature in the lab were kept constant during the test. The EEG data were sampled at 300 Hz and streamed from the measurement device to the recording laptop using the Lab Recorder application based on the Lab Streaming Layer protocol to synchronize the neural data with virtual scenario changes. The Ethical Committee for Scientific Research of the Department approved the protocol.

Figure 32 the test scenario of virtual multisensory green park with EEG measurements

6.2.4 Data pre-processing

The continuous EEG data were imported into MATLAB and EEGLAB toolbox and pre-processed using the automated PREP pipeline for data cleaning. The data of three participants were excluded because of less clean data (both the percentage of invalid data were higher than 50%). Then a 1-45 Hz band-pass filter was applied. After re-referencing the EEG signal to the average (except for A1 and A2 mastoid electrodes), their independent components were calculated using the Infomax algorithm. Eye-blink and ocular movements artifacts were deleted based on the standard topographic profiles of the individual components and the distinctive temporal pattern. After removing eye-movement artifacts, the 1-min EEG data during each scenario's perception were extracted.

6.2.5 EEG spectral analysis

The cleaned EEG data were analyzed using MNE python library (Gramfort et al., 2013). EEG signal could be decomposed into periodic (oscillations) and aperiodic (offset, exponent) (see the spectrogram plot in Figure 24b for the illustration) signals (Donoghue et al., 2020). Aperiodic component can be characterized by a $y + 1/f^{\chi}$ function, where y is the offset parameter, reflects the uniform shift of power across frequencies, and the χ parameter, referred to the pattern of aperiodic power across frequencies of the PSD. The periodic components and aperiodic components of PSD were computed by the Irregular-Resampling Auto-Spectral Analysis (IRASA) method (Wen and Liu, 2016) referencing the code from the open-source tool Yasa (Vallat and Walker, 2021). As for the oscillation analysis, the mean powers of each frequency band (delta band was defined as the range of 1 to 4 Hz; theta band: 4-8 Hz; alpha: 8-13 Hz, beta: 13-30 Hz, low-gamma: 30-45 Hz) were extracted from the PSD of each electrode. Time–frequency-resolved activity was obtained using the multitaper method (4 cycles width) based on Hanning sequences between 1 and 45 Hz (stepsize: 1 Hz), from which the average powers of each frequency band (delta band was defined as the range of 1 to 4 Hz; theta band: 4-8 Hz; alpha: 8-13 Hz, beta: 13-30 Hz, low-gamma: 30-45 Hz) were derived. The interested electrodes were divided into five regions: the frontal (Fp1, Fp2, F3, F4), left temporal (F7, T3, T5), central (Cz, C3, C4), right temporal (F8, T4, T6) and posterior regions (P3, P4, O1, O2), respectively.
The relative power of each given band/sum of power from 1 to 45 Hz was calculated by

$$\boldsymbol{RP(f_{1,}\, f_{2,}) = \left[P(f_{1,}\, f_{2,})/P(1,45)\right] \cdot 100}$$

Where P(·) indicates the power, RP(·) indicates the relative power, and f_1, f_2 indicate the low and high frequency, respectively. The relative power for each band and the power ratios for different frequency bands were averaged in each region. The ratios of power for different frequency bands in each electrode was also computed for possible pairs of frequency bands, such as P(delta)/P(theta), P(theta)/P(alpha) and P(alpha)/P(beta).

6.2.6 EEG sensor-level connectivity analysis

EEG connectivity analysis could be conducted at sensor-level or source-level for network analysis. Sensor-level connectivity helps us understand the dynamical changes of functional networks of the brain in a regional scale (referring to frontal, occipital, parietal, and temporal lobes), but the information of precise neuroanatomy locations of those connectivity changes requires source-level analysis. Sensor-level connectivity analysis was used in our study as for the connectivity changes of brain regional networks were the main points in our study. And it also ensured the analysis reliability since the recommended number of electrodes for source-level connectivity analysis should not less than 32. The 1-minute EEG data during each sound's condition were epoched by 3s fixed length and analyzed by MNE toolbox using spectral connectivity algorithm. The spectral connectivity was computed for the debiased weighted phase lag index (dwPLI). dwPLI is a debiased estimator of the squared wPLI developed by Vinck et al., correcting for sample-size bias in phase-synchronization indices.

6.3 Subjective and EEG results

6.3.1 The subjective results of multisensory experiments

Based on previous founded two dimensions of the subjective results of questionnaire items, the emotion valence (averaging from all the items) and arousal (energetic - calm) were computed. The degree of greenery of the space increased the emotion valence, meanwhile it decreased the emotion arousal. *Green* space had the highest positive effect in all dimensions including attractive, calm, stimulating, calm, happy and energetic, with statistical significance (except for energetic item) among four urban park types. The second was the *Green-x* space, then was the *Colorful* square in most dimensions. From ANOVA test of the simple effects for each sound under different visual scenarios, the interaction effects were shown in emotion valence, indicating the multisensory interaction effects between auditory and visual factors in the perception of urban park spaces. Specifically, the birdsong had higher positive effect in *Colorful* square, and piano music sound brought more positive effect in *Gray* square condition than others. Meanwhile, the water sounds were not so effective in *Gray* square and *Green-x* space than *Colorful* square and *Green* spaces. In emotion arousal, piano music released calm effects on the emotion arousal for all conditions, especially in *Colorful* and *Green* space (see Figure 33).

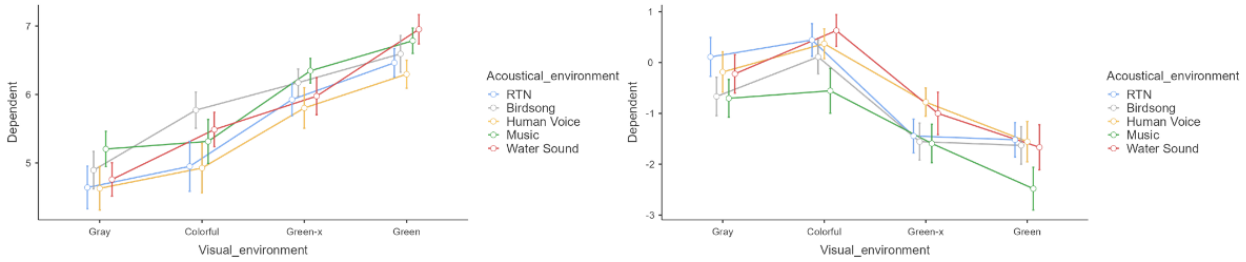


Figure 33 line plots of means and standard errors of each conditions

6.3.2 The relative power and ratio indexes of EEG signals

Limited results were found for four visual spaces (Gray square/ Colorful square/ Green-x space/Green space) under only road traffic noise (RTN). In the Green space, more spectral power in the theta band were found in the right region, while more gamma band power was distributed in the central region in the Gray square and Colorful square spaces (see Table 16, Figure 34).

Table 16 ANOVA table of relative power and ratio indexes of EEG results of four visual spaces under only traffic noise condition.

Spectral characteristics	region	df	F value	*p* value	*Gray*	*Colorful*	*Green-x*	*Green*
theta	right	(3,78)	2.8985	0.0403*	0.1534	0.1467	0.1578	0.1615
gamma	central	(3,78)	2.7459	0.0485*	0.1036	0.1049	0.0859	0.0914

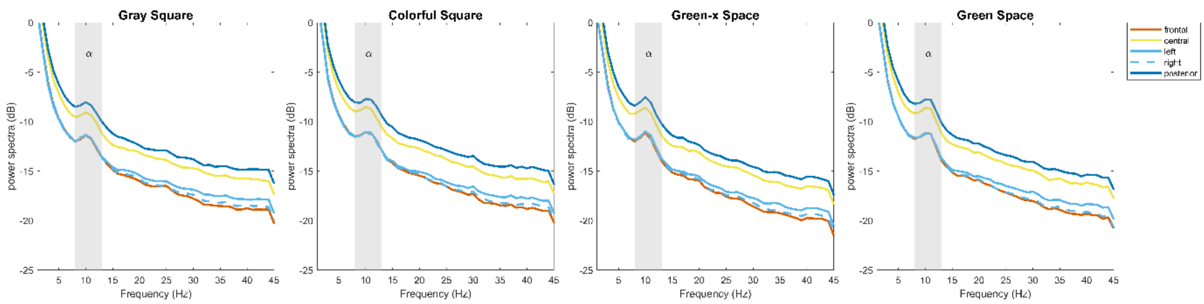


Figure 34 - The spectrogram of different brain regions for four visual scenarios

ANOVA simple effects of the sound conditions in each visual space scenario were also examined. In the Gray square space, more gamma band power was showed in the frontal position for RTN compared to Piano music. The theta/alpha ratios increased for Human voice and Bird song conditions referring to other conditions especially in the frontal and posterior positions (see Table 17, Figure 35).

Table 17 ANOVA table of relative power and ratio indexes of EEG results of five sound conditions in the Gray square.

Spectral characteristics	region	df	F value	*p* value	RTN	Human voice	Bird song	Piano music	Water sound
gamma	frontal	(4,104)	2.6352	0.0382*	0.1016	0.0882	0.0930	0.0774	0.0907
theta/alpha	frontal	(4,104)	3.4661	0.0106*	1.4889	1.6095	1.6911	1.5090	1.3335
	central	(4,104)	2.7654	0.0313*	1.4857	1.5922	1.4863	1.4614	1.3069
	posterior	(4,104)	2.9607	0.0232*	1.4916	1.6005	1.6579	1.4594	1.3570

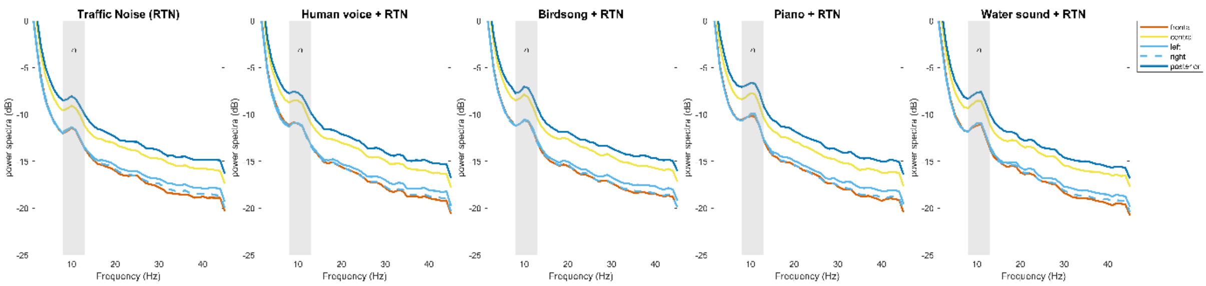


Figure 35 the spectrogram of different brain regions for five sound conditions under Gray square

No difference existed in the Colorful square scenario (see Figure 36).

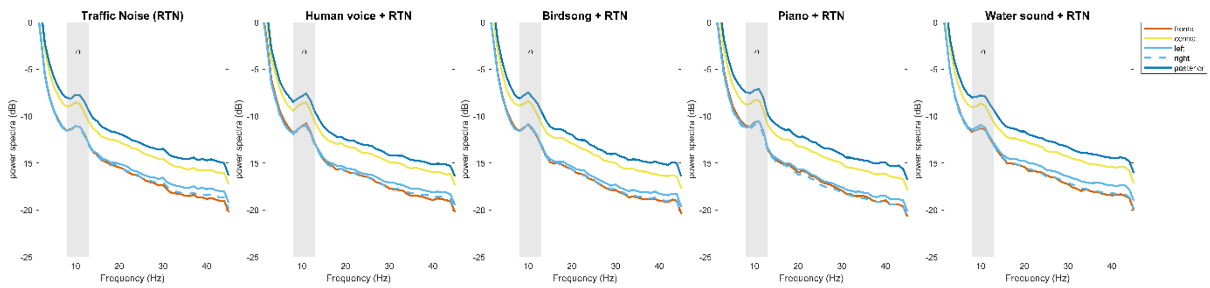


Figure 36 the spectrogram of different brain regions for five sound conditions under Colorful square

For Green-x space, RTN aroused higher level of the alpha band power than all other conditions (see Table 18, Figure 37).

Table 18 ANOVA table of relative power and ratio indexes of EEG results of five sound conditions in the *Green-x* space.

Frequency	Region	df	F value	P value	RTN	Human voice	Bird song	Piano music	Water sound
alpha	frontal	(4,104)	3.1420	0.0175*	0.1679	0.1463	0.1426	0.1498	0.1289
	central	(4,104)	3.1060	0.0185*	0.1645	0.1356	0.1424	0.1495	0.1318
	right	(4,104)	2.5761	0.0418*	0.1668	0.1348	0.1432	0.1494	0.1396

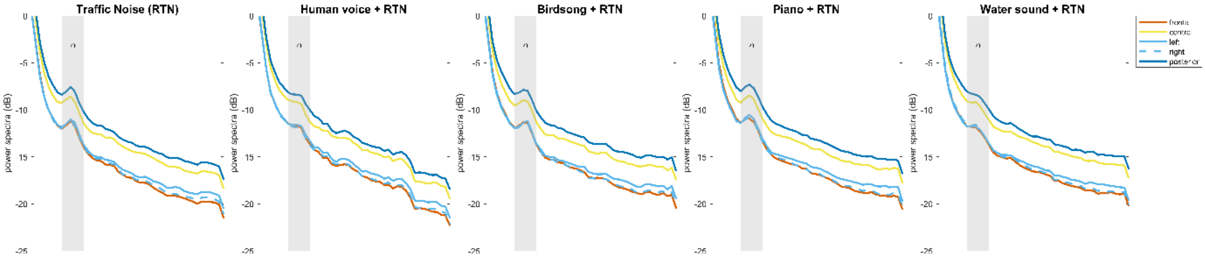


Figure 37 the spectrogram of different brain regions for five sound conditions under Green-x space

As for Green space, there are significant differences between Human voice and Water sound conditions in the delta band. Human voice condition had the lowest delta band power and the Water sound condition had the highest delta band power in most regions, similar results also occurred on the delta/theta, theta/alpha and alpha/beta ratio in responding regions. And Piano music had lowest theta band power compared to all other conditions. The human voice had significantly higher alpha band power in most regions and Water sound had significant lowest beta band power in right region (see Table 19).

Table 19 ANOVA table of relative power and ratio indexes of EEG results of five sound conditions in the Green space.

Frequency	Region	df	Fvalue	Pvalue	RTN	Human voice	Bird song	Piano music	Water sound
delta	frontal	(4,104)	2.9512	0.0235*	0.4642	0.4377	0.4618	0.4641	0.4959
	left	(4,104)	2.5296	0.0449*	0.4497	0.4157	0.4528	0.4497	0.4785
	right	(4,104)	3.3690	0.0123*	0.4611	0.4333	0.4656	0.4610	0.4977
	posterior	(4,104)	4.1200	0.0039**	0.4548	0.4194	0.4589	0.4576	0.4908
theta	frontal	(4,104)	2.5054	0.0466*	0.1644	0.1629	0.1574	0.1480	0.1567
	central	(4,104)	2.7542	0.0318*	0.1593	0.1561	0.1521	0.1424	0.1516
	right	(4,104)	2.5083	0.0464*	0.1615	0.1581	0.1546	0.1444	0.1540
alpha	frontal	(4,104)	2.8095	0.0292*	0.1467	0.1774	0.1475	0.1562	0.1433
	central	(4,104)	2.5202	0.0455*	0.1448	0.1715	0.1477	0.1525	0.1400
	right	(4,104)	2.8859	0.0260*	0.1467	0.1757	0.1475	0.1568	0.1424
	posterior	(4,104)	3.2176	0.0156*	0.1452	0.1728	0.1470	0.1544	0.1360
beta	right	(4,104)	2.5723	0.0421*	0.1872	0.1930	0.1880	0.1878	0.1704
delta/theta	frontal	(4,104)	3.3718	0.0123*	4.2225	4.0319	4.9830	4.9701	5.3860
	left	(4,104)	2.4965	0.0472*	4.3713	4.0745	4.8885	5.3019	5.3245
	posterior	(4,104)	3.3319	0.0131*	4.2487	4.0103	4.9093	5.1154	5.4239
theta/alpha	central	(4,104)	3.1250	0.0180*	1.5309	1.3285	1.5053	1.5023	1.6153
	right	(4,104)	3.4116	0.0116*	1.5833	1.3630	1.5678	1.4421	1.6475
	posterior	(4,104)	3.8461	0.0059**	1.6279	1.3583	1.5576	1.5259	1.6807
alpha/beta	posterior	(4,104)	3.2515	0.0148*	0.8935	1.1124	0.9048	0.9436	0.8388

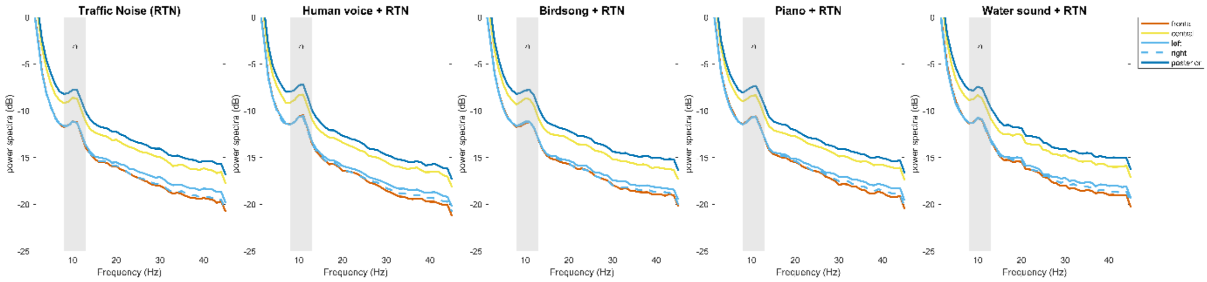


Figure 38 - The spectrogram of different brain regions for five sound conditions under Green space

6.3.3 The EEG sensor-level connectivity results

The connectivity results reflected more information about the multisensory perception of virtual urban park. For four visual scenarios (with only traffic noise as background sound), the significant differences of connectivity in intra- and inter-network were founded across different frequency, including the delta band, the alpha band, and the beta band. Gray square had highest connectivity network activation across all frequency bands. The Colorful square had similar activities in the beta band, but less in the delta and alpha band. And the Green space had showed middle level of activation in the delta and alpha band, meanwhile it inhibited the network activities in the beta band. The activation of the Green-x space in the beta band was between Colorful square and Green space (see the detailed information from Table 20, Figure 39).

Table 20 -ANOVA table of EEG connectivity results of four visual spaces under only traffic noise condition.

frequency band	network	region	df	F value	*p* value	*Gray*	*Colorful*	*Green-x*	*Green*
delta	intra	frontal	(3,78)	2.8236	0.0441*	0.0507	-0.0024	0.0007	0.0203
		right	(3,78)	4.1479	0.0088**	0.0728	-0.0124	-0.0041	0.0318
	inter	frontal-central	(3,78)	3.8307	0.0129*	0.0431	0.0043	-0.0093	0.0247
		frontal-right	(3,78)	3.2856	0.0251*	0.0601	0.0059	0.0008	0.0226
alpha	intra	frontal	(3,78)	4.5340	0.0055**	0.0610	-0.0094	0.0179	0.0223
		right	(3,78)	3.3340	0.0237*	0.0473	-0.0051	0.0532	-0.0019
	inter	frontal-right	(3,78)	2.7434	0.0487*	0.0482	-0.0061	0.0296	0.0119
		frontal-posterior	(3,78)	4.0394	0.0100*	0.0465	-0.0088	0.0205	0.0160
		right-posterior	(3,78)	2.8293	0.0438*	0.0396	-0.0030	0.0323	0.0079
beta	inter	frontal-left	(3,78)	3.8913	0.0120*	0.0281	0.0281	0.0188	-0.0038
		left-posterior	(3,78)	3.2251	0.0270*	0.0299	0.0297	0.0138	-0.0006

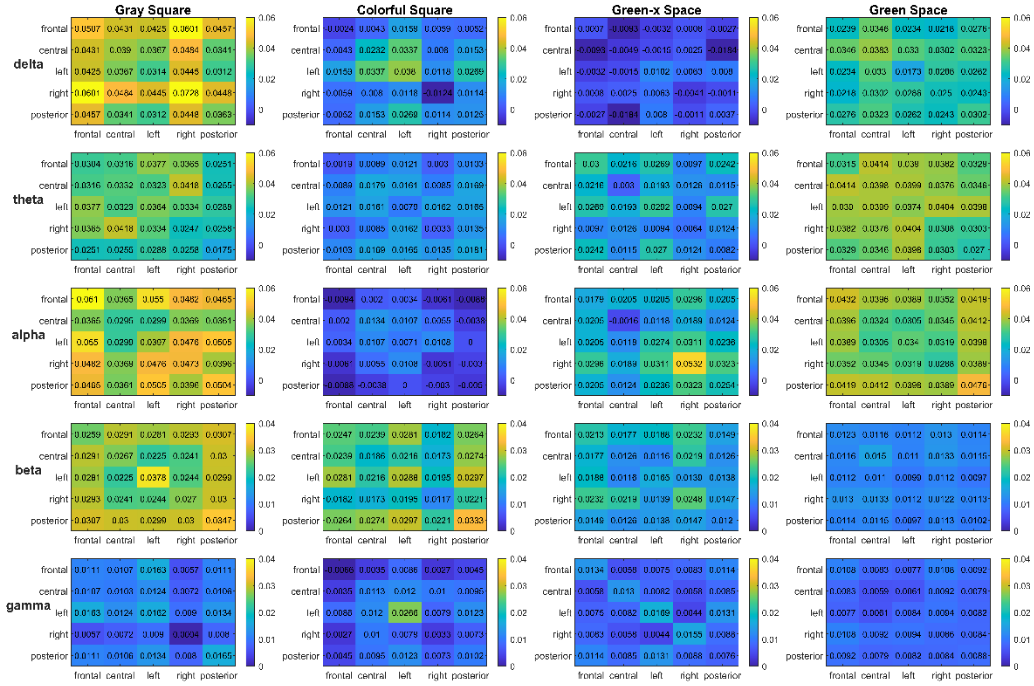


Figure 39 the connectivity heat maps of different brain regions for four visual conditions across different frequency bands.

Simple effects for five sound conditions (RTN / Human voice / Bird song / Piano music / Water sound) under each visual scenario were investigated. For gray square, the significant differences were only found in the delta frequency band. Bird song, Human voice and Water sound were all less activated in the intra- and inter-network in the delta band compared to road traffic noise (RTN), especially for Bird song condition (see the detailed information from Table 21, Figure 40).

Table 21 - ANOVA table of EEG connectivity results of five sound conditions in the Gray square.

Frequency band	Network	Region	df	F value	*p* value	*RTN*	*Human voice*	*Bird song*	*Piano music*	*Water sound*
delta	intra	frontal	(4,104)	2.5926	0.0408*	0.0507	0.0195	-0.0084	0.0533	0.0265
		central	(4,104)	2.6696	0.0362*	0.0390	0.0306	-0.0344	0.0130	0.0139
		left	(4,104)	2.6876	0.0353*	0.0314	-0.0086	-0.0198	0.0511	0.0103
		right	(4,104)	2.4982	0.0471*	0.0728	0.0027	-0.0104	0.0162	0.0456
	inter	frontal-central	(4,104)	3.2703	0.0144*	0.0431	0.0287	-0.0261	0.0443	0.0368
		frontal-left	(4,104)	3.0031	0.0217*	0.0425	0.0156	-0.0109	0.0533	0.0200
		frontal-right	(4,104)	3.7171	0.0072**	0.0601	0.0143	-0.0167	0.0249	0.0258
		frontal-posterior	(4,104)	2.9221	0.0246*	0.0457	0.0255	-0.0158	0.0351	0.0302
		central-left	(4,104)	2.7903	0.0301*	0.0367	0.0248	-0.0239	0.0255	0.0172
		left-right	(4,104)	2.7807	0.0306*	0.0445	0.0167	-0.0167	0.0371	0.0127

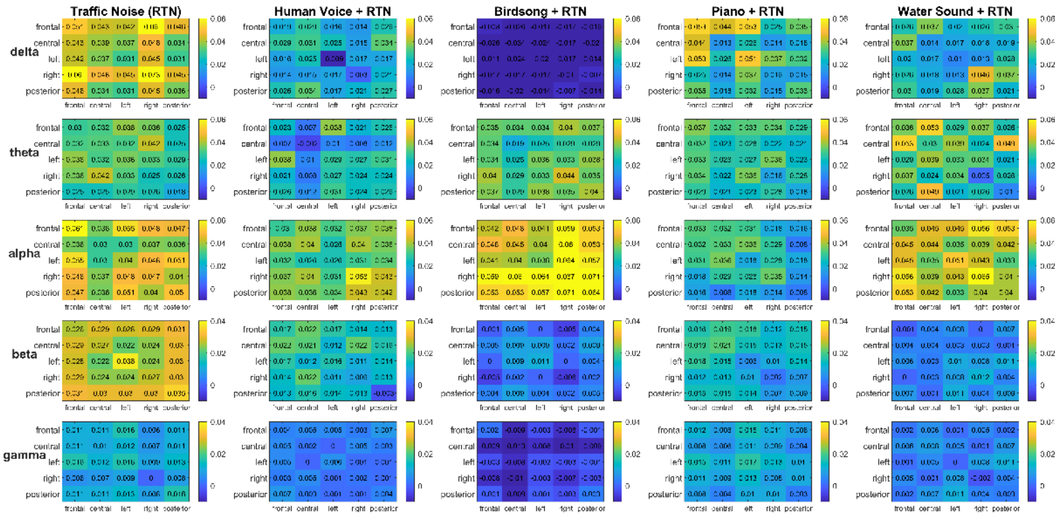


Figure 40 the connectivity heat maps of different brain regions for five sound conditions across different frequency bands under Gray square.

Under the Colorful square scenario, different sounds activated the connectivity network in the alpha and beta band differently. Piano music and Water sound have significantly inhibited the beta band connectivity compared to road traffic noise and human voice, and Bird song increased the alpha band activity compared to other sound conditions (see the detailed information from Table 22, Figure 41).

Table 22 - ANOVA table of EEG connectivity results of five sound conditions in the Colorful square.

Frequency band	Network	Region	df	F value	*p* value	*RTN*	*Human voice*	*Bird song*	*Piano music*	*Water sound*
alpha	intra	frontal	(4,104)	3.9871	0.0047**	-0.0094	-0.0078	0.0318	0.0435	0.0247
		left	(4,104)	4.3433	0.0027**	0.0183	-0.0029	0.0719	-0.0037	-0.0246
	inter	frontal-left	(4,104)	2.7656	0.0313*	0.0125	-0.0100	0.0496	0.0002	-0.0211
		left-posterior	(4,104)	2.8089	0.0293*	0.0150	-0.0077	0.0462	-0.0013	-0.0168
beta	intra	left	(4,104)	2.5336	0.0446*	0.0288	0.0207	0.0133	0.0019	-0.0014
	inter	frontal-left	(4,104)	3.7236	0.0071**	0.0281	0.0208	0.0122	-0.0039	0.0060
		central-right	(4,104)	2.5917	0.0408*	0.0347	0.0102	0.0183	-0.0087	0.0166

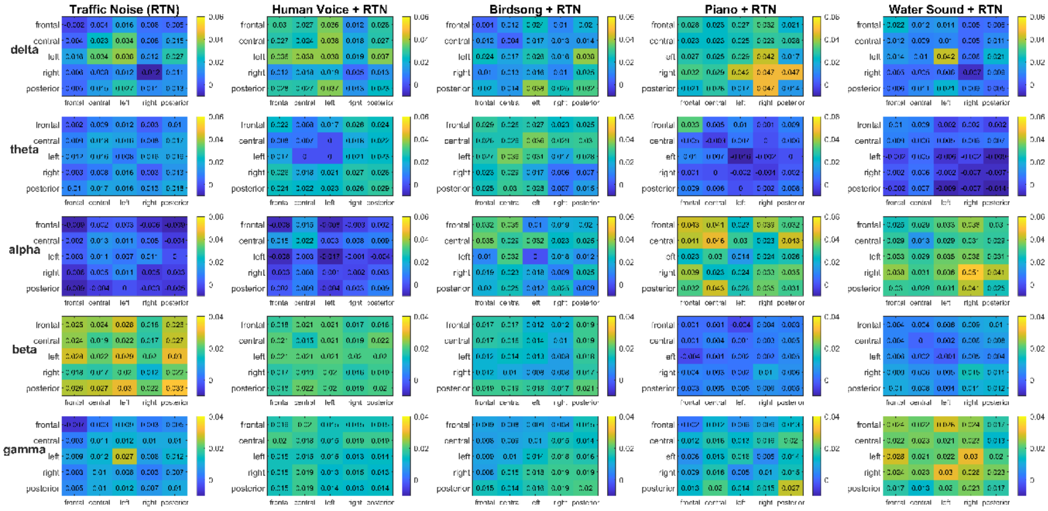


Figure 41 - The connectivity heat maps of different brain regions for five sound conditions across different frequency bands under Colorful square.

As for the Green-x space scenario, significant results had observed from the delta band mostly, with several regions in the theta and alpha bands. The water sound and Bird song increased the delta band network activations compared to road traffic noise and human voice. Additionally, the water sound increased the theta band activation in the left-right inter-network while Bird song increased the alpha band activation locally in the frontal region (see Table 23, Figure 42).

Table 23 ANOVA table of EEG connectivity results of five sound conditions in the Green-x space.

Frequency band	Network	Region	df	F value	*p* value	*RTN*	*Human voice*	*Bird song*	*Piano music*	*Water sound*
delta	intra	central	(4,104)	2.5565	0.0431*	-0.0049	0.0018	0.0431	0.0097	0.0521
	inter	frontal-central	(4,104)	4.3380	0.0028**	-0.0093	-0.0043	0.0355	0.0214	0.0584
		frontal-left	(4,104)	3.0999	0.0187*	-0.0032	0.0086	0.0635	0.0113	0.0535
		frontal-right	(4,104)	2.9240	0.0245*	0.0008	-0.0154	0.0476	0.0304	0.0350
		central-left	(4,104)	2.5672	0.0424*	-0.0015	0.0042	0.0496	0.0111	0.0449
		central-right	(4,104)	3.4063	0.0116*	0.0025	-0.0144	0.0421	0.0201	0.0451
		central-posterior	(4,104)	3.2978	0.0138*	-0.0184	0.0035	0.0467	0.0285	0.0483
		left-right	(4,104)	3.0030	0.0217*	0.0063	-0.0005	0.0591	0.0117	0.0506
theta	inter	left-right	(4,104)	2.6407	0.0379*	0.0094	0.0075	0.0277	0.0125	0.0470
alpha	intra	frontal	(4,104)	2.6180	0.0392*	0.0179	0.0108	0.0578	0.0196	-0.0055

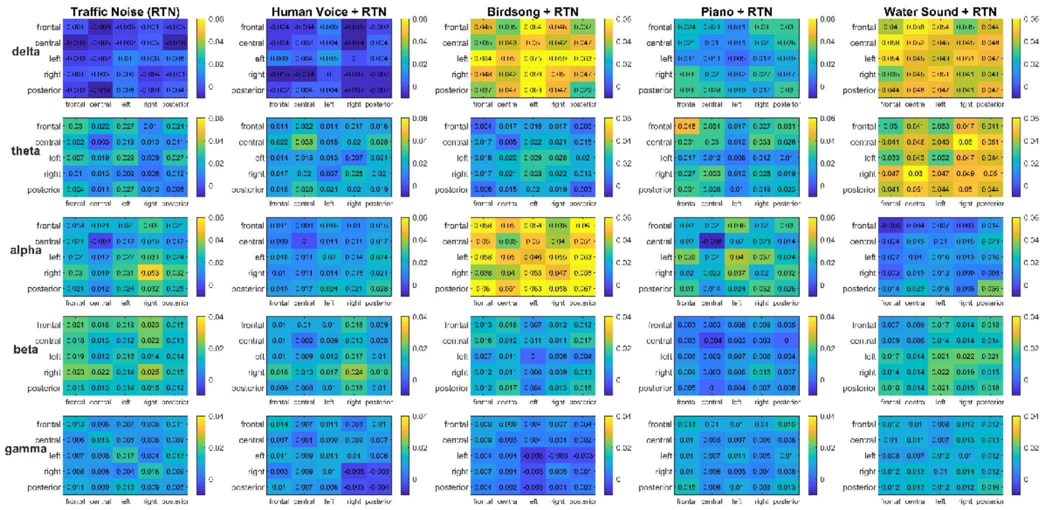


Figure 42 - The connectivity heat maps of different brain regions for five sound conditions across different frequency bands under Green-x space.

In the Green space scenario, road traffic noise and human voice increased the connection networks in different frequency bands. The road traffic noise increased the gamma band connectivity, while the human voice increased the beta band connectivity. No difference was found among the Bird song, Piano music and Water sound conditions (see Table 24, Figure 43).

Table 24 ANOVA table of EEG connectivity results of five sound conditions in the Green space.

Frequency band	Network	Region	df	F value	*p* value	*RTN*	*Human voice*	*Bird song*	*Piano music*	*Water sound*
beta	intra	right	(4,104)	2.6629	0.0366*	0.0065	0.0311	0.0175	-0.0010	0.0000
	inter	Right-posterior	(4,104)	2.5845	0.0413*	0.0053	0.0278	0.0087	0.0005	0.0104
gamma	intra	left	(4,104)	2.5835	0.0413*	0.0324	-0.0055	-0.0057	0.0090	0.0084
		posterior	(4,104)	2.9226	0.0246*	0.0240	-0.0052	0.0074	0.0141	-0.0031
	inter	Frontal-central	(4,104)	2.5729	0.0420*	0.0221	-0.0024	0.0062	0.0144	-0.0006
		Frontal-left	(4,104)	2.7337	0.0329*	0.0256	0.0001	-0.0040	0.0089	0.0077
		Frontal-posterior	(4,104)	2.8283	0.0284*	0.0238	-0.0026	0.0061	0.0147	0.0012
		Central-posterior	(4,104)	2.6114	0.0396*	0.0196	-0.0027	0.0058	0.0152	-0.0033
		Left-posterior	(4,104)	2.7757	0.0308*	0.0252	-0.0018	0.0024	0.0088	0.0024

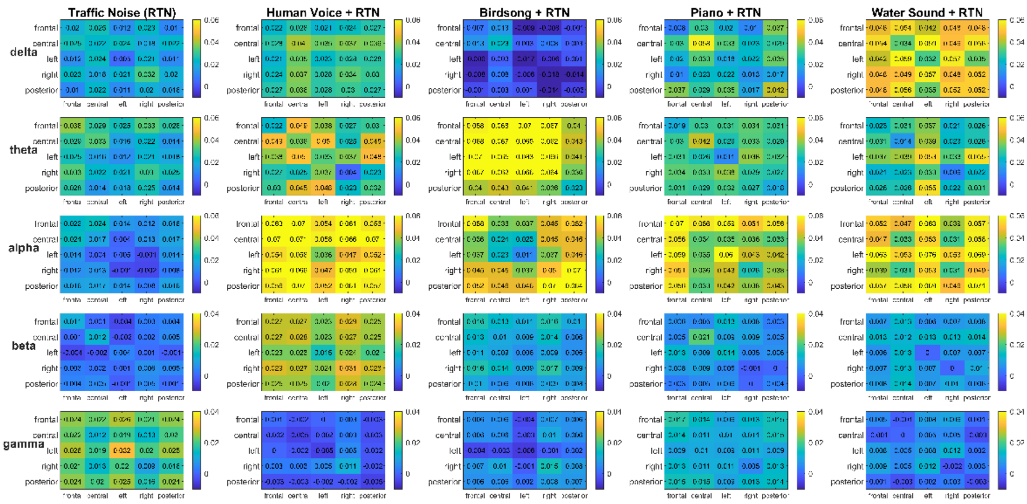


Figure 43 - the connectivity heat maps of different brain regions for five sound conditions across different frequency bands under Green space.

6.4 Discussion and Conclusion

6.4.1 the mental effects caused by visual scenarios

Based on previous studies reported a significant relationship between EEG spectrum and human behavior, cognitive function, or mental states, EEG spectral analysis is now accepted as one of the fundamental methods for cognition and psychology field (Kostyunina and Kulikov, 1996; Fingelkurts and Fingelkurts, 2010; Kim and Im, 2018; Pousson et al., 2021). While higher emotional arousals and less emotion valences were shown from Gray and Colorful square (RTN only presented), the spectral power of the gamma and theta bands also revealed those differences. Previous studies have shown that theta band power responds to visual emotional stimulation (Aftanas et al., 2001; Krause et al., 2000). Meanwhile, recent research has demonstrated that the gamma band's spectral power can reflect the coherent visual perception (Müller et al., 1996) and the arousal effect (Balconi and Lucchiari, 2008; Balconi and Pozzoli, 2008). The evidence indicated that *Green-x* and *Green* space have positive emotion valence and higher readiness to process information, and *Gray* square and *Colorful* square have higher emotion arousal and more active process for visual perception (Crick and Koch, 1998). The later could be the signature for cognitive mapping (Behrens et al., 2018) / predictive coding(Strube et al., 2021; Van Pelt et al., 2016) to prepare for physical activity (White et al., 2012).

The spatial distribution of EEG spectral power density (PSD) can measure the general characteristics of cognitive states as different brain regions have shown different focuses on mental functions (Genon et al., 2018). Meanwhile, the human brain works as a nonlinear dynamical system, is constantly shifting between microstates because of its spontaneous activity to execute cognitive tasks even under resting-state. The human brain functions through interaction between each region along the time course to exchange information and work together in a coordinated manner for specific cognitive tasks. This dynamical process could be reflected by functional connectivity. Connectivity measures are based on statistical interdependencies between signals (Aertsen et al., 1989). The extent to which brain regions are connected is defined by the strength or consistency of this statistical interdependency, also called synchronization (Varela et al., 2001). In dynamical systems, the term synchronization generally refers to (phase) coupling of two or more harmonic oscillators (Boccaletti et al., 2002; Daffertshofer and Van Wijk, 2011). Thus, a stronger synchronization, often reflected by a high coupling or

consistency of oscillating systems, leads to a stronger connection. Increasing evidence suggests that information processing in the brain follows a complex, directional pattern between brain regions (Stephan and Roebroeck, 2012; Van Diessen et al., 2015).
In our experiment, Green space showed higher theta and alpha synchronization with an inhibition effect on beta band connectivity, indicating a more restorative effect caused by the natural settings in the area. Alpha and theta synchronization have been explored for restorative experiences. Higher beta connection and significant desynchronization in alpha band were observed from the *Colorful* square, referring to an active state of cognition, motion planning etc. The *Green-x* space was in the middle of *Colorful* and *Green* space, corresponding to its transfer form from *Colorful* square to *Green* space. Moreover, the *Gray* square condition showed across widespread delta, alpha and beta connectivity. Those less focused and efficient network activations could imply that heavy cognitive load and anti-concentrate attention state while viewing the square space. As the *Gray* square is designed for rest, physical activity, and mobility, it truly induces diverse cognitive abilities and flexibility to accomplish multipronged functions (Bosman et al., 2014; Cantou et al., 2018; Rojas et al., 2018; Rogala et al., 2020; Mateos et al., 2022).

6.4.2 The mental effects caused by acoustical factors

From the subjective results of emotional salience and arousal, interactions between acoustical factors and visual scenarios were well-illustrated. Birdsong in *Colorful* square, Piano music in the *Gray* square, and Water sound in the *Green* space all increased the positive salience on emotions feelings. Moreover, Piano music induced a significant calm effect across all spaces, especially for *Colorful* square. The complex relationship also existed in EEG spectral results, indicating different natural and anthropic sounds induced the brain activity through a complicated way while mitigating the traffic noise, especially for those supposed quiet places (*Green-x* space/*Green* space). In *Gray* space, Piano Music had more calm effects on the human brain for traffic noise mitigation. In *Green-x* space, all introduced sounds decreased the spectral power of the alpha band. But for *Green* space, Human voice increased fast wave activity (alpha/beta) and decreased slow wave activity (delta/theta band), while Water sound induced more slow waves activity like the delta and theta band activity and decreased more fast waves, including alpha, beta and gamma band. Manohare et al. (2023) found that the variations of traffic noise modulate the alpha and theta wave in temporal, parietal and frontal lobe of the brain. And individual noise events impacted the temporal lobe more significantly in quieter locations compared to noisy locations. Moreover, different properties such as the loudness, sharpness, roughness of traffic noise caused alpha and theta band activity in different brain regions (Manohare et al., 2023).
EEG connectivity evoked by different sounds showed consistent results across different visual scenarios. In *Gray* square, natural sounds (bird song/piano music/water sound) inhibited the synchronization of beta and delta band activity. Piano music also decreased the alpha band connectivity compared to bird song and water sound. And bird song decreased the gamma connectivity similarly. In *Colorful* square, natural sounds (bird song/piano music/water sound) increased the alpha band connection and reduced the activation of beta band connectivity. In *Green-x* space, bird song increased the delta band and alpha band connectivity while water sound promoted the coherence of the delta and theta band significantly. In *Green* space, while traffic noise caused high gamma band connectivity, mitigation effects could be found from the inhibition of gamma connectivity caused by other sounds. Human voice decreased the gamma band but increased the beta band connectivity relatively. Natural sounds brought more restorative frequency bands connectivity including the alpha and theta band. The multi-functionality of gamma-band activity has been showed from several studies, by considering its role in neural systems for perception, selective attention, memory, motivation and behavioural control (Bosman et al., 2014). Yang et al. (2020) results revealed that the network connections in the high gamma band with significant differences among the positive, neutral, and negative emotional states were much denser than the network connections in the other frequency bands (Yang et al.,

2020). Chen et al. (2022) provided results support the role of gamma-band coupling between brains for interpersonal conceptual alignment (Chen et al., 2022a). The beta band activity has connected to vigilance, working memory and emotional recognition in some studies (Perrottelli et al., 2022). Meanwhile, evidence showed the theta band connectivity is negatively correlated to working memory, attention vigilance and executive functions (Wichniak et al., 2015; Andreou et al., 2015; Gomez-Pilar et al., 2018; Cea-Cañas et al., 2020; Krukow et al., 2020; Solís-Vivanco et al., 2021).

6.4.3 the interaction effects of multisensory settings

From the subjective assessments, the interaction effects of multisensory inputs are well-demonstrated. The Music improved the feelings in the *Gray* square, the Bird song increased the arousal of the positive emotion in *Colorful* square, and the Water sound enhanced the emotional salience of *Green* space. The EEG spectral and connectivity also revealed those interaction effects. In general, the gamma band power reflected the emotional arousal in the *Gray* and *Colorful* square, and the theta band power observed from *Green* space indicated higher emotional salience. The EEG connectivity could illustrate the dynamic aspects of multisensory perception in different scenarios. Totally, natural sounds would increase the connectivity in the slow wave and inhibit the activation in the fast wave, promoting the restorative effects, while anthropic sounds like traffic noise and human voice caused higher activity in the fast wave (beta/gamma band), indicating higher cognitive load and active consciousness. But those enhancement functions and inhibition effects varied in different urban park spaces. More inhibition founded in *Gray* and *Colorful* square introduced by natural sounds, and higher enhancement effects aroused in the *Green-x* and *Green* space by those sounds. Those results raised the challenge of unveiling the relationship between multisensory environmental inputs and their psychological outcomes for future researchers.

Although the alpha band oscillation in the brain has been treated as an indicator of relaxation of brain state for a long time (Foxe and Snyder, 2011; Klimesch, 2012; Magosso et al., 2019), multi-functionality cognition process still observed from the alpha band connectivity (Klimesch, 1999a; Krukow et al., 2018; Vignapiano et al., 2019; Zhou et al., 2021), indicating the alpha band has more complicated dynamical mechanism for cognitive flexibility during nor matter of the resting-state or active cognitive states (Sadaghiani et al., 2010; Kim and Lee, 2020; Katyal and Goldin, 2021). Zhang et al. (2023) investigated the physiological and psychological mechanisms of short-term exposure to nature through experiments conducted in immersive virtual environments (Zhang et al., 2023). Their results illustrated the theta power in the parietal region was significantly stronger than in other bands. Also, participants showed high functional connectivity among different brain parts during nature exposure, which revealed better cognitive flexibility, indicating a lower cognitive processing load when exposed to nature. A key factor that cannot be neglected is the salience of each input in the multisensory environments (Brewster et al., 2022). Different categories of auditory and visual stimuli were only used in this study. Their perceptual salience could be balanced and cause the difference of perception with varying alpha band activity. Hofmann et al. (2021) combine EEG with virtual reality (VR) to give experimental participants a roller coaster ride with high immersion. The ride, literally leads to large ups and downs in emotional arousal, which the participants quantify during a later rerun. Several different decoding methods were evaluated, and each showed above chance levels of performance, substantiating a link between lower levels of parietal/occipital alpha wave and subjective arousal in a quasi-naturalistic setting (Hofmann et al., 2021).

Chen et al. (2020) compared the neural oscillation during a 20 mins in-situ stay in a garden and a traffic island. They found a negative association between environment-induced fatigue and theta and alpha oscillation. But, this study didn't see a significant difference in the power of neural oscillation during garden and traffic island exposure, contrary to relevant studies using pictures as stimuli (Chen et al., 2020b). All those studies remind us that the salience network raised by multisensory inputs in real-life scenarios could be complicated and reflected by EEG dynamical indicators. Researchers and designers should value the salience of different environmental settings and promote multisensory perception through salience incrementing positive components and decreasement of negative components in urban landscape planning.

6.5 Chapter Summary

Immersive reality technique provides the chance to manipulate multisensory inputs with realistic environments for human perception. With 3D models and binaural sound rendering, participants could perceive the physical settings and finish the assessment more interactively. The results showed multisensory interaction occurred in different urban park spaces from different auditory stimuli for traffic noise mitigation. The scenarios were judged more positively when more greenery was present. Different sounds influenced the perception of those virtual scenarios. Specifically, bird song in the *Colorful* square park significantly improved emotional judgments. For Piano music, it improved judgments of the *Gray* square park. Additionally, Water sound presented with the visual fountain in *Green* space park significantly increased the ratings of perceptual judgments. The EEG measurements revealed more dynamical and procedural information by the EEG spectral power and connectivity changes during experiencing those multisensory scenarios. While *Green* space evoked theta wave for restorative experiences, high attentional vigilance from the gamma band power induced by *Gray* and *Colorful* square spaces. Not only the natural inputs from the visual dimension, natural sounds together would increase the connectivity in the slow wave and inhibit the activation in the fast wave, promoting the restorative effects, while anthropic sounds like traffic noise and human voice caused higher activity in the fast wave (beta/gamma band), indicating higher cognitive load and active consciousness. Furthermore, audio-visual interaction effects were observed from those connectivity results. More inhibition founded in *Gray* and *Colorful* square introduced by natural sounds, and higher enhancement effects aroused in the *Green-x* and *Green* space by those sounds. The alpha power and connectivity would vary for different functions in different audio-visual settings. The salience network distribution should be considered for anchoring those activities during dynamical cognitive processing in further studies.

CHAPTER 7: GAZE BEHAVIORS AND PERCEIVED QUALITIES OF DIFFERENT LIGHTING SETTINGS IN URBAN PARK

7.1 Human Centered Lighting Design of Urban Park

While urban green areas can be considered among the most important spaces of a city, as they affect the local microclimate and the aspect of the city but also the users' mental and physical health and social cohesion, their usability and quality perception of the spaces in the post-sunset hours, depend by several characteristics that foster the frequentation of the park, one of this is its lighting (Senese et al., 2020). Current guidelines related to outdoor lighting design emphasize objective measurements, including luminance distribution, illuminance levels, glare, the directivity of light, colour appearance and colour rendering, and take care of various needs from different perspectives, including energy efficiency, aesthetics and safety (CSN EN 12665, 2018; Donatello et al., 2019; Publikacja, 2010). Most of them were set for the needs of visual accessibility and perceived safety in specific environments such as workplaces (CSN EN 12464-1, 2021), sports places (BS EN 12193, 2018) and pedestrian paths (Commission International de l'Eclairage, 1995; PD CEN/TR 13201-1, 2014). The illuminance levels and the Correlated Colour Temperature (CCT) of the light affect outdoor spaces' appearance and usage (Scorpio et al., 2020). In particular, the illuminance level affected the sense of safety (DiLaura et al., 2011) and the area's visual aspect and attraction (Moyer, 2013). At the same time, the light CCT influences the human perception of the environment and sense of safety (Li et al., 2012; Smith and Hallo, 2019), their emotions and the sense of exploration (Masullo et al., 2022), and the fauna (Schroer and Hölker, 2016). However, less is known about their applicability to urban parks. The main reason is that the luminous environments in urban parks are more complicated and dynamic related to their spatial attributes and functionalities. The main challenge of the lighting research in those places is to clarify the effects of overall lighting level on human perception and behaviors in the urban park during the nighttime meanwhile retaining the naturalness of the complex luminous environments with mimic lighting characters (Łopuszyńska and Bartyna-Zielińska, 2019).

Conventional lighting design tools that consider only objective parameters are insufficient to reflect the total quality of luminous environments. Using immersive virtual reality (IVR) technology makes it possible to improve the quality of the design process through objective parameters controlled and real-time subjective assessments in more realistic lit environments. Several studies have tested the feasibility of Immersive Virtual Reality (IVR) to reproduce realistic physical environments for outdoor lighting research. Chen et al. (Chen et al., 2019) contrasted people's subjective reactions to physical lit space and its reproduction through photography, video, and immersive virtual reality. The results indicated that virtual reality is the best technology to reproduce lighting environments. Chamilothori et al. (Chamilothori et al., 2019b) proposed using rendered images obtained from physically-based software in IVR to conduct subjective investigations of daylit spaces. The results indicated high perceptual accuracy of daylit space in VR settings and few variations compared to real environments. Lee and Lee (Lee and Lee, 2021) built a virtual urban plaza in Unreal Engine to explore the effectiveness of virtual reality simulation on the qualitative analysis of landscape lighting design. More studies were reviewed in the work of Scorpio et al. (Scorpio et al., 2020). In 2022 (Scorpio et al., 2022), the same research group developed a methodology to use a game engine (Unreal Engine 4.22) to reproduce light distribution in a real indoor lighting environment. The results suggested good reliability of the Unreal Engine in reproducing the light distribution. Some researchers focused their effort on evaluating the effects of light level (Nasar and Bokharaei, 2017; Rockcastle et al., 2021; Sanchez-Sepulveda et al., 2019) and CCT values (Baştürk et al., 2011; Sanchez-Sepulveda et al., 2019; Siess and Wölfel, 2019) by using virtual reality (VR). However, the combined effects of overall illuminance level and CCT are hardly investigated, and few works refer to urban green parks (Lee and Lee, 2021). More recently, Masullo et al. (Masullo et al., 2022) investigated the effects of the combination of illumination intensity and CCT on the most favourable psychological impact on users of urban park. With this aim, nine distinct virtual scenarios were created by mixing various CCT and overall brightness levels, and asking the participants to rate how much each scenario contributed to making them feel calm, nervous, energic, weak, happy, and sad. Additionally, it was looked at how much each lighting setting affected people's motivation and feeling of safety.

The previous investigations are mainly focused on assessing the users' preferences, fostering more comprehensive knowledge and deeper insights from the user's perspective. These studies should be extended to evaluate urban park lighting. Along with physical management of objective factors in outdoor lit environments, the human perception and reactions to the environmental lighting must also be considered from a Human-Centered design perspective (Bellazzi et al., 2022; Houser et al., 2021). Flynn et al. (Flynn et al., 1979) published a research report on the Illuminating Engineering Research Institute (IERI) Project 92, providing procedures for evaluating the subjective impression in lighting. According to their suggestion, two aspects of human behaviours should be answered in the effects on spatial illumination: the light effects on subject impression and attitude, as well as on performances and overt behaviours.

Various lighting research focused on outdoor lighting environments has assessed different subjective aspects of lit environments, including perceived quality (Flynn et al., 1979), visual comfort (Allan et al., 2019; Boyce, 2014), and psychological impression (Allan et al., 2019; Flynn et al., 1979). Flynn et al. (Flynn et al., 1979) listed several rating scales that have been discovered to discern between lighted spaces in measuring perceived qualities referring to visual clarity, spaciousness, evaluative responses, social prominence, complexity, spatial modifiers etc. Shikakura and Kikuchi (SHIKAKURA et al., 1992) classified the subjective impression of outdoor lighting into brightness, comfort, and uniformity. Johansson et al. (Johansson et al., 2011) investigated the potential predictors for the perceived visual accessibility and the perceived danger of an urban footpath. The perceived qualities, including light, unpleasant, coloured, weak, concentrated, cold, evenly distributed, soft, focused, unnatural, murky, monotonous, bright, dimmed, and brilliant, were used for subjective lighting assessments. Some works brought the Attention Restoration Theory (ART) to the examination of lighting's role in psychological restoration (Nikunen, 2013; Nikunen et al., 2014). Nikunen et al. (Nikunen et al., 2014) studied the link between the four attributes of ART (being away, fascination, extent and compatibility) and perceived lighting (brightness, distribution, glare, colour quality, feeling of safety and pleasantness). However, no fixed relationship between those attributes and ART components was found. Kim and Noh (Kim and Noh, 2018) evaluated the Perceived Adequacy of Illumination (PAI) effect on walkers' nighttime experiences, including discomfort glare, willingness to stay, pleasantness and liveliness. They found that spaces with a higher percentage of PAI were strongly correlated with the perception of pleasantness, liveliness, and suitability of spaces. Among all of the evaluation scales, Johansson et al. (Johansson et al., 2014) addressed the quality of street lighting in two-side ways: Technical Environmental Assessment (TEA) and Observer-Based Environmental Assessment (OBEA) in the Perceived Outdoor Lighting Quality questionnaire (POLQ). This questionnaire summarized most of the items in the works we mentioned above and could help us combine the objective descriptors and subjective indexes for a deeper investigation.

Besides subjective assessments, objective evaluations referring to human perception and cognition of luminous environments are also necessary for investigating lighting environments. Ocular behaviours recorded by eye-tracker are most considered for investigating human visual perception. Eye movements (such as fixations, saccades, and pupil dilations) reveal the sensory inputs from the external luminous environments and are controlled by the internal brain involving cognitive and affective processing. Two eye-tracking metrics were used for most vision research, including gaze metrics and pupillometry. Foulsham et al. (Foulsham et al., 2011) compared the gaze distribution of people walkers while viewing natural scenes in the lab and the physical environment. The data revealed that eye movements were more centralized in the real world, and locations around the horizon were selected with head movements. Using on-site captured gaze data in the real world could give us more insights into landscape perception and evaluation. Cottet et al. (Cottet et al., 2018) recorded *in situ* gaze data to study how the composition of a landscape affects how people see it. The findings showed that the rating, verbal, and gaze data were highly concordant (based on gaze fixations). The gaze data aided in classifying the effects of nature on urban inhabitants' perceptions and assessments of the landscape and identify landscape items essential in creating landscape valuation judgments. As for the application of eye-tracking in lighting study, Fatio et al. (Fotios et al., 2015a, 2015b) used pedestrians' fixation data to address the importance of people and path visibility for lighting design. The walkers' typical distance and duration of fixation in the street night-lighting environments have been investigated. However, few studies have evaluated saccadic eye movement in VR scenarios, regardless of lighting research. Zhang et al. (Zhang et al., 2019a) propose an integrated approach to cityscape design based on virtual reality and eye-tracking technology to reveal the salient cityscape features. Anderson and Bischof (Anderson and Bischof, 2019) examined the extent to which image content influenced eye and head movements in a VR environment. Haskins et al. (Haskins et al., 2020) examined the effects of active and passive viewing circumstances on gaze behaviour while participants explored new, real-world settings using VR technology and in-headset eye-tracking. They discovered that active viewers paid greater attention to areas of the scene that were semantically significant, indicating more exploratory, information-seeking gaze behaviour. Kim and Kim (Jong Ha and Ju Yeon, 2020) conducted eye-tracking experiments in a VR scenario through real-field panoramic image presentation and provided an empirical framework for quantitative visual data analysis in virtual environments. Using eye-tracking 'in the wild'—in real, naturalistic, and outdoor settings—poses logistical and methodological difficulties, including the gaze-object mapping and gaze behaviour classification during the gaze-head co-locomotion, thus more and further studies are needed (Uttley et al., 2018). Except for the spatio-temporal features of ocular behaviours, pupil diameter measurements could reflect the intensity of the sensory inputs. The pupil size constricts with the increment of light intensity and dilates with the decrement of light intensity. However, there is also evidence indicating that the change in pupil size reflects high-level sensory and cognition processing, including high-level visual features detection (Naber et al., 2013), internal environment representation (Schwiedrzik and Sudmann, 2020), attention (Binda and Gamlin, 2017), affection (Partala and Surakka, 2003) and emotional memory (Sterpenich et al., 2006). The index of pupillary activity (IPA) developed by Duchowski's work is related to cognitive load to pupil oscillation after removing the effect of light reflex because the pupillary response increases with cognitive load (Duchowski et al., 2018). Imaoka et al. (Imaoka et al., 2020) found the pupillary response in HMD display close to previous studies on 2D screen display. However, less is known about the contribution of light luminance and CCT in VR environments to those responses.

This study explores the effects of overall illuminance levels and CCT of the lit environment of urban parks on gaze behaviours and subjective reports. To this objective, a detailed model of an existing city park in the South of Italy was built into Unreal Engine and experienced through a head-mounted display (HMD) at different lighting conditions. Users were asked to see the virtual scenarios and answer a questionnaire to evaluate the perceived outdoor lighting quality.

7.2 3D Model of Virtual Park and Lighting Design with Psychological-behavioral Measurements

7.2.1 Virtual Reality Modeling of Urban Park

The virtual urban park was created based on the existing park Parco Pozzi, Aversa (as mentioned in Chapter 4.3). The scene reproduced an existing layout including different elements: trees, grass, park pavement, some street furniture (i.e. street lamps, benches, dustbins), the sky and other surrounding elements (buildings, walls, road). A fixed observation point inside the park was selected to simulate the perspective of a visitor sitting on a bench. Participants could rotate their heads and sight freely exploring at 360°, ecologically, the virtual environment of the park where they were immersed. The amount and quality of light emitted by each streetlamp were set at different luminous flux values and CCT. A total of 9 different virtual scenarios were obtained considering three luminous flux of the luminaires: 250 (low illuminance level), 500 (medium illuminance level) and 1000 (high illuminance level) lumen, and three CCTs: 2500 K (warm), 4500 K (intermediate), and 6500 K (cold). The nine lighting scenarios are shown in Figure 44.

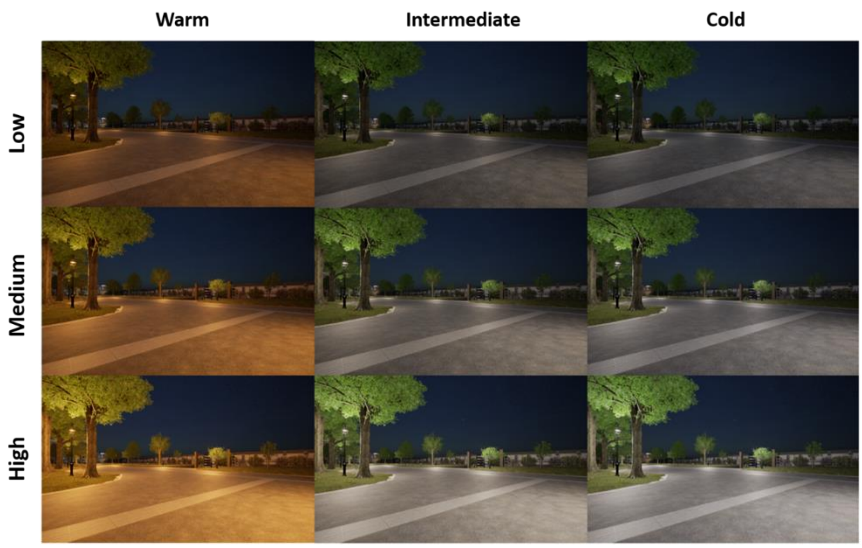


Figure 44 - FOV from the participant's perspective in the virtual environment across different overall illuminance levels and CCT conditions.

An HTC Vive Pro Eye headset provided participants Immersive Virtual Reality experiences. This Head Mounted Display (HMD) consists of two OLED screens (1440 x 1600 pixels each), offering a 110-degree field of view and a refresh rate of 90 Hz. Unreal Engine 4.26 installed on a desktop computer (AMD Ryzen Threadripper 1950X 16-core processor 3.40 GHz, 2 NVIDIA Geforce RTX 2080 Ti, WINDOW 10 Pro 64bit) was used to control the HMD.

The lightness values were calculated from the panoramic image captured from UE4 in the CIE 1976 L*a*b* color space to evaluate the relation between the lighting distribution and gaze behaviour using the built-in function rgb2lab in MATLAB (Robertson, 1977). A Difference of Gaussians (DOG) kernel was applied to each lightness image to simulate the lightness perception based on the work of Safdar et al. (Safdar et al., 2018). The semantic labels were manually labelled with the "Image Labeler" toolbox and "Color Threshold" toolbox in MATLAB, including the bench, grass, tree, road, sky, streetlights, infrastructure (direction board, dustbin), others (surrounding buildings, walls, etc.). The color threshold was used to segment each label with Color Threshold toolbox. Then, the Image Labeler toolbox was used to handle correctly each label (see Figure 45).

Figure 45 - The semantic labels of the panoramic image in one of the VR scenarios.

The light amount received at the eye was evaluated at the eye's positions, acquiring the illuminance values through CRI Illuminance Meter CL-70F (illuminance range: 0 ÷ 200 klux and accuracy: ±5% ±1 digit of displayed value; CCT range: 1563 to 100000 K and accuracy: xy = ±0.003 (at 800 lx)) placed in the HMD at 10 mm from the lens in a completely dark room (Abd-Alhamid et al., 2019; Chamilothori et al., 2019a). The CCT values of the light reaching the participants' eyes were also acquired. The correct positioning of the measuring sensor was guaranteed using an ad hoc adaptor realized by 3D printing. Table 1 lists the values obtained by measurements in the right eye for each scenario. The measures on the left lens showed illuminance differences lower than 1.5 lux (CSN EN 12464-1, 2021) (see Table 25.).

Table 25 Measured illuminance and CCT values at eye position upon varying the luminous flux and CCT of light in the virtual scenario.

			Virtual scene CCT		
			Warm	Intermediate	Cool
Virtual scene Overall illuminance level	Low	CCT (K)	2890	5413	7912
		E (lux)	6.7	5.5	5.4
	Medium	CCT (K)	2727	4918	6922
		E (lux)	12.8	11.3	11.5

High	CCT (K)	2871	4907	6629
	E (lux)	23.2	20.6	19.3

7.2.2 Subjective Questionnaire

The POLQ questionnaire (Johansson et al., 2014) is a tool that laypeople can use to systematically capture the general public's view of outdoor illumination through two dimensions: i) Perceived Strength Quality (PSQ) linked with the sense of brightness and light direction, and ii) Perceived Comfort Quality (PCQ) linked with the light pleasantness and softness. In addition, high PCQ ratings are correlated with not perceiving danger, while high PCQ and PSQ values are related to highly experienced visual accessibility. The questionnaire was translated into Italian and used to assess and compare the qualitative aspect perceived by the participants among the different scenes. A 7-point semantic differential scale question was assigned to each item. The translation of each item was conducted and converged into one-by-one relationships by three field experts. The agreement of the translated items was also confirmed by a reversed translation conducted with ten native speakers from the students' group (see Table 26).

Table 26 The English items and Italian translation of POLQ questionnaire.

	English	Italian
Perceived Strength Quality (PSQ)	Clear - Drab	Chiara - Cupa
	Strong - Weak	Forte - Debole
	Unfocused - Focused	Uniforme - Concentrata
	Subdued - Brilliant	Fioca- Brillante
	Dark - Light	Scura - Luminosa
Perceived Comfort Quality (PCQ)	Mild - Sharp	Morbida - Netta
	Hard - Soft	Intensa - Soffusa
	Warm - Cool	Calda - Fredda
	Glaring - Shaded	Abbagliante - Non Abbagliante
	Natural - Unnatural	Naturale - Innaturale

7.2.3 Eye Tracking Measurements

The built-in eye-tracker of the HTC Vive Pro Eye HMD provided gaze coordinates and pupil diameter data at a sample rate of 120 Hz. After the five-points calibration procedure of eye-tracking, the gaze data stream collected from VIVE SRanipal SDK with LSL API was transferred to Lab Streaming Layer (LSL) (Sipatchin et al., 2021) stream synchronized with lighting condition event triggers and 6-DOF head motion provided by UE4 OSC plugin.

Each gaze position's azimuth angle ($Eye_{azimuth}$) and elevation angle ($Eye_{elevation}$) relative to the screen centre was averaged for real gaze position account. Combined with the rotation data from head motion, such as roll ($Head_{roll}$), pitch ($Head_{pitch}$) and yaw ($Head_{yam}$), the gaze and head position in world coordinate, latitudes ($Eye_{Latitude}$) and longitudes ($Eye_{Longitude}$) on a sphere, were computed by the formula below:

$$Eye_{Latitude} = Head_{pitch} + (Eye_{elevation} \cdot \cos(Head_{roll}) - Eye_{azimuth} \cdot \sin(Head_{roll}))$$
$$Eye_{Longitude} = Head_{yaw} + (Eye_{elevation} \cdot \sin(Head_{roll}) + Eye_{azimuth} \cdot \cos(Head_{roll}))$$

Fixation classification in VR scenarios was difficult since it combined with head motion. Based on the work of Agtzidis et al. (Agtzidis et al., 2019), fixation without head pursuit and smooth pursuit with Vestibule-Ocular Reflex (VOR) were extracted for analysis since both have a fixed gaze position in the VR world coordinates. Duration of both indexes less than 100 ms were excluded.

The pupillometric data were pre-processed by the ET-remove-artifacts Matlab toolbox for blinks and artifacts removal (Mather et al., 2020). The onset of a blink is detected as the moment at which the velocity drops below a negative threshold (-5mm/s), which reflects a rapid shrinking of the pupil due to the closing of the eyelid. The "reversal period" of a blink is detected as the moment at which the velocity exceeds a positive threshold (5 mm/s), which reflects a rapid reopening of the eye. The pupil size during the blink was interpolated using cubic-spline fitting. After the data cleaning, one subject was removed because of too many missing values. Then, the average pupil diameters and the pupil diameter changes indicated by Indexes of Pupillary Activity (IPA) were computed. The algorithm of IPA computation was from Duchowski's paper (Duchowski et al., 2018). A two-level Symlet-16 discrete wavelet decomposition of the pupil dilation signal by selecting a mother wavelet function $\psi_{j,k}(t)$ was used. Upon the wavelet analysis of the signal x(t), the resulting dyadic wavelet generated a dyadic series representation. Then the process followed a multi-resolution signal analysis of the original signal x(t). A level was arbitrarily selected from the multi-resolution decomposition to produce a smoother approximation of the x(t) signal. Finally, thresholded the wavelet modulus maxima coefficients using a universal threshold defined by,

$$\lambda_{univ} = \hat{\sigma}\sqrt{2\log n}$$

where $\hat{\sigma}$ is the standard deviation of the noise. The remaining coefficients represented the IPA reading for the given pupil diameter signal (Mahanama et al., 2022).

7.2.4 Experimental Procedure

Each of the nine-light scenarios was presented to participants using the HMD HTC Vive Pro Eye after giving a different view of the park to make them comfortable with the device. Before the formal experiment, participants were seated in a non-swivel chair, and the built-in eye-tracking module of HMD measured their gaze movements and pupil diameters after they took the 5-points calibration procedure. The participants were asked to free-view each visual scenario and answer the questionnaire on the perceived lighting quality from a rest-sitting view by oral reports (see Appendix B.)(Johansson et al., 2014). After answering the questions, participants rest for a few seconds and turn to the next lighting scenario. The order of all conditions was randomized and balanced between participants.

Twenty-six voluntary participants (Male: 16; Female: 10; Age: 29.72; s.d.=±7.09) were recruited. The experiment took place in the test room of the SENS i-Lab of the Department of Architecture and Industrial Design of the Università degli Studi della Campania "Luigi Vanvitelli". All participants were in good health, had normal eyesight and had no colour blindness or weakness. All participants gave informed consent about their participation in the study after being told about the experiment's purpose and process.

7.3 Questionnaire and Gaze Behavior Results

7.3.1 Questionnaire results

Two-way repeated-measures ANOVA analysis of overall illuminance level and CCT were conducted for each item in the POLQ questionnaire (sphericity assumptions were checked, and Greenhouse-Geisser corrections were used). The results are listed in Table 27.

In the perceived strength quality (PSQ) dimension, the Subdued-Brilliant item showed significant differences in overall illuminance level, as with the increment of the overall illuminance level, participants felt the scene more brilliant; while there was no effect either from CCT conditions or the interaction effect between overall illuminance level and CCT. The same pattern also occurred in Strong-Weak and Dark-Light items, as with the increment of the overall illuminance level, participants felt the scene stronger and with more light. The Unfocused-Focused item showed no significant effects on overall light level conditions, CCT, or the interaction effect between overall light level and CCT. The Clear-Drab item showed significant results both on overall illuminance level and on CCT. In fact, with the increment of the overall illuminance level, participants felt the scene clearer, while the results of CCT condition showed a U-shaped trend of falling first and then rising with the increment of CCT only for the lower lighting level condition. No interaction effect was found (see Figure 46 left part).

In the perceived comfort quality (PCQ) dimension, the Hard-Soft item showed significant differences in overall illuminance level, as participants felt the scene harder with the increment of the overall illuminance level. No effect was found on CCT or on the interaction. Similar results were carried out for Natural-Unnatural, Glaring-Shaded, and Mild-Sharp items. As with the increment of the overall illuminance level, participants felt sharper, more unnatural, and glaring. The Warm-Cool item showed significant results on CCT but not on the overall illuminance level or the interaction effect (see Figure 46 right).

Table 27 ANOVA results of POLQ items with all variables and their interaction effects.

POLQ Dim.	Items	Overall illuminance level			CCT			Overall illuminance level x CCT		
		F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
Perceived Strength Quality (PSQ)	*Subdued-Brilliant*	116.603	<0.001***	0.835	0.719	0.493	0.030	0.631	0.642	0.0027
	Strong-Weak	125.292	<0.001***	0.845	0.034	0.967	0.001	0.172	0.952	0.007
	Dark-Light	66.072	<0.001***	0.742	0.664	0.519	0.028	0.411	0.800	0.018
	Unfocused-Focused	1.251	0.296	0.052	0.652	0.525	0.028	1.479	0.215	0.060
	Clear-Drab	37.03	<0.001***	0.617	5.00	0.011*	0.179	1.23	0.305	0.051
Perceived Comfort Quality (PCQ)	*Hard-Soft*	97.47	<0.001***	0.809	1.60	0.213	0.065	1.27	0.287	0.052
	Warm-Cool	0.089	0.915	0.004	47.151	<0.001***	0.672	1.003	0.410	0.042
	Natural-Unnatural	51.70	<0.001***	0.465	3.08	0.056	0.118	2.29	0.066	0.091
	Glaring-Shaded	87.767	<0.001***	0.792	0.488	0.617	0.021	1.301	0.276	0.054
	Mild-Sharp	43.10	<0.001***	0.652	1.41	0.255	0.058	1.94	0.111	0.078

Table 28 Average values of PSQ and PCQ indices (with standard deviation).

	PSQ		
	warm	intermediate	cold
low	M = 3.62 (SD = 0.87)	M = 3.89 (SD = 0.87)	M = 3.51 (SD = 0.99)
medium	M = 4.79 (SD = 0.98)	M = 4.88 (SD = 0.95)	M = 4.82 (SD = 0.93)
high	M = 5.72 (SD = 1.05)	M = 5.6 (SD = 0.77)	M = 5.97 (SD = 0.43)

	PCQ		
	warm	intermediate	cold
low	M = 5.26 (SD = 0.84)	M = 4.98 (SD = 0.9)	M = 4.75 (SD = 0.81)
medium	M = 4.18 (SD = 1.23)	M = 3.89 (SD = 0.91)	M = 3.75 (SD = 1.07)
high	M = 3.15 (SD = 0.98)	M = 3.13 (SD = 1.23)	M = 2.15 (SD = 0.74)

Table 28 reports the mean values (in the scale 1 to 7) and the standard deviations of the two indices PSQ and PCQ of the POLQ for each light scene investigated. Results show that PSQ values vary from 3.51 (high CCT and low overall illuminance) to 5.97 (high CCT and high overall illuminance), while PCQ values vary from 2.15 (high CCT and high overall illuminance) to 5.26 (low CCT and low overall illuminance).

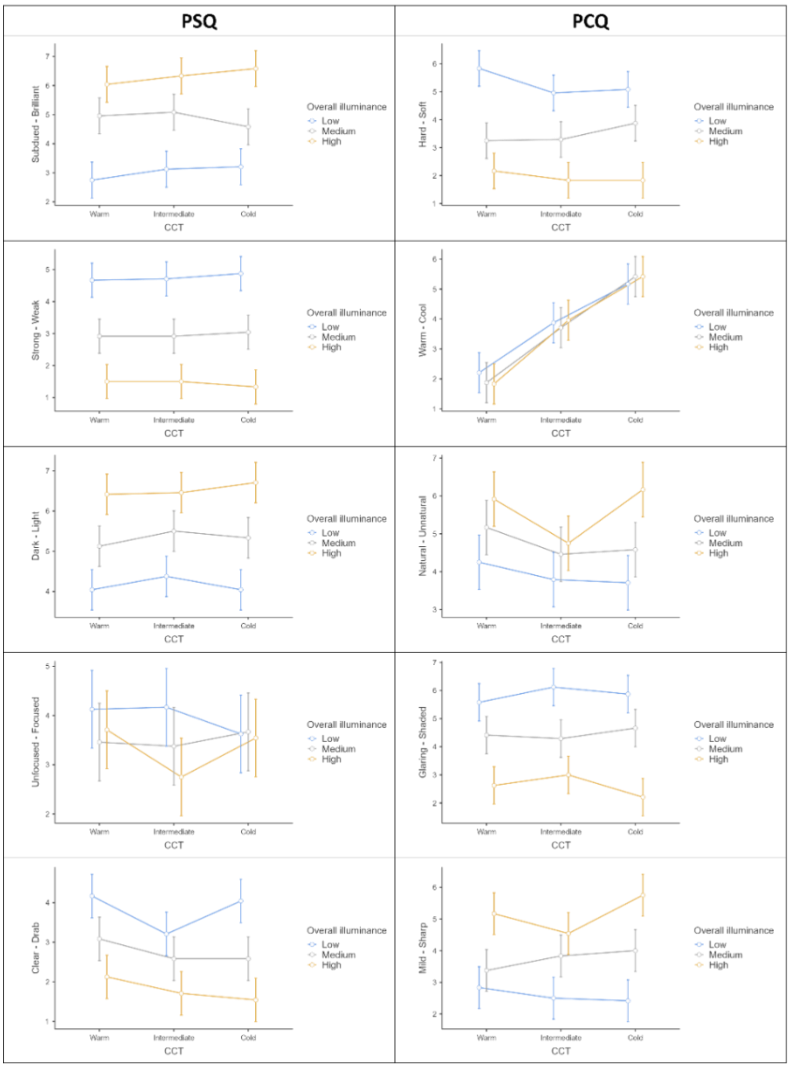


Figure 46 - Results of POLQ items: PSQ dimension items on the left and PCQ dimension items on the right.

7.3.2 Eye-tracking measurements results

From the average data of pupil diameter, normal pupillary light reflex was triggered by all lighting conditions matching the bright environment (varying from 2 to 4 mm), as with the increment of light intensity, the pupil size became narrower ($F(2.46)=74.938$, $p<0.001$***). The CCT didn't show a significant result ($F(2.46)=0.064$, $p=0.852$) (see Figure 47 left part). The IPA results didn't show any significant differences among overall illuminance levels ($F(2.46)=0.909$, $p=0.410$) and CCT conditions ($F(2.46)=0.126$, $p=0.882$). However, interaction effects between CCTs and the overall illuminance levels was observed ($F(4.92)=2.629$, $p=0.039$*)(see Figure 47 right part).

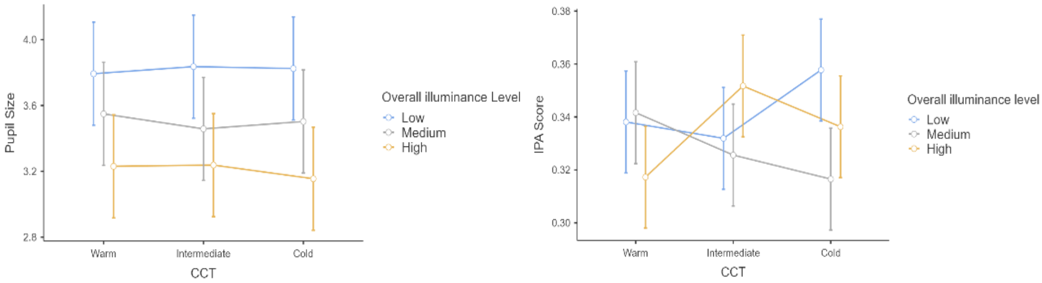


Figure 47 - The results of pupil diameter (left) and IPA index (right) for all conditions.

From the generalized linear model results, neither dwell time nor fixation counts of each area showed significant linear relationships with overall illuminance levels and CCT conditions. Most eye fixed areas were others (including surrounding buildings and walls), road, tree and grass areas, as reported in Figure 48. The generalized linear model analysis indicated the effects of overall illuminance levels with interactions with CCT in fixation duration for each fixation along with the lightness of each fixation position. The area of light, trees, and others (including surrounding buildings and walls) had a more linear relationship with fixation duration. No differences were found in smooth pursuit with VOR behaviors between different lighting conditions (see Table 29).

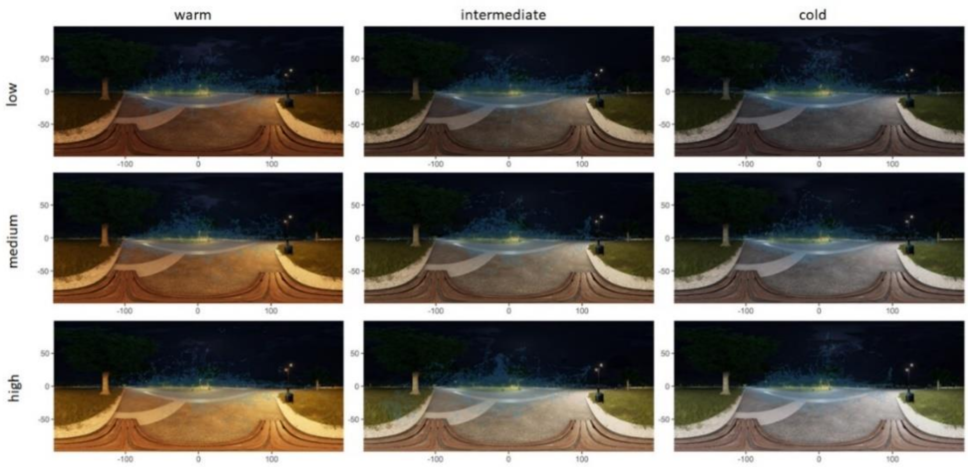


Figure 48 The gaze maps for all conditions.

Table 29 Generalized linear model results of fixation duration with independent variables.

Variables	Generalized linear model		
	X^2	df	p
Overall illuminance level	14.5058	2	<.001***
CCT	0.0619	2	0.970
Labels	149.6701	7	<.001***
Lightness	64.1997	1	<.001***
Overall illuminance level ✻ CCT	10.6036	4	0.031*

X^2 means Chi-square coefficient, df means degree of freedom, * means that p value was less than 0.05, while *** means that p value was less than 0.001.

7.4 Discussion

The POLQ used for the observed-based environmental assessment tool differentiated between lighting conditions of different overall illuminance levels more than CCT in our IVR outdoor environment. The PSQ dimension was used to explain the variance in visual accessibility, while the PCQ was used to explain the not perception of danger in the environment (Johansson et al., 2014). The overall illuminance level influences most aspects of PSQ and PCQ except for Unfocused-Focused and Warm-Cool, while the CCT only showed differences between Clear-Drab and Warm-Cool items in our study, which were different from the previous findings from the work of Johansson et al. (Johansson et al., 2014). They showed PSQ was positively related to brightness and less connected to colour temperature, and PCQ was negatively associated with colour temperature (Johansson et al., 2014). The overall illuminance level in our VR lighting influenced the brightness perception also with the feelings related to pleasantness, hedonic tone and softness, which have been reflected by PCQ dimension from previous studies (Hou et al., 2021; Johansson et al., 2011). And CCT influenced very limited items from PSQ and PCQ. The results are consistent with the works of Davis & Ginthner (Davis and Ginthner, 1990), Fatios (Fotios, 2017), Yang & Jeon (Yang and Jeon, 2020). Results also indicate that low CCT and intermediate overall illuminance can maximize the sense of accessibility. In contrast, surprisingly, the decrease of the overall illuminance values, due mainly to the increasing of softness, mildness, and shadowiness, should be related to a not perceiving danger. This last result, in contrast with previous studies highlight a possible difficulty in using the PCQ dimension to explain the perception of danger in a virtual lighting environment. This aspect should be deeply investigated, especially to understand the level of detail and complexity (e.g. presence of individual, sounds) of virtual scenes to elicit complex emotions like those related to the perception of danger in the visitors.

The lightness of each fixation position could predict the fixation duration within street lights, trees, and surrounding building areas. Rahm et al. (Rahm et al., 2021) showed how the level of urban flora and street lights influenced people's decisions about their routes after dark. Avoidance was aided by entrapment brought on by untidy flora and gloom, whereas human presence may have the reverse effect. The results indicated that urban greenery and street lighting interact with the neighborhood's perceived safety and walkability. Gholami et al. (2022) evaluate the role of landscape values and factors in urban parks for their legibility through eye tracking. Their results showed the “quality of people's cognitive maps” has a direct relation to fixation duration on “human-made factors” and an inverse relation to fixation duration on “natural factors” and “human activities and behavioral factors” in the park (Gholami et al., 2022). Our results also support the idea that more light could help the visual accessibility of greenery areas and street paths.

While previous studies have investigated the effects of illuminance and CCT of light on alertness, task performance, emotion (Li et al., 2021b), and mood (Lan et al., 2021) in indoor environment, the contribution of illuminance level and CCT on cognition in outdoor environment remained unknown. Zhang and Dai (Zhang and Dai, 2021) used virtual reality scenarios to investigate the night light comfort of pedestrian space in urban parks. They found CCT influenced subjective light comfort while the average horizontal illuminance affected physiological fatigue indicated by electroencephalogram signals. They offered a range of average horizontal illuminance and CCT for the light comfort zone in urban park pedestrian spaces. The interaction of overall illuminance level and CCT of cognitive load shown in our study indicates different influences of CCT settings in different overall illuminance level conditions.

7.5 Chapter Summary

The overall illuminance level influences various aspects of perceived outdoor lighting qualities dominantly compared to CCT. The illuminance level affects most items of PSQ and PCQ except for Unfocused-Focused and Warm-Cool, while the CCT only showed differences between Clear-Drab and Warm-Cool items. As the two POLQ indices were associated to the sense of accessibility and sense of danger, our results indicate that designing urban park lighting plants with low CCT and intermediate overall illuminance levels lead to maximizing the sense of accessibility, while the counterintuitive results emerged from the PCQ index, suggest further and deep research on the use of VR environments to investigate the association between PCQ and not dangerous situations. Fixation durations of subject when free viewing the VR scenario have been found to be a close relationship with the lightness of each fixation area. More complex interactional effect between Overall illuminance level and CCT emerged from the IPA index, linked with the cognitive load. In particular, lighting systems with low CCT and high overall illuminance levels or with high CCT and medium overall illuminance levels may foster to minimize cognitive load in the visitors.

While previous results can give some advice for urban parks lighting design with a new human-centred and experiential perspective, Immersive Virtual Reality also confirms several important limits and issues of the applied lighting research. The most important is related to the fact that current HMDs can reproduce only a limited range of luminances than the real lighting conditions and that also the reproduction process of the lighting scenes, from the software to the different HMDs, is still not fully well-known. Moreover, further specific physiological issues related to the visual interaction between the participants and the immersive virtual environment, as it is reproduced by the HMDs needed be deeply investigated.

CHAPTER 8: COMBINING BRAIN MEASUREMENTS AND SUBJECTIVE ASSESSMENTS OF THE SPATIAL SETTINGS OF AUGMENTED WATER SOUNDS IN URBAN PARK

8.1 Integrating Green Space with Augmented Water Sounds

Water spaces have been proven their effects on restorativeness creation and noise mitigation for human well-being. Beute et al. (2020) systematically review the impact of the types and characteristics of blue spaces on human mental health and well-being. Consistent positive results were confirmed of the coast on affective outcomes, with well-being, life satisfaction, (recalled) restoration, general mental health. But the investigation of inland water exposure is still lacking comparative results. The visual openness of the space and fluidity of the water were pointed towards unique and beneficial characteristics of blue space. They concluded that more high-quality research focused on a wider range of inland water and blue space characteristics (including the dynamic and fluid characteristics of water, and the sense of visual space) were deserved to explored (Beute et al., 2020). Thomas R. Herzog (1985) studied the relationships between the preferences for waterscapes and content categories, viewing time and other six variables (spaciousness, texture, coherence, complexity, mystery, and identifiability). A non-metric factor analysis of the preference ratings for the longest viewing-time condition yielded four dimensions: (1) Mountain Waterscapes, (2) Swampy Areas, (3) Rivers, Lakes, and Ponds, and (4) Large Bodies of Water. Mountain Waterscapes was the most preferred category and Swampy Areas by far the least preferred. The Mountain Waterscapes category was characterized by rough surface textures, while within the category spaciousness, coherence, and mystery were positive predictors of preference. The Swampy Areas category was low in spaciousness; within the category, coherence was a positive predictor of preference. Mountain Waterscapes were liked better with longer viewing times, but Swampy Areas were liked less. The results indicate that the type of waterscape, viewing time, and the predictor variables all play a role in determining preference. Some broad implications of these findings for environmental planners were suggested (Herzog, 1985).

Water features are commonly used in urban public spaces for multiple benefits, including visual appreciation, noise masking and recreational activity(Whyte, 1980). As a noise control strategy for its mitigation function, the masking effect of water sound on noise perception can be achieved on sensation level namely "energetic masking" and perception level namely "informational masking". Many studies have tested various water sounds at different physical settings to optimize the soundscape quality and the desired sound levels to set the water sounds playback (Jeon et al., 2012; Galbrun and Ali, 2013; Shu et al., 2018; Chitra et al., 2020; Lee and Lee, 2020;

Puyana-Romero et al., 2021; You et al., 2010; Jeon et al., 2010; Lugten et al., 2018; Rådsten-Ekman et al., 2013; Rådsten Ekman et al., 2015; Nilsson et al., 2010). For the settings of the signal-noise ratio between water sound and traffic noise, it is well-accepted that water sounds at levels 3dB lower than traffic noise could achieve better informational masking effects (Jeon et al., 2010; Masullo and Pascale, 2016; You et al., 2010).

Spatial organization plays a role in auditory perception like information masking in acoustic environments. Evidence showed that spatial separations of water sounds and noise sources influence perceptual assessments (Culling and Lavandier, 2021; Hong et al., 2020a). More specifically, informational masking could be caused by the masker sound from different directions compared to the traffic noise source, the phenomenon is called Spatial release from masking (SRM) (Culling and Lavandier, 2021). Based on the results of the multisensory experiment (S2), water sounds only positively affected Green space. More design features are needed to consider to expand the applications of this strategy to broader scenes. In real-life scenarios, water fountains in urban parks are already demonstrated diverse spatial characteristics for aesthetical appreciation and recreation activities(Ghavampour et al., 2017; Nowacka-Rejzner, 2019; Afonso and Fatah Gen Schieck, 2020). Inspired by SRM, we consider spatial variation setting of water sound, assuming they could improve the perceptual salience of water sounds and cause better masking effects. For practical consideration, introducing a real water infrastructure could be impossible for research purpose due to the difficulties from multiple aspects like space limitation, non-availability of water resource and high cost of infrastructure maintenance and so on. Learning from the works of practical designers and researchers by using digital methods like screen casting and loudspeakers playing in urban parks (Arroyo et al., 2012; Cerwén, 2016; Kreutzfeldt et al., 2019; Van Renterghem et al., 2019; Steele et al., 2021; Hong et al., 2021; Fraisse et al., 2022), augmented sound design was adopted for the introduction of water sound into an urban park in the study.

8.2 Designing Augmented Water Sounds in Urban Parks

8.2.1 Sound Materials

The sound sources included a 3-minute traffic noise recorded with a Zoom H6 Hand-Recorder device and a Soundfield SPS200 microphone (LAeq: 65 dB(A)) as background noise (BGN), and a 5 seconds water stream sound, recorded by the same device with a Rode NTG-2 microphone. To optimize the effect of the water sound-based informational masking, the sound level of the water stream sound was set at -3 dB with respect to the background traffic noise (SNR = -3dB). Water stream sound was used to create three-minute-long soundtracks (A/B) for spatial sound reproduction. The soundtracks combined repeated 5 seconds of water stream sound with 2 seconds fade-in and fade-out alternating between positions with 2 seconds overlap (see Figure 49).

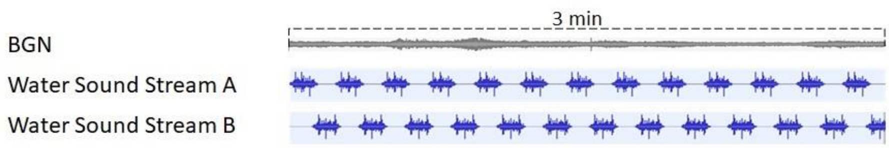
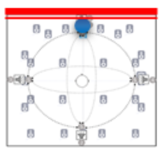
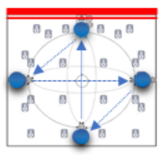
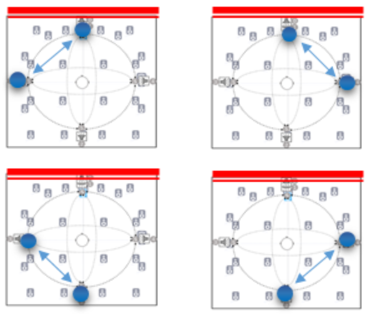


Figure 49 Temporal settings of water sound sequences.

8.2.2 Spatial Variation Settings

The spatial variations of the water sounds were set for studies. Four levels of spatial variations were defined: Frontal Position-fixed Water sound (FPW), a Two-position Switching Water sound (TSW) and a Four-position-randomized Moving Water sounds (FMW), and empty water sound, all of them combined the Road Traffic Noise (RTN) on the frontal position as background. FPW was set as a fixed position of water sound in the frontal position with road traffic noise as background. As for TSW settings, four two-position pairs were defined: the frontal-right, right-back, back-left, and left-front pairs (only adjacent positions were considered for avoiding the distance differences of two-position pairs). The distance between each position soundtrack up to the subject was the same as FPW. For FMW, the pseudo-random routine of the water sound selected from four-position (frontal/back/left/right) was defined (see Table 30). The audio stimuli at listeners' position were recorded using a dual channel system Sympnonie and an Mk1 Cortex manikin. They reproduced realistic auditory scenarios of about 57 dB(A), as those measured inside an existing urban park. The audio stimuli were then imported and analyzed with the software Artemis Head Acoustics. In Figure 50, the spectrograms of the left and right channels at the dummy head were reported for all the sounds spatialization conditions of the experiment.

Table 30 Composition of the sound stimuli. The red line indicated the positions of the background noise source and the blue circles the position of the water stream sound sources.

Conditions	RTN	FPW	FMW	TSW
Sources and layout ● : Point source ▬ Plan source				

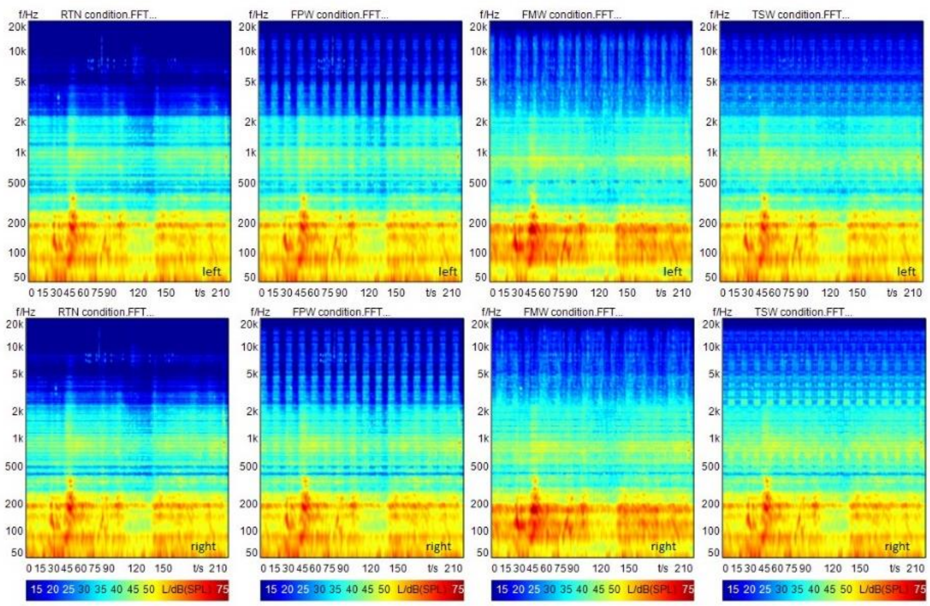


Figure 50 Spectrograms of the sound stimuli at the listener position.

8.2.3 Research Design and Purpose

Within-participants experiment designs were adopted with various platforms, including an online test, a laboratory-based experiment and an *in situ* experiment. The Independent Variable (IV) was the spatial variation settings of water sounds. The dependent variables (DV) were psychological assessment during each condition. In laboratory experiment, EEG signal were also collected for analysis. And for *in situ* study, EEG and eye-tracking measurements were both conducted. Combining psychophysiological and psychological measurements across different platform with different virtual sound production techniques, the spatial variation effects of water sounds on informational masking of road traffic noise and restoration effects were investigated for more generalized applications. The study hypothesized that a more structural spatial representation of water sounds in a noisy environment would improve the perceptual salience of water sound, produce more positive subjective feelings and better efficiency on informational masking than fixed location water sound, leading to decreased mental stress and increased restorative qualities.

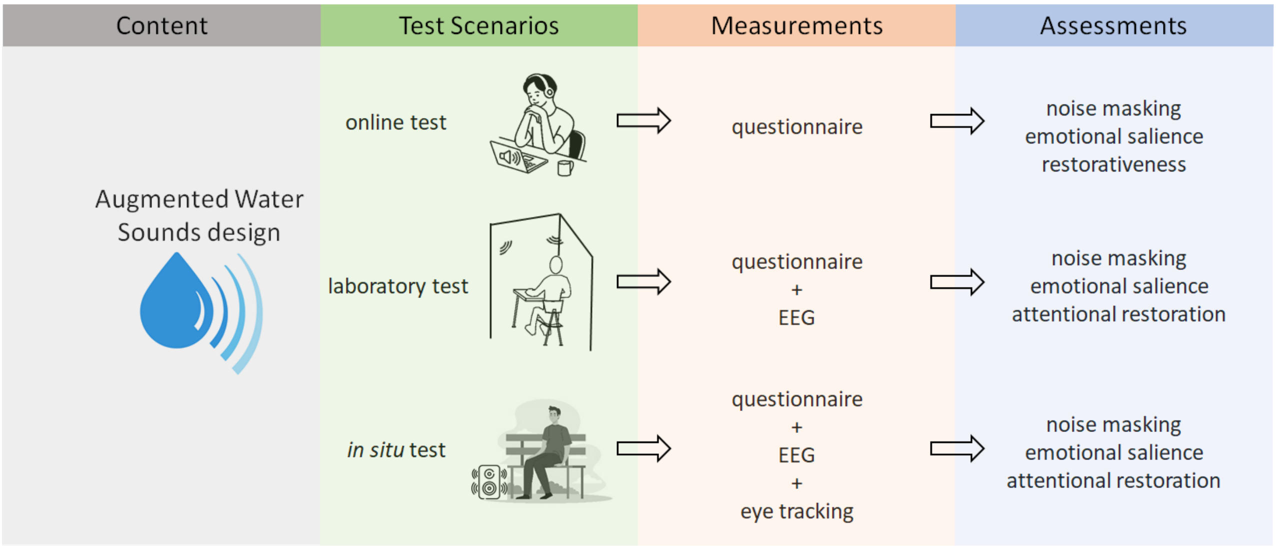


Figure 51 Conducted experiments for augmented water sounds design

8.3 Online Test

8.3.1 Procedure

Participants were invited to finish the test online by email. Thirty-six participants (male:21; female:15; average age: 26 yrs) were equally enrolled from Chinese and Italian universities. Participants were also asked for using headphones in a quiet environment and keeping head steady during the test. A male speech voice recording has been used at the beginning of the test to allow the participants to calibrate the playback level of the sound stimuli, asking them to adjust the system volume until the male voice sounded loud as a normal speech of a talker at about 1m in a quiet room. After the volume setting, participants were asked not to change the system volume. The audio player's settings inside the website were kept constant. For formal test, participants need listen the sound played from Web API and finish the questionnaire in the webpage. The questionnaire included five-sound sequences from four conditions, one for each condition except for TSW, in which two different position-pair water sounds were assigned randomly. The assessment of each sound sequence consisted of three parts across three pages on the online website, including the soundscape perception, subjective evaluations based on previous works (Fraisse et al., 2020; Masullo et al., 2021a) and the Perceived Restorativeness Scale (PRS-11) (Pasini et al., 2014; Payne, 2013)separately. The order of the five sound sequences was randomised. The online test was published on the website (http://braincoder.io/spatial_sound/en/) with a constrained design for appearance controlled. The online test last 15-20 minutes. All data collected was safely stored on a personal database. No private information of those who participated in the online questionnaire was collected.

8.3.2 Results

The Perceived Restorativeness Scale (PRS-11) items based on Kaplan and Kaplan's Attention Restoration Theory were categorised into four dimensions: being away; fascination; coherence, and scope (Kaplan and Kaplan, 1989). In the Being Away factor of PRS-11 scores, repeated measures ANOVA results showed the difference between four conditions was significant ($F(3,105) = 2.91$, $p = 0.038$; see Table 31). The results of post hoc analysis (with Tukey correction) illustrated that the FMW was significantly better than RTN (df =105, t = 2.682, p=0.042). However, other conditions were not significantly different from traffic noise (see Figure 52). In the Fascination factor of PRS-11 scores, the ANOVA results indicated the differences between four condition were significant ($F(3,105) = 7.29$, $p < 0.001$) (see Table 31). The results of post hoc analysis illustrated the scores of TSW, FPW and FMW were all significantly higher than RTN (df = 105, t = 4.538, p < 0.001; df = 105, t = 3.167, p = 0.011; df = 105, t = 2.937, p = 0.021). However, the differences among those three conditions were not significant (see Figure 52). No significant results between four spatialisation conditions were observed for the remaining dimensions of PRS-11 (see Figure 52).

Table 31 Mean Values (Standard Error) and Effect Sizes of Four Conditions in PRS-11 Dimensions.

Variables	Spatial Sounds				df	F	p	Significance
	TSW	FPW	FMW	RTN				
Being Away	2.74(0.343)	2.35(0.343)	2.87(0.343)	1.87(0.343)	3	2.91	0.038	*
Coherence	3.54(0.347)	3.75(0.347)	3.38(0.347)	3.43 (0.347)	3	0.574	0.633	
Fascination	3.31(0.275)	2.87(0.275)	2.80(0.275)	1.87(0.275)	3	7.29	<0.001	***
Scope	4.03(0.377)	4.17(0.377)	4.19(0.377)	3.89(0.377)	3	0.288	0.834	

Note: * p<0.05, **p<0.01,***p<0.001; the same below;

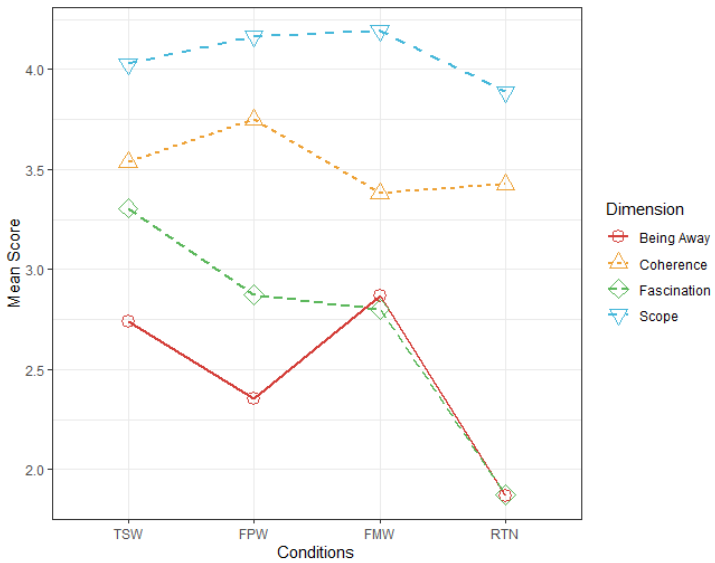


Figure 52 PRS-11 Mean Scores of Four Conditions in Four Dimensions.

The results related to the feature judgements of each sounds included naturalness, mechanicalness, smoothness, rhythmicalness, spaciousness, and familiarity were analysed. From the one-way ANOVA analysis, the naturalness of each sound condition was significantly different ($F(3,105) = 10.2$, $p < 0.001$) (see Table 32). The results of post hoc analysis showed TSW, FMW and FMW were all significantly better than RTN ($df = 105$, $t = 4.807$, $p < 0.001$; $df = 105$, $t = 4.760$, $p < 0.001$; $df = 105$, $t = 2.885$, $p = 0.024$). Significant differences of the mechanicalness of each sound were observed ($F(3,105) = 7.09$, $p < 0.001$; see Table 32). The results of post hoc analysis illustrated FPW and RTN were all significantly higher than TSW ($df = 105$, $t = 3.268$, $p = 0.008$; $df = 105$, $t = 4.445$, $p < 0.001$). But the difference between TSW and FMW was not significant ($df = 105$, $t = 2.385$, $p = 0.086$). The smoothness among each sound was significantly different ($F(3,105) = 2.89$, $p = 0.039$). The results of post hoc analysis illustrated TSW was significantly higher than RTN ($df = 105$, $t = 2.907$, $p = 0.023$). The differences in other descriptors between the four conditions were all insignificant (see Figure 53 a).

Table 32 Mean Values (Standard Error) and Effect Sizes of Four Conditions in Feature Judgements.

Variables	Spatial Sounds				df	F	p	Significance
	TSW	FPW	FMW	RTN				
Naturalness	3.65(0.276)	3.64(0.276)	3.08(0.276)	2.23(0.276)	3	10.2	<0.001	***
Mechanicalness	2.69 (0.280)	3.61(0.280)	3.36(0.280)	3.94 (0.280)	3	7.09	<0.001	***
Smoothness	2.96 (0.231)	2.67(0.231)	2.56(0.231)	2.22(0.231)	3	2.89	0.039	*
Rhythmicalness	2.63(0.217)	2.80(0.217)	2.61(0.217)	2.17(0.217)	3	2.58	0.058	
Spaciousness	3.78(0.269)	3.67(0.269)	3.72(0.269)	3.50(0.269)	3	0.382	0.767	
Familiarity	3.76(0.292)	3.81(0.292)	3.58(0.292)	4.19(0.292)	3	1.78	0.155	

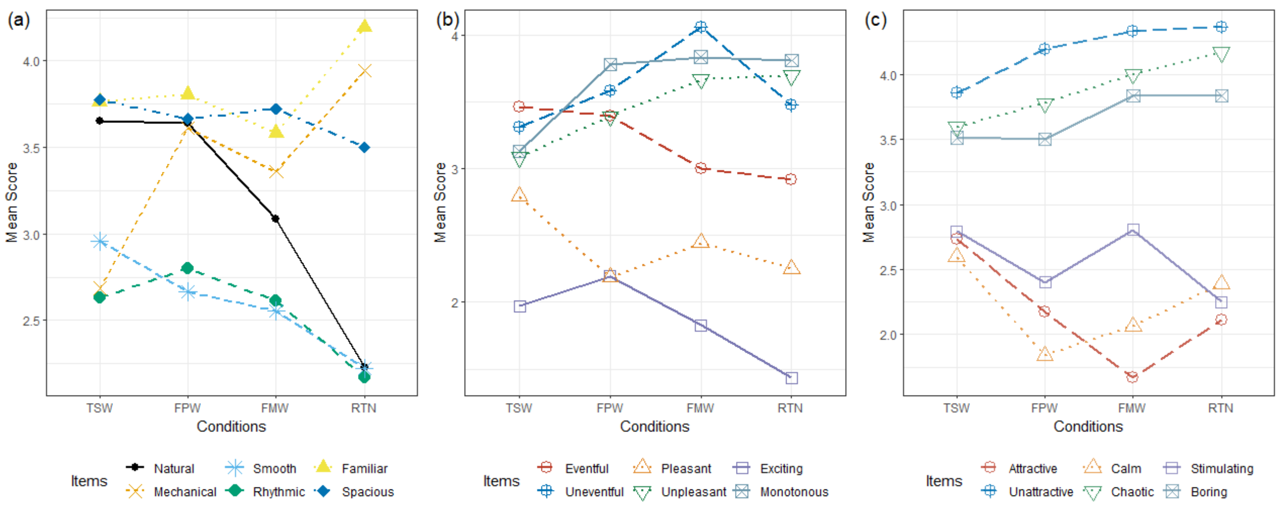


Figure 53 Mean Score of Sound Evaluation Scales. a) items related to feature judgements, b) c) items related to soundscape indicators.

The ANOVA on the soundscape indicators included eventfulness/uneventfulness and pleasantness/unpleasantness within Axelsson and Cain's circumplex model showed no significant differences among the four sounds (Axelsson et al., 2010; Cain et al., 2013). But the calmness and excitement factors in the model illustrated significant differences among those conditions (Calmness: $F(3,105) = 3.80$, $p = 0.012$; Excitement: $F(3,105) = 6.01$, $p < 0.001$; see Table 33). The results of post hoc analysis illustrated the calmness ratings of TSW significantly better than FPW ($df = 105$, $t = 3.103$, $p = 0.013$; see Figure 53). And the excitement ratings of TSW and FPW were all significantly better than RTN (df = 105, t = 2.910, p = 0.023; df = 105, t = 4.122, p < 0.001; see Figure 53). However, the difference between FMW and RTN was not significant (df = 105, t = 2.141, p = 0.147; see Figure 53). Besides, the attractiveness among those sounds was significantly different (F(3,105) = 5.53, p = 0.001; Table 33). The results of post hoc analysis illustrated TSW was significantly better than FMW (df = 105, t = 4.055, p < 0.001; see Figure 53). And the differences in the stimulation of each sound were also significant (F(3,105) = 2.72, p = 0.048; see Table 33). However, the results of post hoc analysis illustrated no significant difference between all conditions.

Table 33 Mean Values (Standard Error) and Effect Sizes of Four Conditions in Soundscape Indicators

Variables	Spatial Sounds				df	F	p	Significance
	TSW	FPW	FMW	RTN				
Eventfulness	3.46(0.242)	3.39(0.242)	3.00(0.242)	2.92(0.242)	3	2.06	0.110	
Uneventfulness	3.31(0.292)	3.58(0.292)	4.06(0.292)	3.47(0.292)	3	1.96	0.124	
Pleasantness	2.79(0.206)	2.19(0.206)	2.44(0.206)	2.25(0.206)	3	2.51	0.063	
Unpleasantness	3.08(0.313)	3.39(0.313)	3.67(0.313)	3.69(0.313)	3	1.67	0.178	
Excitement	1.97(0.158)	2.19(0.158)	1.83(0.158)	1.43(0.158)	3	6.01	<0.001	***
Monotonousness	3.13(0.278)	3.78(0.278)	3.83(0.278)	3.81(0.278)	3	2.04	0.113	
Calmness	2.60(0.200)	1.84(0.200)	2.06(0.200)	2.39(0.200)	3	3.80	0.012	*
Chaoticness	3.60(0.288)	3.78(0.288)	4.00(0.288)	4.17(0.288)	3	2.24	0.232	
Stimulation	2.79(0.219)	2.40(0.219)	2.81(0.219)	2.25(0.219)	3	2.72	0.048	*
Boredom	3.51(0.319)	3.50(0.319)	3.83(0.319)	3.83(0.319)	3	0.785	0.505	
Attractiveness	2.74(0.209)	2.17(0.209)	1.67(0.209)	2.11(0.209)	3	5.53	0.001	**
Unattractiveness	3.86(0.310)	4.19(0.310)	4.33(0.310)	4.36(0.310)	3	0.842	0.474	

For emotional feelings, the nervousness ratings were the only significant results among the six dimensions of the emotional feelings scale (calm/energetic/happy/nervous/sad/weak) for the four sound conditions (F(3,105) = 4.87, p = 0.003; see Table 34). The results of post hoc analysis illustrated TSW was significantly lower than RTN (df = 105, t = -3.793, p < 0.001; see Figure 54). But the differences between the rest two conditions and traffic noise were not significant.

Table 34 Mean Values (Standard Error) and Effect Sizes of Four Conditions in Emotional Responses.

Variables	Spatial Sounds				df	F	p	Significance
	TSW	FPW	FMW	RTN				
Happy	2.24(0.212)	2.06(0.212)	2.11(0.212)	1.71(0.212)	3	2.19	0.093	
Sad	1.99(0.216)	2.08(0.216)	1.97(0.216)	2.17(0.216)	3	0.493	0.688	
Energetic	2.16(0.194)	2.11(0.194)	2.17(0.194)	2.03(0.194)	3	0.217	0.885	
Weak	2.42(0.237)	2.31(0.237)	2.36(0.237)	2.31(0.237)	3	0.175	0.913	
Calm	2.71(0.234)	2.56(0.234)	2.56(0.234)	2.19(0.234)	3	1.53	0.212	
Nervous	2.30(0.261)	2.86(0.261)	2.81(0.261)	3.22(0.261)	3	4.87	0.003	**

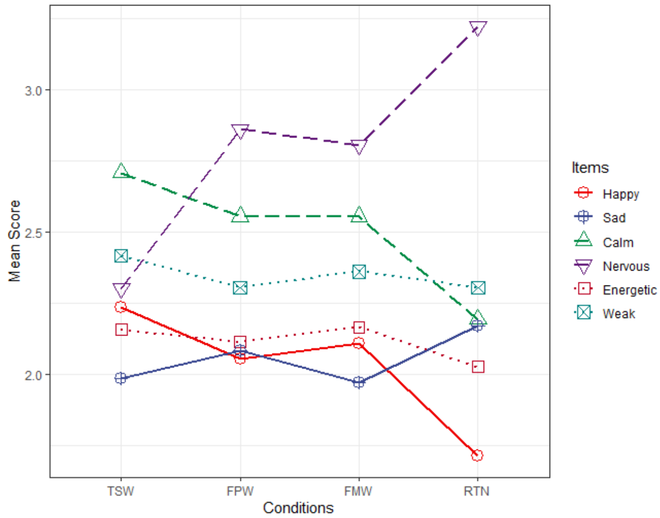


Figure 54 Mean Scores of Four Conditions in Emotion Feelings.

8.4 Laboratory Study

8.4.1 Procedure

Twenty participants gave informed consent and were instructed to sit in the test room's centre, immersed in virtual sound environments. Before the formal experiment, the subject fulfilled two pages of the initial questionnaire, containing basic information such as age (average: 30; SD: 5.90), gender (Male: 12; Female: 8), working environment, Weinstein Noise Sensitivity Scale (Senese et al., 2012; Weinstein, 1978) (average score: 3.73; SD: 0.50), and Personal Well-being scale (Mitchell et al., 2020) (average score: 53.78; SD: 12.59). After wearing the portable EEG device and passing the impedance check of EEG electrodes, the subject was asked to listen to five sequences with a comfortable sitting position and eyes open in the pre-defined balanced order (two TSW conditions were randomly selected from the four TSW conditions, considering the recommended duration of whole EEG test should be less than 30 minutes in case of signal-noise-rate losing caused by the effect of discomfort and fatigue). Each sequence lasted 3 minutes; then, the subject must fill the questionnaire, including the perceived contents and his/her feelings about each sound based on previous works. After finishing the questionnaire, the subject informed the experimenter to play the following sound sequence. Finally, the subject took 1-minute rest with his/her eyes closed. The neural activities during this period were used for baseline correction for EEG analysis. During the whole process, the brain data of each subject were continuously recorded by DSI-24 wireless EEG headset with 20 dry electrodes signals referenced to Pz electrode at locations corresponding to the 10-20 International system (see Figure 55). The light and temperature in the lab were kept constant during the test. The EEG data were sampled at 300 Hz and streamed from the measurement device to the recording laptop using the Lab Recorder application based on the Lab Streaming Layer protocol to synchronize the neural data with sound sequences. The Ethical Committee for Scientific Research of the Department approved the protocol.

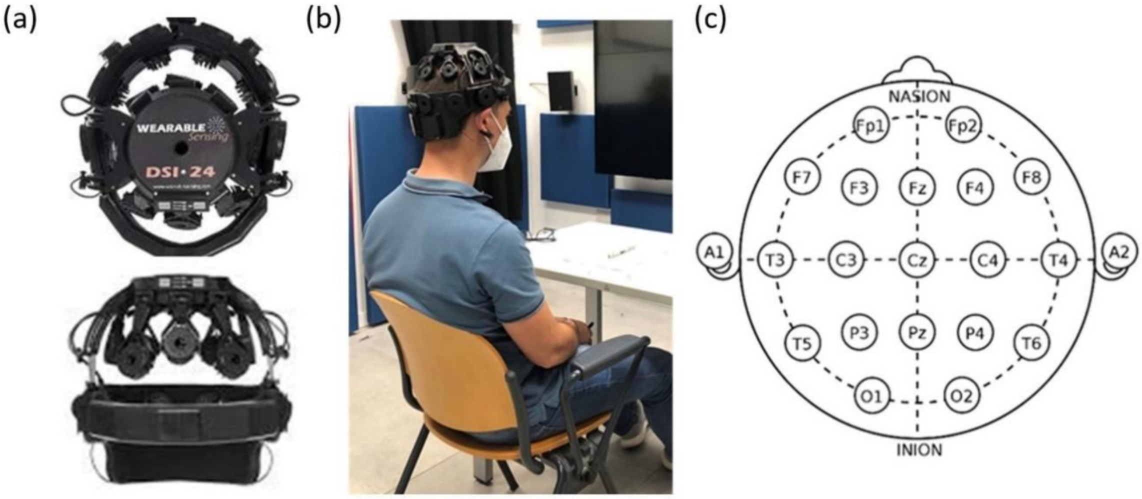


Figure 55 The EEG headset, setup, and electrodes layout. a) the top-view and frontal-view of DSI-24 Headset, b) the EEG setup for the recording, c) the EEG electrodes layout.

8.4.2 Data pre-processing and EEG analysis

The EEG data pre-processing, spectral power and connectivity analysis were conducted with the same workflow as did in Multisensory Design (S2, Chapter 6.2.4-6).

8.4.3 Results

The results related to the objective descriptors of each sound environment (naturalness, mechanicalness, smoothness, rhythmicalness, spaciousness, and familiarity) were analyzed. Two main differences were found between the four conditions. Participants felt more familiar with traffic noise rather than water sound conditions. And more rhythmic features were detected from FMW and TSW conditions than traffic noise (See Table 35 and Figure 56). On the other hands, based on our previous work (Masullo et al., 2021a), the scores of adjectives items' responses, including pleasant, happy, stimulating, attractive, energetic, calm were averaged to compute the positive component of the emotional saliency's (ES+). The results indicated the better masking effect of TSW compared to FPW condition from the ANOVA post-hoc test ($t_{TSW-FPW}$=3.02, p=0.019). But all water sound conditions didn't show significant improvement in terms of ES+ scores compared to RTN condition. To be more specific, the main differences existed in three positive emotional items, which included stimulating, happy, and energetic (See Table 35). FMW and TSW were more stimulating and energetic than FPW rather than RTN, and TSW also felt happier than FPW rather than RTN. There were also no distinctions between the four conditions in the negative component (ES-) (averaged by the scores of boring, unpleasant, nervous, weak, sad, unattractive items).

Table 35 ANOVAs results of subjective assessments for four conditions. Stars indicated the significance level of the ANOVAs results: * p<0.05; ** p<0.01 and *** p<0.001.

Objective Descriptors			Emotional Saliency					
Items	F	p	Items	F	p	Items	F	p
natural	2.1273	0.1068	pleasant	2.5421	0.0652	unpleasant	0.8673	0.4634
mechanical	0.0459	0.9868	attractive	4.9667	0.0778	unattractive	2.5417	0.06526
smooth	0.1653	0.9193	stimulating	6.4523	0.0008**	boring	2.6620	0.05658

rhythmic	5.6859	0.0018 **	happy	3.1435	0.0320*	sad	2.5818	0.0622
spacious	1.4948	0.1415	energetic	8.9109	0.0001***	weak	1.5151	0.2204
familiar	7.1856	0.0004**	calm	0.6577	0.5815	nervous	0.3140	0.8152
			ES+	3.7700	0.0154*	**ES-**	0.8113	0.4929

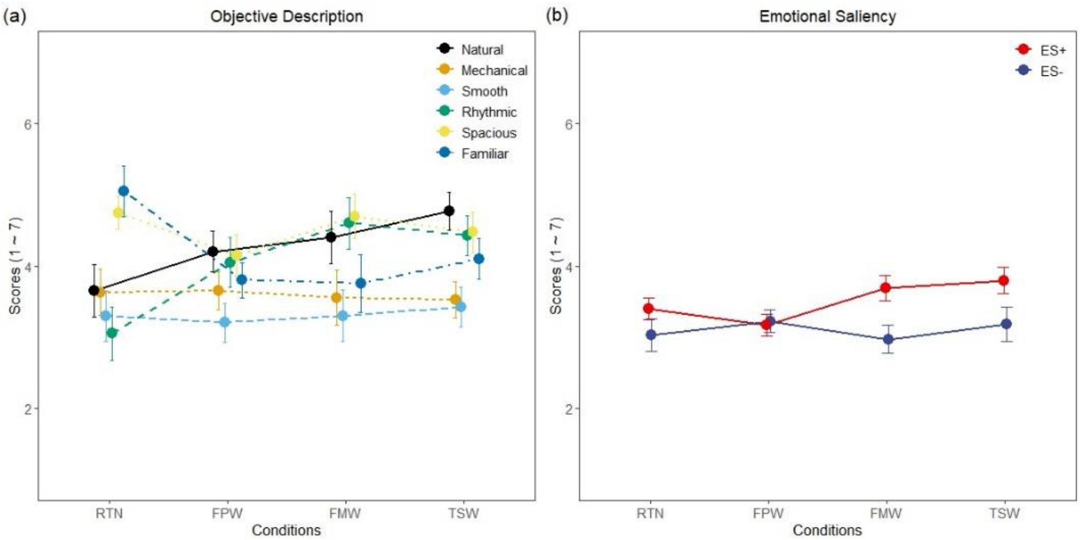


Figure 56 Line plots of the scores for Sound Evaluation Scales (rating scale 1-7 for each item). A) items related to objective description, b) related to positive (ES+) and negative components (ES-) of emotion saliency.

The relative power of the alpha-band showed significant differences between four conditions in the whole brain ($F(3,51)=9.43$, $p<0.001$)(see Table 36 and Figure 57 for the results of each region). FPW and FMW had higher relative power of the alpha-band than RTN in most of the brain regions. The higher relative power of the alpha band of TSW sound only occurred in frontal and left regions compared to RTN condition (see Figure 57 for post-hoc comparison). The relative power of the theta-band showed differences between four conditions in the frontal region from ANOVA results but no post-hoc analysis differences. The relative power of delta, beta and gamma bands showed no significant differences between the four conditions (see Table 36 and Figure 57).

Table 36 ANOVAs results of the relative power of each frequency band for four conditions. Stars indicated the significance level of the ANOVAs results: * p<0.05; ** p<0.01 and *** p<0.001.

Brain region	*delta*		*theta*		*alpha*		*beta*		*gamma*	
	F value	*p* value	F value	*p* value	F value	*p* value	F value	*p* value	F value	*p* value
Frontal	2.0151	0.1564	**4.3206**	**0.0224***	**5.1493**	**0.0212***	0.0545	0.9541	2.1269	0.1253
Central	1.8827	0.1670	0.9945	0.3927	**3.9946**	**0.0234***	0.4476	0.6793	1.7992	0.1735
Left	0.9155	0.3781	1.7240	0.1991	**8.4439**	**0.0033****	0.4295	0.6003	2.6691	0.0723
Right	0.3714	0.6490	1.9489	0.1722	**4.7282**	**0.0144***	0.3259	0.6648	2.3101	0.0993
Posterior	0.8016	0.4301	1.6925	0.2043	**5.4896**	**0.0093****	0.2847	0.6863	1.2515	0.2959

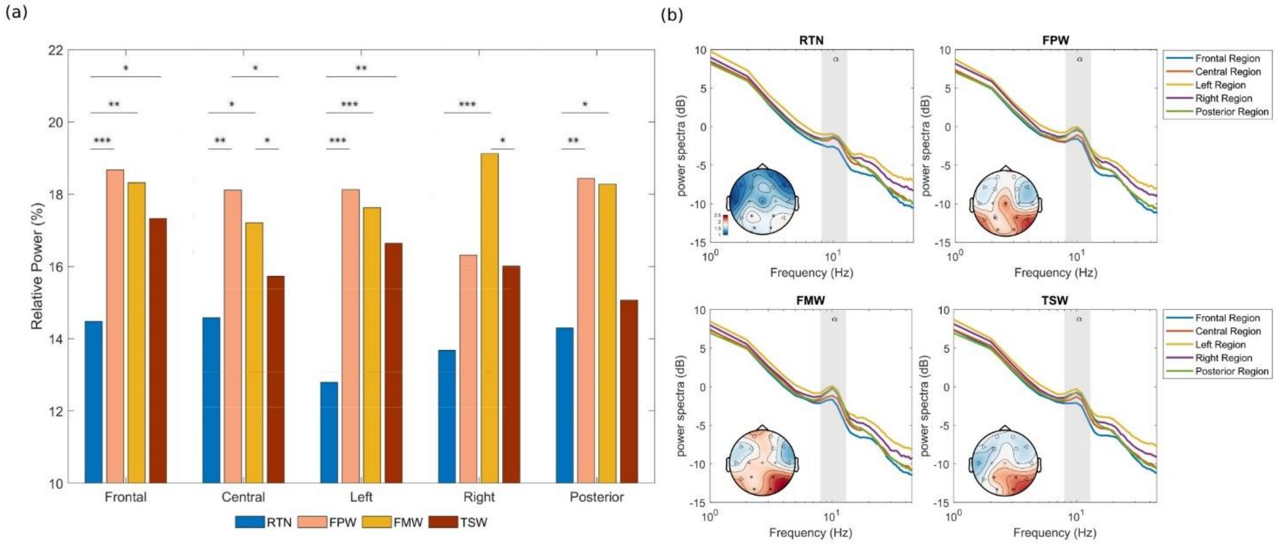


Figure 57 a) the average relative power of alpha-band across five regions between four conditions. b) the power spectrum of EEG across five regions between four conditions with topography of the alpha band. Stars indicated the significance level of the post-hoc ANOVAs results: * p<0.05; ** p<0.01 and *** p<0.001.

The index of theta-alpha ratio showed major differences between different conditions within each brain region except frontal position (see Table 37). From the post-hoc multiple pairwise statistical comparison, RTN ratios were much higher than FPW, FMW and TSW both in the central region and in the left region. And the same ratios of RTN were significantly greater than FPW and FMW both in the posterior region and the right region (see Figure 58). The index of alpha-beta ratio showed significant changes between different conditions within each brain region (see Table 37). From the one-way ANOVA analysis, the ratios of RTN were clearly lower than FPW, FMW, and TSW in most of the regions except for the posterior region. For the central region, FMW was significantly greater than RTN, FPW and TSW (Figure 58).

Table 37 Values of the ratio indices theta/alpha and alpha/beta for four conditions. The stars indicated the significance level of the ANOVAs results: * p<0.05; ** p<0.01 and *** p<0.001.

Brain Regions	*theta/alpha*		*alpha/beta*	
	F value	*p* value	F value	*p* value
Frontal	1.0532	0.3574	7.3588	0.0051**
Central	5.2319	0.0089**	4.6687	0.0103*
Left	6.5272	0.0058**	7.8942	0.0047**
Right	3.7535	0.0342*	3.6801	0.0227*
Posterior	3.7849	0.0243*	4.6140	0.0172*

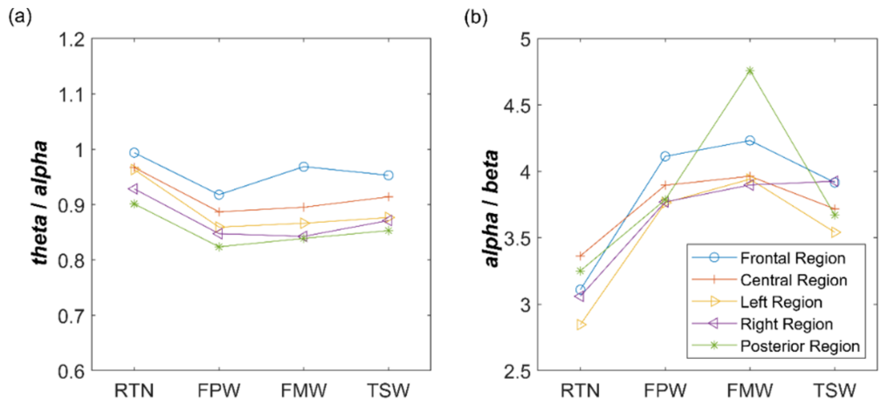


Figure 58 The mean values of theta/alpha (a) and alpha/beta (b) ratios across different regions between four conditions.

The dwPLI connectivity results showed significant differences between different conditions within local regions across frequency bands. In the delta band, the main changes were in the posterior position, while in the alpha band, they differentiated in the central position. The differences between the beta and gamma bands also existed in the frontal position. The inter-regions connectivity metrics also illustrated crucial changes across frequency bands. In the delta band, the connections in the frontal-central, frontal-posterior, central-left, central-posterior regions were significantly distinct between the four conditions. In the alpha band, the connections in the frontal-posterior and central-left regions were significantly different. In the beta band, six inter-regions had large differences, including frontal-right, frontal-posterior, central-left, left-right, left-posterior and right-posterior inter-regions. And in the gamma band, the main differences in inter-network connectivity were only found in left-right and right-posterior regions (see Table 38 for detailed information).

Table 38 The ANOVA results of connectivity metrics of intra- and inter-regions.

Network	Brain region	*delta*		*theta*		*alpha*		*beta*		*gamma*	
		F value	*p* value	F value	*p* value	F value	*p* value	F value	*p* value	F value	*p* value
Intra region	Frontal	1.8351	0.1706	2.4082	0.0873	0.5405	0.6200	**3.5619**	**0.0258***	**3.1399**	**0.0491***
	Central	2.1954	0.1182	1.8657	0.1613	**3.2316**	**0.0337***	0.7381	0.5099	1.3610	0.2700
	Left	2.0350	0.1508	1.3258	0.2774	1.8056	0.1750	1.2951	0.2875	0.4055	0.7314
	Right	2.5975	0.0748	2.5061	0.0917	0.1125	0.9384	1.2511	0.3012	2.4721	0.0958
	Posterior	**5.5882**	**0.0069****	0.4997	0.6436	1.8765	0.1654	3.1468	0.0538	1.2329	0.3070
Inter-regions	Frontal-Central	**3.4208**	**0.0405***	0.9607	0.4111	0.4652	0.6864	0.7956	0.4801	1.2074	0.3126

	Frontal-Left	2.6020	0.0827	2.6879	0.0804	3.1202	0.0528	2.1619	0.1096	0.3979	0.7061
	Frontal-Right	0.9013	0.4355	1.9629	0.1372	0.8947	0.4468	**3.5803**	**0.0305***	2.3524	0.1049
	Frontal-Posterior	**5.0709**	**0.0074****	1.3705	0.2651	**3.5934**	**0.0292***	**3.2619**	**0.0500***	0.5707	0.6266
	Central-Left	**4.6858**	**0.0069****	0.2654	0.8130	**3.2111**	**0.0459***	**3.3513**	**0.0355***	1.9400	0.1448
	Central-Right	0.4052	0.7202	0.4723	0.6633	0.5715	0.6171	1.6155	0.2002	0.0631	0.9515
	Central-Posterior	**4.2271**	**0.0145***	2.6781	0.0639	0.6858	0.5252	0.2859	0.7916	0.8682	0.4485
	Left-Right	0.4481	0.6752	0.7961	0.4937	2.0088	0.1393	**5.3675**	**0.0036****	**3.8879**	**0.0201***
	Left-Posterior	0.4409	0.6693	0.8021	0.4409	1.3867	0.2639	**3.5798**	**0.0318***	1.4203	0.2528
	Right-Posterior	0.3139	0.7562	2.5794	0.0706	1.1463	0.3355	**6.4582**	**0.0037****	**6.1226**	**0.0019****

From the post hoc analysis of delta band connectivity data, the coherence of the local posterior region and most inter-regions in RTN condition were significantly higher than FPW, FMW and TSW conditions (see Figure 59). As for the alpha band connectivity results, only the frontal-posterior connections of TSW were much greater than FPW, FMW and RTN, the central-left connections of FPW and RTN were clearly greater than FMW, and the local central coherence of TSW was significantly higher than FPW, FMW and RTN (see Figure 59). Most of inter-regions coherence of TSW and FMW conditions in the beta band connectivity were higher than FPW and RTN conditions. The frontal-right coherence of FPW was essentially lower than RTN. The local frontal coherence of FPW in the beta band was significantly lower than FMW, TSW and RTN (see Figure 59). Furthermore, gamma band connectivity data showed the differences of RTN in inter-regions network. The left-right coherence of RTN was lower than FPW, FMW and TSW, and similar results happened in the right-posterior region. The local frontal coherence of FPW was much lower than RTN (see Figure 59).

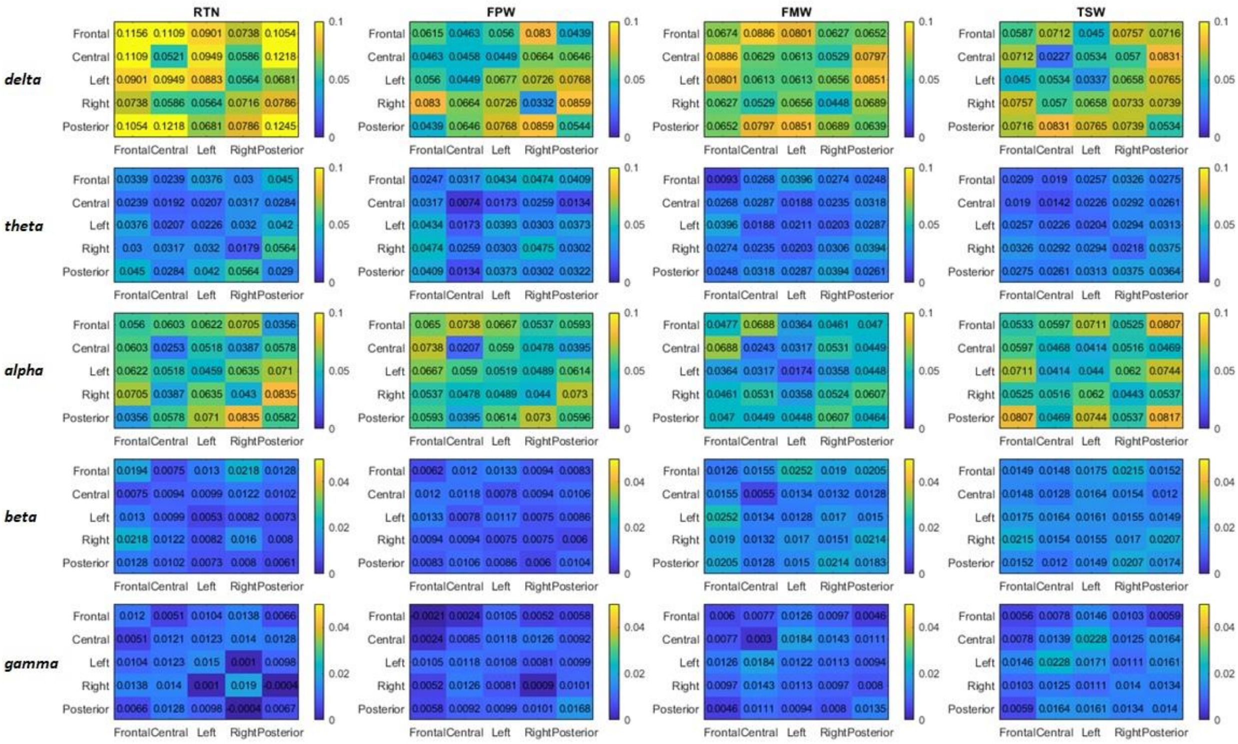


Figure 59 The connectivity matrixes of five brain regions for each frequency band between four conditions.

8.5 *in situ* Investigation

8.5.1 *in situ* setting

The site selected for the measurements of road traffic noise and the in-situ experiment was the open area on Podium adjacent to block Q inside the campus of the Hong Kong Polytechnic University (see Figure 60). Facing the main road with heavy traffic noise in the district, the in-situ scenarios consisted of different kinds of flowers and trees in front of the sitting position of subjects, which could bring visual inputs and a more immersive context for human perception in urban parks.

The test scenario was set as follows: subjects were sitting in the centre of wide-open spaces facing the main road, and Bluetooth loudspeakers (SONY SRS-XB23, SONY, Tokyo, Japan) were positioned at four directions (Frontal/Back/Left/Right) with same distances (1.2 m) to the subject sitting position. A sound level meter (B&K 2270, Brüel & Kjær, Virum, Denmark) was set parallel to the sitting position and the same distance to the nearest loudspeaker (see Figure 61). The soundtracks used were the same as laboratory experiment. The playback of water sounds from the four Bluetooth speakers was programmed by the Pyo library as mentioned before (Chapter 4.2.2) (see Figure 62).

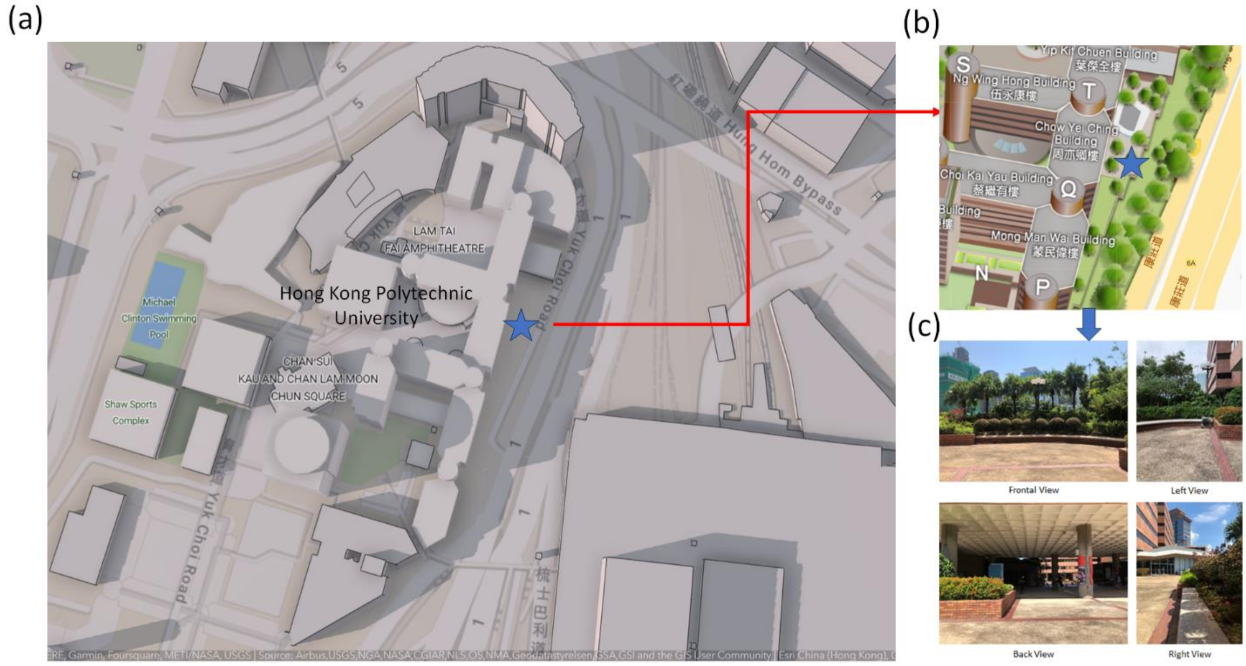


Figure 60 The campus green park chosen for the in-situ experiment: (a) the google map of the selected campus park; (b) the isometric map of the test site; (c) the human perspective images from four directions of the test park.

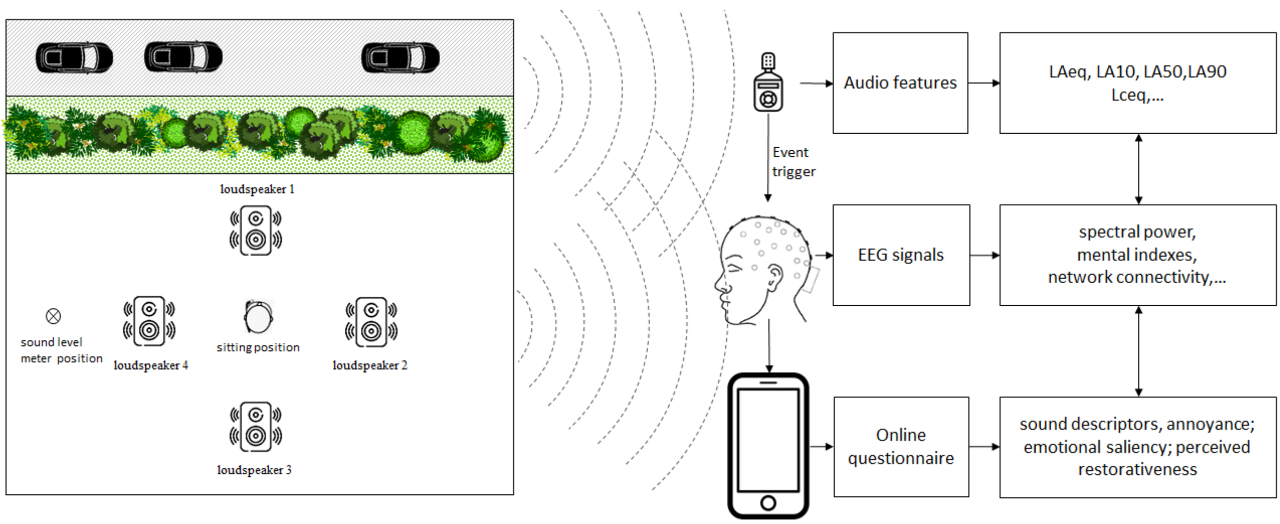
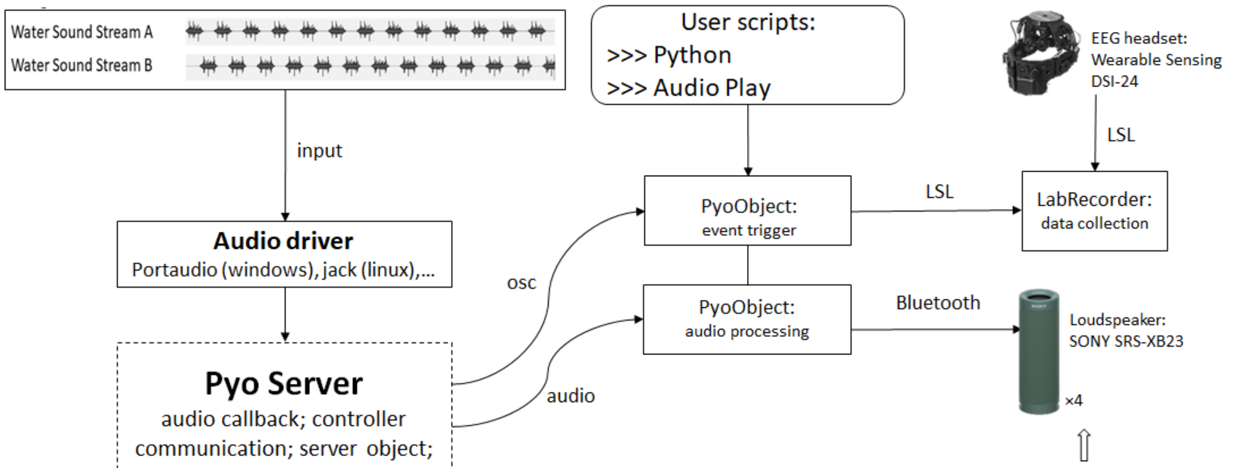


Figure 61 The spatial arrangements of the in-situ test and data collection methods.



Condition	Water Sound Sequence	Condition	Water Sound Sequence
RTN	-	TSW	A: ① or ① or ② or ② or ③ or ③ or ④ or ④ B: ② ③ ① ④ ① ④ ② ③
FPW	A+B:①	FMW	(9s): ①③④②④③①④②③①......

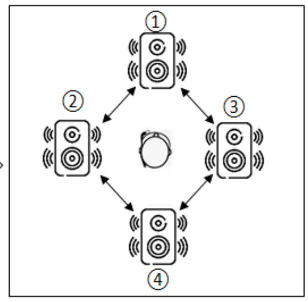
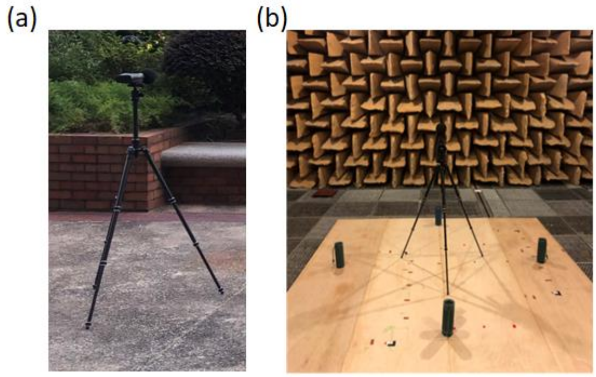


Figure 62 The audio materials for the test and their configurations through Pyo library.

8.5.2 Experiment Procedure

Before the experiment, the sound pressure levels and related A-weighted sound equivalent levels $_{Leq,A}$ of the RTN condition during the whole daytime period were measured by the B&K sound level meter in the test site as the references of the sound level settings of water sounds (see Figure 63). The relationship between sound levels of water sound playback and the volume settings of the four loudspeakers was measured at three-volume level settings (75%/85%/100%) in the anechoic chamber (space size: 6m x 6m x 3m, background noise level < 15 dB(A), at the Department of Mechanical Engineering in the Hong Kong Polytechnic University) with same set-ups in in-situ test (the height of sound level meter was set as 1.2 m referenced from the normal ear height when sitting)(see Figure 64). During the experiment, B&K sound level meter was also used to record the A-weighted sound equivalent levels of the environment. Notably, the $L_{eq,A}$ measured during the RTN condition was used as a baseline for the volume setting of the water sounds to match -3 dB(A) to the sound levels ($L_{eq,A}$) of traffic noise.



(c)

Traffic noise level at daytime before the test:
LAeq: 65.2
LA10.0: 66.9 LA50.0: 64.6 LA90.0: 63.0

condition \ volume	75%	85%	100%
FPW	57.6	62.5	68.9
FMW	57.6	62.4	68.4
TSW	57.6	62.4	68.4

Figure 63 The acoustical measurements of traffic noise in the test site (a) and water sounds playbacks from the loudspeakers (b) with different volume settings (c) in an anechoic chamber.

Twelve subjects gave informed consent and were instructed to sit in the chosen site of the campus park. Before the formal experiment, the subjects completed the initial set of questions in the questionnaires, containing basic information such as age (average: 23.8; standard deviation (SD): 5.0), gender (Male: 5; Female: 7), working environment, Weinstein Noise Sensitivity Scale (Weinstein, 1978) (average score: 3.3; SD: 0.7), and Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988) (positive score: 20.7 (SD: 10.3); negative score: 19.0 (SD: 10.2)). After the preparation for the EEG headset (DSI-24) wearing and passing impedance check along with the starting of the sound level meter measurements, subjects were told to close their eyes for 3-min relaxing. After that, subjects wore eye-tracking glasses (Pupil Labs Core headset) with calibration steps. Then the formal experiment proceeds as follows: (1) 3-min-long traffic noise-only open-eye listening (RTN); (2) psychological questionnaires answering; (3) 1-min-long intervals for breaking; (4) repeating foregoing steps (1-3) with different spatial setting of sounds for four times (one for FPW, FMW separately, two TSW conditions were randomly selected from the four TSW conditions). The psychological questionnaires were presented online (see Appendix C.) (http://braincoder.io/spatial_sound/in_situ/) through a tablet (Apple iPad Air 3, Apple, California, USA) with the advantage of randomized items inside each scale. Finally, the subject took another 3-min rest with his/her eyes closed. The orders of four water sound conditions were balanced between subjects. The neural activities of two eye-closed periods were used for baseline correction for EEG analysis.

Figure 64 The scene pictures of the in-situ test in the park.

8.5.3 Data pre-processing and EEG analysis

The EEG data pre-processing, spectral power and connectivity analysis were conducted with the same workflow as did in Multisensory Design (S2, Chapter 6.2.4-6).

8.5.4 Result

The SPLs of the four conditions measured during the experiment were nearly identical. And the different settings of water sounds decreased the traffic noise annoyances compared to the RTN condition, but the differences between water sound conditions were not statistically significant. The two dimensions of the Perceived Restorativeness Scale (PRS-11) items differed between traffic noise and spatial water sound conditions, and the highest scores were in FMW conditions (See Table 39 and Figure 65).

Table 39 The statistical results of noise levels, noise annoyance and two PRS-11 dimensions between four conditions. The stars indicated the significance level of the ANOVAs results: * p<0.05; ** p<0.01 and *** p<0.001.

Measurements	Dimension	F value	p value	RTN	FPW	FMW	TSW
$L_{eq,A}$	-	0.7780	0.5150	64.9383	65.1775	65.1892	65.2808
Noise annoyance	-	5.0319	0.0056**	3.3333	2.4167	2.3333	2.7917
PRS-11	Being-away	3.7625	0.0199*	3.5833	4.5278	5.5000	4.6806
	Fascination	4.2974	0.0115*	2.9444	3.9722	4.8611	3.9861

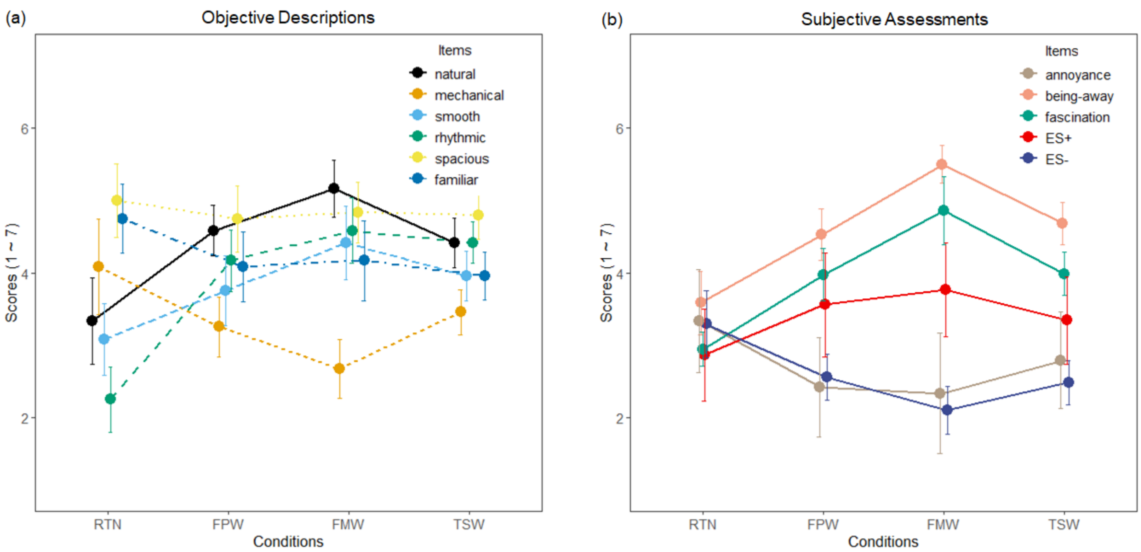


Figure 65 The results of psychological assessments: (a) the objective descriptions between four sound conditions; (b) the subjective results related to noise annoyance, two dimensions of PRS-11, and the emotion saliency between four conditions.

From the results of objective descriptors of each sound condition (naturalness, mechanicalness, smoothness, rhythmicalness, spaciousness, and familiarity), most descriptors were distinguished between four conditions. Subjects felt more mechanical and less natural with traffic noise than water sound conditions, especially for FMW conditions. And more rhythmic and smooth features were detected from FMW and TSW conditions than from traffic noise. Consider the emotional feelings used in the positive component (averaging from the scores of pleasant, attractive, stimulating, happy, energetic, calm items) of the emotional saliency's (ES+) and the negative component (ES-, averaging from the scores of unpleasant, unattractive, boring, sad, weak, nervous items) for evaluation, both emotional saliency (ES+/-) results indicated a better masking effect of all water sounds compared to traffic noise from the ANOVA post-hoc test. But no significant differences between water sound conditions were found. Specifically, the main differences existed in two positive emotional items (calm/energetic) and three negative emotional items (unpleasant/unattractive/boring). All water sounds brought more calm effects and felt less unpleasant (especially for FMW condition). FMW and FPW conditions were more energetic, less unattractive, and boring than the RTN condition (See Figure 63 and Table 40).

Table 40 the statistical results of objective descriptors and emotional saliency between four conditions. The stars indicated the significance level of the ANOVAs results: * p<0.05; ** p<0.01 and *** p<0.001.

Objective Descriptors			Emotional Saliency					
Items	F value	p value	Items	F value	p value	Items	F value	p value
Natural	3.0650	0.0415*	Pleasant	1.5290	0.2253	Unpleasant	8.1332	0.0003***
Mechanical	4.9900	0.0058**	Attractive	1.3349	0.2798	Unattractive	3.6608	0.0221*
Smooth	3.7133	0.0209*	Stimulating	0.3412	0.7957	Boring	3.7349	0.0205*
Rhythmic	8.7818	0.0002***	Happy	0.9945	0.4075	Sad	0.8112	0.4968
Spacious	0.0643	0.9784	Energetic	3.2500	0.0341*	Weak	0.7779	0.5147
Familiar	1.0372	0.3889	Calm	4.9220	0.0062**	Nervous	1.5229	0.2268
			ES+	2.9351	0.0477*	**ES-**	4.2139	0.0125*

The spectral offset differences of aperiodic component of PSD were mainly observed between different brain regions. Posterior region was significantly different from other regions under all conditions ($F(4,32)=15.675$, $p<0.001$). But there no significant changes among different acoustical conditions ($F(3,24)=0.772$, $p=0.521$). The interactions between sound conditions and brain regions suggested that the dissimilarity between brain regions of water sound conditions were greater than RTN condition ($F(12,96)=2.250$, $p=0.015$) (see Figure 66). The spectral exponent of aperiodic component of PSD didn't change differently between RTN and water sound conditions ($F(3,24)=0.757$, $p=0.529$) or brain regions ($F(4,32)=2.219$, $p=0.089$). The periodic components of PSD both revealed remarkable reactions between sound conditions ($F(3,24)=4.270$, $p=0.015$) and brain regions ($F(4,32)=7.120$, $p<0.001$). The relative power of the delta/theta/alpha/beta bands all showed significant differences among four conditions in the whole brain. All water sound conditions had higher relative power of the theta, alpha and beta bands than RTN in most of the brain regions, but less relative power of the delta band (see Table 41 and Figure 66).

Table 41 The statistical results of the spectral power of different frequency bands between four conditions from different brain regions. The stars indicated the significance level of the ANOVAs results: * p<0.05; ** p<0.01 and *** p<0.001.

Brain region	*delta*		*theta*		*alpha*		*beta*		*gamma*	
	F value	*p* value	F value	*p* value	F value	*p* value	F value	*p* value	F value	*p* value
Frontal	**6.6362**	**0.0014****	**6.2376**	**0.0020****	**8.4685**	**0.0003****	2.8987	0.0513	0.1701	0.9157
Central	**9.2271**	**0.0002****	**4.5684**	**0.0094****	**8.7576**	**0.0003****	**6.6337**	**0.0014****	0.9479	0.4299

Left	**6.4420**	**0.0017****	**5.6409**	**0.0035****	**7.4292**	**0.0007****	**3.4340**	**0.0293***	0.2519	0.8594
Right	**9.5328**	**0.0001*****	**4.6390**	**0.0088****	**8.9083**	**0.0002****	**6.7653**	**0.0013****	1.2409	0.3123
Posterior	**8.0951**	**0.0004****	**7.0535**	**0.0010****	**8.4897**	**0.0003****	**5.3710**	**0.0044****	0.5527	0.6503
Total	**8.2088**	**0.0004****	**6.0111**	**0.0025****	**8.8443**	**0.0002****	**5.0038**	**0.0062****	0.3815	0.7670

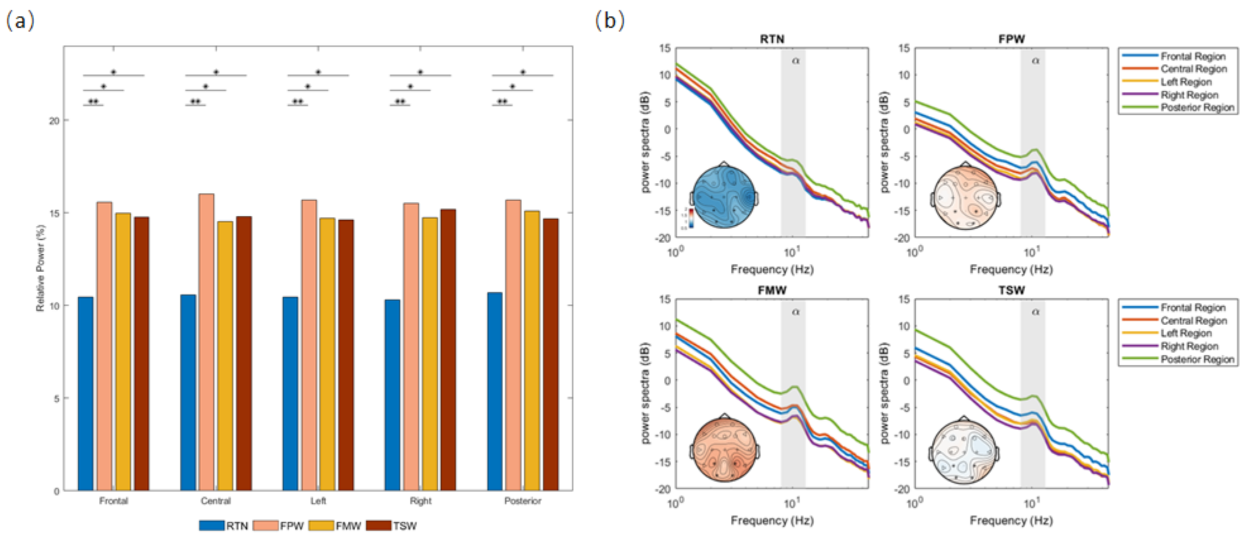


Figure 66 (a) the average relative power of alpha-band across five regions between four conditions. (b) the power spectrum (in dB) of EEG across five regions between four conditions with topography of the alpha band. Stars indicated the significance level of the post-hoc ANOVAs results: * p<0.05; ** p<0.01 and *** p<0.001.

From the ANOVA test results, the index of delta/theta ratio showed significant differences between different conditions within each brain region except frontal position. From the post-hoc multiple pairwise statistical comparisons, RTN ratios were much higher than FPW, FMW and TSW in all brain regions (see Table 42 and Figure 67). The theta/alpha ratio index showed significant changes among different conditions within each brain region. From the one-way ANOVA analysis, the ratios of RTN were clearly higher than those of FPW, FMW, and TSW in all of the regions. No significant difference of alpha/beta ratio was observed (see Table 42 and Figure 67).

Table 42 the statistical results of the EEG indexes between four conditions with different brain regions. The stars indicated the significance level of the ANOVAs results: * p<0.05; ** p<0.01 and *** p<0.001.

Brain Regions	*delta/theta*		*theta/alpha*		*alpha/beta*	
	F value	*p* value	F value	*p* value	F value	*p* value
Frontal	3.4553	0.0731	**4.5205**	**0.0099****	1.3344	0.2817
Central	**3.4553**	**0.0287***	**6.7250**	**0.0013****	0.9263	0.4400
Left	**3.2337**	**0.0361***	**4.2211**	**0.0133****	0.5451	0.6552
Right	**3.1522**	**0.0393***	**6.4841**	**0.0016****	0.4842	0.6958
Posterior	**2.9896**	**0.0466***	**4.9933**	**0.0063****	0.7580	0.5265
Total	**3.0730**	**0.0427***	**5.5617**	**0.0037****	0.8380	0.4837

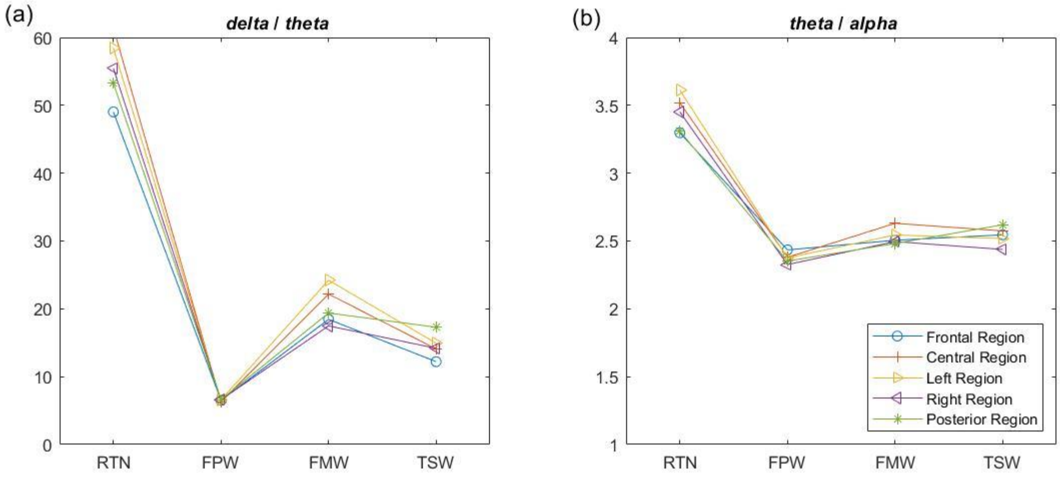


Figure 67 the mean values of delta/theta ratios (a) and theta/alpha ratios (b) across different brain regions among four sound conditions.

The dwPLI connectivity results showed significant differences between four conditions within local regions across frequency bands. In the theta band, the main changes were in the frontal, left and posterior position, while in the alpha band, they differentiated in the left and right region. The differences of the beta band and gamma band also existed in the left region. Meanwhile, the inter-regions connectivity metrics illustrated crucial changes across frequency bands. In the theta band, the connections in the frontal-left, frontal-right, frontal-posterior, left-right, left-posterior regions were significantly different among the four conditions. As for the alpha band, the connections in the central-right, left-right, left-posterior, right-posterior regions were significantly different. When it came to the gamma band, the inter-regions had large differences including frontal-left and left-posterior inter-regions (see Table 43). From the post hoc analysis of the theta band connectivity data, the coherence of the local posterior region and most inter-regions in RTN condition were significantly less than in FPW and TSW conditions. For the alpha band connectivity results, the connectivity of TSW conditions in the intra/inter regions were significantly greater than those of FPW and FMW, and the latter two were both higher than RTN condition (see Figure 68).

Table 43 the statistical results of intra-/inter-regional connectivity between four conditions. The stars indicated the significance level of the ANOVAs results: * p<0.05; ** p<0.01 and *** p<0.001.

Network	Brain region	*delta*		*theta*		*alpha*		*beta*		*gamma*	
		F value	*p* value	F value	*p* value	F value	*p* value	F value	*p* value	F value	*p* value
Intra region	frontal	1.4925	0.2366	**3.6328**	**0.0239 ***	1.3688	0.2712	0.2837	0.8368	1.0031	0.4050
	central	0.3659	0.7781	0.0278	0.9936	1.5719	0.2167	1.1691	0.3379	0.0580	0.9813
	left	0.8540	0.4756	**3.3797**	**0.0310 ***	**4.6156**	**0.0090****	**4.9673**	**0.0065****	**7.0218**	**0.0010****
	right	0.3912	0.7602	1.8957	0.1516	**6.6199**	**0.0014****	1.8784	0.1545	0.3417	0.7953
	posterior	0.5025	0.6835	**3.8078**	**0.0200 ***	2.0616	0.1264	2.4958	0.0788	0.6492	0.5896

Inter-regions	frontal-central	0.4004	0.7537	0.0936	0.9630	1.4531	0.2471	0.1524	0.9273	0.1471	0.9308
	frontal-left	0.4217	0.7388	**4.3911**	**0.0112***	1.8038	0.1678	0.8422	0.4816	**3.0285**	**0.0447***
	frontal-right	0.9658	0.4217	2.8922	0.0516	2.2519	0.1027	1.5826	0.2142	1.4573	0.2460
	frontal-posterior	2.6633	0.0659	**4.2236**	**0.0132***	1.3693	0.2711	1.2282	0.3167	1.4621	0.2446
	central-left	0.9978	0.4073	1.0194	0.3979	2.4952	0.0789	0.2999	0.8252	0.4492	0.7197
	central-right	0.7420	0.5354	0.3033	0.8228	**4.0646**	**0.0155***	1.5058	0.2331	0.1098	0.9537
	central-posterior	0.2340	0.8720	0.5529	0.6502	1.7258	0.1828	1.3036	0.2914	0.1256	0.9442
	left-right	0.2289	0.8755	**2.9389**	**0.0491***	**7.0102**	**0.0010***	0.6426	0.5936	1.2466	0.3103
	left-posterior	0.4932	0.6897	**3.3127**	**0.0332***	**3.8607**	**0.0190***	2.2195	0.1064	**3.8302**	**0.0196***
	right-posterior	1.9299	0.1460	2.6306	0.0682	**5.8032**	**0.0030****	1.5446	0.2234	0.4464	0.7216

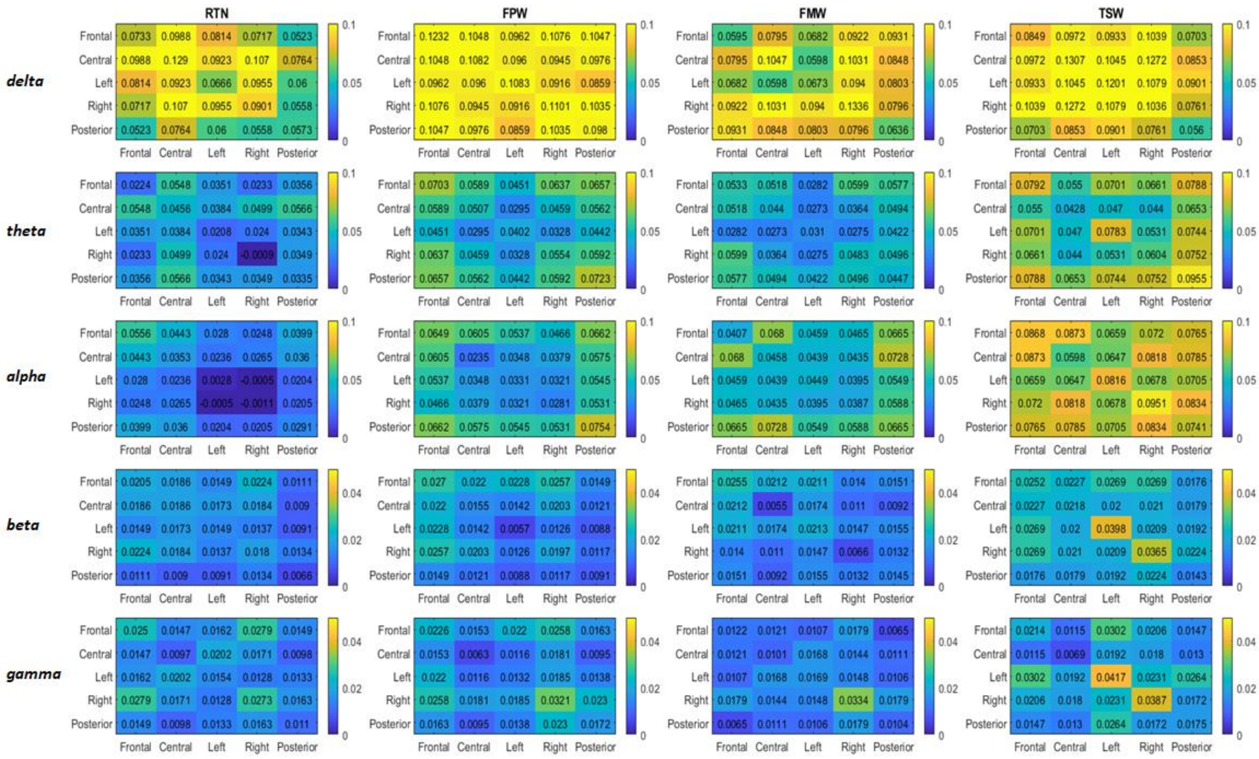


Figure 68 The connectivity matrices of five brain regions for each frequency band and sound condition.

The fixation and pupillometry data (IPA was used) showed no difference between four conditions.

8.6 General Discussion

The spatial settings of water sound (including TSW and FMW) improved the masking effects of traffic noise compared to FPW condition based on the subjective results, including noise annoyance, restorativeness qualities and emotional feelings. And the most varying position water sound, meaning the FMW condition, brought more positive emotional aspects consistently, implying the importance of the spatial arrangement of water design in urban park. Those *in situ* results were consistent with the results from online tests but not in line with our laboratory experiment. Note that the noise-masking effects of water sounds were well-recognized in this real-field study. The controversy results from laboratory experiments could be caused by the contradictory settings between the spatialized sound and the absence of visual context. Therefore, the visual context should not be ignored for investigating auditory perception. The coherence design between auditory and visual aspects for experiment efficiency should be valued for further studies and applications. Different aspects of mental states could be detected from various components of the EEG PSDs in our study. From the aperiodic offset components of each condition in our research, most activations from the occipital lobe of the brain were compared to those from other brain regions, meaning the ongoing visual-related information process (Rehman and Al Khalili, 2019) happened during each condition in real-field scenarios. And the more excitation in water sound conditions (especially for FMW and TSW) indicated the involvement of endogenous spatial attention and increased stimulus-driven salience (Beffara et al., 2022) due to the spatial variations of water sounds. Although the flattened aperiodic exponent components in water sound conditions referring to the excitation/inhibition ratio of brain activity could not be distinguished from the RTN condition statistically, they were still noteworthy for the investigations of more multisensory scenarios and experimental settings in future researches (Voytek and Knight, 2015).

The brain activities in the delta and theta bands contributed to parsing continuous acoustic streams into perceptual units in the studies of auditory perception (Teng et al., 2018; Etard and Reichenbach, 2019). Through the modulation of cortical entrainment to the sound envelope, those activities could track the acoustical rhythm (Horton et al., 2013; O'Sullivan et al., 2015) and organize acoustic information (Riecke et al., 2015; Teng et al., 2018). The related delta/theta band ratios also represented the rhythmic perceptual sampling of auditory scenes (Kubetschek and Kayser, 2021). The natural and regular water sounds masked the traffic noise and released those listening efforts based on the decrement of the delta power and delta/theta ratios based on the spectral and band ratio results. The higher relative powers of the alpha bands and lower ratios of the theta/alpha bands under spatial water sound conditions compared to the RTN condition indicated more relaxation of the mental states induced by water sounds, which is also consistent with our laboratory research. The theta/alpha ratio, often used as task load (Puma et al., 2018) of mental state or mental fatigue (Tran et al., 2020), suggests water sounds ease mental stress and fatigue caused by the background traffic noise. Moreover, the mental states induced by different water conditions did not differentiate from each other, same as aperiodic components and band ratios, indicating the spatial settings of water sounds did not influence the cognitive load or mental fatigue. Contrary to our previous laboratory experiments, the power of the beta band under water sound conditions was increased in parallel with the alpha band in the in-situ test. These changes could be attributed to the near-hand spatial arrangements of water sounds, which arousal more immersion states when subjects were experiencing the campus green space (Kruger et al., 2017; Lim et al., 2019).

In summary, the power of the alpha band and the theta/alpha ratio were two robust indicators for detecting the relaxation of mental state in noisy environments based on the consistent finding from our laboratory and in-situ studies. But in the real field, more spectral changes, including the aperiodic components correlated to visual perception, the delta and theta bands along with the delta/theta ratio could be related to auditory perception and the beta band reflecting immersion state were founded. The differences in the delta and theta oscillations between in-situ and laboratory studies could be caused by not only the added multisensory inputs in the in-situ study, but also the disparity of the characteristics of acoustical environments including the sound levels of the traffic noise and introduced water sounds. The sound level of traffic noise in the laboratory environment was 57 dB(A), while the sound level in the in-situ was 65 dB(A). The water sound levels were kept below the traffic noise at -3 dB(A), irrespective of laboratory or in-situ settings. The high-frequency bands, like the alpha and beta bands with related ratios, confirmed the positive effect of water sounds on traffic noise masking regardless of their spatial configurations. But lacking enough comparable evidence, more clarification of those results is still needed to draw solid conclusions. Therefore, further interdisciplinary studies involving building physics and neuropsychology are necessary to verify the mental implications of different aperiodic and oscillatory components from the EEG spectral results and build a ground truth about the interpretation of diverse neural responses for assessing the mental influences of different multisensory environments in urban green spaces.

Developed by Rachel and Kaplan in the 1980s, the Attention Restoration Theory asserts that people can concentrate better after spending time in nature (Kaplan and Kaplan, 1989). The theory explained the mental benefits of nature interaction based on the summary of literature that merged aesthetics and affective responses to environments as four restorative qualities, including fascination, being away, coherence, and scope, but left few descriptions about the mechanism underlying cognitive restoration and the implementation of restorative aspects of environments into urban context (Neilson et al., 2019).

Attention process raises the activities of three independent brain functional networks: alertness (vigilance, arousal), orientation (between the dorsal network and the ventral network), and execution (Petersen and Posner, 2012). The dorsal network is related to involuntary attention in the superior parietal, occipital and frontal cortex electrodes. And the ventral network refers to the control of attention focus, voluntary attention in the anterior insula, temporoparietal junction, the anterior cingulate cortex and prefrontal cortex (Proskovec et al., 2018). The level of alertness or attention arousal was observed from the records of EEG oscillations since 1929. The phenomenon that the lower power in the alpha band with the increase of the delta band was well-known as an indicator of attentional engagement (Souza and Naves, 2021). But in our results, water sounds seems released the attention engagment based on the decrease of the delta band activity and increase of the alpha band activity. And subjects were instructed to keep in a resting-state in this study, the execution of attention for tasks was omitted, although further studies with neurophysiological measurements could take advantage of this process to reveal a more informational dimension about attention restoration. Therefore, the second activity is the focus in this discussion part. Essentially, attention restoration characterizes the re-orientation of the attention process induced by external nature inputs, which attracts the activation of involuntary attention and limits the need for directed attention (Berto, 2005; Berto et al., 2010; Hartig et al., 2003; Emfield and Neider, 2014; Yap et al., 2022). The changes in spectral components and functional connectivity of EEG signals from different brain regions reported by researchers like (Chen et al., 2020b; Lin et al., 2016; Chung et al., 2018; Hopman et al., 2020; Jacob et al., 2021) provided clues to this fluctuating process. But more work is still needed to quantify this re-orientation process for measuring the restorative effects of real natural environments in real-time. This can help us propose a more efficient operational definition of the perceived restorativeness of different settings and promote more restorative features in practical urban landscape designing and management.

In our study, the alpha band connectivities in all water sound conditions (FPW/FMW/TSW) were significantly stronger than in RTN condition. In comparison, the theta band connectivities only in TSW condition were significantly higher than in other conditions. Those results were also similar and extended with laboratory study. Consistent evidence showed both connectivities in the alpha and theta band were related to attentional restoration (Klimesch, 1999b; Chen et al., 2020b). Similarly, increased brain network statistics in the alpha-theta synchronization were observed during mindful meditation (Van Lutterveld et al., 2017). Synchronization in the alpha rhythm could reflect top-down, inhibitory control processes (Klimesch et al., 2007), while that in the theta rhythm could reveal novel information encoding from external environments (Klimesch, 1999b). Thus, more restorative experiences were reflected by the responses of the alpha-theta synchronization network during the spatial water sound conditions especially for the two-position switching water sound condition.

8.7 Chapter Summary

Introducing water sounds could promote positive effects on human health for urban parks design and management. Using the digital water sound playbacks with different techniques like virtual sound production and surround sound systems, the effects of spatial variations of water sounds were illustrated within virtual/existing urban parks with neuropsychological measurements. The multisensory inputs from the spatial water sound in-situ brought more visual processing correlated to the spatial attention and stimulus-driven salience compared with laboratory environments. And the changes in the relative power of the alpha band and the ratio of the theta/alpha band among four conditions showed more relaxation state induced by the introduction of water sounds. Furthermore, different spatial configurations of water sound, especially the two-position switching setting, modulated the activity of attentional networks related to the restoration process via the alpha-theta synchronization network, reminding us of the importance of salience promotion by spatial organization for natural elements design like water sound design in urban parks.

PART IV RESEARCH CONCLUSION

CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary of Research

Preference for Natural Elements

In urban parks, no matter of visual or auditory dimensions, people prefer those natural elements. The differences in emotional salience and emotional arousal were both founded across different sensory inputs of urban parks revealed from images and audio. *Green* parks brought more positive emotion salience than *Colorful* parks, in the latter people felt better than *Square* parks, indicating the more natural settings, more positive effects could be brought by those spaces. Meanwhile, *Colorful* parks evoked more activation of emotion arousal than *Square* parks and *Green* parks, showing the colorful design could potentially help urban parks achieve more instoration effects for physical activity. As for the auditory elements, humans preferred *Natural* sounds and *Music* sounds rather than *Anthropic* sounds. More findings referred to cultural generalization were also founded. Italian and Chinese people had the same preferences for natural elements. But the emotional arousal induced by those elements in each category lacks cultural consistency. Moreover, the negative components of emotional salience of visual elements in each category also showed discrepancies between Italian and Chinese groups. Those cultural differences could suggest more variations of the human perception of the negative elements of urban parks, which reminds urban park designers and managers that more difficulties exist in controlling negative factors than promoting positive ones, and different positive elements are also needed to be the trade-off for diverse function designs.

Multisensory Interactions of Urban Park Perception

Audio-visual combinations of urban parks reveal multisensory interactions in different urban park spaces. In general, the urban park was judged more positively when more greenery elements were presented. But different sounds could influence the perception of those visual aspects. Specifically, *Bird song* in the *Colorful square* park significantly improved emotional salience. *Piano* music, improved the emotional feelings of *Gray square* park. Additionally, the *Water* sound presented with the Green space park's visual fountain significantly increased the perceptual judgment ratings. From the EEG measurements, more dynamical and procedural information were revealed by the EEG spectral power and connectivity changes during experiencing those multisensory scenarios. While *Green space* evoked theta wave for restorative experiences, high attentional vigilance from the gamma band power induced by *Gray square* and *Colorful square* spaces. Not only the natural inputs from visual dimension, but natural sounds together would also increase the connectivity in the slow wave and inhibit the activation in the fast wave, promoting the restorative effects, while anthropic sounds like traffic noise and human voice caused higher activity in the fast wave (the beta/gamma band), indicating higher cognitive load and active consciousness. Furthermore, audio-visual interaction effects were observed from those connectivity results. More inhibition founded in *Gray* and *Colorful squares* introduced by natural sounds, and higher enhancement effects aroused in the *Green-x* and *Green space* by those sounds. The alpha power and connectivity would vary for different functions in different audio-visual settings. The salience network distribution should be considered for anchoring that activity during dynamical cognitive processing in further studies.

Human-Centered Lighting Design

The overall illuminance level influences various aspects of perceived outdoor lighting qualities dominantly compared to CCT based on the Perceived Outdoor Lighting Quality questionnaire (POLQ). The illuminance level affects most items of Perceived Strength Quality (PSQ) and Perceived Comfort Quality (PCQ) except for Unfocused-Focused and Warm-Cool items, while the CCT only showed differences between Clear-Drab and Warm-Cool items. As the two POLQ indices were associated with the sense of accessibility and sense of danger, designing urban park lighting with low CCT and intermediate overall illuminance levels led to maximizing the sense of accessibility, while the counterintuitive results emerged from the PCQ index suggested further and deep research on the use of VR environments to investigate the association between PCQ and not dangerous situations. Fixation durations of the subject when free viewing the VR scenario was found to be closely related to the lightness of each fixation area. A more complex interactional effect between Overall illuminance level and CCT emerged from the IPA index, linked with the cognitive load. In particular, lighting systems with low CCT and high overall illuminance levels or with high CCT and medium overall illuminance levels may foster to minimize cognitive load in the visitors.

Urban Park Promotion with Augmented Sound Design

The augmented sound design could be deployed to introduce wanted sound into urban parks with spatial sound techniques. The augmented water sounds played in virtual space and *in-situ* both confirmed their positive effects on human emotional feelings and restorative experiences through virtual sound production and surround sound systems. Spatial organizations of water sounds are needed to consider for promoting those mental effects. With stable settings of spatial variation of the water sounds like the two-position switching setting, perceptual salience of water sounds could be enhanced for informational masking on traffic noise, and a more attentional restoration process could be induced. EEG methodology could help us understand more procedure knowledge of those processes. The changes in the relative power of the alpha band and the ratio of the theta/alpha band indicated the relaxation state induced by the introduction of water sounds. And different spatial configurations of water sound, especially the two-position switching setting, modulated the activity of attentional networks related to the restoration process via the alpha-theta synchronization network. Moreover, the multisensory inputs from the spatial water sounds in-situ brought more visual processing correlated to the spatial attention and stimulus-driven salience compared with laboratory environments, reminding us of the importance of multisensory design for urban park planning and management.

Following the Human-Centered principle of urban park design, different design techniques and assessment measurements from the multisensory perspective were explored in the thesis. Different types of urban parks with various visual and auditory elements and their combinations were investigated for promoting the mental functions of urban parks, including noise mitigation, mental restoration and physical instoration. Through multiple experimental platforms including online demonstration, virtual realties display and real field experience, the trade-off between practical control and ecological validity was explored. User responses when experiencing urban parks were evaluated. By using eye-tracking and EEG measurements, deeper insights could be obtained from those responses mainly referring to the procedural knowledge of multisensory perception in urban parks. Facing the challenges of system complexities raised from experiments developments and interpretation difficulties derived from multidimensional signals, we have tried our best to extend the methodologies for research -driven and evidence-based design of urban parks and inspire urban planners and municipal decision-makers to evaluate and foster more environmental settings for human health and well-being. Therefore, citizens could benefit more from the promoted environments based on the human-centred principles.

9.2 Contributions to Knowledge, Practice, and Impact

Contributions to Academic

An evidenced-based iterative framework was developed to assess the objective and subjective outcomes of multisensory inputs in urban parks from Human-Centered approach. Multidimensional analysis has been conducted for subjective assessments, and cross-modal analysis has been deployed to unveil the multifaceted interplay between urban parks and human perception. Those methodologies could provide fundamental references for future studies to develop applications and new computational approaches to promoting urban parks for human wellbeing.

Contributions to Practice

Based on the findings of the studies in the thesis, designers and managers should care more about the negative elements for their bigger variations on human perception of urban park design, and natural elements should be encouraged from both auditory and visual aspects for diverse function designs. And their combinations also need to consider from the multisensory interaction perspective. Green space with visual-auditory coherent design could promote human mental effects like attentional restoration and noise masking while a colorful design strategy could be deployed for physical activity instoration. And the space for mobility and rest could use calm sounds like piano music to improve citizen's experience. The combination of audio-visual stimuli should be used for different space design strategies to achieve different functions. Designers could manage the salience of different environmental settings and promoting multisensory perception through salience increasement of positive components and decreasement of negative components in urban landscape planning.

Not just for the daytime using, the perception of urban park users should also be considered for lighting design. At nighttime, before aesthetical appreciation, urban park visitors would view the road, spatial signage, trees under the lighting area to generate cognitive map for physical activity, mobility etc. The overall illuminance level influences the fixation time of the lit place with the perceived qualities. The lighting design should match the light level with visual information of the elements in urban parks for optimizing visual communication design. Particularly, lighting systems with low CCT and high overall illuminance levels or with high CCT and medium overall illuminance levels may foster to minimize cognitive load in the visitors.

Digital methods could be an alternative strategy when the introductions of natural elements are not possible or not economically efficient. Virtual water sounds could promote positive effects on human health for noise masking and attentional restoration. And by using the spatial variation settings, the perceptual salience of water sound could be strengthened and cause more restoration activities. More strategies could be inspired from the salience promotion by the spatial organization for natural elements design like water sound in urban parks.

Research Impact

The Human-Centered approach is centred on human/user of urban parks. It considers citizens as place-makers, therefore, their perception and reactions determine the functions and values of urban park places. Relying on advanced wearable sensing technology, revealing the dynamical process of human perception in real-time is possible. Through EEG and eye tracking measurements, deeper insights of multisensory perception of physical inputs from urban park users could be obtained. More design strategies could be deployed by identifying the concrete mental effects and optimizing the positive effects. The human centered approach will enable urban planners and policymakers to explore different urban park elements and their combinations on human well-being and they can prioritize, plan, monitor, and allocate resources to optimise the positive effects and constrain the negative aspects.

9.3 Limitations and Future Research

Certain limitations exist in the studies. The number of participants is relatively small due to the COVID-19 situation during the whole research program, especially for the *in situ* study we conducted in Hong Kong, and future studies should include larger and more diverse participants. Facing the same problem with the limited participants sample, the sample of urban parks is also confined to local places, including the Parco Pozzi (Aversa, Italy) and the campus park (PolyU, Hong Kong). More urban parks where various space forms are accomplished should be involved for further studies.

Although wearable sensor technologies have significantly developed, the shortness of those measurements still needs more effort to overcome. The precision loss caused by the head motion should be valued for eye-tracking in the virtual reality platform. And same situation happened in *in-situ* with even more near-infrared imaging problems caused by outdoor light. This could harm the detection sensitivity of human gaze behaviors and be failed to get robust experimental results. As for EEG measurements, the sacrifices of limited channels and low signal-noise ratio for more portable setups should be noted. More importantly, those setups increase the discomfort for participant wearing while doing the experiments. This could influence participants' reactions and restrain the reliability of research outputs. Further studies with neural-behavioural measurements should be conducted with more advanced techniques to overcome those shortages.

To reveal the potential prospect of a Human-Centered approach to urban parks design, cross-modal measurements with sufficient technical details have been explored in the studies. But the research contents are confined to limited aspects, including the resting-state of participants for multisensory perception of urban parks and the perceptual effects of urban parks on noise mitigation, attentional restoration and emotional promotion for conducting more comparable studies with EEG-eye tracking measurements. More physical states of urban park visitors and viewers should be explored, such as urban walking, urban biking, urban playing, etc. Certainly, urban parks are much more than those three functions mentioned in the thesis, including aesthetical values, social interaction, etc. Further research should be conducted to understand the influence of more space forms of urban parks on those aspects. And more hybrid techniques for interactive designs between real-world/virtual environments and humans are also necessary to explore more profound and multifunctional effects of urban parks on human-wellbeing.

PUBLICATION

Conference paper publications

Li, Jian, Masullo, M., & Maffei, L. (2020, October). Using Eye Tracking to Investigate the Audio-Visual Effect of Landscape Perception: A Research Review. In INTER-NOISE and NOISE-CON Congress and Conference Proceedings (Vol. 261, No. 4, pp. 2955-2966). Institute of Noise Control Engineering.

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Li, Jian, Maffei, L., Pascale, A., & Masullo, M. (2022, August). Using spatialized water sound sequences for traffic noise mitigation: correlation analysis of subjective evaluation and neural measurements. In 24th International Congress on Acoustics (ICA 2022 Korea).

Masullo M., Cioffi F., ***Li Jian***, Maffei L., Iachini T., Ruggiero G., Ruotolo F. (2023, June). Traffic noise mitigation in urban multisensory environments: a virtual reality approach to urban sound planning. In IFAU23 IV International Forum for Architecture and Urbanism Climate Change and Cultural Heritage.

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Li, Jian, Maffei, L., Pascale, A., & Masullo, M. (2022). Effects of the spatialisation of water-sounds sequences on the perception of traffic noise. Vibrations in Physical Systems, 33(1).

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I would like to emphasize that any errors or omissions in this thesis are entirely my responsibility.

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18/07/2023

APPENDIX

Appendix A: Questionnaire for Image/Audio Assessments of Urban Park

ITEMS:

How much the stimulus (image/sound) is

PLEASANT	1	2	3	4	5	6	7	8	9
	Not at all								Extremely
UNPLEASANT	1	2	3	4	5	6	7	8	9
	Not at all								Extremely
STIMULATING	1	2	3	4	5	6	7	8	9
	Not at all								Extremely
BORING	1	2	3	4	5	6	7	8	9
	Not at all								Extremely
ATTRACTIVE	1	2	3	4	5	6	7	8	9
	Not at all								Extremely
UNATTRACTIVE	1	2	3	4	5	6	7	8	9
	Not at all								Extremely

How much the stimulus (image/sound) makes you feel

CALM	1	2	3	4	5	6	7	8	9
	Not at all								Extremely
NERVOUS	1	2	3	4	5	6	7	8	9
	Not at all								Extremely
WEAK	1	2	3	4	5	6	7	8	9
	Not at all								Extremely

ENERGETIC	1	2	3	4	5	6	7	8	9
	Not at all								Extremely
HAPPY	1	2	3	4	5	6	7	8	9
	Not at all								Extremely
SAD	1	2	3	4	5	6	7	8	9
	Not at all								Extremely

Appendix B: Questionnaire for Lighting Experiment

How do you rate the PARK LIGHTING:

Subdued	-3	-2	-1	0	1	2	3	Brilliant
Strong	-3	-2	-1	0	1	2	3	Weak
Dark	-3	-2	-1	0	1	2	3	Light
Unfocused	-3	-2	-1	0	1	2	3	Focused
Clear	-3	-2	-1	0	1	2	3	Drab
Hard	-3	-2	-1	0	1	2	3	Soft
Warm	-3	-2	-1	0	1	2	3	Cool
Natural	-3	-2	-1	0	1	2	3	Unnatural
Glaring	-3	-2	-1	0	1	2	3	Shaded
Mild	-3	-2	-1	0	1	2	3	Sharp

Appendix C: Questionnaire for Augmented Sound Design

Questionnaire

1. Your e-mail:

2. Age:

3. Sex:

- (•) Male
- ( ) Female

4. Handedness:

- ( ) Left Handed
- ( ) Right Handed

5. Residential Area:

- ( ) Historical Center
- ( ) Intermediate Area
- ( ) Suburban
- ( ) Rural Area

6. Employment:

- ( ) Student
- ( ) House-wife/husband
- ( ) Pensioner
- ( ) Employee
- ( ) Self Employed
- ( ) Unemployed

7. Type of Work:

- Office Work
- Work in an indoor environment that does not involve physical effort
- Work in an indoor environment that involves physical effort
- Outdoor work that does not involve physical effort
- Outdoor work that involves physical effort
- Work that takes place both inside and outside

8. Select for each statement below, the number 1 (Extremely unlikely) to 6 (Extremely likely) based on how much the statement describes your attitude towards noise.

	Extremely unlikely	Unlikely	More or less unlikely	More or less likely	Likely	Extremely likely
I am more aware of noise than I used to be.						
At movies, whispering and crinkling candy wrappers disturb me.						
I am easily awakened by noise.						
If it is noisy where I am studying, I try to close the door or window or move somewhere else.						
I am good at concentrating no matter what is going on around me.						
I get used to most noises without much difficulty.						
How much would it matter to you if an apartment you were interested in renting was located across from a fire station?						
When I want to be alone, it disturbs me to hear outside noises.						
I find it hard to relax in a place that is noisy.						

	Extremely unlikely	Unlikely	More or less unlikely	More or less likely	Likely	Extremely likely
It would not bother me to hear the sounds of everyday living from neighbors (footsteps, running water, etc.).	◌	◌	◌	◌	◌	◌
There are often times when I want complete silence.	◌	◌	◌	◌	◌	◌
Even music I normally like will bother me if I am trying to concentrate.	◌	◌	◌	◌	◌	◌
Sometimes noises get on my nerves and get me irritated.	◌	◌	◌	◌	◌	◌
I would not mind living on a noisy street if the apartment I had was nice.	◌	◌	◌	◌	◌	◌
I am sensitive to noise.	◌	◌	◌	◌	◌	◌
Motorcycles ought to be required to have bigger mufflers.	◌	◌	◌	◌	◌	◌
In a library, I do not mind if people carry on a conversation if they do it quietly.	◌	◌	◌	◌	◌	◌
I would not mind living in an apartment with thin walls.	◌	◌	◌	◌	◌	◌
No one should mind much if someone turns up his stereo full blast once in a while.	◌	◌	◌	◌	◌	◌
I get mad at people who make noise that keeps me from falling asleep or getting work done.	◌	◌	◌	◌	◌	◌
I get annoyed when my neighbors are noisy.	◌	◌	◌	◌	◌	◌

9. Please indicate for each of the 5 statements which is closest to how you have been feeling over the past 2 weeks.

	All of the time	Most of the time	More than half the time	Less than half the time	Some of the time	At no time
I woke up feeling fresh and rested.	◌	◌	◌	◌	◌	◌
I have felt calm and relaxed.	◌	◌	◌	◌	◌	◌
I have felt active and vigorous.	◌	◌	◌	◌	◌	◌

	All of the time	Most of the time	More than half the time	Less than half the time	Some of the time	At no time
I have felt cheerful and in good spirits.	◌	◌	◌	◌	◌	◌
My daily life has been filled with things that interest me.	◌	◌	◌	◌	◌	◌

Now the formal online test is begining.

You will hear different kinds of water sound mixed with traffic noise, please follow the instruction to answer each question while listening these sounds.

Attention**! Please assure the environment is quiet and you are undisturbed. Please wear a good quality headphone with correct earphones. Please keep your head steady while listening each audio.**

Now please adjust your system volume according to the sound below and make the human voice you heard like 1 meter away from you.

10. What extent do you presently hear the following different type of sounds?

	Not a lot	A little	Moderately	A lot	Dominates completely
Road Traffic	◌	◌	◌	◌	◌
Water Flow	◌	◌	◌	◌	◌
Other	◌	◌	◌	◌	◌

11. What is the number of sound sources you hear presently?

	0	1	2	More than 2
Road Traffic	◌	◌	◌	◌
Water Flow	◌	◌	◌	◌
Other	◌	◌	◌	◌

12. To what extent do you feel annoyed by the following sounds?

	Not at all	Slightly	Moderately	Very	Extremely
Road Traffic	◌	◌	◌	◌	◌
Water Flow	◌	◌	◌	◌	◌
Other	◌	◌	◌	◌	◌

13. Select for each descriptor below, the number (1-not at all to 7-extremely) based on how much the descriptor describes the sound you presently heard:

	1 Not at all	2	3	4	5	6	7 Extremely
Chaotic	◌	◌	◌	◌	◌	◌	◌
Pleasant	◌	◌	◌	◌	◌	◌	◌
Attractive	◌	◌	◌	◌	◌	◌	◌
Exciting	◌	◌	◌	◌	◌	◌	◌
Natural	◌	◌	◌	◌	◌	◌	◌
Smooth	◌	◌	◌	◌	◌	◌	◌
Monotonous	◌	◌	◌	◌	◌	◌	◌
Calm	◌	◌	◌	◌	◌	◌	◌
Eventful	◌	◌	◌	◌	◌	◌	◌
Familiar	◌	◌	◌	◌	◌	◌	◌
Spacious	◌	◌	◌	◌	◌	◌	◌
Boring	◌	◌	◌	◌	◌	◌	◌
Unattractive	◌	◌	◌	◌	◌	◌	◌

	1 Not at all	2	3	4	5	6	7 Extremely
Uneventful	○	○	○	○	○	○	○
Stimulating	○	○	○	○	○	○	○
Mechanical	○	○	○	○	○	○	○
Rhythmic	○	○	○	○	○	○	○
Unpleasant	○	○	○	○	○	○	○

14. Select for each descriptor below, the number (1-not at all to 7-extremely) based on how much the descriptor describes your feeling about the sound you presently heard:

	1 Not at all	2	3	4	5	6	7 Extremely
Calm	○	○	○	○	○	○	○
Nervous	○	○	○	○	○	○	○
Weak	○	○	○	○	○	○	○
Happy	○	○	○	○	○	○	○
Sad	○	○	○	○	○	○	○
Energetic	○	○	○	○	○	○	○

15. The following questionnaire is used to evaluate your experience in places like this. Please read every sentence carefully and then evaluate on a scale from 0 to 10 as each statement corresponds to your experience in this place. To choose your answer mark only one of the numbers on the scale next to each statement with a cross. For example, if you think that the sentence does not correspond at all to your experience in this place mark "0" (not at all), if you think that the sentence matches enough but not completely to your experience, then mark a number from "1 "to" 9 "that reflects what you think about your experience in this place, but if you think that the sentence corresponds very much to your experience in in this place, then mark" 10 "(very much).

	0 Not at all	1	2	3	4	5	6	7	8	9	10 Very much
In places like this my attention is drawn to many interesting things.											
In places like this everything seems to have its proper place.											
To get away from things that usually demand my attention I like to go to places like this.											
To stop thinking about the things that I must get done I like to go to places like this.											
There is a clear order in the physical arrangement of places like this.											
That place is large enough to allow exploration in many directions.											
Places like that are fascinating.											
In places like this it is easy to see how things are organized.											
Places like that are a refuge from nuisances.											
In places like this it is hard to be bored.											
In places like that there are few boundaries to limit my possibility for moving about.											

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