POLITECNICO DI TORINO

Master's Degree in Architcture construction city
A.A. 2024/2025
Sessione di Laurea Luglio 2025

Master's Degree Thesis

The New Civic Central Library of Torino: a study of the perceived simulated noise and its effects on cognitive performance

Supervisors

Prof. ARIANNA ASTOLFI

Prof. LOUENA SHTREPI

Candidate

IOANA GROZEVA

JULY 2025

Summary

As libraries evolve in the recent years into multifunctional environments that support study, collaboration, and cultural activities, effectively managing their indoor sound environments has become increasingly important. In such settings, noise is not only a potential source of distraction but also a factor that may influence cognitive performance and user's comfort. These challenges are further amplified in heritage buildings, where architectural interventions are often limited. This study examines the acoustic environment of the New Civic Central Library of Torino, a historically protected structure with a volume of approximately 160,000 m^3 and a reverberation time of around 6 seconds at mid frequencies. Given its future role as a hub for reading, social interaction, and public events, it is essential to assess how background noise affects both user perception and cognitive performance to inform effective planning and sound management. To simulate a realistic soundscape, detailed three-dimensional modeling was carried out using the acoustic software Odeon 18, with geometrical acoustic simulations performed at five receiver positions corresponding to typical user locations. Simulated sound sources included urban traffic (transmitted through the ceiling), HVAC systems (on the floor and balconies), as well as human-related activity sounds such as unintelligible and intelligible buzz as well as spoken sentences that were syntactically correct but semantically meaningless, footsteps, page turning, pen clicking. The simulation was based on a highly accurate 3D model of the library, with surface absorption and scattering coefficients carefully assigned to each material to reflect real-world conditions. The resulting A-weighted sound pressure levels ranged from 50.2 to 61.8 dB, representing moderate noise levels that may still interfere with concentration in study-oriented settings. To complement the simulation data, an experimental study was conducted involving 50 participants (aged 20–61, all with normal hearing), who completed cognitive tasks under both quiet and noise conditions. Although no statistically significant differences in task performance were observed between the two conditions, subjective reports revealed varying levels of perceived disturbance and focus. A slight trend toward increased arousal in the presence of background noise was noted, though without clear cognitive detriment. These findings underline the complexity of assessing auditory comfort in large, multifunctional library spaces, especially when architectural constraints limit physical acoustic treatment. The study highlights the value of advanced simulation tools in evaluating complex sound environments and proposes a replicable methodology that integrates detailed physical modeling with user-centered perceptual testing. The insights gained are directly applicable to the ongoing development of the new Central Civic Library of Turin, supporting informed design decisions that balance heritage preservation with acoustic functionality.

Acknowledgements

First and foremost, I would like to express my deepest gratitude to God for helping me reach this important step in my life. He gave me the strength and the chance to make my dream come true. A huge thank-you goes to my family, to whom I dedicate this thesis and everything I've achieved so far. They've always stood by me, supporting me through every challenge. Without their constant help, patience, and encouragement, I wouldn't be here today. Finally, but not least, I would like to express my sincere gratitude to Professors Arianna Astolfi and Louena Shtrepi, as well as to the entire research group I had the pleasure of working with, for their invaluable guidance throughout this rewarding journey in the field of acoustics. Their constant support, availability, and kindness played a crucial role not only in the successful completion of this project but also in providing meaningful insights that I will carry with me into the future.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

In recent decades, libraries have evolved into multifunctional spaces that go far beyond their traditional role as quiet sanctuaries for reading and study. While older libraries were often designed with grand reading rooms, high vaulted ceilings, and reflective materials that naturally encouraged silence and self-restraint, contemporary libraries serve a much broader set of purposes. They now host a diverse array of activities, from collaborative work and group learning to cultural events, digital media engagement, and social interaction. This transformation has resulted in an increasingly complex soundscape, where managing acoustic comfort poses new challenges for designers and researchers. The presence of overlapping functions within the same architectural environment, such as quiet study areas adjacent to cafes or children's sections, complicates the traditional notion of what a library should sound like. As libraries become more inclusive and dynamic, noise levels have risen, particularly during peak hours. This new reality has made it difficult to balance the need for quiet with the vibrancy of shared public use. Modern library design must now consider a wide range of acoustic sources, including human activity, HVAC systems, noise from traffic and multimedia content. Consequently, there is growing recognition that traditional acoustic parameters are no longer sufficient for evaluating these environments. Instead, attention has shifted toward user-centered approaches and the study of the indoor acoustic environment and the way people perceive it.

It is within this broader context that the new Civic Central Library of Torino is being developed. Located inside one of the historic Torino Esposizioni complex pavilions, a vast, highly reverberant space subject to cultural heritage restrictions, the library presents a unique case. The building's surfaces cannot be acoustically modified, and its architectural features were not originally designed to support multifunctional modern use, such as the one of a library. Nevertheless, the new library aims to combine conventional functions like reading and individual study with more contemporary concepts of digital engagement, social activity, and open cultural exchange, all within the same open-space environment. This thesis explores how such a setting, characterized by acoustic constraints and diverse usage patterns, might impact cognitive performance and user perception. A comprehensive research methodology was adopted to assess these aspects, integrating literature review, acoustic modeling, and experimental testing. Through this approach, i.e. combining spatial acoustic simulation with human-centered testing, the thesis investigates not only the direct impact of noise on cognitive performance but also the perception of the simulated acoustic environment.

Chapter 2

Literature research

2.1 Research methodology

To investigate the existing literature on the topics this study aims to analyze, a scoping review methodology was employed, as it aligns with the exploratory nature of this research. Rather than addressing a narrowly focused question or evaluating the effectiveness of specific interventions, this approach aims to map the breadth, scope, and nature of research activity in the field. While systematic reviews are designed to answer specific research or policy questions, often involving strict inclusion criteria, critical appraisal, and quantitative synthesis, the topics analyzed in the present study span multiple disciplines, including architecture, environmental psychology, sound engineering, and information science. This diversity in study types and methodological approaches makes a scoping review the most suitable strategy, as it allows for inclusive synthesis without excluding relevant contributions due to methodological heterogeneity. Scoping reviews are particularly effective for identifying research gaps, thematic patterns, and conceptual ambiguities, which are essential for informing future research directions and supporting evidence-based design or policy decisions.

2.2 Protocol

The literature research was conducted in accordance with the PRISMA-ScR 2018 checklist, a standardized reporting guideline consisting of 22 essential items organized into key sections: title, abstract, introduction, methods, results, discussion, and funding. These items are intended to ensure transparency, methodological rigor, and reproducibility, while allowing flexibility in the inclusion of heterogeneous evidence. The PRISMA-ScR checklist also supports a systematic approach to data collection and synthesis, facilitating the identification of research gaps, thematic patterns, and areas of conceptual ambiguity. This protocol guided all stages of the literature research, from formulating the research question to selecting and charting relevant studies, culminating in a thematic synthesis of findings. Figure 2.1 summarizes visually the process showing the most important steps that have been considered. The full checklist of the 22 reporting items as well as more information about the process and the protocol can be found on the official website of PRISMA: https://www.prisma-statement.org/scoping.

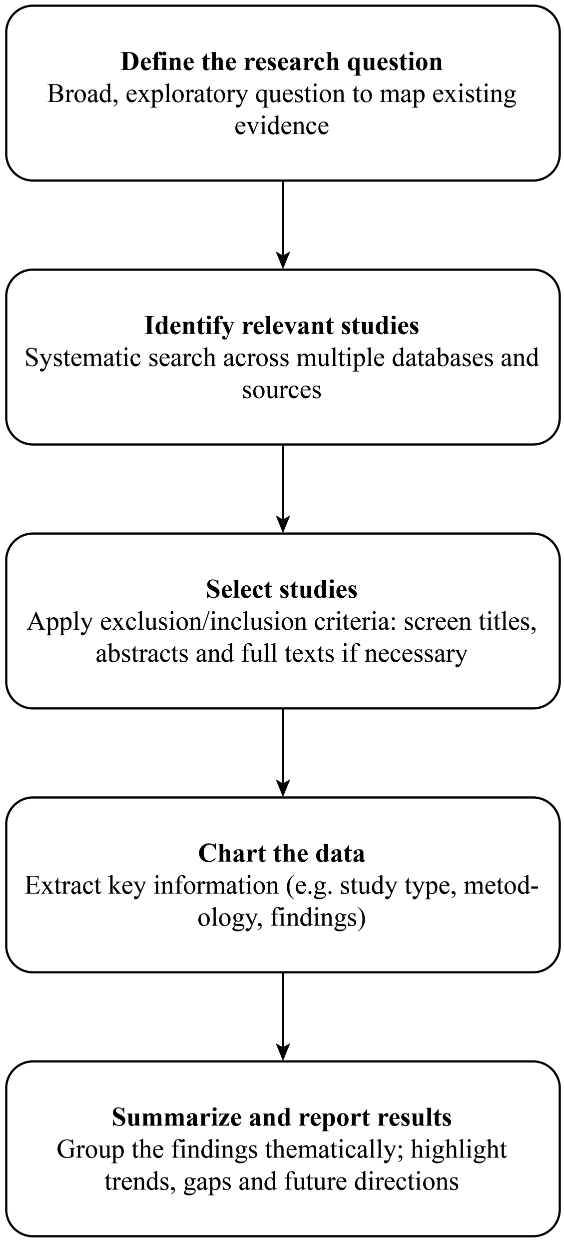


Figure 2.1: Scoping review process based on PRISMA-ScR 2018 guidelines.

2.3 Eligibility conditions

The submitted papers had to fulfill the following requirements for review:

- Document type: article or review article;

- Conduct studies on the acoustics of libraries;
- Conduct studies on the effect of noise on cognitive activities;
- Conduct studies on the relation between noise and emotions;
- Contain the search terms within the title and/or the abstract and/or the keywords;
- Official language of the publication: English;
- Period of publication: 2015–2025;
- Document availability: full text.

2.4 Sources of information

The sources of information used for the research were exclusively well-known, official and scientific platforms such as Scopus, Web of Science and ERIC.

2.5 Research execution

In the period of May 2st and May 4th 2025, the literature research was conducted using the scientific databases specified in Section 1.5. The papers were required to address the research questions and meet the established eligibility conditions reported in Section 1.4. No additional selection conditions were applied during the research. Table 2.1 illustrates the two research questions of this study as well as the terms with which was done the research.

Table 2.1: Summary of Research Questions and Corresponding Search Terms

Research Question	**Terms Used for the Research**
What are the main characteristics of the acoustics of the libraries?	acoustics OR soundscape AND of AND libraries OR modern AND libraries OR traditional AND libraries

Research Question	Terms Used for the Research
How does noise affect cognitive performance?	libraries AND effect AND of AND noise AND on AND cognitive AND performance OR cognitive AND ability OR cognitive AND impairment OR cognitive AND test OR informative AND background AND noise OR meaningful AND noise OR arousal

2.6 Identification and selection of relevant evidence

Firstly, the publications identified for the analysis contained the terms from the research questions either in the title, in the abstract, or as keywords. Then, a preliminary screening was conducted based on titles and abstracts. Where relevance could not be determined from these alone, full-text articles were retrieved and assessed to ensure alignment with the eligibility criteria.

2.7 Data extraction process

Once the relevant studies were selected, they were carefully reviewed following the PRISMA-ScR guidelines. The evidence mapping procedure, typical for scoping reviews, involved systematically extracting key information from each paper, including authorship, year of publication, journal's name, study design, population/sample characteristics, methods and main findings. A standardized data extraction form was used to ensure consistency and transparency throughout the process.

2.8 Data elements

For the first research question, the selected papers were analyzed with a specific focus on the acoustic conditions of the libraries. Particular attention was also given to the architectural nature of the libraries, mainly the typology and the overall concept, distinguishing between contemporary and traditional library designs. For the second research question, the selected papers were investigated focusing on the effect of noise on cognitive performance. Special attention was paid to main concepts in this topic such as Arousal theory, noise sensitivity, and individual characteristics. In general, both the researches took into consideration the characteristics of the population involved in the experiments, and the methodologies employed in the case studies.

2.9 Restitution of the results

To present the results of the research, a tabular method was chosen. The outcomes from each study were organized into tables containing information relevant to the research. For the first research question, which focuses on library acoustics, the table highlights not only general information such as the authors but also details about the type of library examined in the referenced paper, including the library's name, its conceptual design as either traditional or modern, and key acoustic parameters such as sound pressure level (SPL) and reverberation time (RT). The table outlines also the case study analyzing the conducted experiment by providing information about the study's aim, the population involved, the methodology used, the experimental results, as well as any additional findings reported by the authors.

Chapter 3

Research N.1

3.1 Research N.1 – Acoustics of libraries in the world

Search terms: acoustics OR soundscape AND of AND libraries OR modern AND libraries OR traditional AND libraries

Although the acoustics of libraries remain an underexplored research area, existing studies provide a meaningful overview of the current state of knowledge. Findings suggest that spatial layout and user activity often have a greater impact on acoustic comfort than measured sound levels. Users tend to prefer a moderate, lively background noise over complete silence. While new buildings can effectively integrate acoustic treatments, historic buildings present unique challenges due to preservation constraints and a lack of targeted research. These insights support the need for user-centered acoustic strategies across both modern and heritage environments suggesting the soundscape approach.

3.2 Identification and selection of the relevant papers

Figure 3.1 illustrates the search and selection process conducted in the initial review. The database search yielded 575 papers. After eliminating duplicates 481 unique records remained. These were assessed for relevance by examining their titles and abstracts, and in cases requiring further clarification, the full texts were reviewed. From this process, 8 papers were identified as relevant. A subsequent review of their reference lists led to the inclusion of 2 additional articles, resulting in a final total of 10 papers included in the review. As illustrated in Figure 3.2, the publication dates of these articles range from 2016 to 2024, with the majority having been published in 2016 and in 2024.

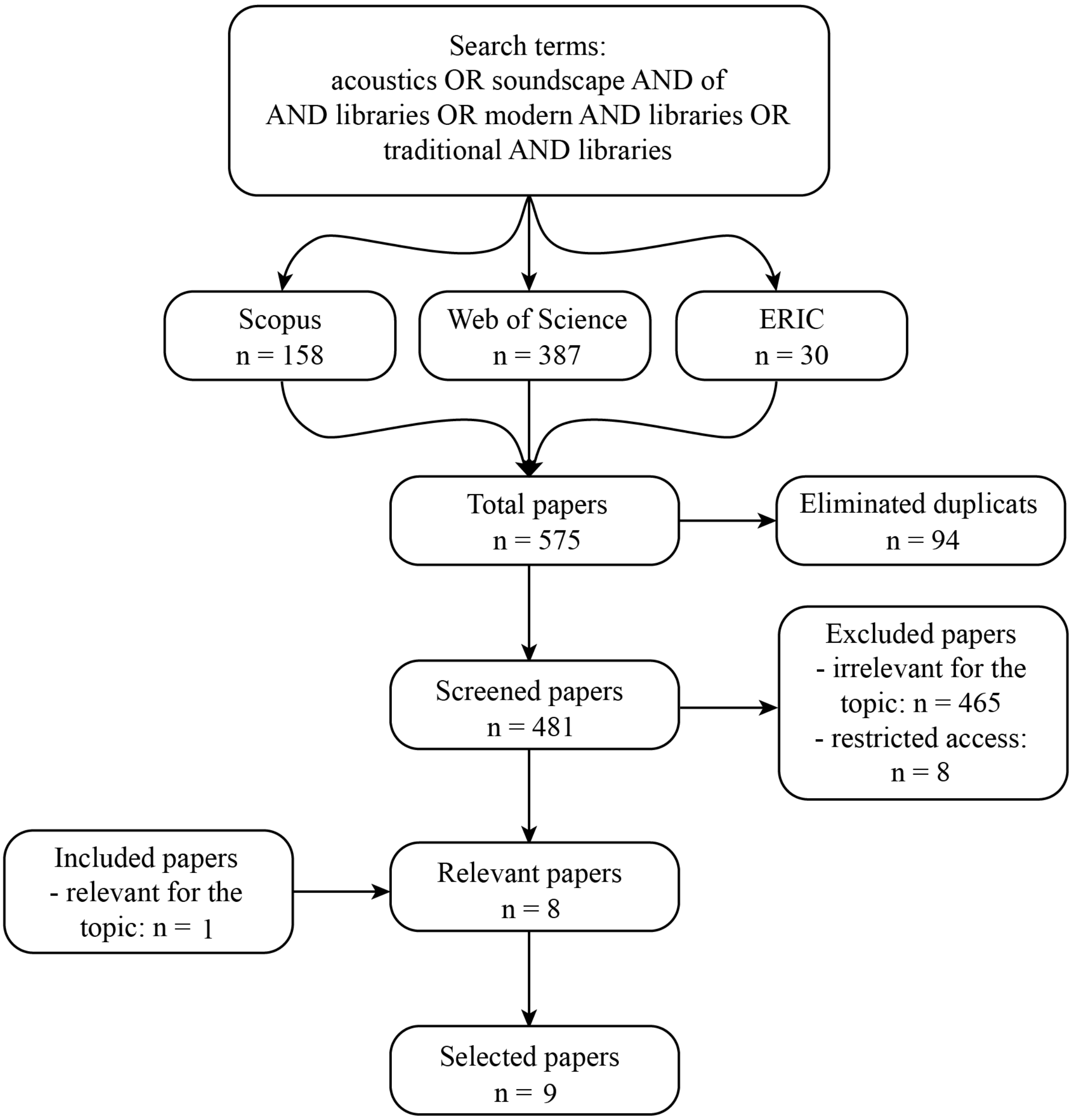


Figure 3.1: Workflow for database identification and selection of the relevant papers.

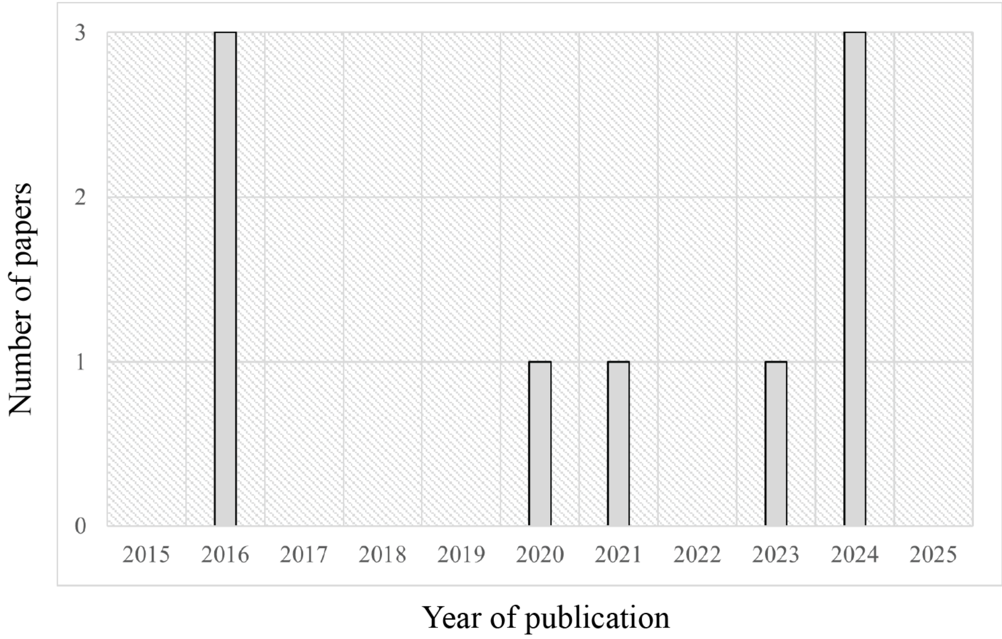


Figure 3.2: Publication years of the selected papers for Research N.1.

3.3 Analysis of the selected papers

Figure 3.1 presents the general information for the ten studies included in the review. The sections that follow provide an overview on the methodologies used to assess the acoustic quality in the studied environments as well as a review of the acoustic conditions in both contemporary and traditional historical libraries.

Table 3.1: Summary of the articles from Question 1

Title	Authors	Journal	Year of publication	CASE STUDY - BUILDING		CASE STUDY - EXPERIMENT			
				Investigated place	Concept (modern/traditional)	Aim of the study	Sample dataset	Investigation methodology	Findings
Application of Machine Learning Techniques for Predicting Students' Acoustic Evaluation in a University Library	Zhang et al.	Acoustics	2024	A university library in Hong Kong, China	contemporary	1) investigate the potential of using machine learning methods to anticipate how students assess acoustic environments in a university library context 2) provide deeper insights into how acoustic characteristics influence user satisfaction and overall experience	398 students 1 library 4 reading rooms	• on-site data collection: sound pressure levels (SPL) were measured, and participants completed questionnaires assessing acoustic perception along with providing basic personal information • preliminary analysis: data were cleaned and screened, followed by correlation and relationship assessments to identify relevant predictive variables • machine learning exploration: models were trained and compared to determine the most effective approach for predictive analysis	• individual characteristics play a key role in shaping how students perceive and assess the acoustic environment, and should therefore be treated as critical variables in related evaluations • the study confirms the potential of machine learning as a reliable tool for predicting users' acoustic assessments within educational settings
Investigating library users' perceived indoor environmental quality: SEM-Logit analysis study in a university library	Hou et al.	Journal of Building Engineering	2024	A university library in Hong Kong, China	contemporary	determine the main elements that shape user satisfaction regarding indoor environmental quality (IEQ) in a modern academic library, taking into account both users' perceptions of IEQ and their individual traits	404 students 1 library 4 reading rooms	An integrated methodological framework using Structural Equation Modeling (SEM) and Generalized Ordered Logit Regression (GOLRM) is applied to investigate how indoor environmental variables and personal traits influence perceived comfort within indoor spaces, as measured through surveys.	• adapting library environments to accommodate varied user preferences has a significant positive effect on user satisfaction • incorporating both environmental conditions and individual user characteristics into library design is essential for creating supportive and effective spaces • users' impressions of interior layout and acoustic conditions play a direct role in shaping their overall satisfaction with the indoor environment

Title	Authors	Journal	Year of publication	CASE STUDY - BUILDING		CASE STUDY - EXPERIMENT			
				Investigated place	Concept (modern/traditional)	Aim of the study	Sample dataset	Investigation methodology	Findings
A soundscape approach to exploring design strategies for acoustic comfort in modern public libraries: a case study of the Library of Birmingham	Xiao and Aletta	Noise mapping	2016	Library of Birmingham, UK	contemporary	examine the experience of acoustic comfort in a contemporary public library and assess how the sound environment is perceived in terms of quality, with particular attention to how the spatial layout supports reading and writing tasks performed by users	12 students 1 library 4 floors of the library	This study employed a modified version of the "soundwalk" technique to investigate the characteristics of the library's soundscape. Simultaneously, sound pressure levels (SPL) were recorded at each designated observation point.	• soundscape quality differed across floors, and these variations could not be fully explained by general suitability or measured sound pressure levels alone • the spatial configuration of the library emerged as a key factor influencing users' perception of acoustic comfort • the study identified three distinct patterns of soundscape perception: communicative and interactive, adaptive engagement, and quiet reflection for reading and thinking
Indoor soundscape in primary school classrooms	Visentin et al.	The Journal of the Acoustical Society of America	2023	Three schools' classrooms	-	assess how children personally perceive the existing acoustic environment in their classroom and explore their preferences regarding an ideal soundscape	143 children 3 primary schools	This research adapted the 'soundscape' approach using a questionnaire.	• school environments often expose children to disturbing or unpleasant noise during daily activities • grade level, perceived loudness in unoccupied rooms, and how frequently children hear voices from adjacent classrooms all significantly influence their acoustic experience
Perceived productivity in open-plan design library: Exploring students' behaviors and perceptions	Kim et al.	Journal of Learning Spaces	2021	Dorothy M. Crosland Tower, Atlanta, USA	contemporary	investigate how different patterns of library use (such as individual study, group work, or co-presence without interaction) relate to the use of available resources, satisfaction with ambient conditions and spatial layout, perceived environmental support, and users' sense of productivity within the library setting	66 students	This study applied a user-centered perspective by utilizing a questionnaire to gather data on individual perceptions and experiences.	• students show distinct spatial preferences based on their intended activity, such as studying alone, collaborating in groups, or working individually in a shared setting within the library • despite the library's design aiming to promote student interaction and group collaboration, only about 36% of students reported preferring the library for group work, opting instead for alternative locations like communal areas or departmental spaces • clearly designated zones within the library would assist students in choosing spaces that align with their specific work needs and intended use

Title	Authors	Journal	Year of publication	CASE STUDY - BUILDING		CASE STUDY - EXPERIMENT			
				Investigated place	Concept (modern/traditional)	Aim of the study	Sample dataset	Investigation methodology	Findings
Acoustic performance of contemporary public libraries: an evaluation of public libraries in Melbourne, Australia	Rajagopalan et al.	Architectural Science Review	2016	7 public libraries in Melbourne: State Library of Victoria, City Library, North Melbourne Library, Kathleen Syme Library, Southbank Library, East Melbourne Library, Library at the Dock	traditional / contemporary	investigate the acoustic conditions of seven public libraries	-	This study employed a mixed-methods approach, combining quantitative noise level measurements with qualitative data gathered through on-site observations.	• high noise levels in public libraries can pose difficulties for users who need quiet environments for reading and studying • recent library constructions reflect a more integrated and holistic design strategy, where acoustics are considered as important as other functional and performance-related aspects • although certain noise problems have been addressed in other types of buildings, managing indoor noise remains a relevant issue in many modern public libraries
The Historical Building and Room Acoustics of the Stockholm Public Library (1925–28, 1931–32)	Fleming	Acoustics	2024	Stockholm Public Library	traditional	describe the fundamental historical acoustic features of the library's central rotunda and reading rooms	-	In the library, assessments were carried out to measure background noise levels, reverberation time, as well as airborne and impact sound insulation performance.	the evolution of modern architecture during the 1920s and 1930s was closely intertwined with advancements in architectural acoustics and construction techniques, reflecting a mutually influential relationship among these disciplines.
Analysing Sound Environment and Architectural Characteristics of Libraries through Indoor Soundscape Framework	Yorukoglu and Kang	Archives of acoustics	2016	Western Bank Library, Information Commons Library, St. George's Library, Sheffield, UK	contemporary	present a novel framework for indoor soundscaping and provide a structured explanation of the key variables that influence how an indoor sound environment is assessed overall	-	Audio recordings were employed to examine key acoustic parameters such as sound pressure level (SPL) and perceived loudness (N), while architectural analysis methods and theoretical frameworks were applied to assess the selected library spaces.	• specific configurations of layout, volume relationships, and spatial orientation result in varying levels of sound pressure (SPL) and loudness (N) • greater overall spatial volume, including features like atrium height and openness, tends to produce higher SPL and loudness values • the number of occupants within a space has a direct impact on both sound pressure levels and perceived loudness

Title	Authors	Journal	Year of publication	CASE STUDY - BUILDING		CASE STUDY - EXPERIMENT			
				Investigated place	Concept (modern/traditional)	Aim of the study	Sample dataset	Investigation methodology	Findings
The Soundscape of Twenty-First-Century Libraries	Siebein et al.	Acoustical Society of America	2020	Library of the Ringling College of Art and Design in Sarasota, FL, USA	contemporary	investigate the evolution of library architecture and layout over time, highlighting how design strategies have changed across different historical periods	-	Literature review	• contemporary libraries, characterized by large and multifunctional open areas, demand a comprehensive approach to acoustic planning, incorporating diverse soundscape design strategies to ensure optimal acoustic conditions • design elements such as spatial distance, surface materials, furnishings, partial-height dividers, traditional walls and doors, and varying ceiling heights and finishes can be strategically employed to act as sound buffers and filters, minimizing acoustic interference between adjacent zones

[1]Zhang, D., Mui, K.-W., Masullo, M., & Wong, L.-T. (2024). Application of machine learning techniques for predicting students' acoustic evaluation in a university library. Acoustics, 6, 681–697. https://doi.org/10.3390/acoustics6030037.

[2]Hou, H. (C.), Lan, H., Lin, M., & Xu, P. (2024). Investigating library users' perceived indoor environmental quality: SEM-Logit analysis study in a university library. Journal of Building Engineering, 93, 109805. https://doi.org/10.1016/j.jobe.2024.109805.

[3]Xiao, J., & Aletta, F. (2016). A soundscape approach to exploring design strategies for acoustic comfort in modern public libraries: A case study of the Library of Birmingham. Noise Mapping, 3, 264–273. https://doi.org/10.1515/noise-2016-0018.

[4]Visentin, C., Torresin, S., Pellegatti, M., & Prodi, N. (2023). Indoor soundscape in primary school classrooms. The Journal of the Acoustical Society of America, 154(3), 1813–1826. https://doi.org/10.1121/10.0020833.

[5]Kim, Y., Hong, S., & Yang, E. (2021). Perceived productivity in open-plan design library: Exploring occupant behavior and perception. Journal of Learning Spaces, 10(3). https://libjournal.uncg.edu/jls/article/view/2104.

[6]Rajagopalan, P., Nguyen, H. T. H., & Carre, A. (2017). Acoustic performance of contemporary public libraries: An evaluation of public libraries in Melbourne, Australia. Architectural Science Review, 60(2), 104–115. https://doi.org/10.1080/00038628.2016.1265483.

[7]Fleming, P. H. (2024). The historical building and room acoustics of the Stockholm Public Library (1925–28, 1931–32). Acoustics, 6, 754–771. https://doi.org/10.3390/acoustics6030041.

[8]Dokmeci Yorukoglu, Papatya & Kang, Jian. (2016). Analysing Sound Environment and Architectural Characteristics of Libraries through Indoor Soundscape Framework. Archives of Acoustics. 41. 10.1515/aoa-2016-0020.

[9]Siebein, G. W., Siebein, K. M., Roa, M., & Paek, H. G. (2020). The soundscape of twenty-first-century libraries. Acoustics Today, 16(4), 57–66. https://doi.org/10.1121/AT.2020.16.4.57.

3.4 The soundscape approach

The conducted research showed that modern approaches to acoustic design tend to prioritize the regulation of sound pressure levels and reverberation times, adjusting them according to the type of activity performed in a given space. This is typically achieved through the use of materials engineered to absorb, diffuse or resonate sound. Nonetheless, conventional noise control strategies, based mainly on physical measurements such as the A-weighted equivalent sound pressure level, often cannot represent efficiently the complexity of acoustic environments and tend to overlook how users actually experience those spaces. In response, more attention is now being given to psychoacoustic parameters, including loudness, which better reflect how sound is perceived by the human ear [1]. Unlike traditional methods, the soundscape perspective adopts a user-centered view, focusing on how individuals perceive and interpret sounds within a specific spatial and contextual framework. This approach integrates both quantitative acoustic measurements and the subjective experiences of users, with the aim of improving overall comfort. Research into indoor soundscapes has progressively incorporated variables such as architectural design, acoustic performance, and user perception, positioning sound not only as a potential disturbance, but as an integral part of the environment with the potential to enhance well-being. Soundscape analysis looks at how various sound sources interact with spatial configurations and user expectations, supporting the creation of environments that are both acoustically functional and emotionally pleasant. This broader shift reflects a growing consensus in the literature toward rethinking acoustic design from a user-focused rather than a purely building- or regulation-oriented standpoint, an evolution that is particularly relevant in educational environments [2, 3]. According to ISO 12913-1, a soundscape is defined as "the acoustic environment as perceived and/or understood by a person or people in context" [4]. This emphasizes that auditory perception is context-dependent and influenced by factors such as the user's role, their ongoing activities, and the specific characteristics of the space. While most of the foundational work in soundscape research has concentrated on outdoor settings, where perceptual models based on dimensions like pleasantness and eventfulness have been formalized [5, 6], there is a rising interest in extending this framework indoors, especially in relation to health, comfort, and quality of life [2, 7].

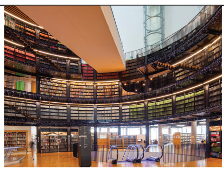
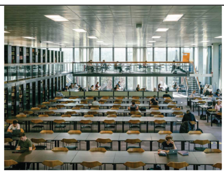
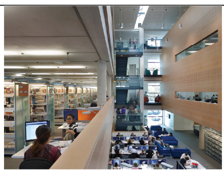
3.5 Acoustics of contemporary libraries

A recent study evaluated the Library of Birmingham [1], a typical example of a modern public library built in 2013, with large open-plan reading spaces and multiple functions, including a café, lecture rooms, a children's section, performance spaces, etc. A mixed-method approach was adopted involving noise measurements and a socio-acoustic questionnaire. Results revealed no straightforward correlation between measured sound levels and user expectations for different spaces. Using an adapted "soundwalk" method, 12 architecture students assessed SPL values that were around 57 dB(A) and shared their subjective impressions. Findings indicated that users in reading zones were more sensitive to verbal noise, while social areas were more tolerant of both verbal and non-verbal sounds. Generally, users preferred a moderately lively sound environment over silence. Similarly, Dokmeci and Kang [8] examined three Sheffield libraries with similar architectural layouts: Western Bank Library built in 2013, Information Commons library built in 2007, and St. George's Library built in 1992, showing that spatial features significantly influence SPL and loudness. Average sound pressure levels of 56.5 $\pm$ 1.9 dB(A), 51.3 $\pm$ 2.0 dB(A), and 57.8 $\pm$ 3.7 dB(A) were recorded for volumes of 1548 m^3, 1945 m^3, and 2667 m^3, respectively, indicating that there is no correlation between the two variables. Instead, spatial configurations such as atriums, interconnected zones, and overlapping spaces had a greater impact on acoustic parameters. Crowding also raised SPL and loudness in foyer areas. It should be noted that some modern libraries have successfully integrated acoustic treatments. At the Library at the Dock in Melbourne [9], built in 2014 and constructed from cross-laminated timber, the recorded indoor noise levels were between 41.5 and 48.5 dB(A). Measures such as carpeted floors and perforated wooden ceilings proved effective in noise reduction.

3.6 Acoustics of traditional historical libraries

While achieving good acoustic conditions in new libraries is relatively straightforward through design interventions, historic libraries present greater challenges due to limited research and preservation constraints. Most existing work on historical acoustics has focused on performance venues like theaters and churches [10], where speech and musical clarity are essential. Libraries, however, are unique because they prioritize quiet reading environments, necessitating consideration of both room and building acoustics [8]. Recent research on Victoria State Library [9], built in 1854 and known for its iconic domed La Trobe Reading Room, with a 35-meter-high domed ceiling and a volume of 32000 m^3, showed that recorded noise levels are from 45 to 47.6 dB(A) in workshops and 38.7 to 43.4 dB(A) in reading rooms during early mornings. Peak daytime activity raised levels to 47.2–52.2 dB(A) and 56.5–61.4 dB(A) in reading and workshop areas, respectively, with key sources being HVAC systems and external traffic. In another reading room, the Redmond Barry reading room, with a volume of 12000 m^3, the background noise level is 49.7 dB(A) and the reverberation time is up to 2.5 s. Another monumental building, the Stockholm Public Library [11] where the main Reading Room has a volume of 12000 m^3, was assessed during nighttime measurements between 10 PM and 3 AM due to daytime renovation works. Despite being unoccupied, background noise from metro lines and urban activity resulted in SPLs ranging from 35.6 to 50.1 dB(A) in the Reading Room. Additionally, noise level measurements were conducted by the Authors in several historic libraries in Paris, in 2024. The Richelieu Library's Main Reading Room, built in 1856 and with a 19,600 m^3 volume, recorded 47 dB(A). Similar levels were found at the multifunctional Beaubourg Library built in 1997, while Saint-Geneviève Library, a traditional quiet study space, built in 1851, showed slightly higher SPLs of 49–53 dB(A), despite its 20,400 m^3 size. Table 3.2 represents the most significant libraries chosen for the analysis and their main architectural and acoustic characteristics.

Table 3.2: Architectural and acoustic characteristics of the reading rooms of libraries in the world.

Library	Location	Year	Volume [m³]	SPL [dB(A)]	RT [s]
 Birmingham	Birmingham, UK	2013	-	57	-
 Western Bank	Sheffield, UK	1959	1945	54–58	-
 Information Common	Sheffield, UK	2007	2667	49–53	-
 Saint George	Sheffield, UK	1992	1548	54–62	-
 At the Dock	Melbourne, Australia	2014	-	41.5–48.5	-

Library	**Location**	**Year**	**Volume [m³]**	**SPL [dB(A)]**	**RT [s]**
 Victoria State, La Trobe Reading Room	Melbourne, Australia	1854	32000	47.2 - 52.2	5.6
 Victoria State, Redmond Reading Room	Melbourne, Australia	1854	12000	49.7	2.5
 Stockholm Public	Stockholm, Sweden	1925–28	12000	36–50 (unoccupied)	5–6
 Richelieu	Paris, France	1856	19600	47	-
 Saint-Geneviève	Paris, France	1843–50	20400	49–53	-
 Beaubourg	Paris, France	1977	17000	47	-

Chapter 4

Research N.2

4.1 Research N.2 – Effects of noise on cognitive performance

Search terms: libraries AND effect AND of AND noise AND on AND cognitive AND performance OR cognitive AND ability OR cognitive AND impairment OR cognitive AND test OR informative AND background AND noise OR meaningful AND noise OR arousal

Numerous studies have shown that noise can impair cognitive functions, particularly attention and short-term memory, especially when the sound is variable or intelligible, such as speech. However, findings are not always consistent, as the impact depends on factors like noise type, task difficulty and individual sensitivity. Prolonged exposure to high noise levels can lead to stress, fatigue, and reduced motivation, indirectly affecting performance. Individuals with high noise sensitivity tend to be more vulnerable to both the emotional and physical effects of noise. According to the Arousal theory, in some cases, moderate levels of noise may temporarily enhance activation and efficiency in simple tasks.

4.2 Identification and selection of the relevant papers

The initial review process involved a systematic search that identified 3886 papers, as shown in Figure 4.1. After removing duplicates and retracted papers, 3304 papers were retained. These were screened for relevance based on their titles and abstracts, with full-text reviews conducted for clarification when necessary. This process resulted in 10 relevant papers. Additional 4 articles were included following their reference lists, bringing the total number of studies included in the review to 14. As shown in Figure 3.2, these publications span from 2020 to 2025, with most appearing in 2020 and 2023.

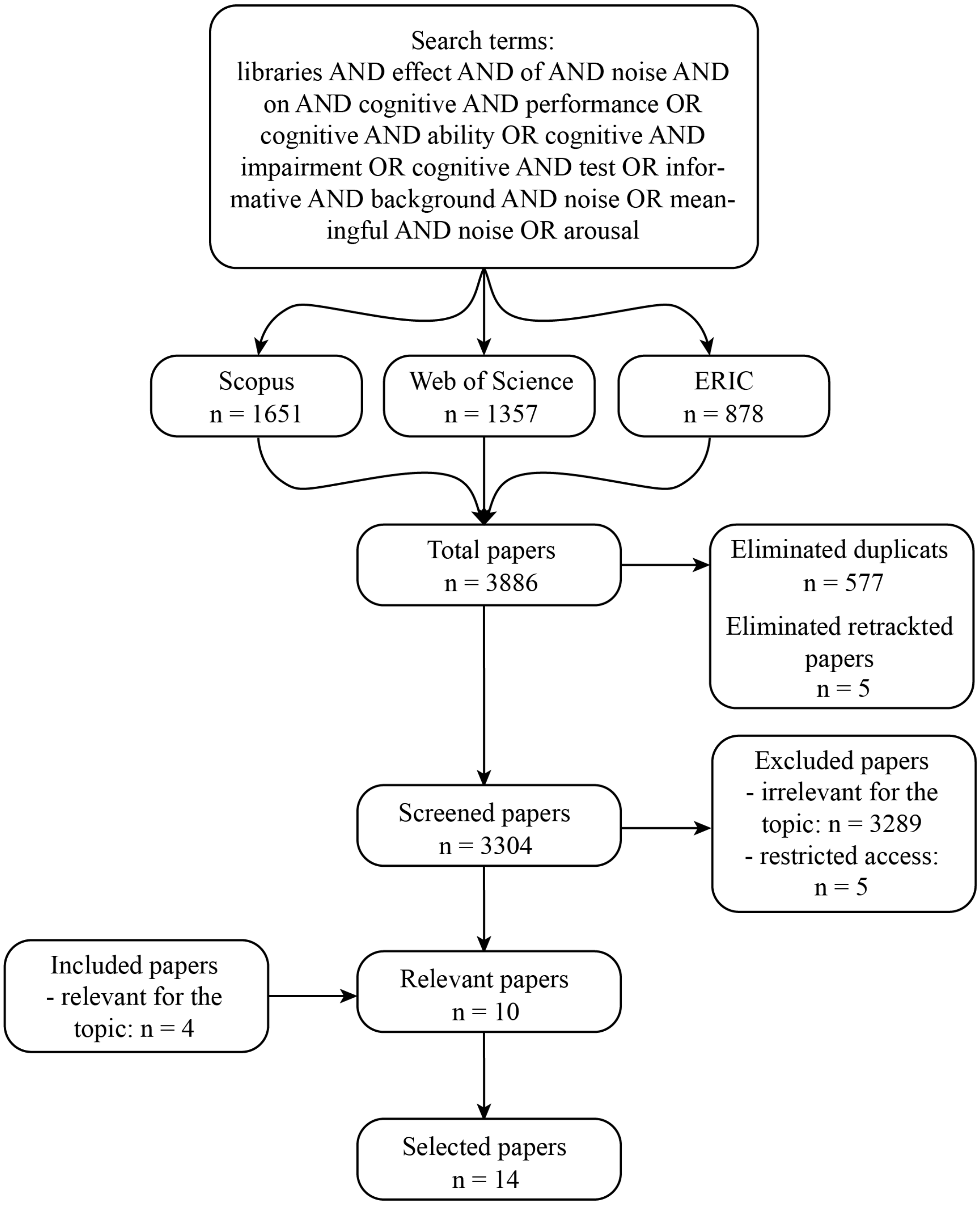


Figure 4.1: Workflow for database identification and selection of the relevant papers.

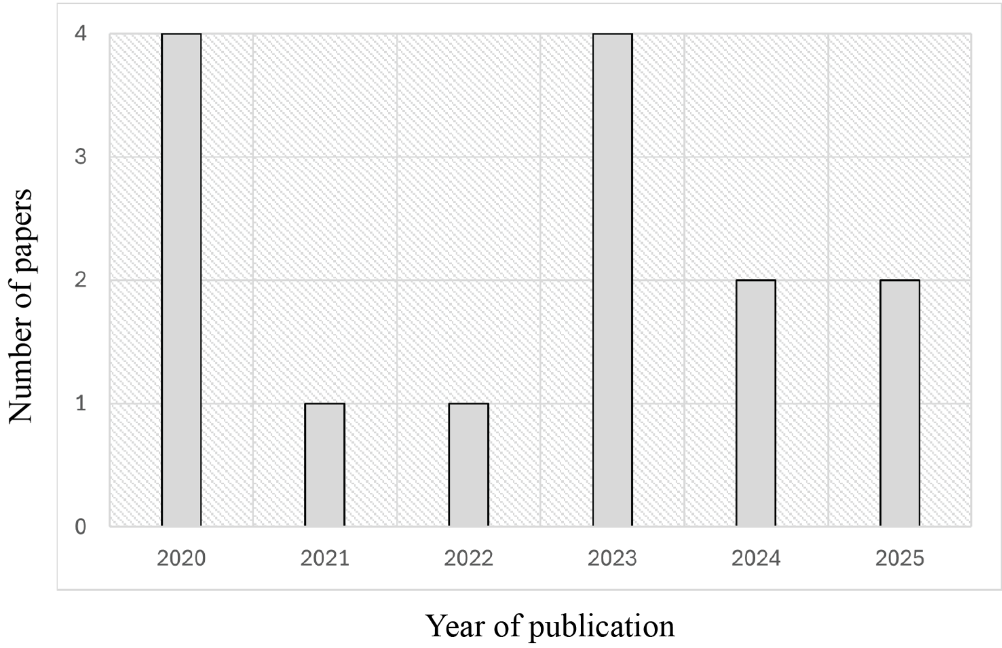


Figure 4.2: Publication years of the selected papers for Research N.2.

4.3 Analysis of the selected papers

Table 4.1 presents the general information for the 14 studies included in the review. The sections that follow provide an overview on the effect of noise exposure on cognitive performance, the arousal theory, and the effect of the noise sensitivity and individual differences.

Table 4.1: Summary of the articles from Question 2

Article	Authors	Journal	Year of publication	Aim of the study	Sample	Study design	Type of noise	Type of test	Effect of noise on cognitive performance	Findings
Experimental Evaluation of Noise Exposure Effects on Subjective Perceptions and Cognitive Performance	Zhang et al.	Buildings	2024	•examine the impact of high-intensity noise on cognitive performance, particularly executive functions, and explore the moderating role of emotional state in shaping this relationship	12 college-age students	within-subject design with repeated mesures	Three continuous noise conditions: • 75 dB(A) • 80 dB(A) • 85 dB(A) The precise type of noise is not specified.	Seven computer-based cognitive tests: • Hearing threshold test (perception) • Duration discrimination test (perception) • Frequency discrimination test (perception) • PVT test (Attention) • 2-back test (Working memory) • Mental arithmetic test (Mental arithmetic) • Stroop test (Executive function)	mixed	• lowering noise levels led to improvements in perceived sound quality, enhanced emotional responses, and better auditory processing, while also reducing the likelihood of false alarms and increasing task execution speed • emotional state plays a moderating role in the connection between noise exposure and cognitive task performance • optimal performance in the Psychomotor Vigilance Task (PVT) was observed when noise levels were reduced from 85 dBA to 80 dBA • in the Stroop test, both overall and conflict-specific reaction times improved significantly when noise dropped from 85 dBA to 80 dBA, but remained stable when noise was further reduced to 75 dBA
Effects of noise on employees during a concentration task: Results from performance and subjective assessments and a critical view of the chosen performance test	Sukowski	Applied Acoustics	2025	• study the effects of noise on cognitive performance and well-being	68 adults	within-subject design with repeated mesures; laboratory study	Four acoustic conditions: • silent condition • checkout at fashion retailer with 62 dB(A) (sounds from the checkout process, speech from employees, customers waiting at the checkout or passing this point, music, or sounds caused by the workflow of other colleagues) • multi-space office with 50 dB(A) (speech from different persons and different distances, such as conversations inside the office, but also sounds from doors or footsteps of passing colleagues) • construction site with 65 dB(A) (sounds from different machines used on the site at different distances as well as construction vehicles)	• Concentration-performance test (KLT-R) (Mental arithmetic)	negative	• participants completed a slightly higher number of items in the quiet condition compared to the noise-exposed conditions • performance improved significantly during the second test session, with more correct responses than in the initial session
Effects of Noise Type and Noise Sensitivity on Working Memory and Noise Annoyance	Song et al.	Noise Health	2022	• investigate how different types of noise and individual sensitivity to noise influence working memory performance and perceived annoyance	60 people	within-subject design with repeated measures; questionnaires and experiments	Three sound conditions: • quiet: 35 dB(A) • road traffic noise: 70 dB(A) • speech noise, pure human voice dialogue, meaningful noise but not task-related: 70 dB(A)	• The working memory task was based on the N-back paradigm, specifically a 2-back test, in which participants had to identify whether the number currently displayed matched the one shown two steps earlier on the screen.	negative	• the combined influence of noise type and individual sensitivity to noise significantly impacted working memory accuracy • participants exposed to road traffic noise performed less accurately than in silent conditions, suggesting that this type of noise interfered with concentration and hindered task performance • both the type of noise and the participants' sensitivity levels had a notable effect on reaction times
The Effects of Noise on Children's Cognitive Performance: A Systematic Review	Gheller et al.	Environment and Behavior	2023	• examine various noise sources and categories to understand their cognitive effects and how they influence children's learning processes • assess which executive functions and educational activities are particularly vulnerable to disruption from both verbal and non-verbal noise • explore the role of individual differences, such as age, attention span, and memory capacity, in shaping or moderating how noise impacts children's cognitive performance and academic outcomes	26 studies	systematic review following the PRISMA statement	Different sound conditions with different SPLs: • speech noise multitalker babble noise • speech noise single-talker intelligible • unintelligible speech noise • road traffic noise • aircraft noise • classroom activity noise	Cognitive tasks testing the most common exectuive functions: • working memory • problem-solving • creativity • reading	negative	• children's verbal working memory is particularly vulnerable to interference from speech-related noise • environmental noise that does not involve speech can significantly hinder academic performance, especially in tasks related to reading • some non-verbal noise sources may actually enhance cognitive performance, but primarily among children with lower levels of attentional control • exposure to babble noise at 40 dB has been shown to significantly reduce children's attentional focus, with this effect observed regardless of age • noise has also been found to negatively impact creative thinking abilities

Article	Authors	Journal	Year of publication	Aim of the study	Sample	Study design	Type of noise	Type of test	Effect of noise on cognitive performance	Findings
Indoor soundscape, speech perception, and cognition in classrooms: A systematic review on the effects of ventilation-related sounds on students	Pellegatti et al.	Building and Environment	2023	• evaluate how sound stimuli generated by natural and mechanical ventilation systems in classrooms influence students' speech intelligibility, cognitive performance, and overall comfort perception	37 studies	systematic review following the PRISMA statement	Different sound conditions with different SPLs ranging between 30 and 79 dB(A): • traffic noise • aircraft noise • fan noise • human noise (ranged from 55 to 75 dB(A)) • railway noise	Cognitive tasks testing: • memory (single-word repetition) • attention (phonological awareness, Simple reaction time) • language skills (sentence recognition) • mathematical skills	mixed	• introducing fan noise at 40 and 50 dBA significantly reduced performance in episodic memory tasks, while semantic memory remained stable across noise levels • natural ventilation in classrooms generally had neutral or negative effects, depending on the type of task and the nature of the noise present • environmental sounds entering through open windows, such as those from nature, were associated with improved learning outcomes and greater comfort, whereas human-related noise tended to produce no benefit or even hinder performance
The Influence of Noise Exposure on Cognitive Function in Children and Adolescents: A Meta-Analysis	Fernández-Quezada et al.	NeuroSci	2025	• conduct a structured review of research examining how noise exposure affects cognitive functioning in children and adolescents	8 studies	systematic review following the PRISMA statement	Different sound conditions with different SPLs ranging between 55 and 80 dB(A): • aircraft noise • traffic noise • environmental noise	Cognitive tasks testing: • verbal and non-verbal reasoning, • problem-solving • memory • processing speed • numerical figural reasoning	negative	• exposure to noise has a detrimental impact on cognitive functioning in both children and adolescents • the extent and nature of this impact can differ based on variables specific to each study, including the type of noise, the demographic characteristics of the sample, and the research design employed
The effect of the acoustic environment of learning spaces on students' learning efficiency: A review	Liu et al.	Journal of Building Engineering	2023	• investigate how varying acoustic conditions influence students' ability to learn effectively	67 studies	systematic review	Different sound conditions with different SPLs ranging between 44 and 85 dB(A): • traffic noise • speech • aircraft noise • natural environmental noise • music	Cognitive tasks testing: • reading comprehension • memory • math skills • listening	mixed	• different types of sound sources influence learning efficiency to varying degrees • higher sound pressure levels are associated with reduced learning performance • background speech contributes to cognitive decline and increases perceived distraction • noise from traffic and spoken voices are particularly disruptive to learning activities • speech that is clearly intelligible poses a greater threat to memory tasks than other background sounds • once ambient sound levels exceed 50 dBA, the negative impact on performance becomes more evident • extended reverberation time may enhance cognitive outcomes, as it tends to obscure environmental noise and reduce the intelligibility of distracting speech
Does background sounds distort concentration and verbal reasoning performance in open-plan office?	Liu et al.	Applied Acoustics	2020	• investigate how six common types of background noise typically found in office settings influence individuals' concentration and verbal reasoning abilities	79 people	within-subjects design with repeated measures that consisted of an objective evaluation (cognitive tasks) and subjective evaluation of activation and annoyance	Six kinds of sound conditions presented at three different conditions with 40 dBA, 50 dBA, and 60 dBA: - music group: • running water sound • pure classic music • classic music with lyrics - noise group: • intelligible speech • mechanical noise of keyboard and printer • telephone ring - queit condition (ambient sound that consisted mainly of the ventilation system,) with 30 dB(A)	• Feature matching task: participants were required to rapidly determine whether two visually similar shapes presented on the screen shared identical or differing features • Grammatical reasoning task: participants were shown a sentence describing a relationship between two geometric figures (a square and a circle) displayed beneath it. Their task was to evaluate whether the sentence correctly matched the visual arrangement and respond by selecting "True" or "False"	mixed	• participants exposed to background noise experienced greater declines in task performance compared to those who listened to music • intelligible speech had the most detrimental effect on both concentration and verbal reasoning tasks • while background sounds generally increased arousal, exposure to 60 dBA sounds resulted in a negative arousal rating • low-intensity background music was shown to support concentration to some degree, reinforcing the notion that background noise and music affect cognitive performance differently • in tasks requiring concentration, higher noise intensity was linked to stronger performance impairments, whereas background music at moderate frequencies produced the most beneficial effects

Article	Authors	Journal	Year of publication	Aim of the study	Sample	Study design	Type of noise	Type of test	Effect of noise on cognitive performance	Findings
The effects of environmenta noise on children's cognitive performance and annoyance	Zhang and Ma	Applied Acoustics	2021	• investigate how varying noise levels and types affect children's subjective perception of annoyance • assess the impact of different noise conditions on children's performance in cognitive tasks • analyze how noise influences distinct cognitive processes to determine which are more vulnerabl to disruption	248 students	within-subjects design with repeated measures	Different sound conditions with SPLs ranging from 35 dB(A) to 65 dB(A) with a 5 dB(A) difference: • road traffic noise • low-frequency noise • white noise	Different cognitive tasks testing: • attention task: participants were asked to identify a specific target image from a sequence of rapidly presented slides, count its occurrences, and record the correct total • short-term memory task: a slide displaying four items (e.g., images, numbers, or letters) appeared for five seconds, followed by another slide showing only three of the original items; participants had to recall and identify the missing element • mathematical ability task: participants completed seven sets of arithmetic exercises to assess calculation skills • reading comprehension task: participants read four short texts and answered questions designed to evaluate their understanding of the material	mixed	• noise level influenced participants' perceived annoyance but had little direct impact on cognitive task outcomes, regardless of the noise type • cognitive performance was more affected by the nature of the noise than by its volume, particularly in younger children • interactions between noise characteristics and non-acoustic variables, such as age and gender, significantly shaped both annoyance ratings and task performance • younger children were more sensitive to different types of noise, with low-frequency sounds generally producing the most pronounced negative effects on cognition • boys demonstrated greater vulnerability to noise compared to girls, both in terms of perceived annoyance and performance impacts • complex cognitive tasks were more negatively influenced by noise exposure than simpler ones • in reading and math-related activities, low-frequency noise had a more disruptive effect on younger children tha typical road traffic noise
The effects of irrelevant speech on physiological stress, cognitive performance, and subjective experience – Focus on heart rate variability	Radun et al.	International Journal of Psychophysiology	2024	• investigate the use of heart rate variability (HRV) as a simple, non-invasive indicator of stress in the context of an irrelevant speech task paradigm	30 people	within-subjects design with repeated measures. The condition served as a withinsubject variable, while the presentation order was a between-subjects variable.	Two sound conditions: • quiet condition given mostly by ventilation systems (33 dB(A)) • irrelevant speech given by level-equalized sentences (50 dB(A))	• N-back test for the reaction time (press "YES" each time the presented letter was the same as that presented n letters back) • Visual serial recall task: participants were asked to memorize and recall a series of nine digits displayed in a random order on the screen	negative	• performing tasks in the presence of irrelevant speech, as opposed to silence, led to lower accuracy in verbal serial recall, increased perceived annoyance and workload, and a decline in perceived sound environment quality • when participants were first exposed to the speech condition, their accuracy in the 3-back task decreased, and response times for serial recall increased • conversely, when silence was the initial condition, participants exhibited slower reaction times in the 3-back task under quiet compared to speech conditions
Irrelevant speech effect in open plan offices: Comparison of two models explaining the decrease in performance by speech intelligibility and attempt to reduce interindividual differences of the mental workload by task customisation	Kostallari et al.	Applied Acoustics	2020	• offer additional empirical data quantifying the decline in task performance in scenarios where speech intelligibility plays a critical role • adjust task complexity to match individual short-term memory capacity through the use of a mnemonic span assessment, aiming to determine whether this personalization amplifies the observable impact of speech intelligibility on cognitive load	55 people	The initial phase took place in a quiet environment and aimed to assess participants' memory span and collect psychological data that might account for individual differences in performance. In the second phase, participants completed a short-term memory task while exposed to one of five distinct acoustic conditions.	Five noise conditions: • silent condition • four of them simulated the presence of speech sounds including a more or less intelligible speech signal (55 dB(A)) The signals for this experiment were composed of a stationary babble noise and perfectly intelligible speech signals.	• Serial word recall test	negative	• older participants showed greater difficulty in filtering out background noise while performing short-term memory tasks • higher speech intelligibility had a clearly detrimental effect on task performance, with accuracy declining as the Speech Transmission Index (STI) increased • the sequence in which the sound conditions were presented did not influence cognitive performance
Loudness and Intelligibility of Irrelevant Background Speech Differentially Hinder Children's Short Story Reading	Guerra et al.	Mind, Brain, and Education	2020	• examine how background speech characteristics, specifically intelligibility and volume, affect children's reading fluency and comprehension skills	63 students	within-subjects design with repeated measures	Two noise conditions: • intelligible speech (Dutch female talker) • unintelligible speech (native Hungarian female talker reading a newspaper article in their native language Sounds were presented at two different intensity levels, 45–50 dB(A) and 65–72 dB(A)	• Word Reading fluency (reading comprehension and reading speed) • Block Design • Vocabulary	negative	• reading comprehension and reading speed were affected in distinct ways by the intensity and intelligibility of background speech • increased speech loudness led to a notable reduction in reading speed • speech intelligibility had little to no effect on how quickly children read • louder background speech primarily disrupted reading fluency, while comprehension was more negatively impacted by semantically meaningful (intelligible) speech

Article	Authors	Journal	Year of publication	Aim of the study	Sample	Study design	Type of noise	Type of test	Effect of noise on cognitive performance	Findings
Auditory distraction in school-age children relative to individual differences in working memory capacity	Nagaraj et al.	Attention, Perception, & Psychophysics	2020	• investigate how vulnerable individuals are to auditory distractions and how this susceptibility relates to their working memory capacity	125 students	within-subjects design with repeated measures	• Meaningful noise: Digits one through nine (excluding seven because it was bi-syllabic) spoken by female speaker in standard American English set at 75 dB(A) • irrelevant-noise condition: multi-talker speech babble (67 dB(A))	• Auditory working-memory task (repeat the words first in the correct order followed by the numbers in the same order) • Digit working-memory task (The child was asked to judge if the two squares they saw were the same or different and provide their answer by touching a box labeled "Same" or "Different")	negative	• children with greater working memory capacity showed a higher error rate when exposed to multi-talker speech babble, compared to conditions without background speech • specifically, those with high working memory capacity made approximately 2.5 times more intrusion errors under multi-talker conditions, while children with lower capacity exhibited similar error rates regardless of the sound environment • age was not a significant factor in determining vulnerability to auditory distraction, as irrelevant speech affected working memory performance similarly in both children and adults
Effects of lighting and sound factors on environmental sensation, perception, and cognitive performance in a classroom	Yang and Jeon	Journal of Building Engineering	2023	• explore how variations in lighting and acoustic conditions influence individuals' environmental experience, sensory perception, and cognitive task performance	60 students	within-subjects design with repeated measures	Five sounds conditions and two different equivalent sound levels: • ambient sound of 41 dBA • music (45 dBA and 65 dBA) • traffic (45 dBA and 65 dBA)	• working memory test	negative	• among the sound conditions tested, ambient noise at 41 dBA produced the most favorable working memory outcomes, while traffic noise at 65 dBA resulted in the poorest performance • male participants generally reported more positive perceptions of the environment and obtained higher scores on the working memory task compared to female participants • no significant effect of age was observed on either environmental perception or cognitive performance

[1]Zhang, J., Pang, L., Yang, C., Fan, Y., Zhao, B., & Cao, X. (2024). Experimental evaluation of noise exposure effects on subjective perceptions and cognitive performance. Buildings, 14, Article 1100. https://doi.org/10.3390/buildings14041100.

[2]Sukowski, H. (2025). Effects of noise on employees during a concentration task: Results from performance and subjective assessments and a critical view of the chosen performance test. Applied Acoustics, 231, Article 110533. https://doi.org/10.1016/j.apacoust.2025.110533.

[3]Song, C., Li, H., Ma, H., Han, T., & Wu, J. (2022). Effects of noise type and noise sensitivity on working memory and noise annoyance. Noise & Health, 24, 173–181.

[4]Gheller, F., Spicciarelli, G., Scimemi, P., & Arfé, B. (2024). The effects of noise on children's cognitive performance: A systematic review. Environment and Behavior, 55(8–10), 698–734. https://doi.org/10.1177/00139165241245823.

[5]Pellegatti, M., Torresin, S., Visentin, C., Babich, F., & Prodi, N. (2023). Indoor soundscape, speech perception, and cognition in classrooms: A systematic review on the effects of ventilation-related sounds on students. Building and Environment, 236, Article 110194.

[6]Fernández-Quezada, D., Martínez-Fernández, D. E., Fuentes, I., García-Estrada, J., & Luquin, S. (2025). The influence of noise exposure on cognitive function in children and adolescents: A meta-analysis. NeuroSci, 6, Article 22. https://doi.org/10.3390/neurosci6010022.

[7]Liu, C., Zang, Q., Li, J., Pan, X., Dai, H., & Gao, W. (2023). The effect of the acoustic environment of learning spaces on students' learning efficiency: A review. Journal of Building Engineering, 79, Article 107911. https://doi.org/10.1016/j.jobe.2023.107911.

[8]Huimin Liu, Hui He, Junjie Qin, Does background sounds distort concentration and verbal reasoning performance in open-plan office?, Applied Acoustics, Volume 172, 2021, 107577, ISSN 0003-682X, https://doi.org/10.1016/j.apacoust.2020.107577.

[9]Zhang, L., & Ma, H. (2022). The effects of environmental noise on children's cognitive performance and annoyance. Applied Acoustics, 198, Article 108995. https://doi.org/10.1016/j.apacoust.2022.108995.

[10]Radun, J., Maula, H., Tervahartiala, I.-K., Rajala, V., Schlittmeier, S., & Hongisto, V. (2024). The effects of irrelevant speech on physiological stress, cognitive performance, and subjective experience – Focus on heart rate variability. International Journal of Psychophysiology, 200, Article 112352. https://doi.org/10.1016/j.ijpsycho.2024.112352.

[11]Kostallari, K., Parizet, E., Chevret, P., Amato, J.-N., & Galy, E. (2020). Irrelevant speech effect in open plan offices: Comparison of two models explaining the decrease in performance by speech intelligibility and attempt to reduce interindividual differences of the mental workload by task customisation. Applied Acoustics, 161, Article 107180. https://doi.org/10.1016/j.apacoust.2019.107180.

[12]Guerra, G., Tijms, J., Vaessen, A., Tierney, A., Dick, F., & Bonte, M. (2021). Loudness and intelligibility of irrelevant background speech differentially hinder children's short story reading. Mind, Brain, and Education, 15, 77–87. https://doi.org/10.1111/mbe.12264.

[13]Nagaraj, N. K., Magimairaj, B. M., & Schwartz, S. (2020). Auditory distraction in school-age children relative to individual differences in orking memory capacity. Attention, Perception, & Psychophysics, 82, 3581–3593. https://doi.org/10.3758/s13414-020-02056-5.

[14]Yang, W., & Jeon, J. Y. (2023). Effects of lighting and sound factors on environmental sensation, perception, and cognitive performance in a classroom. Journal of Building Engineering, 76, Article 107063. https://doi.org/10.1016/j.jobe.2023.107063.

4.4 Noise exposure and its effects on cognitive performance

Noise is widely recognized as an environmental stressor capable of interfering with essential mental processes such as attention, memory, processing speed, and auditory perception. Moreover, it is a significant psychological stressor that affects also people's emotions and well-being. Numerous studies have confirmed that elevated noise levels impair cognitive tasks such as memory, attention, and verbal reasoning. Nevertheless, the results are not always consistent [12]. This inconsistency is partly due to the variety of noise types ranging from traffic to intelligible speech and the diversity of tasks used in experimental settings. Numerous studies have shown that exposure to noise, particularly when it includes intelligible speech or alarm-like features, can disrupt attention, impair memory and generate negative emotional states such as irritation and anxiety [30, 14, 15, 16, 17, 18]. These studies confirm the Irrelevant Speech Effect (ISE), widely documented in both children and adults. This phenomenon occurs when task-irrelevant verbal noise intrudes upon verbal short-term memory, reducing recall accuracy even when participants are instructed to ignore the auditory stimuli. This effect is explained by either the redirection of attentional resources or the automatic interference with the rehearsal process in the phonological loop. Studies have shown that speech noise has a significantly more detrimental impact on performance than non-speech or steady-state background noise, particularly when the speech is intelligible. In educational settings, environmental noise, particularly speech and traffic noise, has been shown to impair students' learning efficiency, attention, memory, and emotional well-being [14, 19, 20, 15]. For example, Fernandes et al. 20 found that children's attention was markedly diminished when children were exposed to 40 dB of background unintelligible babble. Guerra et al. [18] examined the reading abilities of 63 children in third and fourth grade under two acoustic conditions in which they were exposed to speech noise from a single speaker, a Dutch female talker, and to unintelligible speech of a native Hungarian female talker. The noise varied in intelligibility, being either understandable or not, and was presented at two SPLs ranging 45–50 dB(A) and 65–72 dB(A). Their findings showed that different aspects of reading, such as fluency and comprehension, were impacted differently depending on the noise's sound pressure level and intelligibility. Specifically, an increase in noise volume led to slower reading speed, whereas the intelligibility of the speech noise had little detrimental effect on how fast the children read. Conversely, reading comprehension was more sensitive to the meaning of the background speech, with intelligible noise causing a greater decline in understanding. In terms of memory, Yang et al. [21] demonstrated that children performed better with the ambient sound condition at 41 dB(A) given by the typical noise in a classroom than with traffic noise with a SPL of 65 dB(A). In workplace settings, especially in open-plan offices, noise, particularly intelligible background speech, has been shown to significantly impair employees' concentration and verbal reasoning performance [22, 15, 23]. Experimental studies demonstrate that task-irrelevant speech leads to the highest annoyance levels and the most pronounced cognitive disruption when compared to other background sounds. Sukowski [22] examined how different acoustic environments affect concentration. The study tested four conditions: complete silence; the checkout area of a fashion retailer with a SPL of 62 dB(A), featuring background noise such as employee conversations, customer chatter, music, and operational sounds; a multi-space office with an SPL of 50 dB(A), characterized by typical office noises; and a construction site with an SPL of 65 dB(A), dominated by the sounds of heavy machinery. Results indicated that participants performed better in the silent condition compared to the noisy ones.

4.5 Task complexity and the arousal theory

It is important to highlight that the effect of noise is strongly related to the complexity of the cognitive task. In order to compare the effect of noise in different cognitive processes Zhang and Ma [24] conducted a study involving 248 students. The design of the study considered that children do different cognitive tasks with a various complexity under different sound conditions such as road traffic noise or low-frequency noise at sound pressure levels ranging from 35 dB(A) to 65 dB(A) with a constant increase of 5 dB(A). They found that in tasks involving simple cognitive processes, performance remained largely unaffected by both the level and type of noise. However, when it came to more complex cognitive activities, different types of noise had varying effects on performance. In other words, complex tasks were more vulnerable to auditory interference than simpler ones. This finding is aligned with what the Arousal Theory suggests. The relationship between noise and cognitive performance, illustrated in Figure 4.3, is often explained using this hypothesis, which posits that an individual's level of physiological and psychological arousal can significantly influence task performance. A central concept within this theory is the inverted U-shaped relationship between arousal and performance, often referred to the Yerkes-Dodson law [25]. As shown in Figure 4.4, for tasks of low complexity, performance tends to increase sharply with initial increments in arousal before plateauing. Conversely, in the case of more complex tasks, performance improves more gradually; however, both the attainment of optimal arousal and the subsequent change in performance trajectory occur at earlier stages. According to this principle, performance improves with increasing arousal, but only up to an optimal point beyond which further increases in arousal can lead to a decline in performance due to stress, distraction, or cognitive overload.

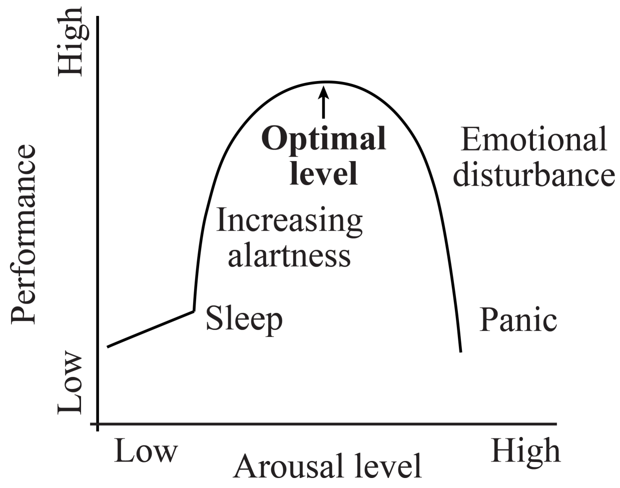


Figure 4.3: Relation between arousal level and cognitive performance.

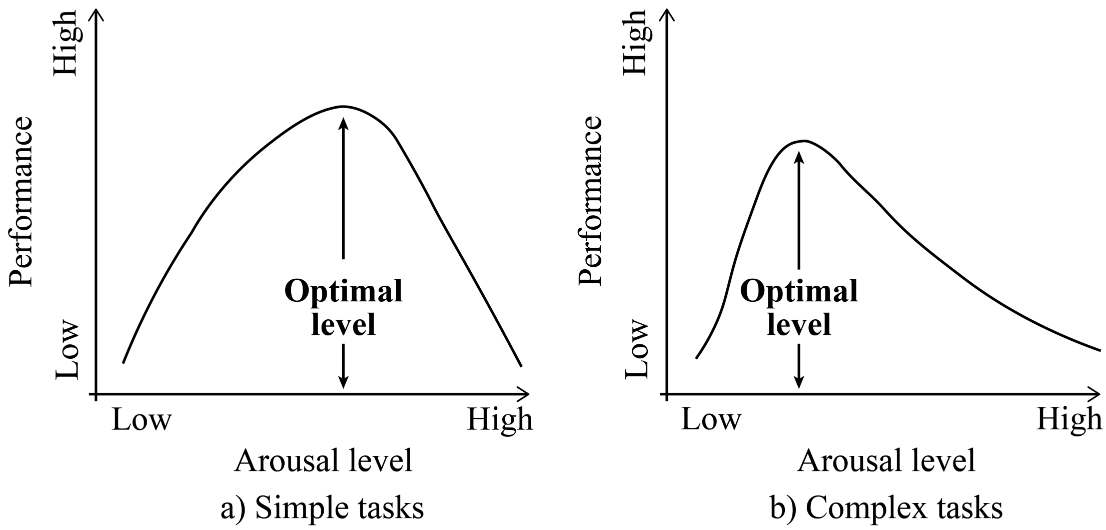


Figure 4.4: Relation between arousal level and task complexity.

This model is particularly useful in explaining the dual effects of noise on human cognition. At moderate levels, noise can increase arousal to a point that enhances alertness, vigilance, and short-term cognitive efficiency. In such cases, performance may actually improve, especially for simple or repetitive tasks that benefit from heightened stimulation [26]. For instance, low-intensity noise may prevent under-arousal in monotonous environments, helping individuals stay engaged and avoid mental fatigue [27], article about Mozart effect. However, the same noise exposure can produce negative effects when the task is complex, or the exposure is prolonged.

Complex cognitive tasks such as problem-solving, memory recall, or tasks requiring sustained attention are more susceptible to arousal-related disruption. These tasks typically require greater executive control and working memory capacity, which can be compromised when arousal exceeds the optimal threshold [28]. In such situations, noise becomes a stressor that overloads cognitive resources and impairs performance. This dynamic is reflected in the Poulton arousal model, which suggests that initial exposure to noise may prompt a temporary increase in arousal that serves a compensatory function, helping individuals maintain cognitive performance [29]. However, as exposure continues, the beneficial effects of arousal diminish and performance begins to deteriorate, particularly under cognitively demanding conditions. Importantly, this framework indicates that task complexity moderates the effect of arousal on performance under noise. High-arousal states may enhance performance on low-demand tasks but are more likely to impair outcomes when the cognitive load is high [26]. Thus, the relationship between noise, arousal, and performance is not linear but rather depends on a balance between stimulus intensity and cognitive demands, as described by the inverted U-curve.

4.6 Noise sensitivity and individual differences

Research also showed that the cognitive and emotional responses to noise are significantly modulated by the noise sensitivity and the individual variability. The environmental stress theory suggests that a person's perception plays a crucial role in determining whether an environmental event is experienced as stressful. This judgment is influenced both by the nature of the uncertain situation like exposure to noise and by personal characteristics. One of the most distinctive and significant characteristics linked to how individuals respond to noise is their level of noise sensitivity. Song et al. [30] investigated this concept and found that people vary in how noise affects their emotions and thinking. In particular, those sensitive to noise feel more annoyed and perform worse on tasks when exposed to distractions like speech or traffic sounds. This sensitivity may come from stronger brain reactions in emotion-related areas. Noise sensitivity, considered a stable personality trait, is closely associated with psychological conditions like neuroticism, lower emotional resilience, and increased physiological arousal. Highly sensitive individuals are more likely to report higher levels of annoyance and exhibit impaired performance on cognitive tasks, especially in the presence of disruptive noise such as speech or traffic sounds. In educational contexts, these effects are especially pronounced. For example, school-aged children and adolescents demonstrate varying degrees of susceptibility to noise based on age, cognitive development, and attentional control. Younger children and those with lower selective attention skills or interference control tend to perform significantly worse in noisy environments, particularly in tasks involving verbal working memory or reading comprehension.

Chapter 5

Methodology

5.1 The New Civic Central Library of Torino

Turin is on the path to becoming a key center for cultural innovation through the construction of the New Civic Central Library. The building is located within the Torino Esposizioni complex, specifically in pavilions 2, 2b, and 4. It was designed in 1938 by Ettore Sottsass and Pier Luigi Nervi, and is now under the protection of the Superintendence for Archaeology, Fine Arts, and Landscape (SABAP) for the Metropolitan City of Turin. The realization of the new library represents both an architectural restoration and a future-focused investment in education and community life. The design, created by the architecture studio Isolarchitetti, will stretch across three levels and cover 20 000 square meters. The library will hold around 680,000 books and documents, with 250,000 available directly to visitors. It will offer 707 formal study seats and another 762 informal ones, including armchairs and other comfortable seating options.

Figure 5.1: Render of the entrance of the New Civic Central library.
Authority: SCR Piemonte SpA. Professional grouping: ICIS Srl, RTP ICIS Srl, Arch. R. Moneo, ISOLARCHITETTI Srl, Ing. G. B. Quirico, ONLECO Srl, MCM ENGINEERING Srl

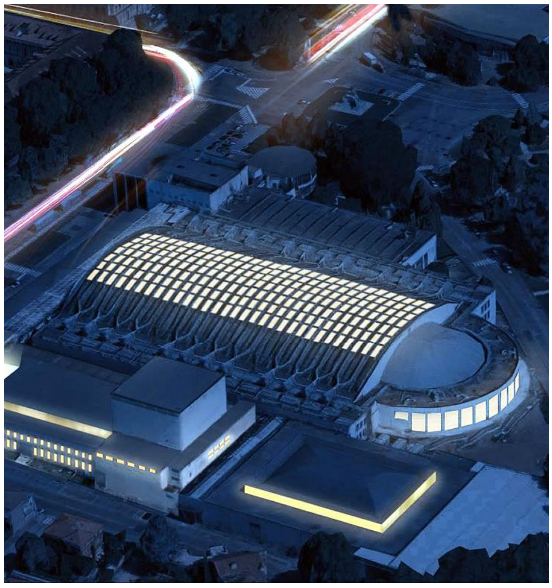


Figure 5.2: Aerial view render of the New Civic Central library during night.
Authority: SCR Piemonte SpA. Professional grouping: ICIS Srl, RTP ICIS Srl, Arch. R. Moneo, ISOLARCHITETTI Srl, Ing. G. B. Quirico, ONLECO Srl, MCM ENGINEERING Srl

The future library redefines what such a place can be, not only a place for books and study, but a lively environment where people of all ages can come together to learn, create, and interact [31]. The library's design mixes modern ideas with traditional features, creating a space that feels both familiar and new. Taking inspiration from leading examples around the world such as the Oodi Library in Finland and the Médiathèque in Thionville, France, shown in Figure 5.3 and Figure 5.4, the design borrows global best practices while developing its own unique identity. Technological innovation is also a key element, with features such as automated archive systems, similar to those used in Virginia's Thomas Jefferson Library.
The New Civic Central Library of Torino will incorporate a variety of areas for different purposes. These will include more than 20 rooms for workshops and hands-on activities, a large hall for conferences, themed spaces like the Memory Machine, the Knowledge Gallery, and the Street of Stories, as well as places to relax such as a café and recreational areas.

Figure 5.3: Helsinki Central Library OODI.

Figure 5.4: Médiathèque in Thionville.

One of the most notable architectural features of the New Civic Central Library of Torino is the open-plan design of its ground floor represented in Figure 5.5. By avoiding the addition of unnecessary internal structures, the architects have preserved the original architectural integrity of the building, allowing for uninterrupted views of the impressive vaulted ceiling, as shown in Figure 5.6. This approach not only enhances the sense of space and light but also respects the historical value of the Torino Esposizioni complex in which the library is housed. The main entrance is marked by a shaded portico, illustrated in Figure 5.7, which acts as a transitional space between the vibrant, fast-paced urban surroundings and the quieter, reflective atmosphere within the library. This area will feature a literary café and a public meeting zone, both of which are designed to encourage informal conversation and community engagement.
Upon entering, visitors are immediately introduced to the "Gallery of Knowledge," a central corridor that forms the ground floor layout. This space accommodates a variety of user needs, offering both traditional study areas with desks and quieter corners for focused work, as well as more relaxed zones furnished with armchairs and casual seating. The gallery's design supports multiple patterns of movement, allowing users to navigate through three main linear paths or follow a ring-like route that encourages leisurely browsing and exploration. The layout reflects the library's dual identity as both a place for individual research and a welcoming social environment.
The library will provide more than 1,400 seats in total, with a thoughtful balance between formal and informal arrangements to accommodate different user preferences. Approximately 250,000 volumes will be made readily accessible to the public, drawn from a total archive of around 680,000 items. These resources will be distributed across three floors, offering visitors a layered and varied experience that supports deep study, discovery, and cultural participation. At the rear of the

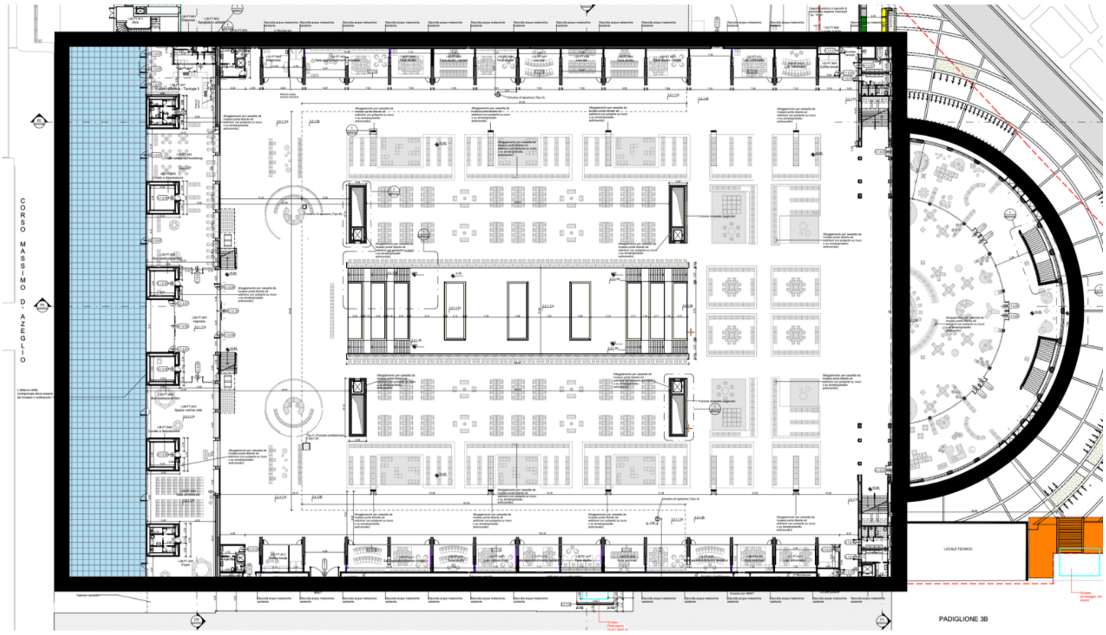


Figure 5.5: Plan of the ground floor of the New Civic Central Library of Torino. Authority: SCR Piemonte SpA. Professional grouping: ICIS Srl, RTP ICIS Srl, Arch. R. Moneo, ISOLARCHITETTI Srl, Ing. G. B. Quirico, ONLECO Srl, MCM ENGINEERING Srl

ground level, the apsidal section of the building serves as a secondary entrance, shown in Figure 5.8, which opens out toward the nearby Parco del Valentino. This area is planned to house a series of important functional spaces. Among them are a newspaper library for periodical reading and current events, a room dedicated to the theme "The Challenges of Change," which will focus on contemporary social and environmental issues, and a dedicated section for early childhood visitors, designed to serve the needs of infants (0–3 years) and young children (4–6 years) with appropriate furniture, resources, and learning materials. The part of the exedra that will be a childrens' area is depicted in Figure 5.8. The remaining part of the ground floor is intended to accommodate a wider age group, featuring dedicated zones for children and teenagers between the ages of 7 and 14, along with a multimedia area designed for interactive learning and digital engagement. Administrative offices and staff support rooms will also be located on this level, positioned strategically along the front and lateral sides of the structure to ensure smooth operation and accessibility [31]. The basement floor will function as both a technical and cultural zone. In addition to serving as a logistics and archive area, it will include two important spaces: the "Memory Machine" and the "Enchanted Forest". The "Memory Machine" will house rare and historical collections and serve as a center for preservation and scholarly engagement with archival materials. On the other hand, the “Enchanted Forest”, shown in Figure 5.10, will provide a more informal, serene atmosphere. Designed as a garden-like indoor reading space, it will offer users a quiet retreat with tables, seating, and soft lighting, reinforcing the library’s goal of creating spaces for rest, reflection, and inspiration. Above the ground level, the design incorporates balcony walkways that overlook the central spaces of the library. As illustrated in Figure 5.11, these elevated corridors not only enhance the visual connection between floors but also create additional reading and study areas that feel more intimate and private. The balconies offer users the opportunity to engage with the library’s collections from a different perspective, while still maintaining a strong visual link to the open and spacious atmosphere of the main hall below. Their presence contributes to the vertical layering of the library’s spatial experience, reinforcing the sense of openness and fluidity that defines the overall architectural concept.

More than just a library, the building will also host the new Architecture Campus of the Politecnico di Torino and include the restoration of the nearby Teatro Nuovo. In addition, the broader plan involves improving the surrounding Parco del Valentino, bringing back boat routes on the Po River, and enhancing infrastructure throughout the area. Funded by the National Complementary Plan and other public programs, the construction of the New Civil Central Library of Torino is already in progress. The library is expected to open to the public by 2026, marking a new chapter in the city’s cultural and educational development.

Figure 5.6: Render with a whole view of the New Civic Central Library.
Authority: SCR Piemonte SpA. Professional grouping: ICIS Srl, RTP ICIS Srl, Arch. R. Moneo, ISOLARCHITETTI Srl, Ing. G. B. Quirico, ONLECO Srl, MCM ENGINEERING Srl

Figure 5.7: Render of the shaded portico at the entrance.
Authority: SCR Piemonte SpA. Professional grouping: ICIS Srl, RTP ICIS Srl, Arch. R. Moneo, ISOLARCHITETTI Srl, Ing. G. B. Quirico, ONLECO Srl, MCM ENGINEERING Srl

Figure 5.8: Render of the entrance from the Parco del Valentino.
Authority: SCR Piemonte SpA. Professional grouping: ICIS Srl, RTP ICIS Srl, Arch. R. Moneo, ISOLARCHITETTI Srl, Ing. G. B. Quirico, ONLECO Srl, MCM ENGINEERING Srl

Figure 5.9: Render of childrens' area in the exedra.
Authority: SCR Piemonte SpA. Professional grouping: ICIS Srl, RTP ICIS Srl, Arch. R. Moneo, ISOLARCHITETTI Srl, Ing. G. B. Quirico, ONLECO Srl, MCM ENGINEERING Srl

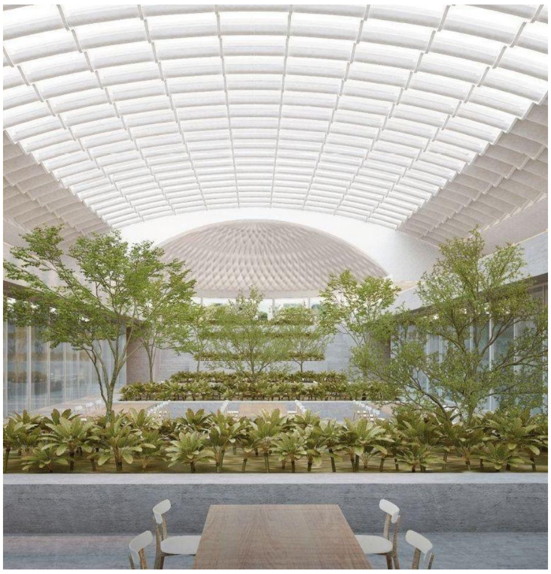


Figure 5.10: Render of the "Enchanted Garden" located on the basement floor of the library.
Authority: SCR Piemonte SpA. Professional grouping: ICIS Srl, RTP ICIS Srl, Arch. R. Moneo, ISOLARCHITETTI Srl, Ing. G. B. Quirico, ONLECO Srl, MCM ENGINEERING Srl

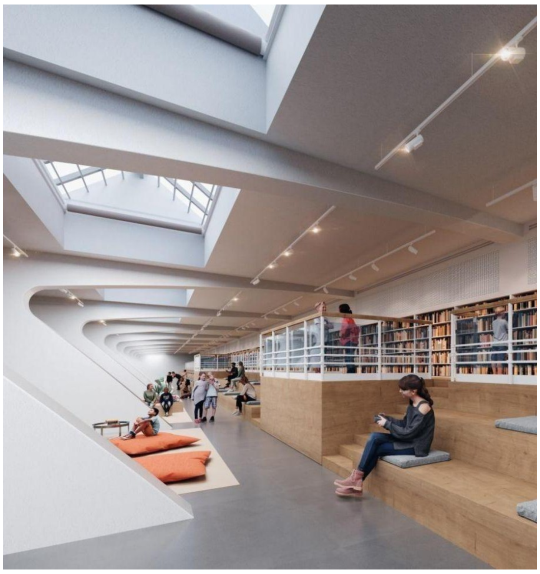


Figure 5.11: Render of one of the balconies located in the first floor of the library.
Authority: SCR Piemonte SpA. Professional grouping: ICIS Srl, RTP ICIS Srl, Arch. R. Moneo, ISOLARCHITETTI Srl, Ing. G. B. Quirico, ONLECO Srl, MCM ENGINEERING Srl

5.2 3D Geometrical Acoustics model of the New Civic Central Library of Torino

5.2.1 Odeon software

As part of the acoustic evaluation of the New Central Civic Library of Turin, a detailed three-dimensional model of the building was created using Odeon 18, a specialized and widely recognized software used for the simulation and analysis of room acoustics. With over forty years of continuous development, it has established itself as a benchmark tool among acousticians and acoustic consultants worldwide. In this study, all simulations and analyses have been carried out using ODEON Combined 18, the latest and most comprehensive edition of the software, which integrates the full range of functionalities required for both room acoustics and industrial applications. Its primary function is to model how sound propagates and interacts within architectural spaces, offering precise predictions of key acoustic parameters such as reverberation time, clarity, speech intelligibility, and sound pressure levels.

The software supports a full range of sound source types, including point, line, surface, and array sources [32], which enables it to simulate a broad spectrum of acoustic emitters from human voices and musical instruments to traffic and industrial noise.

- Point sources: the most common and versatile type in ODEON. The point sources radiate sound equally in all directions from a single point, making them suitable for simulating speech, instruments, or basic loudspeakers. Their emission pattern can also be customized to reflect directional behavior, enhancing realism.

- Line sources: these sources are used to model continuous sound emission along a linear path. This type is ideal for representing elongated noise sources such as traffic on roads or running water in pipes. They are also used to represent the noise of ventilation systems.

- Surface sources: emit sound across one or more selected surfaces within a space. They are well suited for large, distributed sources like industrial machinery or groups of people, offering a more accurate depiction of widespread sound generation.

- Array sources: designed to simulate complex loudspeaker configurations. Commonly used in performance venues, they allow for precise modeling of loudspeaker arrays and are essential for assessing the acoustic performance of sophisticated sound systems.

- Natural sources: these sources refer to emitters like human voices or acoustic instruments, whose directivity patterns include their real frequency response. To avoid duplicating this response during auralisation, ODEON uses specially equalized “Natural” directivity patterns. This ensures accurate simulation of parameters such as sound pressure level and speech intelligibility, while maintaining realistic playback [32].

In addition to defining sound sources, receivers are also a key element in ODEON simulations. They are represented as point-based virtual microphones placed within the 3D model. While standard analyses require only basic positioning, more advanced applications such as auralisation benefit from specifying the listener’s head orientation to achieve a more realistic audio experience. These source and receiver configurations form the basis of ODEON’s simulation environment, which is further enhanced by the software’s advanced computational methods and auralisation features. In particular, ODEON employs a hybrid computational approach that combines image-source and ray-tracing algorithms, balancing simulation accuracy with computational efficiency.

Among the most advanced features of the software is its ability to produce auralisations, realistic audio simulations that help to understand how sound will behave within a given space. This functionality allows users to preliminarily assess the expected acoustic performance [32]. As such, it serves as a vital instrument in both the design of new environments and the acoustic verification and optimization of existing ones.

5.2.2 3D model development

The process of the 3D model design began with a careful analysis of the executive architectural documentation, including floor plans, construction sections, and detailed information about materials used on walls, ceilings, and floors. These resources served as the foundation for developing an accurate virtual model of the library's interior spaces as illustrated in Figure 5.12. To construct the model within Odeon, the geometry of the building was first drawn using the native tools of the software, allowing for the precise delineation of spatial elements such as walls, floors, and ceilings. These surfaces were closed to form volumes, and key architectural features, including doors and windows, were modeled by creating polygonal openings within the walls. Attention was paid to the complexity of the meshes, ensuring that a balanced number of polygons was used to maintain computational efficiency without compromising model accuracy.

Once the geometric model was completed, each surface was assigned materials from Odeon's database, with absorption and scattering coefficients, reported in Figure 5.13 and Figure 5.1. The coefficients were applied according to the specifications outlined in the architectural project. These acoustic properties were defined across octave bands to reflect the real-world performance of the materials within different frequency ranges, which is essential for capturing the spatial behavior of sound within the building. The model incorporated a second-order reflection limit, ensuring that only two sound reflections were considered during the simulation. To enhance the precision of the results, a total of 50,000 rays were traced during the simulation process. Before any simulations were performed, the model underwent a verification phase using Odeon's diagnostic tools to identify and correct geometric inconsistencies, such as open surfaces or intersecting elements. With a validated model, sound sources and receiver points were strategically placed throughout the space to simulate realistic acoustic conditions. These positions were chosen based on architectural functions and user pathways, including quiet study areas, reading rooms, and public gathering spaces. A detailed information about the receivers and the sound sources will be provided in the following sections.

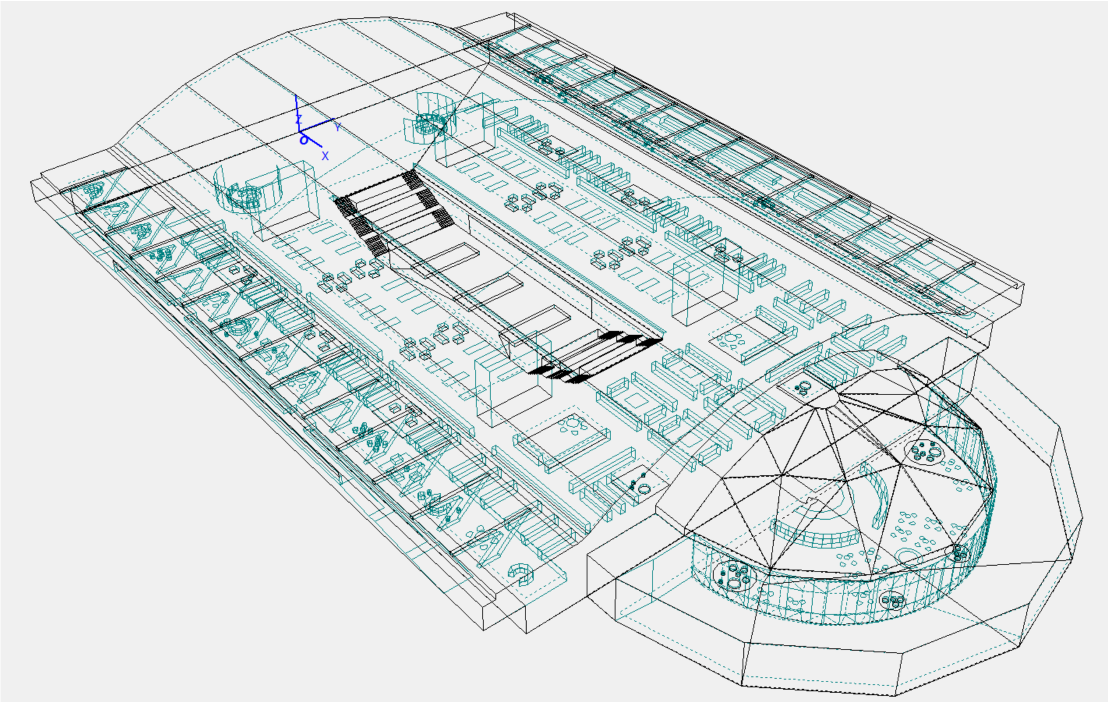


Figure 5.12: 3D model of the library created in Odeon.

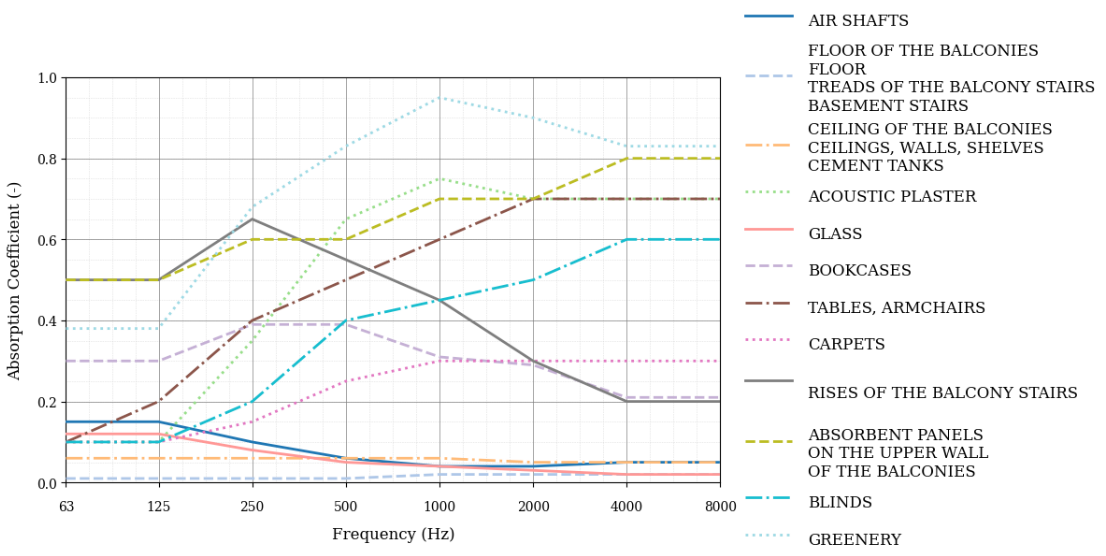


Figure 5.13: Absorption coefficients of the materials for the frequences between 63 and 8000 Hz.

Table 5.1: Scattering coefficients of the materials.

Material	Scattering coefficient	Material	Scattering coefficient
Air shafts	0.1	Armchairs	0.5
Floor of the balconies	0.1	Carpets	0.1
Ceiling of the balconies	0.2	Rises of the balcony stairs	0.1
Ceilings	0.8	Treads of the balcony stairs	0.5
Walls	0.1	Absorbent panels on the upper wall	0.1
Acoustic plaster	0.1	Shelves	0.2
Floor	0.1	Blinds	0.1
Glass	0.1	Cement tanks	0.2
Bookcases	0.5	Greenery	0.2
Tables	0.8	Basement stairs	0.1

5.2.3 Sound sources and receivers

Once the geometry of a room has been imported into ODEON, the next step was defining the positions of sound sources and receivers. Their accurate placement in the model is a critical step in acoustic simulation using ODEON.

Sound sources represent the origin of sound within the modeled environment and must be positioned accurately to reflect their real-world counterparts, whether they are human voices, ventilation systems, traffic noise or other. In the present study, a detailed analysis was conducted to identify the main sound sources typically found in a contemporary library. Based on this investigation, the acoustic consultancy firm VIBES S.r.l., a company based in Turin and specialized in building acoustics, developed a final list of selected options, presented below.

- S1: HVAC (Heating, Ventilation, and Air Conditioning) system, modeled as a single surface source uniformly distributed across the entire floor area.

- S2: HVAC system, modeled using two line sources, positioned at a height of 8.4 meters above the floor, to simulate the ceiling-mounted diffusers.

- S3: Traffic noise, modeled as a surface source distributed across three sub-areas, S3.1, S3.2 and S3.3, located on the building's roof. Sub-area S3.1 is near the busy street, S3.2 is positioned midway between the street on the one side of the library and the river on the opposite side, while S3.3 is adjacent to the river, extending over the rear section of the roof and the exedra.

- S4: Unintelligible speech, modeled as a surface source positioned above the tables in the reading areas, at 1.2 meters above the floor, and at 1.5 meters in the semi-toroidal space. Moreover, unintelligible speeching was simulated in the transit area near the main entrance, as well. These heights correspond to the typical mouth level of seated and standing speakers, respectively.

- S5: intelligible speech, modeled as an omnidirectional point natural source simulating a person engaged in a conversation.

- S6: When the source is positioned near a certain receiver, it is replaced by equivalent intelligible five-sentence phrases from the Matrix Sentence Test (REF...) representing a clearly articulated speech, ensuring a more realistic representation of speech perception.

- S7: Background noise generated by turning pages, pen clicks and notifications from personal electronic devices, a calculator, papers, a notebook, a pencil case, pens and pencils, sounds typical for a contemporary library. Omnidirectional point sources are used to represent this type of noise.

- S8: Sound of footsteps, representing a person descending the stairs rapidly. This source was modeled by an array of 35 omnidirectional point sources.

- S9: Sound of footsteps, representing a person walking at a middle speed. This source was modeled by an array of 35 omnidirectional point sources each at a distance of 0.80 m from the previous one, simulating a typical person's walking pattern.

Once the sources had been positioned, they were oriented towards the specific receiver that was analyzed in the certain moment. Figure 5.14 illustrates the general plan of the library with the positioning of the different sources oriented towards the specific receiver of interest, i.e. R1. There is a tailored map for each receiver, so the presented map is an example of only one receiver.

Moreover, ODEON provides the opportunity to make a visual representation of room acoustic parameters within the three-dimensional model. It enables the evaluation of parameter variation across the space and supports the identification of acoustically critical areas. Below are represented the maps showing the distribution of every type of simulated sources.

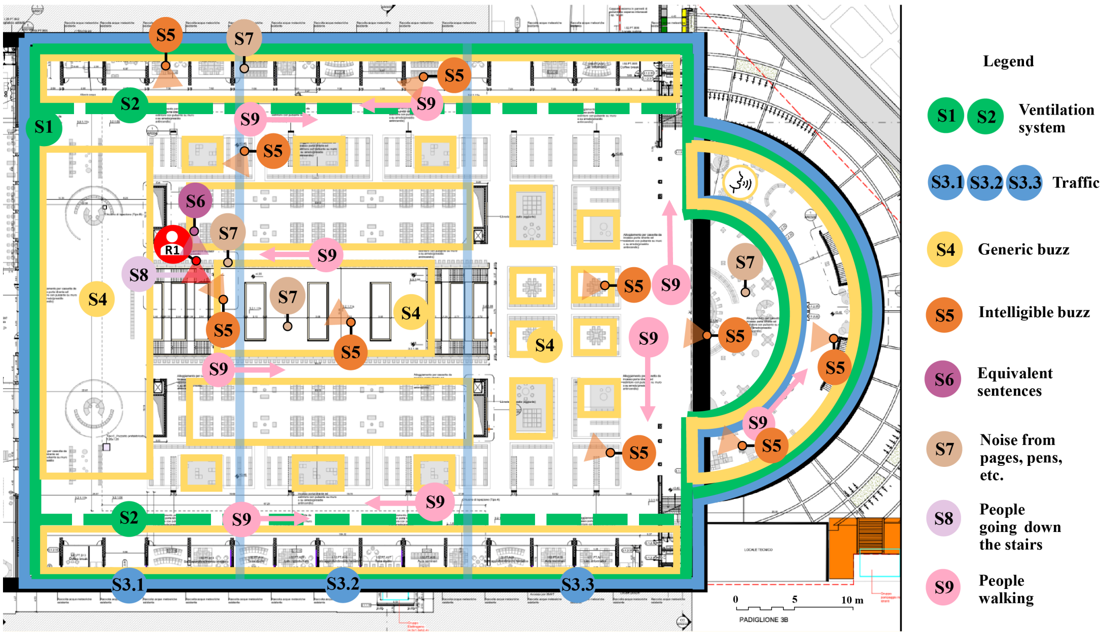


Figure 5.14: Positioning of the sound sources in the 3D model of the library. This is a tailored configuration made specifically for R1, i.e. the sound sources are oriented towards this receiver.

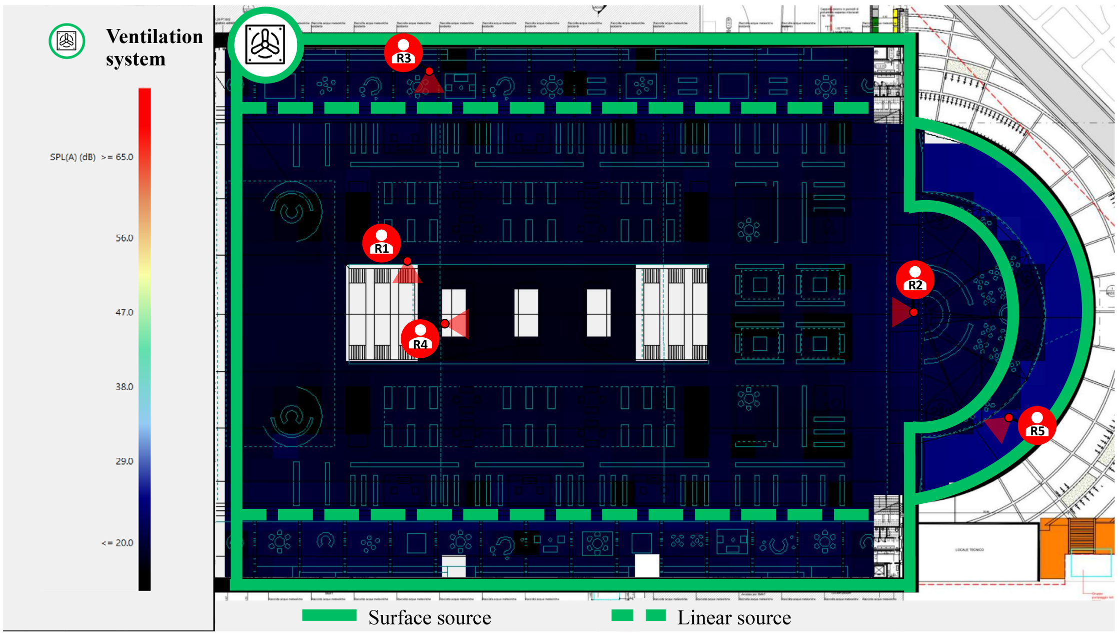


Figure 5.15: Map showing the distribution of the noise given by the ventilation system.

Figure 5.16: Map showing the distribution of the noise given by traffic.

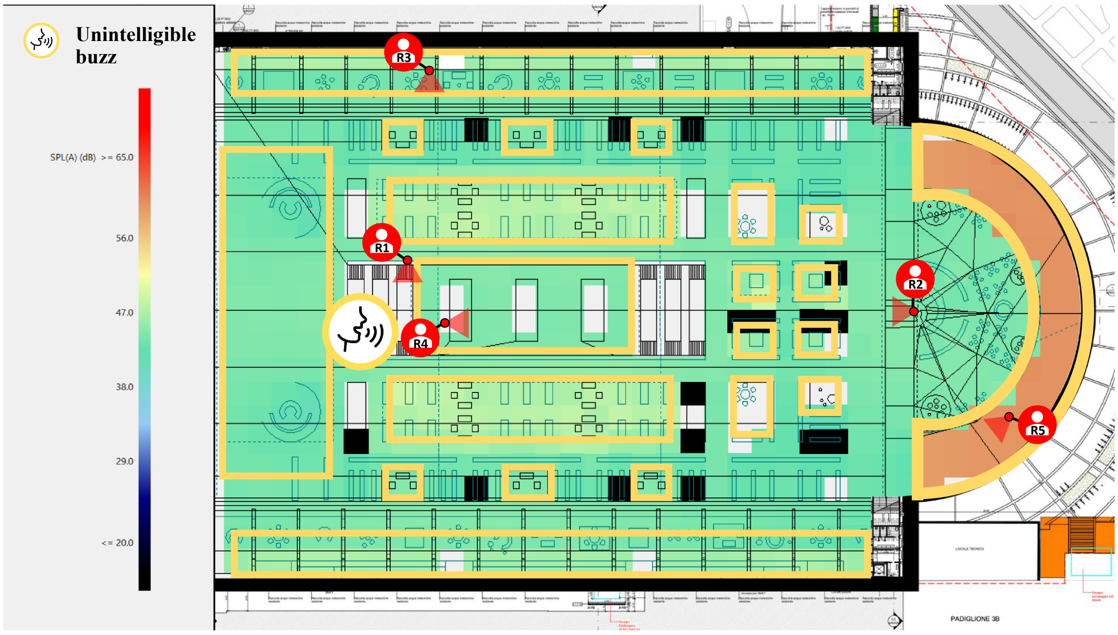


Figure 5.17: Map showing the distribution of the noise given by the unintelligible speech.

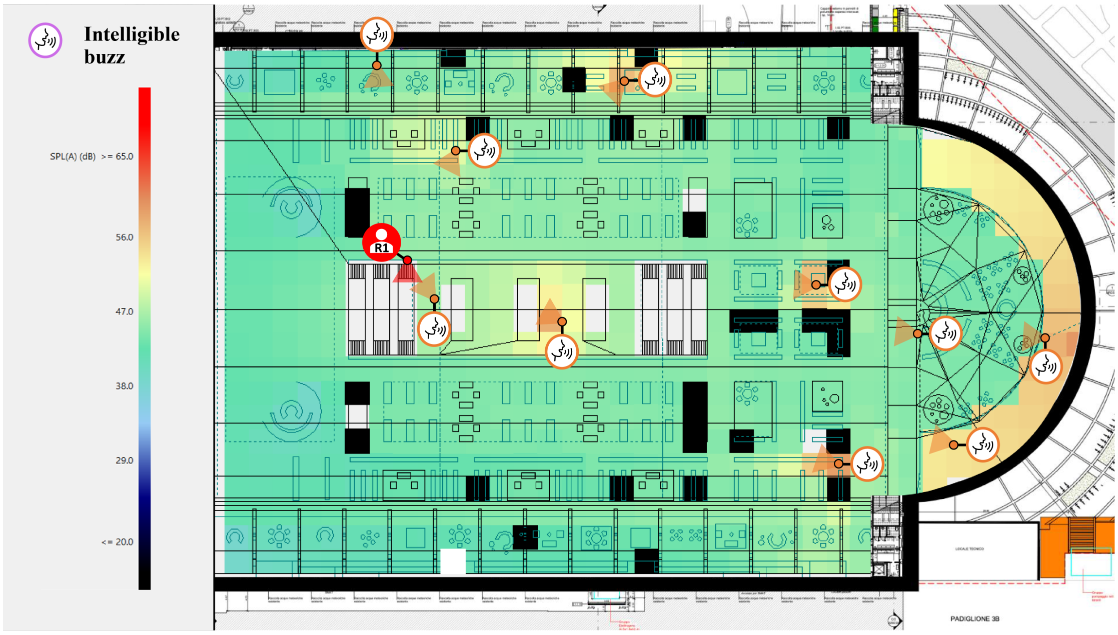


Figure 5.18: Map showing the distribution of the noise given by the intelligible speech.

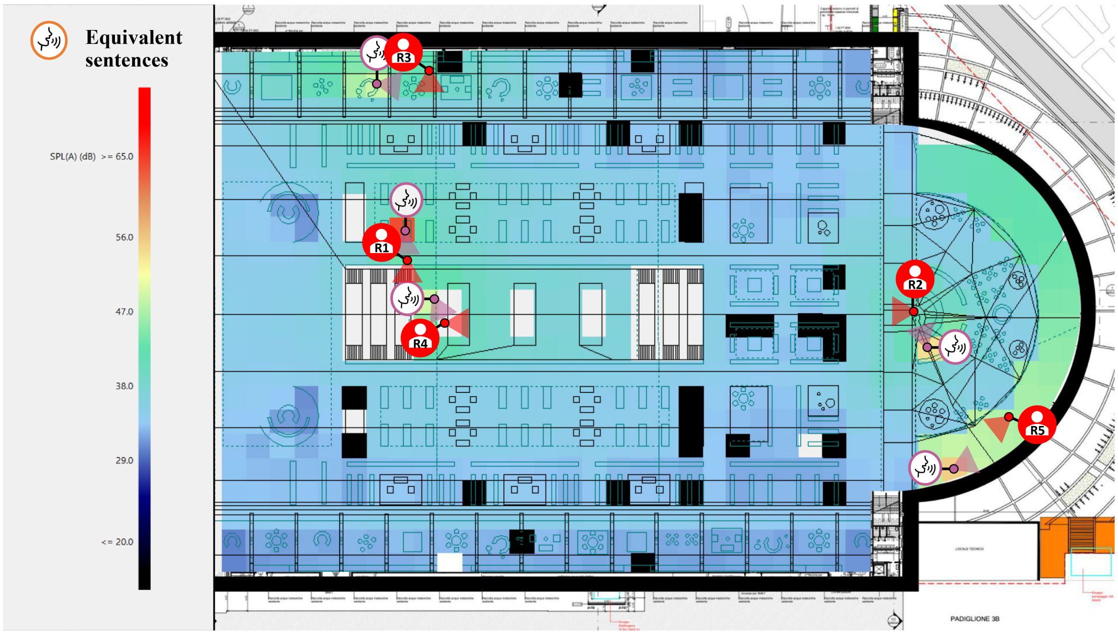


Figure 5.19: Map showing the distribution of the noise given by the equivalent sentences.

Figure 5.20: Map showing the distribution of the noise given by pen clicks, turning pages and notifications from personal electronic devises.

The receivers (R1-R5), modeled as point-based virtual microphones, are strategically placed in five different positions, as shown in Figure 5.21. The positions of the receivers are the following:

- R1: in the center of the main area on the ground floor, oriented towards the basement floor with the underground courtyard known as the "Enchanted Garden". This point simulates a seated person at 1.2 meters above the floor and working on one of the tables.
- R2: in the center of the exedra but still in the main area on the ground floor; it simulates a standing person with a height of 1.6 m from the floor and oriented towards the main area of the library.
- R3: positioned on one of the balconies, this point simulates a seated person at a height of 1.2 meters above the balcony floor, within one of the niches created from the structural walls. The listener's feet are positioned 4.3 meters above the main ground level and oriented towards the main area of the library.
- R4: positioned in the underground area known as the "Enchanted Garden" located in the basement floor which is 5 meters below the main ground level, this point simulates a standing person with a height of 1.6 meters above the basement floor and oriented towards the exedra.

- R5: positioned in the semi-toroidal exedra at the rear front of the library, this point simulates a standing at 1.6 m height person oriented towards the main area of the library.

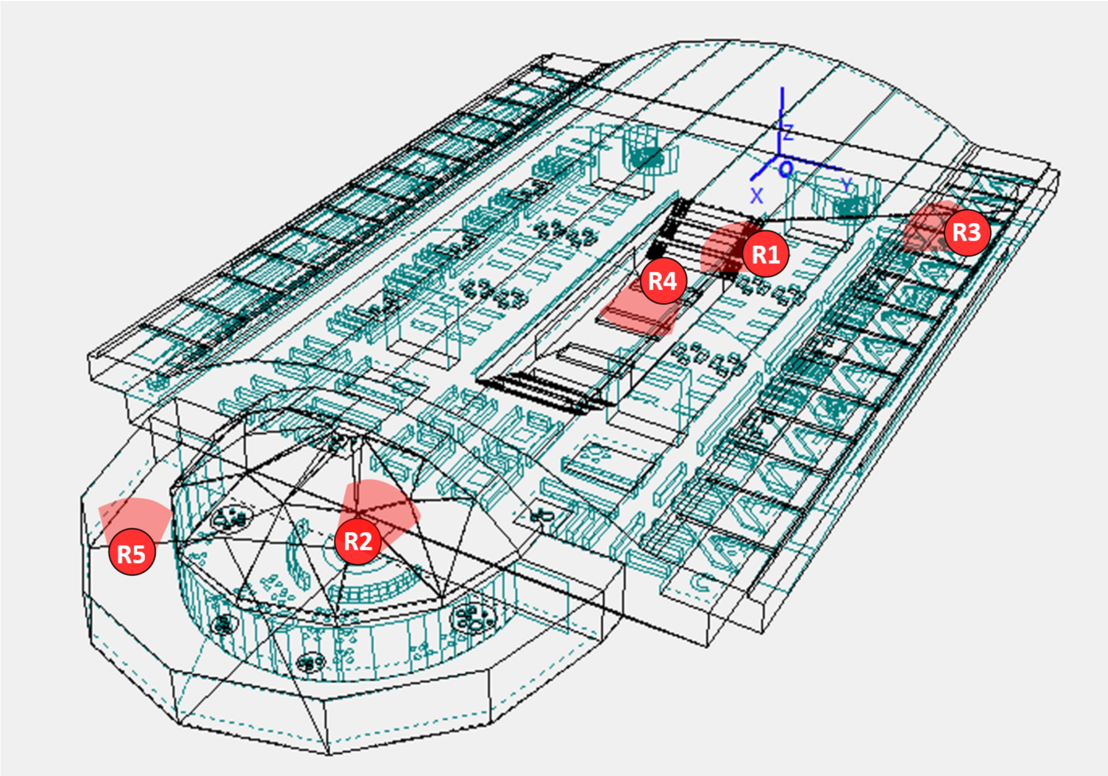


Figure 5.21: Positioning of the receivers in the 3D model of the library.

5.2.4 Acquisition of the sounds

An accurate auralisation within acoustic simulation tools like ODEON depends on both suitable sound recordings and a carefully structured setup of the virtual acoustic scene. For the purposes of this study, all required audio material was sourced in advance. The recordings were produced under controlled conditions, either in anechoic environments, open free-field settings, or synthesized through a MIDI keyboard, to ensure neutrality and precision of the sound input.

5.2.4.1 Recording of the sounds in anechoic chamber

The intelligible speech (S5) as well as the background noise generated by turning pages, pen clicks and notifications of personal electronic devises (S7) were recorded in an anechoic chamber. An anechoic chamber is a highly specialized environment designed to completely eliminate sound reflections and shield the interior from external acoustic interference, effectively creating a space of absolute silence. At the Politecnico di Torino, the chamber's walls are covered with wedge-shaped sound-absorbing materials, shown in Figure 5.22, that attenuate the sound waves from nearly every direction, including low frequencies. The floor, depicted in Figure 5.23, consists of a suspended mesh structure placed above the absorptive wedges, allowing for effective sound absorption from below while still enabling people to move freely within the space. Located in a sound-isolated area, the chamber ensures minimal intrusion from external noise, thus preserving the fidelity of recorded audio data.

Figure 5.22: The walls covered with sound-asborbing materials at the anechoic chamber of the Politecnico di Torino.

Figure 5.23: The suspended mesh on the floor at the anechoic chamber of the Politecnico di Torino.

The sound recordings were performed using an NTI sound level meter, which enabled both the calculation of sound pressure levels and the analysis of frequency spectra related to the recorded parameter. To enhance control over the recording process, the sound level meter was connected to a sound card, which interfaced directly with the Audacity software. This setup provided detailed configuration options such as adjusting input gain, applying filters and managing equalization. Before initiating the measurements, the device was calibrated using a professional acoustic calibrator to ensure precision and consistency in the data collection. To replicate the acoustic environment of a library, a dedicated platform was assembled inside the anechoic chamber, as illustrated in Figure 5.24. It was equipped with a table and one or two chairs to resemble a typical reading setting. Various everyday items were placed on the table to create realistic sound events such as a smartphone receiving notification tones, a calculator, papers, a notebook, a pencil case, pens and pencils.

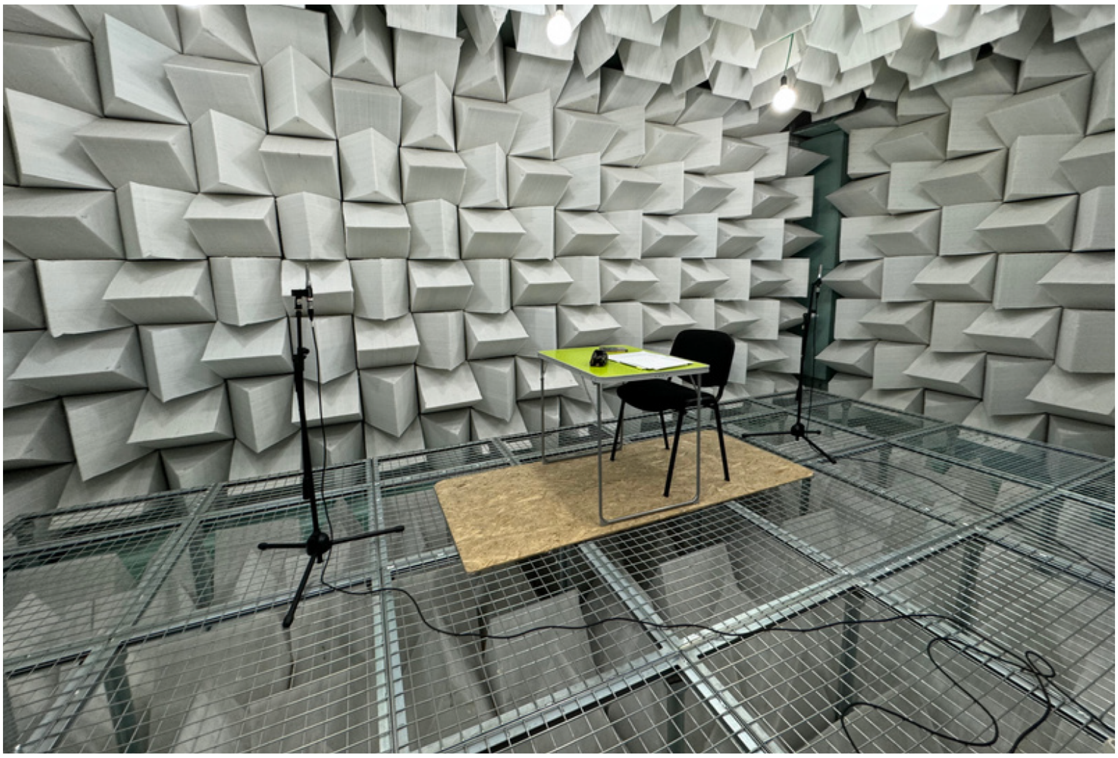


Figure 5.24: The workstation used for the recordings of the sounds at the anechoic chamber of the Politecnico di Torino.

For the measurement of sound events such as pen movements and background buzz, three microphones were placed in different positions based on the spatial relationship between the sources and receivers, as illustrated in Figure 5.25. The microphones were arranged at angular intervals of -135°, 0° and 180° relative to the source to ensure an optimal coverage of directional sound characteristics. For all recordings the microphones were set at a consistent distance of 1.5 meters from the sound source, with vertical placement varying depending on the simulated receiver position: 1.2 meters to replicate a seated listener and 1.84 meters for one positioned above. To verify accuracy, these measurements were taken using both a manual tape measure and a laser distance meter. In the first recording session, the sound source was positioned at the center of the table. In the following session, it was placed at the typical height of a speaker's mouth, aligned centrally between two speaking individuals. This carefully structured methodology allowed for highly accurate and contextually realistic sound recordings, replicating the auditory conditions experienced by listeners in an actual library environment.

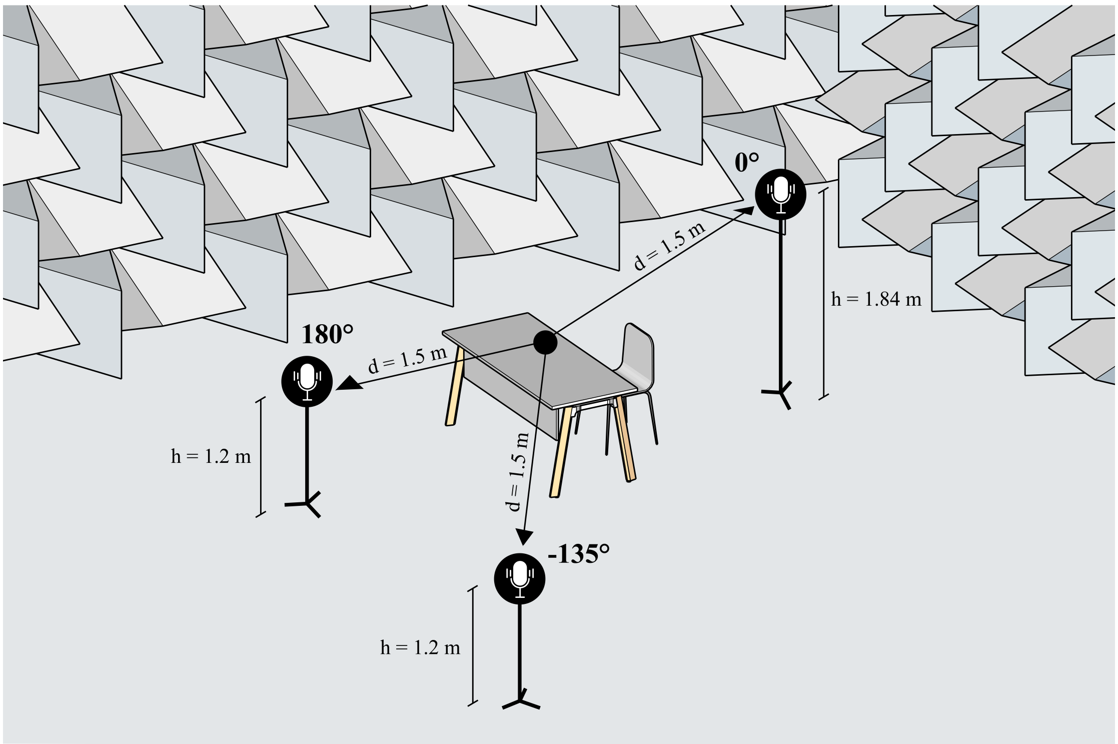


Figure 5.25: A 3D representation of the anechoic chamber of Politecnico di Torino with the three positions of the microphones used for the sound acquisitions.

5.2.4.2 In-field acoustic data collection

As part of the data collection process, environmental audio recordings were carried out in an open-air context, specifically from the rooftop of the library building. These recordings mainly captured urban traffic noise, which varied in different parts of the building. A total of three outdoor and one indoor positions were selected for the measurements, as illustrated in Figure 5.26. All data were collected using the same NTI phonometer, positioned at a height of 1.5 meters above the roof, as shown in Figure 5.27. The choice of the three rooftop recording sites was made due to the considerable size of the building and the variability in the exposure of surrounding traffic. Each location provided distinct spectral data due to differences in traffic intensity. The first recording spot, positioned near a major road, unsurprisingly registered the highest sound levels among the three.

Initially, an indoor measurement was also attempted. However, due to the ongoing construction phase at the time, marked by the presence of a large sinkhole inside the building, these recordings were severely compromised by excessive reverberation, making them acoustically invalid for analysis.

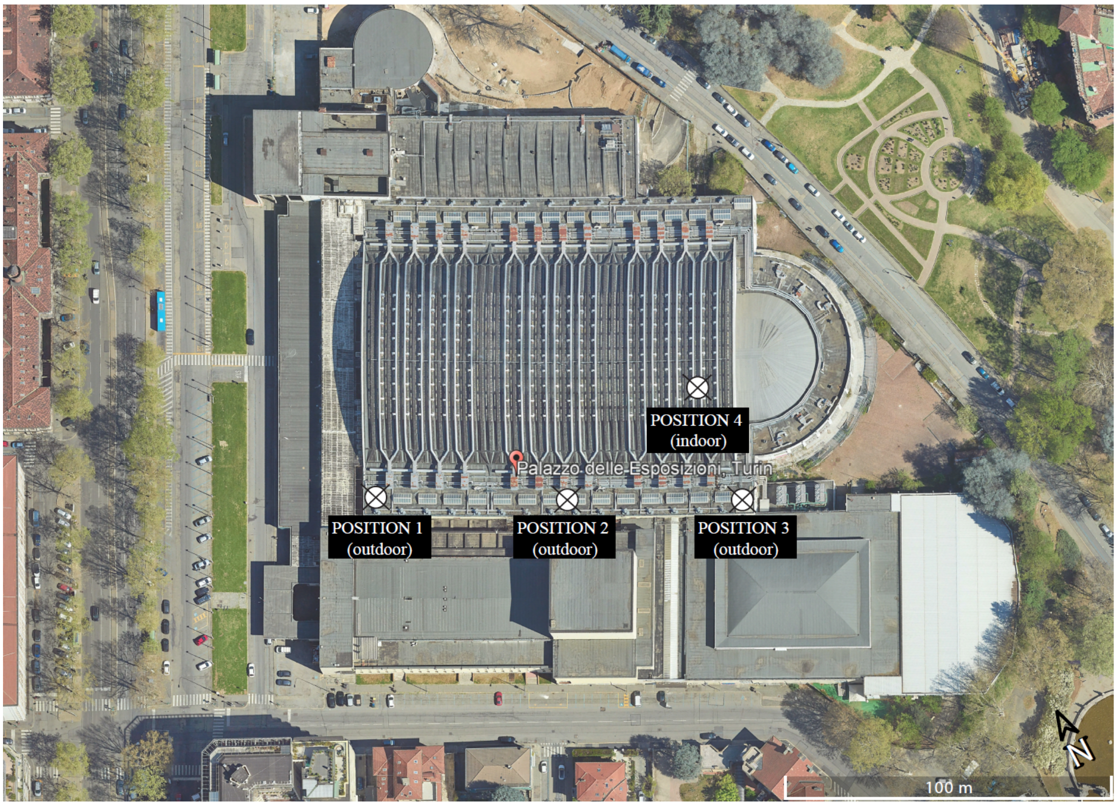


Figure 5.26: An orthophoto of the roof the library with the four positions which were chosen for the measurements.

Figure 5.27: Photograph of the phonometer used for the traffic noise measurements.

5.2.4.3 MIDI acoustic data collection

In order to simulate realistic footsteps sounds in an anechoic environment, the Edward Foley Art sound library [33], depicted in Figure 5.28, was used in combination with the VST Kontakt virtual instrument platform [35]. This setup allowed for detailed customization of the sound parameters, including the type of shoes and the walking surface. For the purpose of this project, high-heeled shoes worn by a woman were selected, with the contact surface set to ceramic, chosen to reflect the typical flooring material found in public libraries. A total of 49 footstep samples were created, 35 of which were assigned to source S8 and 14 to source S9. While all samples shared the same general acoustic properties, slight variations in dynamics and tonal quality were introduced to enhance realism and avoid artificial repetition. Each individual footstep was paired with its corresponding impulse response (IR), previously measured and processed, to create spatialized auralizations tailored to the source layout. The MIDI keyboard was used to trigger each sample in real time, connected to the Pro Tools digital audio workstation (DAW) [36]. The Edward plug-in allowed for responsive input, with faster keystrokes used to simulate hurried steps such as a person descending stairs (S8) and slower presses representing normal walking pace (S9). Once recorded, the sequences were arranged in Pro Tools with interstep intervals of 0.25 seconds for the fast track and 0.5 seconds for the slow one, resulting in two distinct footstep sequences ready for integration into the simulation model.

Figure 5.28: Edward plug-in displayed inside the Pro Tools DAW, reported in [34].

5.2.4.4 Remaining sound sources collection

Several audio assets used in this thesis originate from archived material previously recorded by the Politecnico di Torino for unrelated academic projects. All sources have been selected in compliance with applicable copyright and usage regulations.

Among the materials integrated into this study are background recordings of mechanical ventilation systems, assigned to sources S1 and S2, shown in Figure 5.14, which serve to recreate realistic environmental noise conditions.

A second category includes generic crowd noise, used for source S4. This particular track, captured in an anechoic chamber, consists of a layered mixture of indistinct overlapping voices, intentionally rendered unintelligible to avoid semantic interference.

In addition, a series of acoustically standardized speech recordings was used to simulate low-density verbal background noise presented as S6. These speech samples, denominated in this thesis as equivalent sentences, were recorded under controlled conditions and consist of five-word phrases that are grammatically correct but semantically meaningless. Designed to be acoustically equivalent, they enable controlled comparisons across experimental conditions involving one or two speakers.

5.2.5 Determination of the sound pressure levels of the sources

In preparation for the acoustic simulations, it was necessary to define the sound pressure level, the sound power level as well as the spectral characteristics of each sound source. To accurately characterize sound sources for simulation within Odeon, a systematic methodology was adopted to determine the sound pressure levels (SPL) in octave bands, derive corresponding sound power levels (Lw) and create both flat and frequency-dependent spectral representations. This procedure ensures that all sources are acoustically consistent and usable across different simulation contexts.

5.2.5.1 Spectral analysis and octave-band SPL calculation

Each mono-channel WAV file of the different sound sources was analyzed using a customised MATLAB script that performed a spectral decomposition via Fast Fourier Transform (FFT). The obtained spectral data was divided into standardized octave bands with center frequencies at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz, in accordance with Odeon's input requirements. For each octave band, the script calculates the signal energy by summing the relevant frequency components that fall within the defined band limits. The resulting values are then converted into sound pressure levels (SPL) expressed in decibels (dB):

$$\text{SPL}_i = 10 \cdot \log_{10}\left(\frac{p_i^2}{p_0^2}\right) \tag{5.1}$$

where:

- $p_0 = 20\,\mu\text{Pa}$ is the reference pressure;
- p_i^2 is the mean square pressure in the i-th band.

5.2.5.2 Calculation of the global sound pressure level

The calculation of the global sound pressure level (SPL) required an energy-based averaging procedure due to the logarithmic nature of decibel values. A simple arithmetic mean of SPL values would not be physically meaningful, as decibels are a logarithmic representation of sound energy. Therefore, each individual SPL value was first converted from the logarithmic decibel scale to its corresponding linear power value. The conversion was performed using the following equation, where N

represents the number of bands and SPL_i is the sound pressure level in decibels for the i-th octave band:

$$\text{Average} = \frac{1}{N} \sum_{i=1}^{N} 10^{\text{SPL}_i/10} \tag{5.2}$$

This linear average represents the mean acoustic energy across all octave bands, expressed in relative power units. Once this intermediate result was obtained, it was converted back into decibels through a logarithmic transformation, in order to express the final result using the same scale as the input data:

$$\text{SPL}_{\text{avg}} = 10 \cdot \log_{10} (\text{Average}) \tag{5.3}$$

This method ensures that the energetic contribution of each frequency band is correctly represented in the final overall SPL value, preserving the physical meaning of the calculation.

5.2.5.3 Conversion to sound power level

The sound power level L_w was then calculated from SPL values using the standard area-based formula:

$$L_w = L_p + 10 \cdot \log_{10} \left(\frac{A}{A_0} \right) \tag{5.4}$$

where:

- L_w: Sound power level in decibels (dB),
- L_p: Sound pressure level in decibels (dB),
- A: Measurement area (m^2),
- A_0: Reference area, typically $1\,\text{m}^2$.

In free-field conditions with a reference distance r, a simplified version is used:

$$L_w = L_p + 20 \cdot \log_{10}(r) + 11 \tag{5.5}$$

For this study, a reference distance of $r = 1\,\text{m}$ was assumed, resulting in:

$$L_w = L_p + 11 \tag{5.6}$$

5.2.5.4 Construction of the flat spectrum

A flat spectrum was derived by distributing the total sound power equally across all octave bands. The total power was first converted to linear scale, divided by the number of bands N, and converted back to dB:

$$L_{w,\text{flat}} = 10 \cdot \log_{10}\left(\frac{10^{L_{w,\text{global}}/10}}{N}\right) \tag{5.7}$$

This configuration was used in auralization to evaluate the room's acoustic effect without spectral coloration from the source.

5.2.5.5 Use of frequency-dependent spectrum and spectral normalisation

A fundamental step in preparing audio sources for use in acoustic simulations is the definition of their spectral content. In this work, two distinct spectral representations were computed for each source: a flat spectrum and a real spectrum distributed across octave bands. These two spectral approaches were applied with distinct purposes depending on the simulation goal. The flat spectrum was employed for auralization tasks, where the aim was to evaluate the perceptual influence of the room's acoustic response independently from the source's spectral characteristics. Conversely, the octave-band spectrum was used to obtain accurate SPL values and to calculate the corresponding sound power levels, both unweighted and A-weighted. This dual strategy made it possible to balance analytical control and perceptual realism according to the context. This method allowed for greater versatility in the simulation process in Odeon and a more comprehensive understanding of how each source interacts with the environment. From a practical point of view, MATLAB provided also the actual spectrum divided in the frequency bands. It reflects the real frequency-dependent emission of each sound source and was used when a realistic spectral profile was necessary (e.g., speech or mechanical noises). The bandwise values were corrected to L_w using the same +11 dB rule as above.

Both the flat and real spectra were normalized to ensure the same global sound power level. This allowed them to be used interchangeably in simulations, depending on whether neutrality or realism was required.

5.2.6 Characterisation of the specific sound sources

5.2.6.1 HVAC noise

To acoustically define the ventilation system sources, the sound pressure levels (SPL) in decibels (dB) were first extracted from the selected anechoic recordings using the MATLAB procedure previously described. These SPL values were then organized within a dedicated Excel sheet to facilitate further analysis. To evaluate the compatibility of the source with the acoustic standards required in library environments, the NR 35 curve, defined by ISO 1996-2 [37] as the reference criterion for acceptable indoor noise, was also incorporated into the spreadsheet. This curve sets target noise limits to ensure an adequate level of acoustic comfort and minimal distraction in spaces intended for study or concentration. Using the initial SPL values, A-weighted corrections were applied to obtain both linear and A-weighted sound pressure levels. The corresponding sound power levels were then derived from these values in both dB and dB(A) units. To validate the consistency of the spectral results, the average energy levels for both pressure and power data were calculated, again using logarithmic summation in decibels. A spectral adjustment was then performed by determining, for each one-third octave band, the difference between the average A-weighted sound power level and the unweighted SPL values computed via MATLAB. These differences were treated as correction factors. The design constraint for the ventilation system noise in the library imposed a maximum emission level of 25 dB(A). This value was incremented by the previously calculated correction factors in order to reconstruct a spectrum that met both the NR 35 standard and the project's acoustic requirements. The resulting bandwise pressure levels were then converted back into sound power levels, yielding a relative average of 51.7 dB. Finally, a 10 dB reduction was applied to this average level to account for additional design constraints or margin adjustments, resulting in a final average sound power level of 41.7 dB. This spectrum was ultimately used to characterize the ventilation source within the Odeon simulation environment.

5.2.6.2 Intelligible and unintelligible speech noise

To simulate background conversational noise within the library environment, different types of buzz sources were implemented, each designed to reflect specific acoustic and spatial conditions. A preliminary distinction was made between intelligible speech sounds and generic background buzz, corresponding to varying levels of clarity and engagement among occupants. For the simulation of intelligible speech, comprising both the intelligible speech and the equivalent phrases, the built, in natural source object available in Odeon [32] was employed. This source type reproduces speech signals using temporally and spectrally dynamic patterns, avoiding the repetitive playback of a static WAV file. As a result, natural sources are particularly well-suited to model individuals engaged in intelligible conversation, such as seated users at tables or speakers addressing others in shared spaces. They also streamline the auralization process by mitigating potential artifacts linked to waveform looping. In particular, the `BB93_Normal_Natural` source type was selected, which emulates a male speaker using a typical vocal effort. According to Odeon's documentation, when this source type is used, both the gain and EQ parameters in the Point Source editor should be set to zero to ensure spectral accuracy. Moreover, it provides a reasonable approximation of a female voice as well, provided that the 63 Hz and 125 Hz bands are excluded from the analysis, due to their limited relevance for higher-pitched voices [32]. For the intelligible sources, i.e. intelligible speech and equivalent sentences, the sound pressure levels were first analyzed using the previously described MATLAB script. The SPL values in octave bands were then imported into an Excel spreadsheet, where the corresponding sound power levels (L_w) were computed. Gain adjustments were subsequently applied to reach the desired levels for each source. Specifically, the intelligible speech source was assigned a global sound power level of 64.9 dB, representing collective low-level conversation. Conversely, the equivalent phrases source, based on standardized speech material, was set at 56.0 dB, reflecting more isolated or subdued vocal input.

For the simulation of generic buzz, intended to represent a more diffuse, less intelligible background buzz such as that produced by a large number of people speaking simultaneously in low voices, different methods were adopted. In this case, surface sources were used considering the spatial distribution required. One such source was created using an anechoic recording of background buzz acquired from a previous project. In this case, the output levels were adjusted manually using an appropriate gain correction. Following SPL analysis and power level computation, the overall level for the generic buzz was intentionally increased, reaching a global Lw of 73.9 dB. This elevated level was chosen to simulate a denser crowd and increase the perception of occupancy within the simulated library space. In the present study, the acoustic environment of the library was simulated to represent the full occupacy of the building which is approximately 1200 people.

By combining both types of sources, those with intelligible speech content and those with diffuse buzz, it was possible to achieve a more realistic and immersive acoustic environment. The layered approach reflects both localized intelligible communication and broader, less directional conversational background noise.

5.2.6.3 Noise from traffic

To properly represent the contribution of traffic noise in the simulation, a dedicated method was developed to estimate its indoor acoustic effect based on rooftop measurements and building transmission characteristics. Unlike other sound sources used in the simulation, the traffic signal was recorded on the roof of the building, making it necessary to consider the transmission effects of the roofing material in order to obtain a realistic estimation of its indoor impact. The initial step involved processing the recorded sound pressure levels (SPL) using a MATLAB script, from which the external noise levels in decibels (dB) were obtained. Since the signal had to pass through the roofing system before reaching the interior space, an acoustic correction was applied to account for the material's insulating performance. The indoor sound level L_{int} was estimated from the outdoor SPL L_{ext}, using the following relationship:

$$L_{\text{int}} = L_{\text{ext}} - R + 10\log_{10}\left(\frac{S}{A_{\text{tot}}}\right) \tag{5.8}$$

Where:

- L_{int} is the estimated internal sound level (in dB),
- L_{ext} is the external sound level recorded on the roof (in dB),
- R is the sound reduction index of the roof material (in dB),
- S is the surface area through which sound is transmitted (m^2),
- A_{tot} is the total sound-absorbing area inside the room (m^2).

The term R accounts for the attenuation introduced by the roof, while the ratio $\frac{S}{A_{\text{tot}}}$ adjusts the sound level according to the relationship between transmitted energy and the room's total absorptive surface. This approach captures both the barrier effect of the roof and the acoustic characteristics of the interior space. In this case, the roof was composed of polycarbonate panels, selected primarily for their transparency and ability to enhance natural lighting. However, polycarbonate has relatively poor acoustic performance in terms of sound insulation and absorption, which was taken into account in the analysis. Once the internal sound pressure level was estimated, it was used to calculate the corresponding sound power level L_W by applying the following expression:

$$L_W = L_P + 10\log_{10}(A_{\text{tot}}) - 6 \tag{5.9}$$

Where:

- L_W is the sound power level (in dB),
- L_P is the internal sound pressure level, assumed equal to L_{int},
- A_{tot} is the sound-absorbing area (m^2),
- -6 dB is a constant used to compensate for roof transmission losses and other correction factors.

This methodology made it possible to assign realistic values to the traffic noise sources in the simulation. The final calibrated power levels assigned in Odeon were:

- 69.4 dB for the first subdivision of the traffic source,
- 56.6 dB for the second,
- 55.5 dB for the third.

These values account for both the insulation properties of the building's roof system and the distribution of the sound energy within the interior environment.

5.2.6.4 Noise generated by pages-turning, pen-clicking and notifications of personal electronic devises

The sound generated by clicking pens, turning pages and notifications from mobile phones was recorded in an anechoic environment at the Politecnico di Torino to eliminate any reflections or environmental interference, as previously described. The recording was then processed using a customised MATLAB script in order to extract the sound pressure level (SPL) values across octave frequency bands. These SPL values, expressed in decibels (dB), provided a detailed representation of the spectral content of the noise. Following this, the spectral pressure data were used to calculate the corresponding sound power levels, as reported in the previous section. This step was carried out according to the standardized procedure outlined in the general methodology, which ensures the correct conversion from pressure-based to power-based acoustic descriptors, taking into account the acoustic absorption properties of the receiving environment. The outcome of this process yielded an average power level of 42.2 dB per one-third octave band. When integrated over the full spectrum, this resulted in a total sound power level of 51.2 dB, which was subsequently used to define the source parameters within the Odeon simulation environment.

5.2.6.5 Noise generated by footsteps

To realistically recreate the dynamic acoustic conditions of a traditional library, several moving sound sources were implemented in the simulation: a person descending a staircase (source S8) and 9 individuals walking across the floor (sources denominated as S9). Since Odeon does not currently support true animated source movement, an alternative solution was developed. Multiple point sources were placed in succession along the intended path, spaced closely enough to simulate continuous motion. For the simulations of walks at normal speed, the sources were aligned along straight linear paths across the floor, while for S8, the arrangement followed a vertical profile, with discrete points positioned at different elevations to represent individual stair steps. This layout was designed to emulate the natural progression of a person walking down a staircase, providing both horizontal and vertical acoustic variation. The footstep sounds were recorded via MIDI input and then segmented into smaller audio units. Each segment was assigned to a different point source along the path. Temporal offsets were introduced between segments to simulate progression in time. Once the sequence was defined, the sounds were convolved and mixed to create a seamless acoustic impression of a moving person. To define the correct sound power level values for the simulation, the sound pressure levels were first analyzed in MATLAB, following the general procedure previously described. For sources S9, which were associated with medium-paced walking, the resulting sound pressure and power levels were initially higher than desired due to the nature of the MIDI input. To bring them in line with realistic values, a correction gain of –57 dB was applied, leading to a final sound power level of 45.7 dB. Similarly, for source S8, representing faster steps down the stairs, the initial power level was also high and was corrected using the same gain adjustment. The resulting final level assigned in Odeon was 46.7 dB.

5.2.7 Job configuration

To ensure realistic and spatially consistent auralisations within the simulated library environment, it was necessary to calculate individual acoustic responses between each sound source and a fixed receiver position. This approach allowed for precise control of the direct and reflected sound components arriving at the listener, ensuring that each element of the auditory scene was properly represented. In Odeon 18, this task is managed through the use of *Jobs*, simulation instances that define the interaction between specific sources and receivers [32]. For each sound source used in the project, a dedicated job was created and configured. These included conversational buzz (both intelligible and unintelligible), sounds of turning pages and writing, multiple walking paths, stair descent, ventilation noise, various traffic positions, and individually treated speaker pairs. Each job was set up to compute the impulse response between a single source and the designated receiver. Since spatial averaging or multi-point calculations were not required in this case, only single-point response configurations were used. Within the Odeon job interface, jobs were initialized by naming them and selecting source–receiver pairs, as shown in Figure 5.29. To ensure accurate directional behavior, each sound source was explicitly oriented toward the receiver assigned to that job applying the appropriate orientation angle, as shown in Figure 5.14. Sources were manually activated for each job through the dedicated controls, and simulations were executed using the *Run Single Job* or *Run All Jobs* functions. A successful computation was visually confirmed when the job status indicator turned green. Once the simulations were completed, the *Single-Point Response* viewer was employed to analyze the output for each job. This tool, illustrated in Figure 5.30, provides a set of diagnostic visualizations, including:

- Frequency-band bar graphs displaying SPL and other parameters;
- Tabulated acoustic metrics such as EDT, T20 and C80;
- Energy decay curves illustrating the reverberation profile;

- Graphs showing how energy is distributed temporally and spatially in the room;
- Reflection-related analyses: reflection density, reflectograms, and 3D reflection trajectories;
- Binaural Room Impulse Response (BRIR) visualizations;
- Dynamic Diffusivity Curves (DDC);
- Dietsch echo curves, used to assess perceived echo risk.

For the purposes of source calibration, particular attention was paid to the A-weighted SPL values. These were extracted from the bar charts and tables, compiled into a comparison sheet, and used to identify inconsistencies. Sources that produced excessive or insufficient sound levels were then corrected by adjusting the gain applied during the job setup, ensuring perceptual uniformity across all simulated signals.

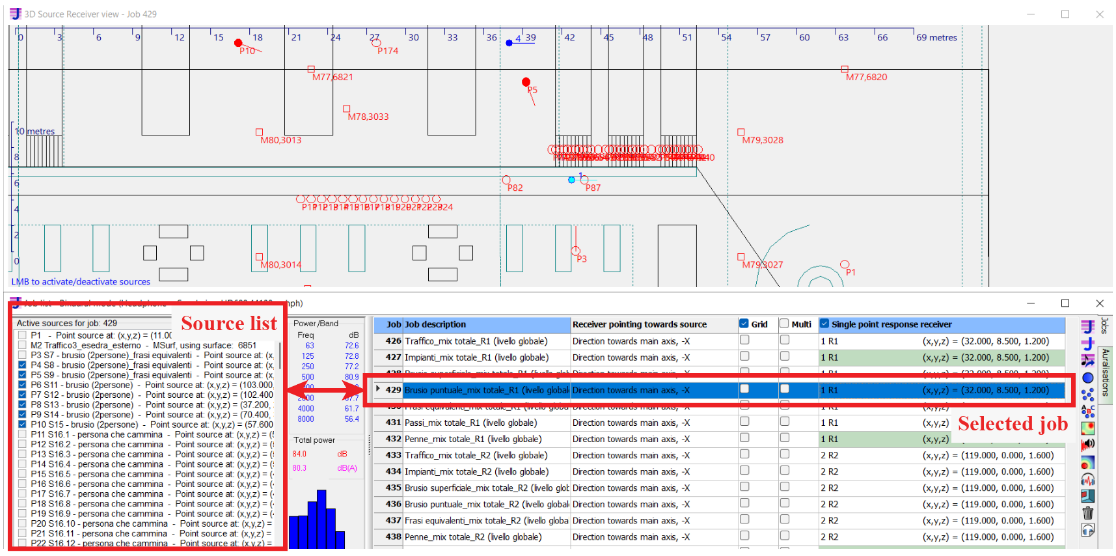


Figure 5.29: Odeon interface and Job creation.

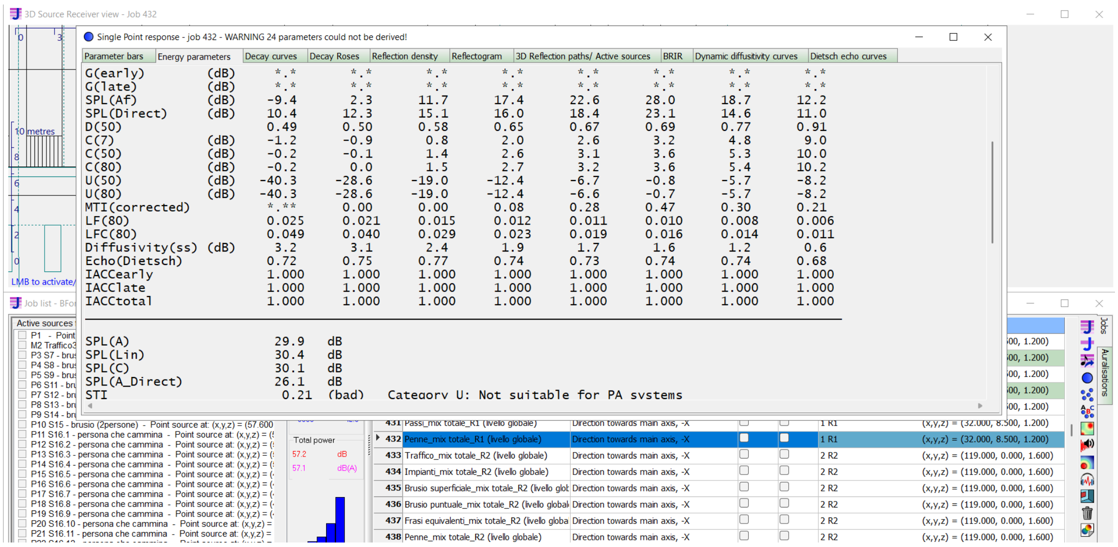


Figure 5.30: Odeon interface and Single-Point Response panel.

5.2.8 Anechoic audio samples

The auralisation phase of the simulation was carried out using anechoic recordings representing various typical sound events within the library environment. These included isolated footsteps, different configurations of conversational buzz (both intelligible and unintelligible), noises from pens, turning pages and mobile devices, ventilation system activity and external traffic noise. Each of these recordings was processed by convolving it with the room's impulse response, previously computed in Odeon for specific source–receiver combinations. This convolution process produces an audio signal that reflects the acoustic characteristics of the modeled space, such as reflections, reverberation and possible echo components, perceived at the receiver position. The acoustic impulse response characterizes how a given environment shapes sound propagation at a specific receiver location and orientation. It includes the acoustic effects of the environment, such as direct sound, early reflections, and late reverberation, as perceived at the receiver position. In this study, all impulse responses were generated through Odeon's simulation engine and correspond to specific job configurations defined earlier. For each auralisation, a single receiver position was selected, and particular attention was paid to its orientation, as this parameter significantly influences the perceived directionality and realism of the reproduced sound. The impulse response used for each convolution was retrieved from the corresponding job entry, ensuring consistency between the spatial setup and the simulated acoustic environment. To ensure consistency across all auralisations and enable direct comparison between sources, all audio files were standardized to a sampling rate of 44.1 kHz. The original input signals, captured at 44.1 kHz, were later resampled to 48 kHz in order to meet the specifications of ambisonic convolution rendering. This step ensured that all signals were compatible with the convolution process and maintained consistent time resolution and fidelity across playback systems.

5.2.9 Convolver and Mixer tools in Odeon

To apply auralisation to specific source–receiver configurations within Odeon, the *Convolver* and *Mixer* modules were employed [32]. These components facilitate the generation and combination of convolved audio files by associating preprocessed impulse responses with anechoic recordings. The convolution operation involves processing an input signal, typically an anechoic sound recording, through the room's impulse response to obtain an output signal that simulates the acoustical characteristics of the modeled space.

The *Convolver* interface is located on the left side of the auralisation window in the software and shown in Figure 5.31. It allows users to manually assign an audio file to a simulation job by selecting the signal path, audio file, channel (in case of multichannel recordings), and calibration settings. The calibration option can be enabled to match the input to a predefined A-weighted reference level, promoting consistency across different recordings [32]. Each job line corresponds to a source–receiver pair for which the convolution is computed. On the right side of the same window lies the *Mixer*, which enables the user to combine several convolved results into a single output file. This is particularly useful for simulating complex acoustic scenarios such as environments with multiple active sound sources. The mixer allows many convolutions, provided they share the same receiver and orientation. Within the mixer, each convolution can be delayed and level-adjusted individually to avoid artifacts such as unwanted overlapping or echo buildup. To streamline the otherwise manual process of assigning multiple sound files to their respective sources, the *Multi-source/signal auralisation expert* feature was utilized. This tool enables batch configuration by letting the user define a mix, select a receiver and its direction, and then associate each listed source with a corresponding sound file, as illustrated in Figure 5.32. Once defined, the selected files are automatically assigned and the software performs the necessary convolution calculations. Each mix is defined by a short description and includes delay settings, source gain, maximum output level, record levels and file association fields. The final mixes were computed and exported for playback in ambisonic environment and further evaluation. For the purposes of the project, the following mixes were defined and generated:

- a mix containing only the ventilation system-related sources;
- a mix containing only the traffic-related sources;

- a mix containing only the unintelligible speech sources;
- a mix containing only the intelligible speech sources; simulating a conversation between two people;
- a mix containing only the intelligible speech sources given by the equivalent sentences in 6 acoustically equivalent versions;
- a mix containing only the sources simulating the noise from pens, pages and mobile devices;
- separate mixes for each of the moving sources (S8 and S9), allowing full-step sequence evaluation.

These configurations made it possible to verify the realism of the simulations, particularly for dynamic elements like footsteps, and to ensure that the combined output conveyed a coherent and spatially plausible acoustic experience.

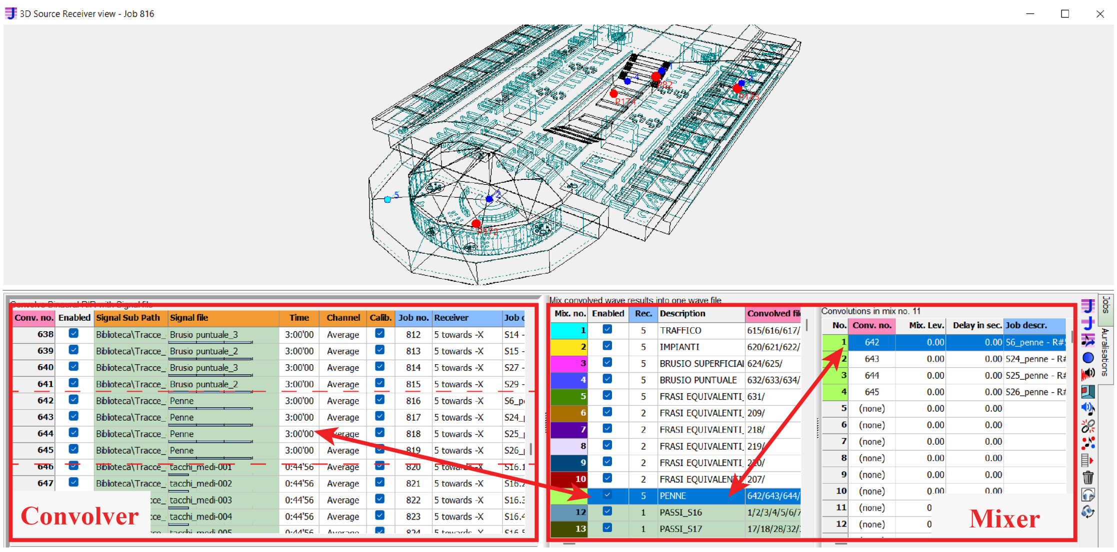


Figure 5.31: Odeon interface of the Convolver and the Mixer panels.

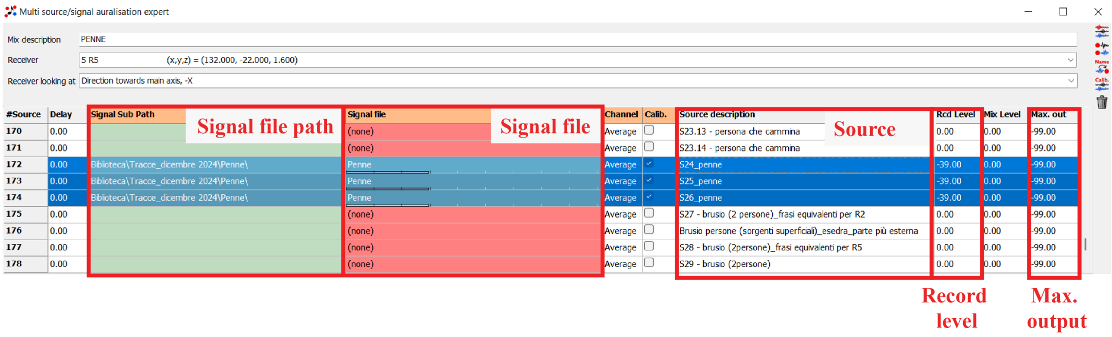


Figure 5.32: Odeon interface of the Multi-source/signal auralisation expert.

5.2.10 Auralisation of the simulated sounds

The term auralisation refers to the process of rendering audible a simulated acoustic environment, allowing the listener to perceive how a specific sound would be experienced in a defined spatial context [22]. This is typically achieved by convolving an anechoic sound recording with a measured or simulated room impulse response (RIR), thus reproducing the spatial and spectral characteristics of the chosen environment. Through this process, it becomes possible to virtually place a sound source within a modeledace and to evaluate how it would be perceived from a given listener position. In the present project, auralisation was carried out using Odeon 18, but instead of generating binaural output for headphone playback, as commonly done in subjective listening tests, ambisonic rendering was adopted to allow spatial reproduction over a loudspeaker array or through a virtual reality environment. This approach enables three-dimensional spatialisation of the sound field, making it suitable for immersive simulations of complex acoustic environments such as the New Civic Central Library of Torino. The simulated soundscape included all defined sound sources within the model, and the auralised signals were generated for multiple receiver positions. Odeon provided directional room impulse responses, which were then encoded into an ambisonic format, preserving spatial cues across the horizontal and vertical planes. Unlike binaural playback, which collapses the spatial image into two channels tailored to the human head-related transfer function (HRTF), the ambisonic output supports a more flexible and immersive reproduction, adaptable to different playback systems.

5.3 Composition of the final mixes

Once the convolution has been done, a set of audio tracks was carefully composed and structured using the Reaper digital audio workstation, as shown in Figure 5.33. Each track had a fixed length of three minutes, a duration chosen to balance the need for participant adaptation and the execution of the cognitive tasks. The sound material was organised using a system of time-structured matrices. Each matrix represented a different cognitive noise condition and was tailored for each of the five receiver positions considered in the simulation, as shown in Table 5.2 - Table 5.7. These matrices, structured in 20-second intervals, allowed precise control over the temporal arrangement of the various audio elements across the full duration of the stimulus, guaranteeing at the same time an equal overall sound pressure level.

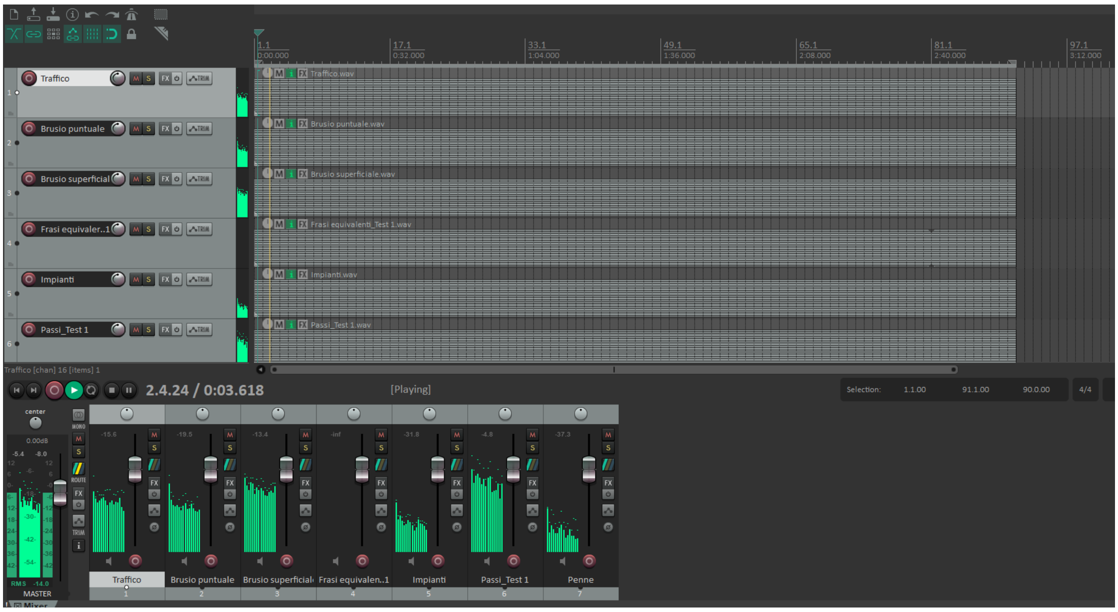


Figure 5.33: The set of audio tracks of the different sound sources imported to the software REAPER.

Some sources such as traffic noise, ventilation, unintelligible speech and intelligible speech given by overlapping two-person speech were intended to play continuously throughout the test. To ensure consistency in these long-duration signals, the original recordings were seamlessly looped using cross-fading techniques, avoiding noticeable repetitions or abrupt transitions. Other elements, particularly those representing transient events like footsteps or sentence fragments, followed different logic. Footstep sources were arranged in alternating patterns, with 20-second active segments followed by 40 seconds of silence. These patterns were systematically varied across the six tracks to avoid repetition and predictability. In a similar way, the equivalent sentence recordings were introduced in short bursts of 20 seconds, interspersed with silent intervals. These were deliberately mixed in non-identical combinations across the test conditions in order to prevent from any duplication of acoustic patterns within the same receiver channel. A key design principle was to assign the equivalent sentence source to nearest point to each receiver position, ensuring acoustic plausibility.

Table 5.2: Structure of the matrix applied to generate the 3-minute sound file for Track 1.

TRACK 1	Source Name	20"	20"	20"	20"	20"	20"	20"	20"	20"
S1, S2 - 1 surface source and 2 line sources	HVAC	■	■	■	■	■	■	■	■	■
S3	Traffic	■	■	■	■	■	■	■	■	■
S4	Unintelligible speech	■	■	■	■	■	■	■	■	■
S5 - 9 distributed point sources	intelligible speech	■	■	■	■	■	■	■	■	■
S6 - 1 point source close to each receiver	Equivalent sentences		■			■			■	
S7 - 1 point source close to Receiver 1	Pages, pens, etc.	■	■	■	■	■	■	■	■	■
S8 - 35 point sources in a row	Footsteps (people going down the stairs)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 1)	■			■			■		
S9 - 14 point sources of the second row	Footsteps (walk 2)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 3)			■			■			■
S9 - 14 point sources of the second row	Footsteps (walk 4)	■			■			■		
S9 - 14 point sources of the second row	Footsteps (walk 5)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 6)			■			■			■
S9 - 14 point sources of the second row	Footsteps (walk 7)	■			■			■		
S9 - 14 point sources of the second row	Footsteps (walk 8)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 9)			■			■			■

Table 5.3: Structure of the matrix applied to generate the 3-minute sound file for Track 2.

TRACK 2	Source Name	20"	20"	20"	20"	20"	20"	20"	20"	20"
S1, S2 - 1 surface source and 2 line sources	HVAC	■	■	■	■	■	■	■	■	■
S3	Traffic	■	■	■	■	■	■	■	■	■
S4	Unintelligible speech	■	■	■	■	■	■	■	■	■
S5 - 9 distributed point sources	intelligible speech	■	■	■	■	■	■	■	■	■
S6 - 1 point source close to each receiver	Equivalent sentences	■			■			■		
S7 - 1 point source close to Receiver 1	Pages, pens, etc.	■	■	■	■	■	■	■	■	■
S8 - 35 point sources in a row	Footsteps (people going down the stairs)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 1)		■			■			■	
S9 - 14 point sources of the second row	Footsteps (walk 2)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 3)			■			■			■
S9 - 14 point sources of first row	Footsteps (walk 4)		■			■			■	
S9 - 14 point sources of the second row	Footsteps (walk 5)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 6)			■			■			■
S9 - 14 point sources of first row	Footsteps (walk 7)		■			■			■	
S9 - 14 point sources of the second row	Footsteps (walk 8)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 9)			■			■			■

Table 5.4: Structure of the matrix applied to generate the 3-minute sound file for Track 3.

TRACK 3	Source Name	20"	20"	20"	20"	20"	20"	20"	20"	20"
S1, S2 - 1 surface source and 2 line sources	HVAC	■	■	■	■	■	■	■	■	■
S3	Traffic	■	■	■	■	■	■	■	■	■
S4	Unintelligible speech	■	■	■	■	■	■	■	■	■
S5 - 9 distributed point sources	intelligible speech	■	■	■	■	■	■	■	■	■
S6 - 1 point source close to each receiver	Equivalent sentences			■			■			■
S7 - 1 point source close to Receiver 1	Pages, pens, etc.	■	■	■	■	■	■	■	■	■
S8 - 35 point sources in a row	Footsteps (people going down the stairs)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 1)		■			■			■	
S9 - 14 point sources of the second row	Footsteps (walk 2)			■			■			■
S9 - 14 point sources of first row	Footsteps (walk 3)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 4)		■			■			■	
S9 - 14 point sources of the second row	Footsteps (walk 5)			■			■			■
S9 - 14 point sources of first row	Footsteps (walk 6)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 7)		■			■			■	
S9 - 14 point sources of the second row	Footsteps (walk 8)			■			■			■
S9 - 14 point sources of first row	Footsteps (walk 9)	■			■			■		

Table 5.5: Structure of the matrix applied to generate the 3-minute sound file for Track 4.

TRACK 4	Source Name	20"	20"	20"	20"	20"	20"	20"	20"	20"
S1, S2 - 1 surface source and 2 line sources	HVAC	■	■	■	■	■	■	■	■	■
S3	Traffic	■	■	■	■	■	■	■	■	■
S4	Unintelligible speech	■	■	■	■	■	■	■	■	■
S5 - 9 distributed point sources	intelligible speech	■	■	■	■	■	■	■	■	■
S6 - 1 point source close to each receiver	Equivalent sentences		■			■			■	
S7 - 1 point source close to Receiver 1	Pages, pens, etc.	■	■	■	■	■	■	■	■	■
S8 - 35 point sources in a row	Footsteps (people going down the stairs)			■			■			■
S9 - 14 point sources of first row	Footsteps (walk 1)			■			■			■
S9 - 14 point sources of the second row	Footsteps (walk 2)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 3)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 4)			■			■			■
S9 - 14 point sources of the second row	Footsteps (walk 5)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 6)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 7)			■			■			■
S9 - 14 point sources of the second row	Footsteps (walk 8)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 9)	■			■			■		

Table 5.6: Structure of the matrix applied to generate the 3-minute sound file for Track 5.

TRACK 5	**Source Name**	**20"**	**20"**	**20"**	**20"**	**20"**	**20"**	**20"**	**20"**	**20"**
S1, S2 - 1 surface source and 2 line sources	HVAC	■	■	■	■	■	■	■	■	■
S3	Traffic	■	■	■	■	■	■	■	■	■
S4	Unintelligible speech	■	■	■	■	■	■	■	■	■
S5 - 9 distributed point sources	intelligible speech	■	■	■	■	■	■	■	■	■
S6 - 1 point source close to each receiver	Equivalent sentences	■			■			■		
S7 - 1 point source close to Receiver 1	Pages, pens, etc.	■	■	■	■	■	■	■	■	■
S8 - 35 point sources in a row	Footsteps (people going down the stairs)			■			■			■
S9 - 14 point sources of first row	Footsteps (walk 1)			■			■			■
S9 - 14 point sources of the second row	Footsteps (walk 2)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 3)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 4)			■			■			■
S9 - 14 point sources of the second row	Footsteps (walk 5)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 6)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 7)			■			■			■
S9 - 14 point sources of the second row	Footsteps (walk 8)	■			■			■		
S9 - 14 point sources of first row	Footsteps (walk 9)		■			■			■	

Table 5.7: Structure of the matrix applied to generate the 3-minute sound file for Track 6.

TRACK 6	**Source Name**	**20"**	**20"**	**20"**	**20"**	**20"**	**20"**	**20"**	**20"**	**20"**
S1, S2 - 1 surface source and 2 line sources	HVAC	■	■	■	■	■	■	■	■	■
S3	Traffic	■	■	■	■	■	■	■	■	■
S4	Unintelligible speech	■	■	■	■	■	■	■	■	■
S5 - 9 distributed point sources	intelligible speech	■	■	■	■	■	■	■	■	■
S6 - 1 point source close to each receiver	Equivalent sentences			■			■			■
S7 - 1 point source close to Receiver 1	Pages, pens, etc.	■	■	■	■	■	■	■	■	■
S8 - 35 point sources in a row	Footsteps (people going down the stairs)	■			■			■		■
S9 - 14 point sources of first row	Footsteps (walk 1)	■			■			■		
S9 - 14 point sources of the second row	Footsteps (walk 2)			■			■			■
S9 - 14 point sources of first row	Footsteps (walk 3)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 4)	■			■			■		
S9 - 14 point sources of the second row	Footsteps (walk 5)			■			■			■
S9 - 14 point sources of first row	Footsteps (walk 6)		■			■			■	
S9 - 14 point sources of first row	Footsteps (walk 7)	■			■			■		
S9 - 14 point sources of the second row	Footsteps (walk 8)			■			■			■
S9 - 14 point sources of first row	Footsteps (walk 9)		■			■			■	

5.4 Sound pressure levels of the final mixes

Once the sound power levels had been assigned to each source, using the methodology described in the previous sections, Odeon computed the convolution between the source signals and the room impulse responses for each receiver. This operation yielded spatialised signals from which the global A-weighted sound pressure levels (SPLs) were extracted. To achieve both perceptual realism and analytical accuracy, the simulation was performed in parallel on two identical 3D models within Odeon. The only difference between them was the spectral content of the sources. In the first model, all sources were configured with flat spectra, ensuring uniform energy distribution across octave bands. This configuration was specifically used for generating faithful auralisations. In the second model, sources retained their real spectral profiles, obtained from prior analysis of the anechoic recordings, guaranteeing the same values of the sound power levels between the two models. This allowed the estimation of more accurate global SPLs at each receiver. The global A-weighted SPLs obtained from the two models (flat vs. real spectrum) are reported for each receiver in Figure 5.34 and Table 5.8.

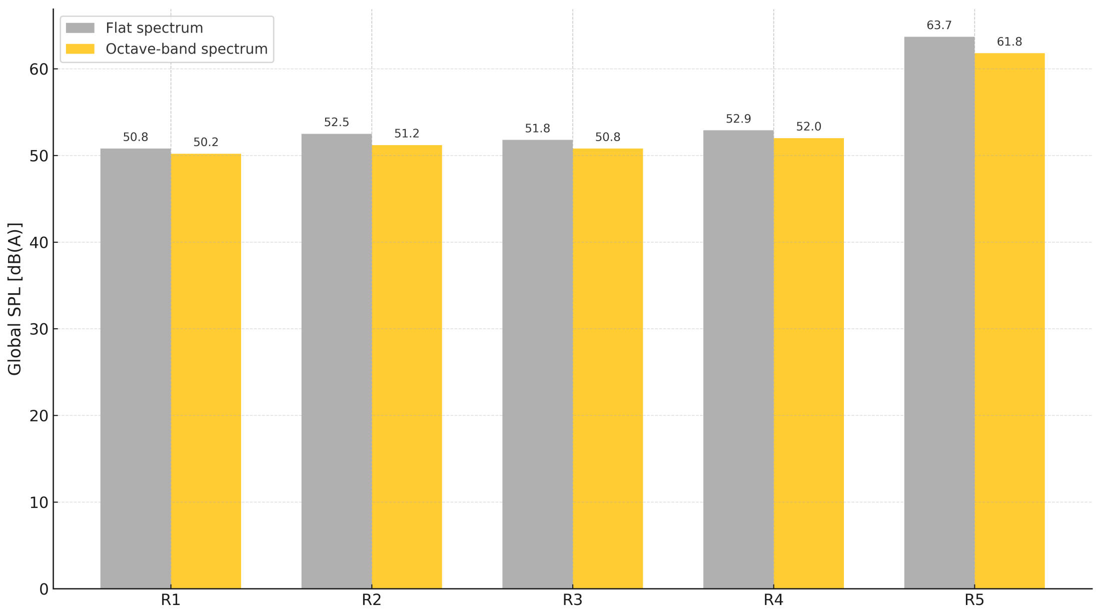


Figure 5.34: Comparison of global sound pressure level between flat spectrum and octave-band frequency spectrum for each receiver.

It can be notices that there are only very minor differences, with deviations between corresponding receivers remaining well within a perceptually negligible range (typically less than 3 dB(A)). This demonstrates that, under consistent calibration, flat-spectrum and real-spectrum models can yield almost equivalent energetic outcomes, validating the methodological choice to employ flat spectrum signals for perceptual evaluation, i.e. the auralised mixes, while relying on real-spectrum signals for quantitative acoustic assessments such as SLP. While the absolute values differ slightly, the variation is sufficiently small to be considered negligible for most practical purposes. Both versions are nonetheless included in the documentation for comparative purposes and completeness.

Table 5.8: A-weighted sound pressure levels (SPL) for each individual source, as well as for the combination of all sources, were obtained at each receiver position using the 3D Geometrical Acoustics (GA) model implemented in Odeon 18.

Source No.	Source Name	Source Type	SPL with flat spectrum, dB(A)					SPL with octave band spectrum, dB(A)				
			R1	**R2**	**R3**	**R4**	**R5**	**R1**	**R2**	**R3**	**R4**	**R5**
1	HVAC	Surface	17.0	22.4	14.1	15.3	28.2	14.3	19.0	11.1	13.1	24.4
2	HVAC	Line (2 above the balconies)	28.2	15.9	22.0	16.3	3.3	15.3	13.7	17.9	14.0	0.3
S1.3, S2.3, S3.3	Traffic	Surface	38.0	32.0	34.4	37.4	36.0	27.9	23.0	24.2	27.2	24.4
4	Unintelligible speech	Surface	45.4	50.0	48.3	48.8	62.9	44.3	47.7	46.1	46.8	60.8
5	intelligible speech	Point (9 distributed)	47.6	46.8	48.0	48.0	55.0	47.6	46.8	48.0	48.0	55.0
6	Equivalent sentences	Point (1 close to each receiver)	41.2	42.6	40.8	45.1	47.5	41.2	42.6	40.8	45.1	47.5
7	Pages, pens, etc.	Point (1 close to Receiver 1)	27.7	22.5	29.0	25.2	11.7	29.9	25.0	31.3	27.6	12.6
8	Footsteps (people going down the stairs)	Point (35 in a row)	36.2	31.2	33.0	42.1	19.5	36.5	31.9	33.0	41.4	19.7
9	Footsteps (people walking)	Point (14 for two rows)	38.8	41.0	37.1	38.6	49.0	37.9	39.6	36.0	37.7	47.2
1, 2, S3.1, S3.2, S3.3, 4, 5, 6, 7, 8, 9	All sources	-	50.8	52.5	51.8	52.9	63.7	50.2	51.2	50.8	52.0	61.8

In addition, the octave-band representations of SPL for each configuration were also plotted in Figure 5.35 to offer a more detailed spectral analysis and facilitate a frequency-by-frequency comparison of the resulting sound fields. The graph displays the sound pressure levels (SPL) recorded by the five receivers (R1–R5) across octave bands ranging from 63 Hz to 8000 Hz. As can be seen, all receivers exhibit a similar trend, with a peak between 250 Hz and 500 Hz, which is consistent with the presence of sources such as intelligible speech and HVAC systems. The lower frequency bands (63–125 Hz), while less prominent, suggest potential contributions from traffic noise or mechanical equipment. Receiver R5 stands out with significantly higher SPL values across all frequencies, particularly above 250 Hz. This can be attributed to its position inside a semi-toroidal, enclosed section of the space, where a high level of generic background noise is present. Additionally, the graph includes the spectrum for Richelieu library in Paris, which presents a distinct profile compared to the other receivers. Its SPL values are generally lower in the mid and high frequency bands (500 Hz and above), with a noticeable gradual decline starting from 500 Hz up to 8000 Hz. This pattern suggests a quieter and more acoustically controlled environment, with fewer high-frequency components such as speech or mechanical noise. The elevated value at 63 Hz, however, indicates a possible presence of low-frequency background noise, potentially from mechanical system. Overall, Richelieu appears to represent a more acoustically insulated area, less affected by human activity and airborne noise sources.

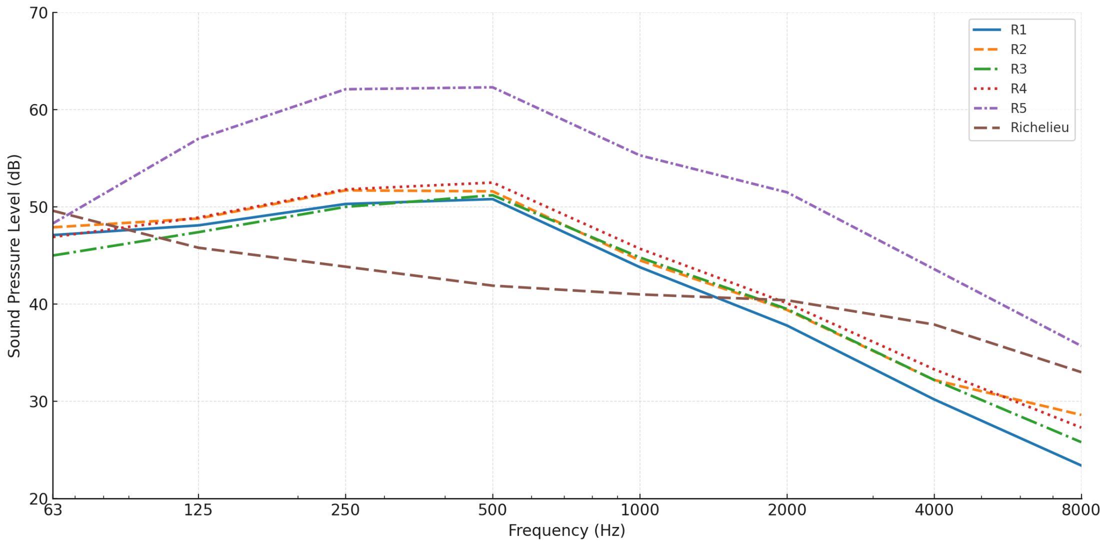


Figure 5.35: Sound pressure levels with octave-band frequency spectrum for each receiver and a comparison with the spectrum of Richelieu library in Paris.

5.5 Calibration of the mixes

Once the six final audio mixes for each receiver had been generated, a calibration phase was carried out at the Audio Space Lab of Politecnico di Torino, with the aim of reproducing the sound pressure levels consistent with those calculated using the octave-band spectrum in Odeon, which was considered more acoustically faithful. The Audio Space Lab is equipped with a high-resolution ambisonic playback system consisting of 16 loudspeakers arranged in a spatial array to provide immersive multichannel audio. At the center of this reproduction space, a measurement microphone was placed and calibrated using a reference sound level calibrator. A calibration recording was created specifically for the day of testing, to ensure that the microphone response reflected the exact environmental conditions during the calibration session. Once the microphone had been calibrated, each mix was played back in the room and the microphone captured the resulting audio signal. This signal, transmitted via an audio interface, was analyzed in real time by a custom MATLAB script, which computed the SPL value received and compared it to the target level derived from the Odeon simulations. The script then returned the gain adjustment necessary to bring the playback level in line with the expected value. The new gain was applied, and the audio was played again. If the resulting SPL still deviated from the target, the process was repeated: the signal was re-recorded, a new gain calculated, and the audio played again. This iterative procedure continued until the SPL measured by the microphone matched the expected value. In this way, each mix was individually calibrated to achieve the desired sound pressure level at the listener position, ensuring accurate alignment between simulated acoustic data and physical playback conditions in the ambisonic environment.

5.6 Testing environment

A total of 50 individuals, aged between 20 and 61, participated in the experimental session. The cognitive tests were conducted inside the Audio Space Lab (ASL), a specialized facility located within the Department of Energy at the Polytechnic University of Turin. Figure 5.36 illustrates the ASL which has dimensions of approximately 5.45 meters by 2.67 meters, with a height of 2.43 meters. Thanks to the sound absorption treatment, the environment offers a controlled acoustic response with an average reverberation time of around 0.17 seconds across the critical frequency range (250 Hz to 4 kHz), ensuring ideal listening conditions for experimental audio [38]. Additionally, the background noise level at the listening position remains extremely low, between NR 10 and NR 15 for frequencies below 1 kHz, providing an acoustically neutral setting well-suited to psychoacoustic and cognitive testing. The ASL is equipped with a third-order ambisonic loudspeaker array made up of 16 Genelec 8030B speakers for mid-to-high frequencies (90 Hz to 20 kHz) and two Genelec 8351A speakers dedicated to low-frequency reproduction (30 Hz to 90 Hz), as shown in Figure 5.37. The speakers are arranged in a spherical formation centered on the listener's position, allowing for precise and immersive spatial audio rendering. This setup was used to simulate the library acoustic environment during the listening tasks. The use of this room, rather than an anechoic chamber, was deliberate; it offers a high level of acoustic control while preserving a degree of naturalness in the auditory experience, an important factor in studies aiming to replicate realistic listening conditions.

Figure 5.36: A photography of the Audio Space Lab, reported by [39].

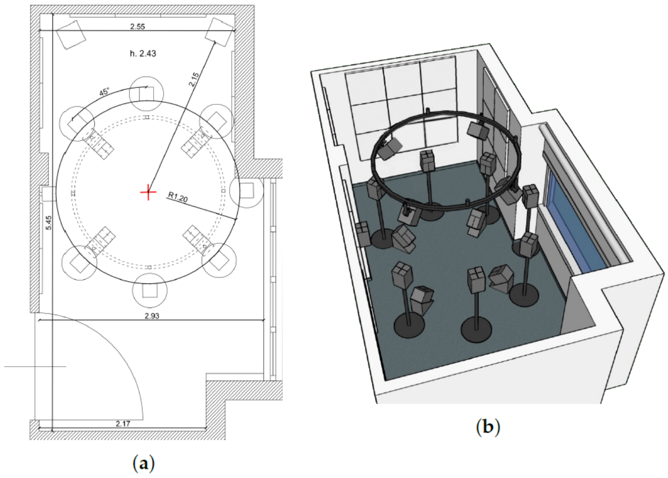


Figure 5.37: (a) The plan of the Audio Space Lab with the audio system. The red sign indicates the position of the listener. (b) A 3D model of the Audio Space Lab with the spherical 16-speaker array, reported by [40].

5.7 Cognitive tests

Each test lasted approximately one hour per participant and focused on a single simulated receiver position (R1, R2, R3, R4 or R5). The experimental procedure followed a structured protocol, illustrated in Figure 5.38, and was organized into three main phases:

1. **Phase 1 – Preliminary assessments**
   The first stage included a short introduction of the library and the experiment, followed by three standardized tests: a personal questionnaire, a noise sensitivity test, and a noise disturbance test. These assessments were designed to capture baseline information about each participant's relationship with sound. The duration of each test is listed in Figure 5.38.

2. **Phase 2 – Cognitive tasks in silence**
   In the second phase, participants performed six cognitive tasks while exposed to different audio scenes reproducing the simulated soundscape of the library. These tasks were designed to measure cognitive domains such as attention, verbal processing, memory and response speed. The tests included:

   - Silent reading of a 15-word list
   - Reading aloud a written passage
   - Trail Making Test (TMT)
   - Semantic Verbal Fluency Test (SVFT)
   - Reaction time task using the Open-Source Open-Access Reaction Time Test (OORTT)
   - Free recall of the words from the task A

   When it comes to the tasks C and E, a short training session of one minute preceded the task to ensure familiarity.

3. **Phase 3 – Cognitive testing under noise exposure**
   In the second stage, participants repeated the same six cognitive tasks, this time listening to the simulated soundscape of the library. No prior training was need anymore because the participant have already been familiarized with the tasks. As with the earlier phase, a time of 2 minutes and 30 seconds was given for completion of each task. Differently from the phase without sound stimulus, this phase did not considered a 30-second acclimatization period before the start of the tasks.

The second and third phases followed the same structure, differing only in the acoustic condition—noise versus silence. The silent phase served as a baseline for evaluating the impact of noise exposure on cognitive performance. To avoid order effects and ensure balanced task sequencing across sound conditions, a predefined matrix was used to randomize the order of cognitive tasks for each participant. This matrix, shown in Table 5.9, was applied consistently across both noise and silent phases, maintaining structural consistency while minimizing potential learning or fatigue biases. Moreover, to implement randomization while maintaining task equivalence, two different test versions (Test A and Test B) were created. These versions consisted of highly similar tasks of the same type and cognitive demand, ensuring comparability across participants and conditions. In order to introduce variability in the listening experience, the sound sequences were randomized, as well, as shown in Table 5.10.

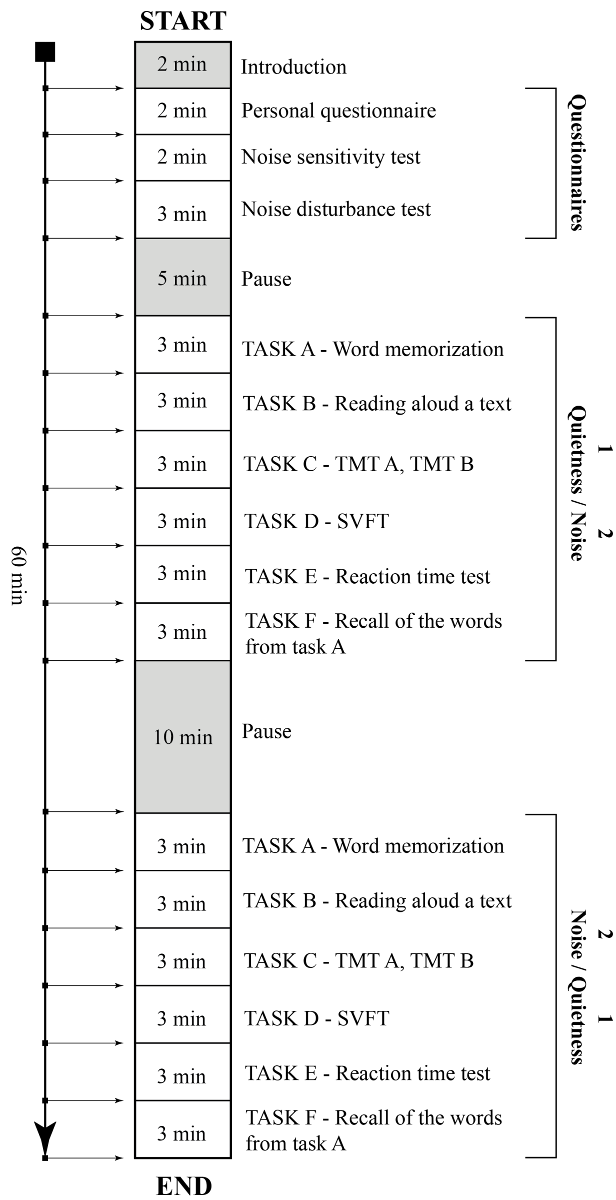


Figure 5.38: The structured protocol of the cognitive tests.

This procedure was consistently applied across all receivers and participants.

Each subject listened to six distinct tracks containing the same auditory content, but differing in the temporal arrangement of the sounds. These files were specifically tailored to each receiver and composed of short audio segments, each lasting approximately 20 seconds, as described previously and shown in Table 5.2-Table 5.7. These segments were repeated several times and altered with silent intervals, whose placement varied across files. Although the acoustic content as well as the sound pressure level of the audio remained unchanged, the sequence of sound and silence differed in each file, ensuring variation without altering the overall structure.

Table 5.9: The matrix used for the randomization of the order of cognitive tasks for each participant.

Participant	Test A	When?	Test B	When?
1 - 7 - 13 - 19 - 25 - 31 - 37 - 45	Noise	2 (second)	Quietness	1 (first)
2 - 8 - 14 - 20 - 26 - 32 - 38 - 46	Noise	1 (first)	Quietness	2 (second)
3 - 9 - 15 - 21 - 27 - 33 - 39 - 47	Noise	2 (second)	Quietness	1 (first)
4 - 10 - 16 - 22 - 28 - 34 - 40 - 48	Quietness	1 (first)	Noise	2 (second)
5 - 11 - 17 - 23 - 29 - 35 - 41 - 49	Quietness	2 (second)	Noise	1 (first)
6 - 12 - 18 - 24 - 30 - 36 - 42 - 50	Quietness	1 (first)	Noise	2 (second)

Table 5.10: The matrix used for the randomization of the order of the tracks for each participant.

Participant	Task A	Task B	Task C	Task D	Task E	Task F
1 - 7	Track 1	Track 2	Track 3	Track 4	Track 5	Track 6
2 - 8	Track 2	Track 3	Track 4	Track 5	Track 6	Track 1
3 - 9	Track 3	Track 4	Track 5	Track 6	Track 7	Track 8
4 - 10	Track 4	Track 5	Track 6	Track 1	Track 2	Track 3
5	Track 5	Track 6	Track 1	Track 2	Track 3	Track 4
6	Track 6	Track 1	Track 2	Track 3	Track 4	Track 5

5.7.1 Introduction of the project to the participants

The session began with an introductory presentation aimed at familiarizing participants with the library project. This introduction included visual renderings of the main architectural spaces and highlighted the distinctive features of the contemporary library in contrast to traditional models. During this phase, participants were encouraged to ask questions and engage in discussion regarding aspects of the project that captured their interest. Following this, the testing protocol was outlined: participants were shown a floor plan indicating the positions of both receivers and sound sources, providing spatial context for the upcoming auditory simulations. The sequence of tests was then explained in detail. It began with assessments focused on individual sensitivity to noise and perceived disturbance, followed by a series of six cognitive performance tasks, each to be completed under both quiet and noisy conditions to examine the potential influence of sound on attention and comprehension. Finally, QR codes and direct links were provided for accessing the personal questionnaires required for the test phase.

5.7.2 Introductory participant personal survey

The personal questionnaire is designed to collect essential background information from each participant. This includes demographic details such as age, gender, and native language, as well as any self-reported visual or hearing impairments. Additional questions address participants' acoustic familiarity or expertise, along with their current professional field. To preserve anonymity throughout the testing process, each individual is identified by an alphanumeric code (e.g., ASL 1, ASL 2, etc.) entered at the start of the session.

5.7.3 Noise sensitivity test

The assessment of how individuals respond to everyday environmental sounds can be carried out using a tool known as the WNSS, or Weinstein Noise Sensitivity Scale. Rather than measuring objective hearing ability, this questionnaire focuses on subjective sensitivity, that is, how easily a person becomes disturbed or distracted by common noise events. Participants are asked to express their level of agreement with a set of noise-related statements, each scored on a six-level Likert scale. These statements explore reactions to various auditory scenarios, such as disturbances at home, in public spaces, or during moments of concentration. The instrument, developed by Marvin Weinstein in 1978, was originally published in English but has since undergone multiple linguistic and cultural adaptations, including an Italian version created through a careful translation and validation process to ensure conceptual fidelity and psychometric robustness. This adaptation not only involved literal translation but also adjustment of content to match cultural references and expectations [41]. In terms of scoring, each response is assigned a numerical value. For items that are phrased negatively (i.e., where agreement implies lower sensitivity), scores must be reversed to maintain consistency across the scale. The final outcome is a cumulative score representing overall noise sensitivity: the higher the total, the greater the individual's predisposition to find noise intrusive or bothersome in daily life.

Table 5.11: The questions representing the Noise Sensitivity Test, formulated in Italian language.

N°	Question (Affermations)
1	Non mi dispiacerebbe vivere in una strada rumorosa se avessi un bell'appartamento.
2	Oggi sono più sensibile al rumore di quanto lo fossi in passato.
3	Nessuno dovrebbe infastidirsi se qualcuno alza lo stereo a tutto volume una volta ogni tanto.
4	Quando sono al cinema, sentire bisbigliare e scartocciare caramelle mi disturba.
5	Sono facilmente svegliato dal rumore.
6	Se c'è rumore nel luogo dove studio, cerco di chiudere la porta o la finestra o di spostarmi da un'altra parte.
7	Mi irrito quando i miei vicini fanno rumore.
8	Mi abituo alla maggior parte dei rumori senza troppa difficoltà.
9	Qualche volta i rumori mi innervosiscono e mi irritano.
10	Perfino la musica che normalmente mi piace mi dà fastidio se provo a concentrarmi
11	Non mi infastidirebbe ascoltare i rumori quotidiani dei vicini (rumori di passi, acqua corrente, etc.)
12	Quando voglio stare da solo, mi disturba ascoltare i rumori provenienti dall'esterno.
13	Riesco a concentrarmi indipendentemente da ciò che mi accade intorno.
14	In una biblioteca, non mi importa se le persone parlano tra loro a patto che lo facciano sottovoce.
15	Spesso vorrei un completo silenzio.
16	Le motociclette dovrebbero essere dotate di silenziatori più potenti.
17	Trovo che sia difficile rilassarsi in un luogo rumoroso.
18	Mi arrabbio con le persone che facendo rumore mi impediscono di addormentarmi o di portare a termine un lavoro.
19	Non mi dispiacerebbe vivere in un appartamento con pareti sottili.
20	Sono sensibile al rumore.

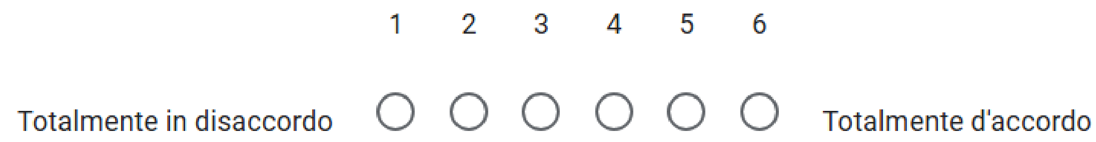


Figure 5.39: The 6-point scale for the questions of the Noise Sensitive Test.

5.7.4 Noise disturbance test

To complete the perceptual evaluation phase, participants were asked to answer a set of questions following the playback of a segment from one of the final audio mixes. The questionnaire, delivered in Italian to reflect the participants' native language, consisted of six items designed to capture subjective responses to the acoustic scene [42]. The first item utilized a numerical rating scale to gauge the listener's affective reaction to the stimulus, specifically in terms of perceived annoyance. This was implemented as a 0–10 Likert scale, where 0 represented complete absence of annoyance and 10 indicated a highly annoying experience. The remaining five items were structured according to the Semantic Differential Method (SDM), a psychometric technique used to quantify subjective impressions along bipolar adjective pairs. Each response was registered on a 7-point scale ranging from −3 to +3, with 0 denoting a neutral or balanced perception. These items explored psychoacoustic impressions along dimensions related to auditory texture and spectral characteristics. The bipolar scales included the following adjective pairs (with Italian equivalents in parentheses):

- Non-fluctuating vs. Fluctuating (*non fluttuante / fluttuante*)
- Smooth vs. Rough (*non ruvido / ruvido*)
- Dull vs. Sharp (*non acuto / acuto*)
- Quiet vs. Loud (*non forte / forte*)
- Non-whistling vs. Whistling (*non fischiante / fischiante*)

Through this two-part structure, anchored by both affective evaluation and detailed auditory profiling, the test aimed to capture a comprehensive picture of how each acoustic scene was perceived by the listener.

Figure 5.40: The 10-point scale for the question 1 of the Noise Disturbance Test.

Table 5.12: The questions representing the Noise Disturbance Test, formulated in Italian language.

N°	Question
1	Quanto reputi fastidioso il suono che hai ascoltato?
2	Quanto reputi fluttuante il suono che hai ascoltato?
3	Quanto reputi ruvido il suono che hai ascoltato?
4	Quanto reputi acuto il suono che hai ascoltato?
5	Quanto reputi forte il suono che hai ascoltato?
6	Come definiresti la tonalità del suono che hai ascoltato?

Figure 5.41: The 7-point scale for the questions 2 of the Noise Disturbance Test. The same type of 7-point scale was used for the other remaining questions, as well.

5.7.5 Cognitive task A - Word memorisation

In this experimental phase, verbal memory was assessed through a modified version of a classic neuropsychological tool originally proposed by Rey in 1958 [43]. The test, known for evaluating long-term verbal retention and learning ability, typically requires participants to listen to a list of 15 unrelated words, carefully chosen to avoid semantic associations and to recall them in any order. The original procedure includes five consecutive learning trials followed by a delayed recall phase conducted after a 15-minute interval, making it particularly effective for examining both acquisition and memory consolidation processes. It is suitable for adults with varied educational levels, typically between the ages of 20 and 80. For the present study, the protocol was adapted to match the specific conditions of the experimental setup. Because the participants were wearing headphones throughout the test, auditory presentation was replaced by visual exposure to the word list. Words were displayed on-screen, eliminating the need for a human examiner's voice. As a result, the focus was placed solely on delayed recall. After a fixed interval, each subject was instructed to write down as many words as they could remember from the previously shown list. Performance was quantified based on the number of correct responses, with a scoring range from 0 to 15, as later described. To ensure standardization and minimize learning effects between conditions, two separate but balanced word sets (labeled List A and List B) were used. These lists, shown in Figure 5.42 and Figure 5.43, allowed consistent testing under varying acoustic environments—both with and without external auditory stimuli, enabling comparison of memory retention under different perceptual loads.

VIOLINO	BASTONE	CAMPAGNA
TEMPO	LAGO	NOTTE
BRODO	ISOLA	CORNICE
FRECCIA	PALAZZO	LIRA
FIAMMIFERO	BARCA	PARETE

Figure 5.42: Test version A of Task A.

TENDA	TAMBURO	CAFFÈ
CINTURA	SOLE	GIARDINO
BAFFI	FINESTRA	FIUME
PAESANO	COLORE	TACCHINO
SCUOLA	CASA	CAPPELLO

Figure 5.43: Test version B of Task A.

5.7.6 Cognitive task B - Reading aloud task

In the second experimental task, participants' reading speed was assessed through an oral reading exercise. This evaluation method considers validated models for adult reading performance, notably the frameworks established in the Advanced MT Tests [44] and the MT-16-19 [45] protocols, which are widely used to measure decoding fluency and accuracy beyond adolescence. These tools acknowledge that reading proficiency continues to evolve into adulthood [46], and therefore provide a robust basis for assessing even subtle inefficiencies. For the purposes of this study, the test protocol was adapted to focus specifically on reading speed. Each participant was instructed to read aloud a passage taken from "Marcovaldo" by Italo Calvino [47], a literary work known for its linguistic complexity, specifically the stories "Funghi in città" and "Un viaggio con le mucche". These texts are commonly used in Italian reading assessments due to their rich vocabulary and syntactic variety, making them effective for identifying subtle reading challenges even in individuals with no overt impairments [48]. Reading speed was calculated in terms of correctly pronounced syllables per second. The number of syllables in each passage was predefined (571 for "Funghi in città", and 605 for "Un viaggio con le mucche") and used to compute the speed score by dividing the total syllables read by the time in seconds taken to complete the task. If the participant did not finish within the limit of 2:30 minutes, the number of syllables read up to that point was used for scoring. Accuracy was evaluated separately, based on the number and type of reading errors, which included elisions, substitutions, insertions, or inversions. More minor issues, such as accent shifts or self-corrections that preserved meaning, were considered less severe. The reading material was extracted from a publicly available PDF source on Italian reading speed assessments, which included syllable counts line by line to facilitate scoring. During the task, the passage was kept hidden and only revealed at the start of the test. Each passage yielded two distinct scores: one for speed (seconds per syllable) and one for accuracy (error count). These metrics were then compared to standardized performance benchmarks [46, 49].

5.7.7 Cognitive task C - Trail making test

The Trail Making Test (TMT), originally developed by Reitan (1979), is a neuropsychological assessment composed of three subtests: A, B, and G. In the present study, only parts A and B were included, as the total testing duration was restricted to 2.5 minutes, rendering the inclusion of the G component impractical. TMT-A involves connecting a series of 25 numbered circles in ascending numerical order (1 to 25) as quickly and accurately as possible. This initial subtest primarily evaluates cognitive domains such as visual search efficiency, number recognition, and psychomotor processing speed. In contrast, TMT-B introduces a more complex alternating sequence. Participants are required to connect circles by alternating between numbers and letters (e.g., 1–A–2–B–3–C, etc.), involving a total of 25 elements: 13 numbers (1–13) and 12 letters (A–L). This portion of the test is particularly effective for assessing cognitive flexibility, task-switching ability, and executive control functions. The test is administered on paper. Instructions are provided verbally by the examiner before the test begins, accompanied by an illustrative example. The test sheet is kept covered until the moment of execution, at which point a stopwatch is started. In this experimental setup, the overall duration allocated for the cognitive task included a one-minute training phase, a 30-second exposure to the auditory stimulus (in the noise condition), and a minimum of two minutes for performing the tests themselves. Both illustrative examples were presented prior to the beginning of Part A to ensure understanding, and no additional clarification was needed during execution due to the simplicity of the tasks. Scoring was based on the time, in seconds, required to complete each part of the test correctly, with interpretation adjusted according to the participant's age and educational background [50]. Comparing the performance in TMT-A and TMT-B provides insight into cognitive flexibility: a significant increase in completion time from A to B may suggest difficulties in executive functioning, particularly in shifting attention between task components. Additionally, errors such as sequencing mistakes or omissions, were monitored as indicators of attentional deficits or impaired cognitive control. While TMT-A is related to basic visual-motor processing speed and sequencing abilities, TMT-B is more diagnostic of higher-order executive functions, such as working memory, inhibitory control, and cognitive set-shifting.

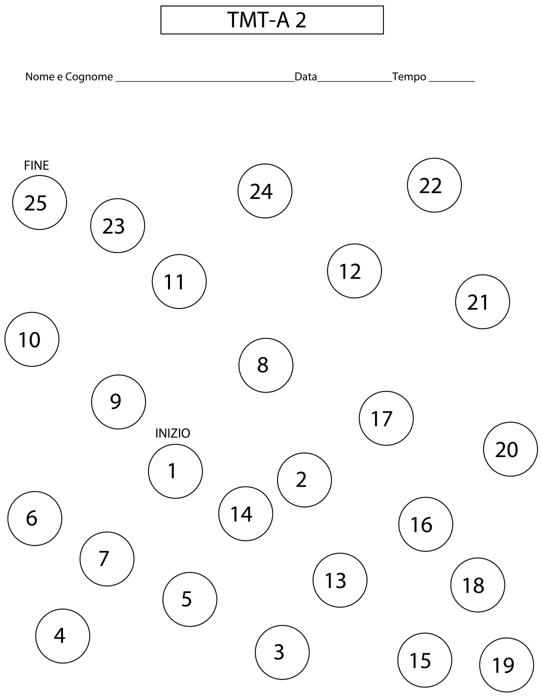


Figure 5.44: Test version A2 of Task C.

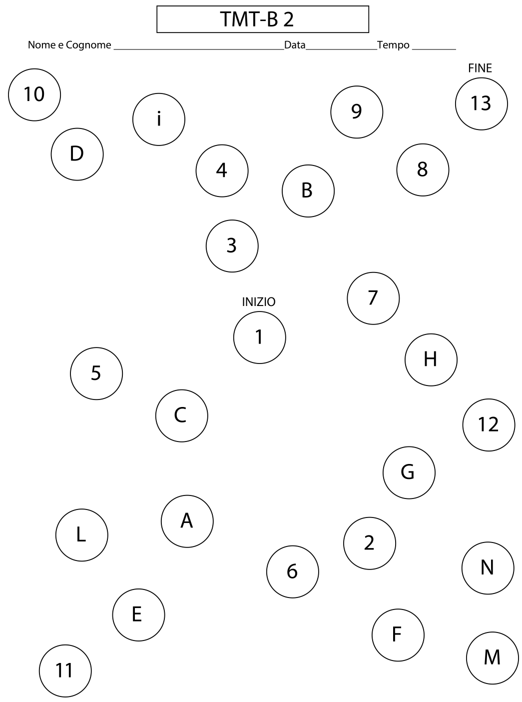


Figure 5.45: Test version B2 of Task C.

5.7.8 Cognitive task D - Semantic verbal fluency test

The Semantic Fluency Test (SVF) is a neuropsychological tool used to evaluate an individual's ability to retrieve and generate words that belong to specific semantic categories. In this study, the test was developed based on the article *"Standardization, clinical validation, and typicality norms of a new test assessing semantic verbal fluency"* [51], focusing on two distinct semantic domains. The primary objective of the test is to assess verbal fluency and semantic retrieval. Prior to the test, participants were informed that they would have 2.5 minutes to produce as many items as possible within each category. The categories used were:

- **Fruits and Vegetables:** participants were asked to name as many fruits and vegetables as possible, such as "apple", "banana", "carrot", "spinach," etc.
- **Articles of Furniture:** participants were instructed to list objects typically found in home furnishings, such as "chair," "table," "sofa," and similar items.

During the test, all words generated were recorded by the examiner, who also marked each word for further analysis related to its typicality, namely, how representative the word is within its semantic category.

Several analyses were carried out on the responses:

- Total number of correct words: This is referred to as the raw score and represents the participant's overall verbal fluency. Repeated or irrelevant words were excluded from the total count.
- Word typicality: The quality of responses was evaluated based on the sample's mean and standard deviation in order to assess how typical each word was.
- Influence of demographic variables: Variables such as age, education level, and gender were taken into account, as they may influence performance.

5.7.9 Cognitive task E - Open-source open-access reaction time test

The Open-access Reaction Time Test (OORTT) is a freely available tool specifically created to evaluate reaction times (RT) through a set of brief, standardized computerized tasks. This software-based test runs on the OpenSesame platform, an open-source application designed for constructing and conducting experiments in psychology and neuroscience. OpenSesame supports scripting in Python, includes plugin support for customization, and is compatible with Windows, macOS and Linux operating systems. In the context of this study, the required experimental files in the `.osexp` format were retrieved from the OSF.io repository, where they had been shared by Professor A. Facchin [52]. These files are directly compatible with OpenSesame and can be executed within the program. The test setup requires minimal effort. Once the appropriate files are downloaded, the user can launch them by double-clicking within OpenSesame. Upon loading the test, the user is presented with a configuration screen, which allows them to adjust visual parameters such as screen resolution, background color, and font style to ensure compatibility with the display settings of the device used. This calibration step is essential, as misalignment could affect the accuracy of the measurements during the task. Additionally, this interface provides access to the full experimental script. The complete version of the test consists of three distinct modules, each downloadable as a separate item:

1. **Simple Reaction Time (SRT):** The participant is required to react as swiftly as possible to a visual stimulus by pressing a key when a green circle appears in the center of the screen.
2. **Go/No-Go (GNG):** This task assesses the participant's ability to control automatic responses. The participant must press a key only when a designated "Go" stimulus is shown, while refraining from responding to the "No-Go" signals.

3. **Four-Position Reaction Time (4PRT):** In this version, participants must quickly and accurately respond to stimuli that appear in one of four possible screen locations.

Due to time limitations imposed by the 3-minute test duration, only the second task, i.e. Go/No-Go (GNG), was used in this study. Participants were instructed to press the space bar whenever a green dot was displayed on the screen and to withhold responses when a red dot appeared, as shown in Figure 5.46 and Figure 5.47.

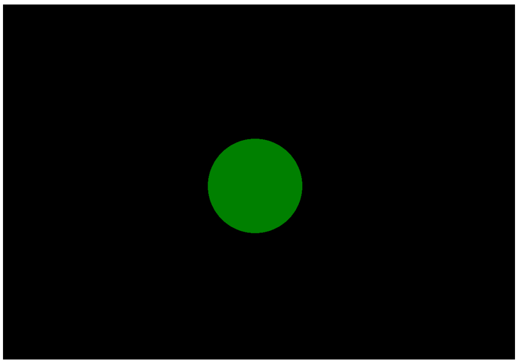


Figure 5.46: Task E - Green visual signal (press the space bar immediately).

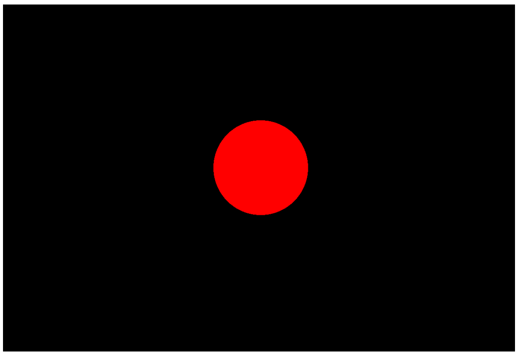


Figure 5.47: Task E - Red visual signal (do not do anything).

The testing procedure was designed to be straightforward and efficient. At the start of the session, each participant entered a unique identifier (name or code). Following this, a 1-minute warm-up phase was conducted to familiarize participants with the task format. The main testing phase then began and lasted 2.5 minutes. Upon completion, the final screen, depicted in Figure 5.48 presented a summary of the participant's performance, including average reaction time, standard deviation, response accuracy, and the rate of false alarms.

A perfect accuracy score, i.e. 100%, indicates that the participant pressed the space bar for every green stimulus and refrained from pressing it during all red stimuli. The software offers a reliable and precise method for capturing RT data and allows users to export individual reports for each session, facilitating subsequent analysis. Because OORTT is open-source, it can be freely used by clinicians, educators, and researchers without any licensing restrictions, making it a highly accessible and practical tool for a wide range of experimental needs.

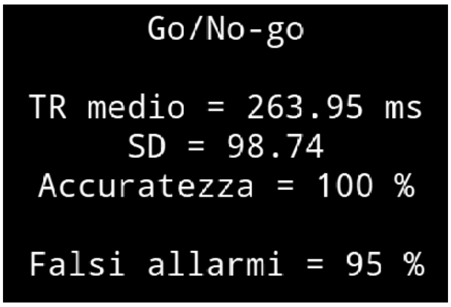


Figure 5.48: Task E - Final window showing the results from the test.

5.7.10 Cognitive task F - Recall of the memorised words from Task A

In the final part of the cognitive testing session, approximately 15 minutes after the initial memorising phase, the participant is asked to recall as many words as possible from the original list presented during Phase A. The list, both versions of which are illustrated in Figure 5.42 and Figure 5.43 includes 15 items, and performance is evaluated based on the number of correctly remembered words, with a maximum possible score of 15. Any mistakes or omissions made during this recall task reduce the score as the wrong words are not considered in the number of recalled words and are recorded by the examiner for descriptive purposes or further qualitative assessment. Participant characteristics such as age and level of education, which are known to influence memory performance, will be taken into account during the analysis phase to support a more accurate interpretation of the results.

Chapter 6

Results

6.1 Statistical analyses

The statistical analysis described in this chapter represents a crucial phase of the research, as it enables an objective and structured interpretation of the data collected during the experimental phase. The main goal is to identify trends, correlations or significant differences in behavior and cognitive performance to explore the effects of noise on task execution. Box plots were used as the primary visualization tool, well-suited for illustrating data distribution and facilitating comparisons across multiple variables. These plots present key descriptive statistics, including the median, data spread, and outliers, making them ideal for analyzing metric-scale data. In a box plot, the central box reflects the interquartile range (IQR), encompassing the middle 50 percentile of values. The bottom and top edges of the box represent the 25th (Q1) and 75th (Q3) percentiles, while the whiskers typically extend to 1.5 times the IQR. Points beyond this range are identified as outliers. Each plot also shows a solid blue line for the median and a red dashed line for the mean. The comparison between these two lines can indicate skewness in the data distribution. In addition to visual analysis, statistical measures such as variance and standard deviation were calculated to assess data dispersion.

To evaluate the effects of different acoustic conditions on cognitive performance, non-parametric tests have been used, as well. The Wilcoxon signed-rank test assessed performance differences between noise and silence, while the Kruskal–Wallis test evaluated differences across receiver positions, accounting for spatial acoustic variations. These tests were chosen due to the non-normal distribution of the data and the small sample size, which violated parametric test assumptions. A p-value threshold of 0.05 was used to determine statistical significance. This inferential approach complemented the descriptive data, offering a comprehensive view of the impact of noise, space, and acoustic characteristics on performance.

To further refine the analysis and control for individual variability, a Linear Mixed Model (LMM) was applied. This method incorporates both fixed effects, capturing variables consistent across the sample, and random effects, which account for variability specific to each participant. In this study, factors such as age, gender, test version, session order, noise sensitivity, and psychoacoustic parameters (i.e., fluctuation, roughness, loudness, sharpness, tonality) were included to account for their influence. Modeling participants as random effects allowed the analysis to isolate the effect of acoustic conditions from natural inter-individual differences, enhancing the accuracy and interpretability of the results.

6.2 Noise sensitivity test

To investigate individual differences in responsiveness to noise, a questionnaire consisting of 20 questions, reported in Table 5.11 was administered. Participants rated each item on a 6-point Likert scale, shown in Figure 5.39, where each value represented a different degree of noise sensitivity. Lower values corresponded to minimal sensitivity, while higher values indicated greater sensitivity to auditory disturbances.

To minimize potential response biases, such as answering patterns driven by habit or social desirability rather than actual beliefs or experiences, a number of questions in the questionnaire, in particular, questions 1, 3, 8, 12, 14, 15, 20, were intentionally written in a reverse format. In these reverse-formulated items, the meaning of the scale was inverted: for instance, selecting a low numerical value (e.g., 1) indicated a higher sensitivity to noise, while a high value (e.g., 6) indicated lower sensitivity. However, since these reversed questions follow an opposite scoring logic compared to the standard items, it is necessary to convert their raw responses during data processing. This is done by applying a transformation that re-aligns the scoring direction with that of the non-reversed items. For example, a response of 1 is converted to a 6, 2 becomes 5, and so on. The precise conversion of the scores is illustrated in Figure 6.1. This correction ensures that all items contribute to the total noise sensitivity score in a consistent way, regardless of how they were phrased. Figure 6.1 and Figure 6.2 show the box plots of the scores of the questions from Q1 to Q20 for all participants before and after the conversion of the reverse questions. Only after this realignment of scores can the full dataset be analyzed accurately, as it guarantees that higher total scores uniformly reflect higher levels of noise sensitivity across all 20 questions.

Table 6.1: The conversion of the scores for the reverse questions.

Reverse score	Converted score
1	6
2	5
3	4
4	3
5	2
6	1

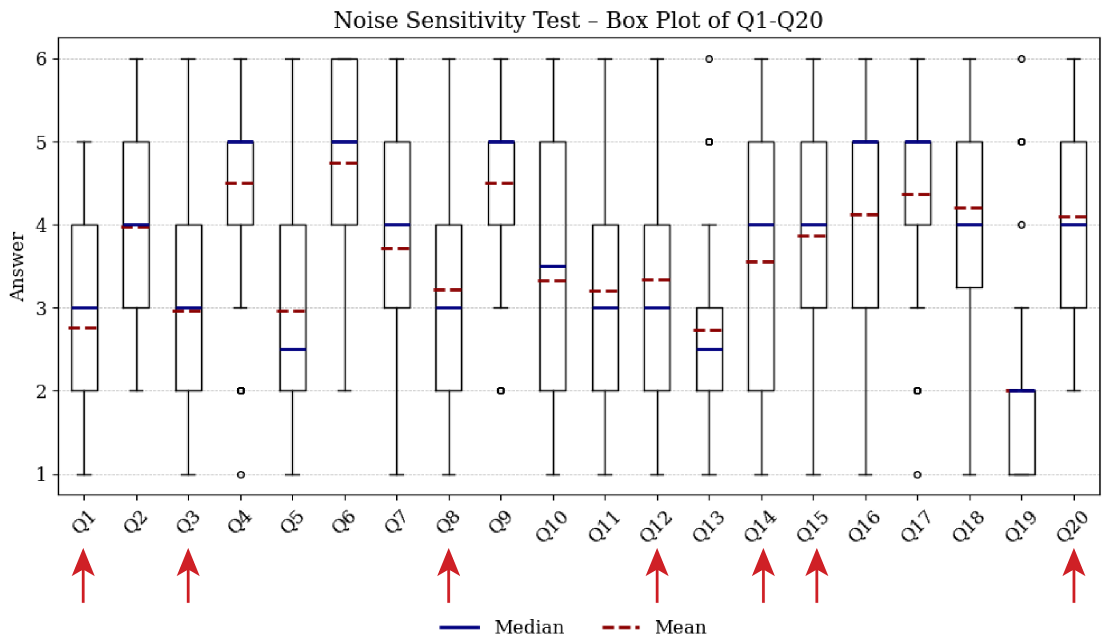


Figure 6.1: Box plots of the scores of the questions Q1-Q20 of the Noise Sensitivity Test for all participants before the conversion of the reverse questions.

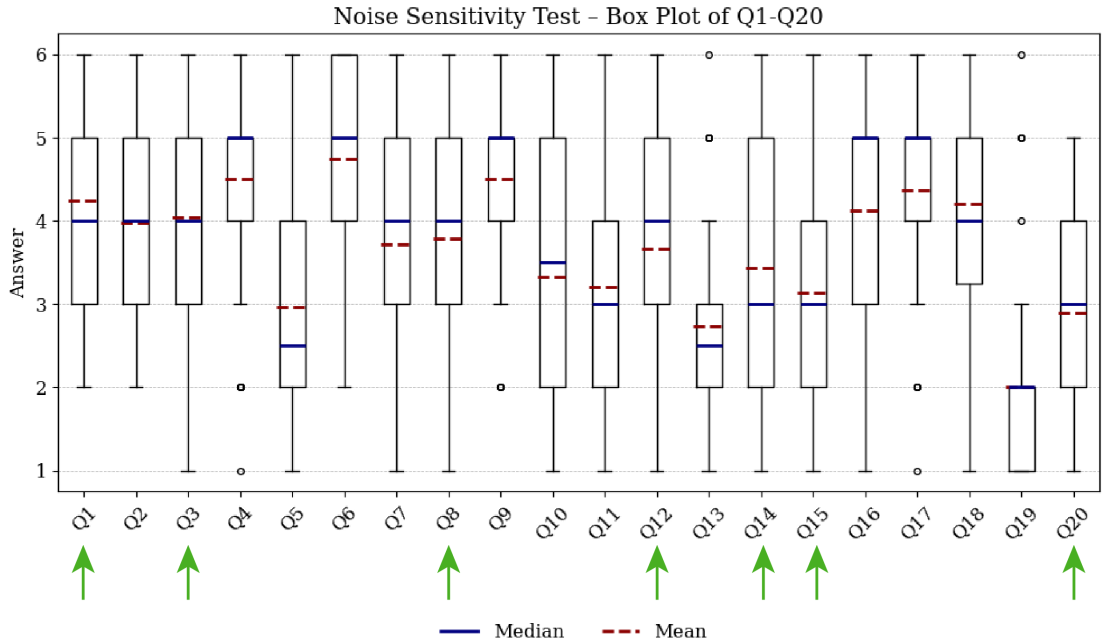


Figure 6.2: Box plots of the scores of the questions Q1-Q20 of the Noise Sensitivity Test for all participants after the conversion of the reverse questions.

After adjusting the data accordingly, a total score was computed for each participant by summing the points from all 20 items. The minimum achievable score was 20 (i.e., selecting the lowest value on every item), and the highest possible was 120. This score served as a quantitative indicator of the individual's overall sensitivity to noise.

Firstly, to assess whether participants assigned to different receivers differed significantly in their noise sensitivity scores, a Kruskal-Wallis test was conducted. This non-parametric test was chosen due to its robustness in handling potential violations of normality. The analysis revealed no statistically significant differences among the five receiver groups, p-value = 0.825. Based on this result, it is statistically justified to consider the entire participant pool as a single group for the purpose of analyzing noise sensitivity.

After that, the descriptive statistical analysis was made. The overall distribution of sensitivity scores for all participants is displayed in the box plot in Figure 6.3 and Figure 6.2. Scores ranged from a minimum of 58 to a maximum of 85, with a mean of 73.44 and a median of 74, suggesting a symmetric distribution around the center. The interquartile range, spanning from 70 (25th percentile) to 78 (75th percentile), captures the majority of the responses. The standard deviation of 6.39 reflects a moderate level of variability. Although a second box plot, illustrated in Figure 6.4 illustrates individual distributions by receiver (R1–R5), the overall shape of the distributions is visually similar. Based on the box plot, participants assigned to Receiver 1 appear to be the most sensitive to noise. This is indicated by their higher median score and a generally elevated range of values compared to the other groups. In contrast, Receiver 2 has the lowest minimum value and the lowest median, suggesting that participants in this group were, on average, less sensitive to noise. The variability in R2 is also quite large, indicating diverse sensitivity levels within that group. Receiver 3 also shows a relatively wide range, but with a median similar to the overall sample. Receivers 4 and 5 are positioned in the middle, with moderate medians and ranges, suggesting average sensitivity levels. However, the lack of statistically significant differences confirmed by the Kruskal-Wallis test supports the conclusion that noise sensitivity is uniformly distributed across the sample.

In summary, the data suggest that participants, regardless of receiver group, exhibit comparable levels of noise sensitivity. This statistical homogeneity strengthens the reliability of treating the sample as a unified group in subsequent analyses involving noise sensitivity.

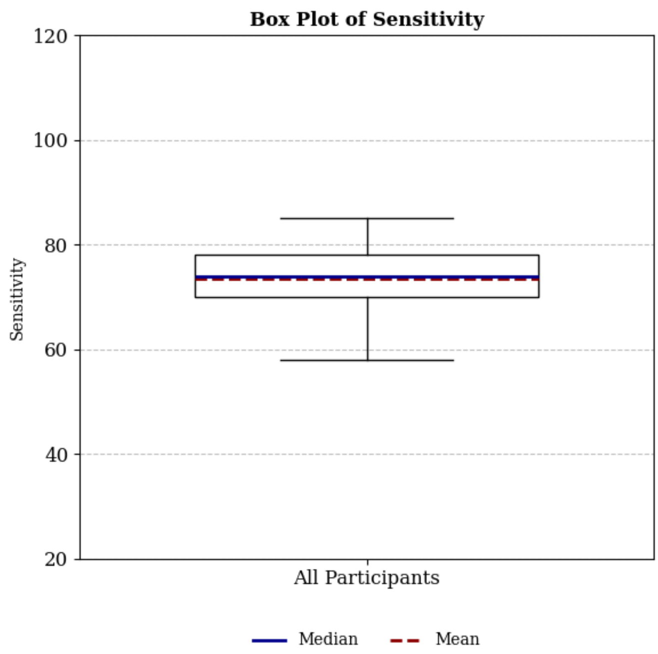


Figure 6.3: Box plot of the noise sensitivity for all receivers together.

Table 6.2: Statistical parameters for the noise sensitivity for all receivers together.

	Value
Mean	73.44
SD	6.39
Min	58.00
25th perc.	70.00
Median	74.00
75th perc.	78.00
Max	85.00

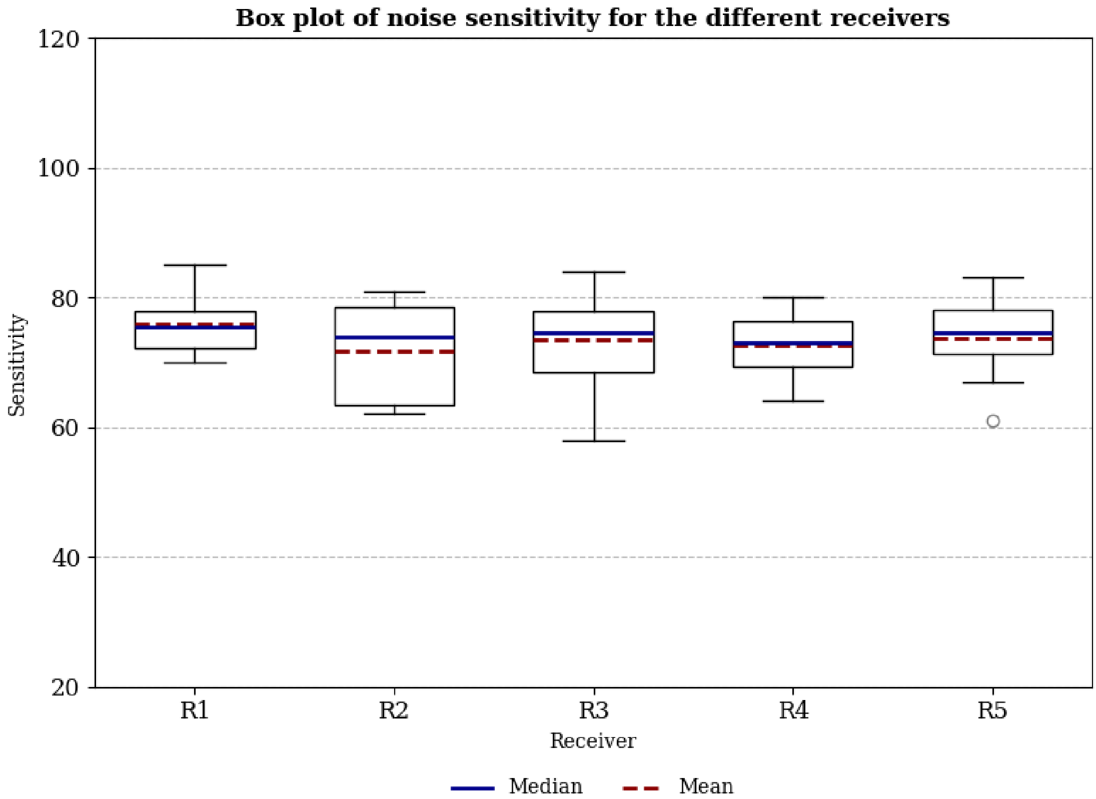


Figure 6.4: Box plots of the noise sensitivity for the different receivers.

6.3 Noise disturbance test

The Noise Disturbance Test was designed to evaluate both the level of annoyance perceived by participants and the presence of specific auditory qualities in a given sound sample. The questionnaire consisted of two types of items. The first, labeled Q2, asked participants to rate how annoying they found the sound on a scale from 1 (not annoying at all) to 10 (extremely annoying). The remaining items, labeled Q3 through Q7, explored the perception of five distinct sound characteristics: fluctuation, roughness, sharpness, loudness, and tonality. For these questions, a bipolar scale from -3 to $+3$ was used, allowing respondents to express the degree to which each characteristic was present or absent. A score of 0 represented a neutral perception, whereas negative and positive values indicated disagreement or agreement, respectively, with the presence of the trait in the sound. In the first phase of the test, participants listened to the audio stimulus and evaluated it using this structured questionnaire, reported in Table 5.12. The responses were then analyzed both visually, through box plots, and statistically, through descriptive metrics.

When it comes to the analysis of the results, firstly, to assess whether the data from the Noise Disturbance Test could be aggregated across all receivers or if analysis should be stratified by group, a Kruskal-Wallis test was conducted for each of the investigated parameters, i.e. annoyance, fluctuation, roughness, sharpness, loudness and tonality. The results revealed that, with the sole exception of loudness (p-value = 0.002), there were no statistically significant differences between receivers for the remaining dimensions (p-value > 0.05). Consequently, the analysis of annoyance, fluctuation, roughness, sharpness and tonality could be conducted across the entire participant sample, while loudness required a group-wise comparison.

Descriptive analysis was then carried out to explore the distribution of responses. Regarding perceived annoyance, represented in Figure 6.5 and Figure 6.3, participants tended to score toward the upper-middle portion of the scale, as shown by a median of 6 and a mean slightly lower. This indicates a moderate level of annoyance in response to the audio stimulus, although a degree of variability was evident across individuals.

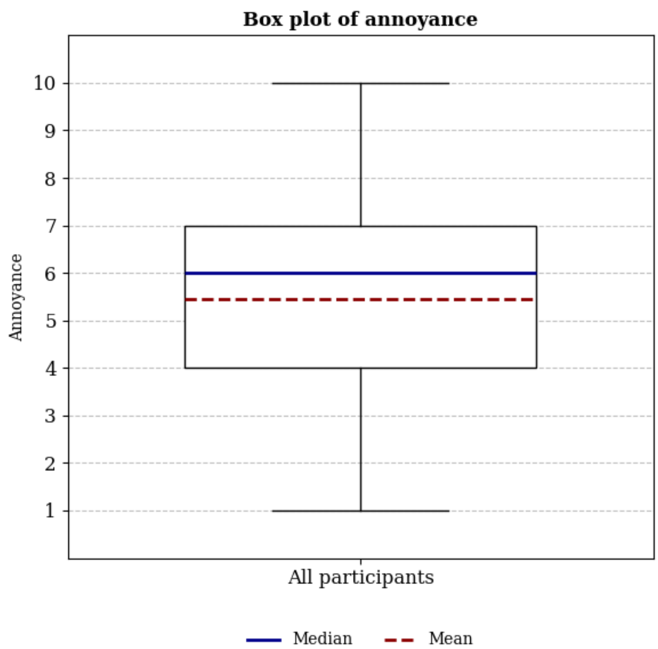


Figure 6.5: Box plot of the annoyance for all receivers together.

Table 6.3: Statistical parameters for the annoyance for all receivers together.

	Value
Mean	5.46
SD	2.04
Min	1.00
25th perc.	4.00
Median	6.00
75th perc.	7.00
Max	10.00

In evaluating psychoacoustic characteristics, analysed with a box plot in Figure 6.6, responses for fluctuation exhibited positive values, with both mean and median above zero. This suggests that the sound was generally perceived as fluctuating. In contrast, roughness and sharpness were mostly evaluated negatively, with medians close to -1, indicating that participants typically did not find the sound rough or sharp. Similarly, tonality received low scores, with the median at -1, suggesting the perceived absence of tonal qualities. Overall, fluctuation emerged as the only positively connoted attribute among the examined sound features.

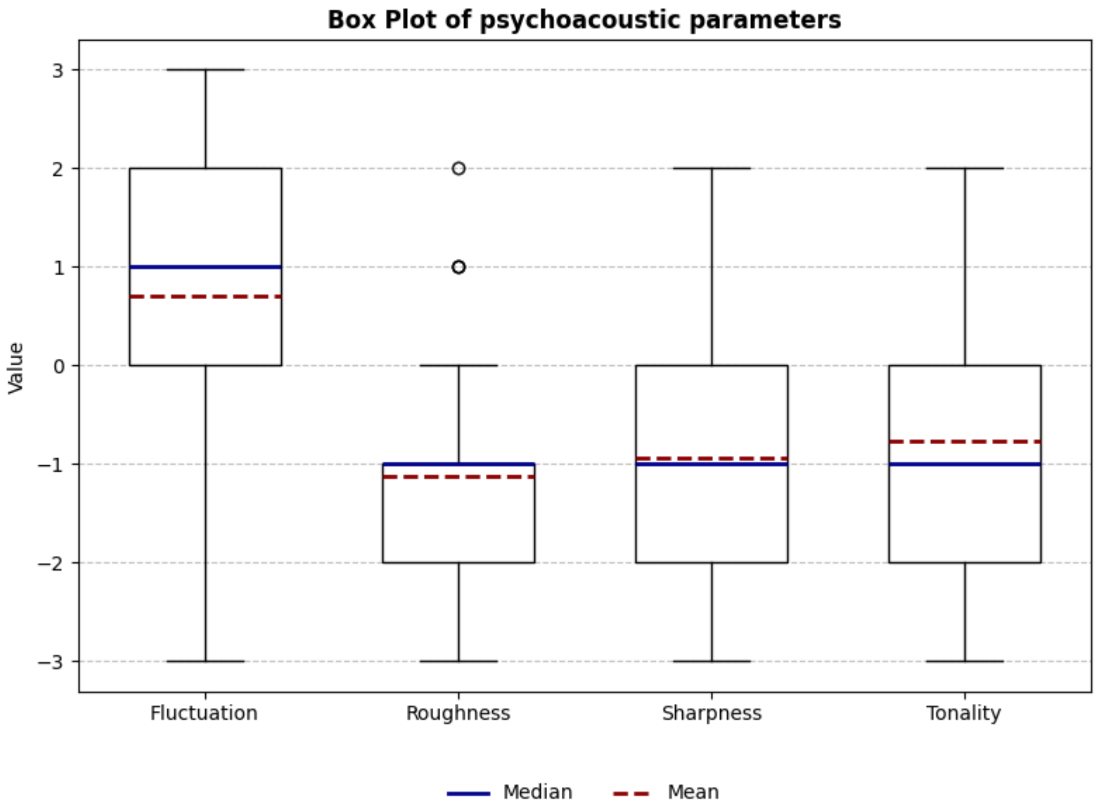


Figure 6.6: Box plots of the perception of the psychoacoustic parameters (Q3, Q4, Q5, Q7) for all participants.

For loudness, due to the significant differences identified by the Kruskal-Wallis test, a pairwise comparison using the Mann-Whitney test was performed between receivers. The results indicated statistically significant differences between several receiver pairs. Specifically, Receiver 1 differed significantly from Receivers 2 (p-value = 0.002), 3 (p-value = 0.035), and 5 (p-value = 0.002); and Receiver 3 differed from Receiver 5 (p-value = 0.023). These results are summarized in Table 6.4.

The analysis of the loudness box plot for the different receivers, shown in

Table 6.4: Summary of the p-values obtained from the pairwise Mann-Whitney test for loudness

	R1	R2	R3	R4	R5
R1	-	0.002	0.035	0.143	0.002
R2	-	-	0.105	0.165	0.579
R3	-	-	-	0.912	0.023
R4	-	-	-	-	0.075
R5	-	-	-	-	-

Figure 6.7, confirms the findings of the Mann-Whitney tests. Receiver 1 stands out with the lowest loudness ratings, showing a median value of approximately -1.5 and a narrow interquartile range, indicating that participants exposed to this condition generally perceived the sound as distinctly less loud. In contrast, Receivers 2 and 5 exhibit higher ratings, with median values above zero, suggesting a tendency to perceive the sound as louder. Receivers 3 and 4 present more moderate ratings, clustered around -1, indicating a less pronounced perception of loudness. These differences are consistent with the statistically significant results identified between Receiver 1 and the others (R2, R3, R5), as well as between R3 and R5. Overall, the box plot highlights that Receiver 1 consistently elicited lower loudness responses.

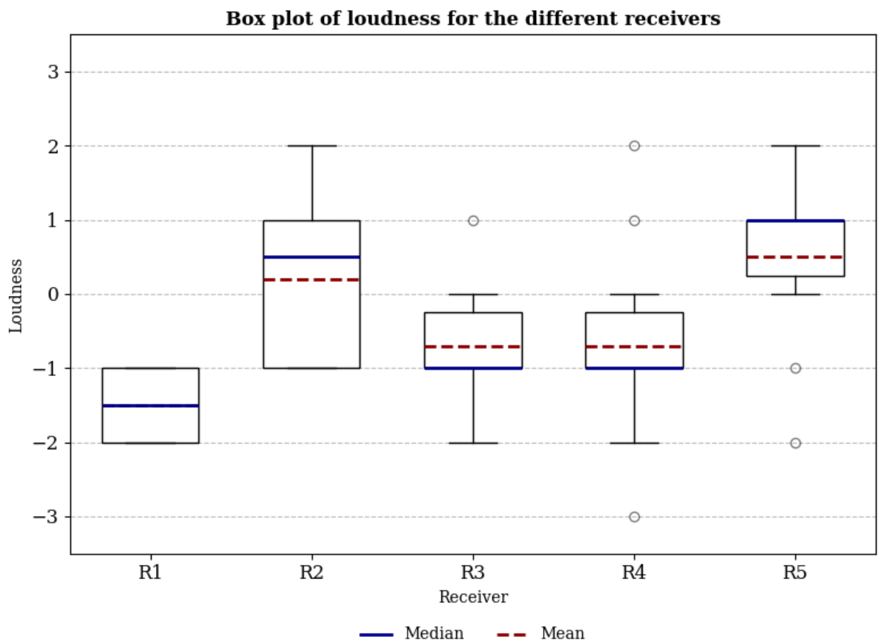


Figure 6.7: Box plots of the perception of the loudness (Q6) for different receivers.

6.4 Cognitive tasks

In the context of this study, the analyzed data originate from the responses provided by participants in relation to specific tasks (Tasks A–F), which were designed to investigate the effect of noise on cognitive performance. In particular, box plots were produced to graphically represent the distribution of answers for each task. The following figures in this chapter display the box plots corresponding to Tasks A through F, offering a visual overview of the trends and dispersions observed under both noise and quiet conditions. The analysis considered also the calculation of means, medians, standard deviations and other relevant statistical indicators, in order to deepen the interpretation of the results. Moreover, statistical analyses including non-parametric tests and Linear Mixed Model was applied to verify the significance of the observed differences.

6.4.1 Task A-F

Receiver 1

Figure 6.8 displays the box plots comparing participants' performance in the Verbal memory task at Receiver 1 under two environmental conditions: noise and quietness. In this cognitive exercise participants were required to complete a word recollection task in two distinct acoustic conditions: one with background noise and one in silence. The descriptive statistics for Receiver 1 suggest a modest improvement in performance when noise was present. The mean number of correctly recalled words in the noise condition was 11.20 (SD = 3.65), compared to a slightly lower mean of 10.40 (SD = 3.47) in the quiet condition. The median also favored the noise condition (11 in noise versus 10 in quiet), and the interquartile range was higher under noise (25th percentile = 10.00; 75th = 14.75) than in silence (25th = 8.25; 75th = 12.75). These descriptive trends suggest that participants may have recalled slightly more words in the presence of background noise, and the data distribution suggests generally better or at least comparable performance under this condition. To determine whether this observed difference was statistically significant, a Wilcoxon Signed-Rank Test was applied, as the sample consisted of paired, non-normally distributed scores and the number of participants was relatively small ($n = 10$). The test yielded a p-value of 0.306, which is well above the conventional threshold for significance ($p < .05$). This result indicates that the difference in performance between the noise and quiet conditions cannot be considered statistically significant. In other words, although numerically more participants performed better in the noise condition, this trend did not reach significance and may simply reflect normal variability within the sample. Therefore, it is not possible to conclude that noise has a consistent or systematic impact on word recollection performance for this receiver group. These findings suggest that, at least in this case, background noise did not have a detrimental or beneficial effect strong enough to be reliably detected through statistical analysis.

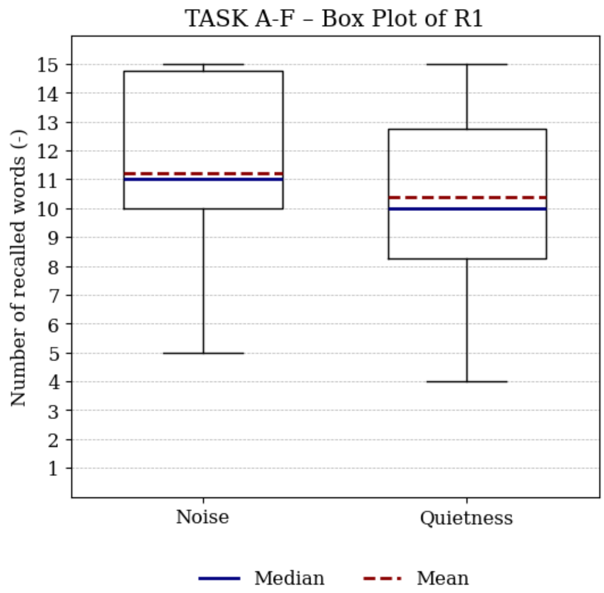


Figure 6.8: Box plot of the results of Task A-F for Receiver 1.

Table 6.5: Statistical parameters for Task A-F for Receiver 1.

	Noise	Quietness
Mean	11.20	10.40
SD	3.65	3.47
Min	5.00	4.00
25th perc.	10.00	8.25
Median	11.00	10.00
75th perc.	14.75	12.75
Max	15.00	15.00

Receiver 2

Figure 6.9 displays the box plots of participants' performance in the Verbal memory task at Receiver 2, comparing the noise and quiet conditions. The statistic analyses revealed only minimal differences between the two conditions. The average number of words recalled was 10.60 (SD = 3.66) in the noise condition and 10.90 (SD = 3.90) in the quiet condition, with identical median scores of 10.00 and maximum values of 15.00 in both settings. The percentile distribution showed slightly higher values under quiet (25th = 8.50; 75th = 15.00) than under noise (25th = 7.25; 75th = 14.50), indicating a small upward shift in the central portion of the data when no noise was present. However, the overall pattern of scores remained very similar between the two environments. To test whether these small differences were statistically significant, a Wilcoxon signed rank test was performed. The analysis showed a p-value of 0.734, far above the conventional threshold for significance. This result confirms that the observed differences are not statistically reliable. The rank distribution showed that four participants performed better in the quiet condition, three performed better in the noise condition, and three exhibited no change, reflecting a fairly balanced and inconsistent pattern. These results suggest that, for Receiver 2, the presence of background noise did not have a systematic effect on word recollection performance. The slight numerical advantage for the quiet condition appears to reflect normal individual variation rather than an effect attributable to the acoustic context.

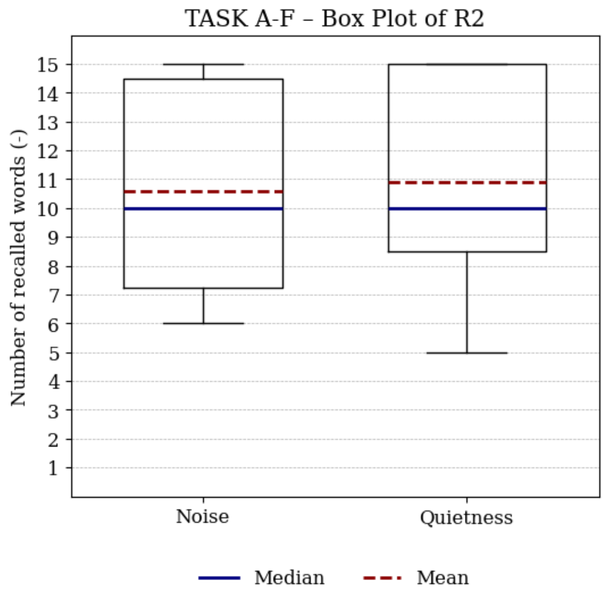


Figure 6.9: Box plot of the results of Task A-F for Receiver 2.

Table 6.6: Statistical parameters for Task A-F for Receiver 2.

	Noise	**Quietness**
Mean	10.60	10.90
SD	3.66	3.90
Min	6.00	5.00
25th perc.	7.25	8.50
Median	10.00	10.00
75th perc.	14.50	15.00
Max	15.00	15.00

Receiver 3

Figure 6.10 presents the box plots comparing performance in the Verbal memory task at Receiver 3 under the two noise conditions. Results showed a slight descriptive advantage for the quiet condition. Participants recalled an average of 10.30 words (SD = 3.71) in the quiet condition compared to 9.70 (SD = 4.24) under noise. The median score was marginally higher in silence (10.50 vs. 10.00), and the 25th percentile was also elevated in the quiet condition (8.50 vs. 7.25), suggesting that participants generally performed slightly better without background noise, especially among the lower-scoring individuals. However, the maximum score remained the same across both conditions (15.00), and the 75th percentile was identical (13.00), indicating similar upper-range performance regardless of the acoustic context. Despite these descriptive trends, the Wilcoxon Signed-Rank Test did not reveal a statistically significant difference between the two conditions. The p-value obtained was 0.959, indicating that the observed variation is extremely unlikely to reflect a real effect of noise. The rank distribution showed that six participants performed better in the quiet condition, while four performed better in the noise condition, with no ties recorded. The near-equal distribution of ranks, combined with the high p-value, strongly suggests that performance differences were due to individual variability rather than a systematic effect of noise exposure. Taken together, the results for Receiver 3 indicate no significant influence of background noise on verbal memory performance in this task. Although a slight numerical advantage was observed in the quiet condition, this difference was not supported statistically and should be interpreted as part of normal fluctuation rather than a replicable effect. The consistency of maximum scores and upper percentiles across both conditions further supports the conclusion that the presence or absence of noise did not meaningfully alter performance for this group.

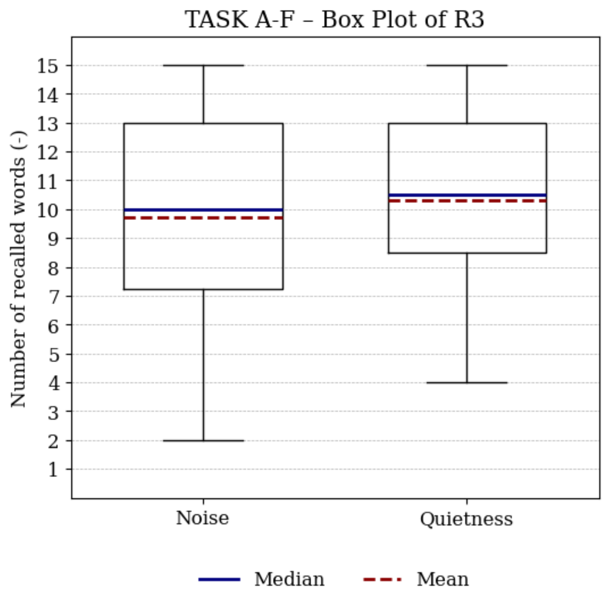


Figure 6.10: Box plot of the results of Task A-F for Receiver 3.

Table 6.7: Statistical parameters for Task A-F for Receiver 3.

	Noise	**Quietness**
Mean	9.70	10.30
SD	4.24	3.71
Min	2.00	4.00
25th perc.	7.25	8.50
Median	10.00	10.50
75th perc.	13.00	13.00
Max	15.00	15.00

Receiver 4

Figure 6.11 illustrates the boxplots representing participant performance in the Verbal memory task at Receiver 4, comparing the noise and quiet conditions. For this receiver results revealed a modest advantage in word recollection performance under the noise condition. The mean number of words recalled was 10.40 (SD = 4.81) with background noise, compared to 9.10 (SD = 3.45) in silence. The median score was notably higher in the noise condition (11.50 vs. 9.00), and the upper quartile also favored noise (75th percentile = 14.00) over quiet (75th =

12.00). Similarly, the maximum score was higher by one point under noise (15.00 vs. 14.00). While the 25th percentile was slightly lower with noise (7.25 vs. 6.50), the overall distribution suggests that a greater number of participants tended to achieve higher scores in the noise condition. The larger standard deviation observed in noise also indicates increased variability in performance, which might reflect a more heterogeneous response to the auditory environment among participants in this group. To test whether the observed differences were statistically significant, a Wilcoxon Signed-Rank Test was conducted. The analysis yielded a p-value of 0.135, which does not meet the standard threshold for significance. Although six participants performed better in the noise condition, only two showed better scores in quiet, and two remained unchanged, this imbalance was not strong enough to reach statistical significance. The direction of the ranks does support the descriptive trend, but the relatively small sample size limits the ability to detect effects unless they are substantial. Taken together, these results suggest a tendency toward improved memory recall in the presence of noise for Receiver 4, at least at a descriptive level. However, this trend is not statistically confirmed and should be interpreted with caution. The findings indicate that while some participants may benefit from noise in this context, the effect was not robust or consistent enough to generalize with confidence in this group alone.

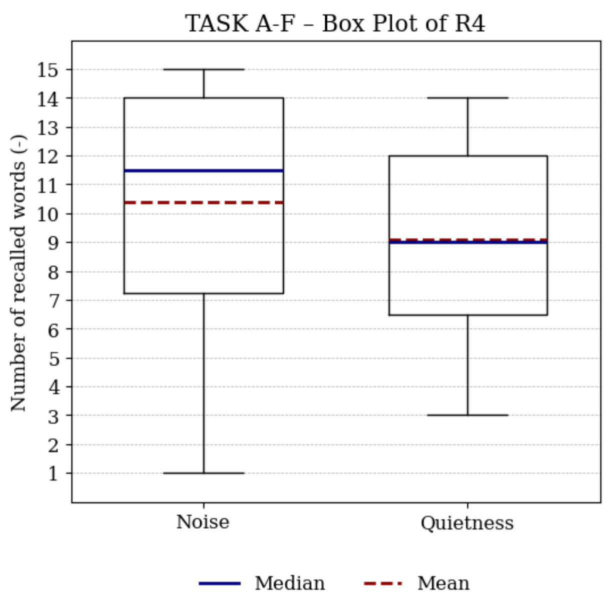


Figure 6.11: Box plot of the results of Task A-F for Receiver 4.

Table 6.8: Statistical parameters for Task A-F for Receiver 4.

	Noise	**Quietness**
Mean	10.40	9.10
SD	4.81	3.45
Min	1.00	3.00
25th perc.	7.25	6.50
Median	11.50	9.00
75th perc.	14.00	12.00
Max	15.00	14.00

Receiver 5

Figure 6.11 shows box plots of participant performance in the Verbal memory task at Receiver 4, comparing noise and quiet conditions. Results indicated a modest advantage under noise: the mean number of words recalled was 10.40 (SD = 4.81) with background noise, versus 9.10 (SD = 3.45) in silence. The median score was higher in the noise condition (11.50 vs. 9.00), as was the 75th percentile (14.00 vs. 12.00) and the maximum score (15.00 vs. 14.00). Although the 25th percentile was slightly lower with noise (7.25 vs. 6.50), the distribution overall suggests more participants achieved higher scores under noise. The greater standard deviation in the noise condition reflects increased variability, possibly indicating more individual differences in response. A Wilcoxon Signed-Rank Test yielded a p-value of 0.135, which was not statistically significant. Six participants performed better in noise, two in silence, and two showed no change, an imbalance supporting the trend but insufficient for significance. These findings suggest a possible benefit of noise for memory recall at Receiver 5, though the effect was not statistically confirmed and should be interpreted with caution.

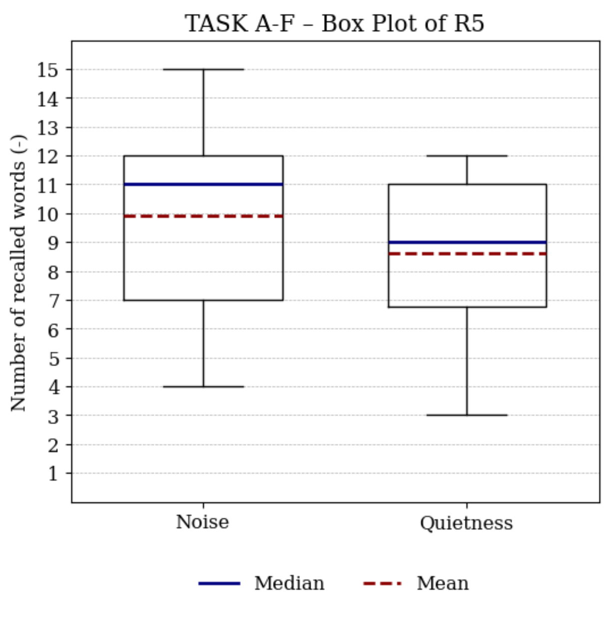


Figure 6.12: Box plot of the results of Task A-F for Receiver 5.

Table 6.9: Statistical parameters for Task A-F for Receiver 5.

	Noise	**Quietness**
Mean	9.90	8.60
SD	3.67	3.24
Min	4.00	3.00
25th perc.	7.00	6.75
Median	12.00	9.00
75th perc.	15.00	11.00
Max	15.00	12.00

All receivers

To examine whether the receiver position within the library influenced participants' verbal memory performance, Kruskal-Wallis tests were conducted separately for the noise and quiet conditions across all five receiver locations. In both cases, the tests revealed no statistically significant differences between groups (p-value = 0.916 for noise; p-value = 0.605 for quiet), indicating that performance did not vary meaningfully depending on spatial position in either acoustic condition. This confirms that all five receiver locations can be treated as comparable in terms of their influence on memory outcomes.

Figure 6.13 shows the box plots for all receivers combined, allowing for a visual comparison of performance patterns. Receiver 1 exhibited the highest mean rank in the noise condition (11.20), followed by Receivers 2 and 4 (10.60 and 10.40, respectively), while Receivers 3 and 5 showed lower ranks (9.70 and 9.90), suggesting a modest trend toward better recall under noise exposure of the participants in R1, R4 and R5. However, these differences were not statistically significant and may reflect normal inter-individual variability rather than true spatial effects. When examining each receiver individually, some minor descriptive trends emerge. Receiver 1 showed slightly higher scores under noise. Receiver 2 yielded near-identical distributions across acoustic conditions, and Receiver 3 performed marginally better in quiet, although these differences were negligible. Receiver 4 and Receiver 5 showed a more pronounced descriptive trend favoring the noise condition, particularly in terms of median and upper quartile values. Yet, none of these patterns reached statistical significance. The similar shape and range of the box plots across all receivers support the conclusion that spatial position did not exert a systematic influence on task performance.

To deepen the investigation beyond spatial and acoustic variables, a Linear Mixed Model (LMM) analysis was conducted on the full dataset to identify whether individual-level characteristics could predict performance on the verbal memory task. The model included fixed effects for age, gender, sensitivity to noise, fluctuation strength, and test version (Version A vs. Version B), with participant ID as a random intercept to account for repeated measures. Among these predictors, only the test version emerged as statistically significant with a p-value of 0.027. The estimate for the Version variable was 1.020, indicating that participants who completed Version B recalled, on average, one word more than those who completed Version A. This trend was also investigated by producing the box plots representing the correlation between the number of recollected words and the version of the test, as shown in Figure 6.27. The result is statistically robust, as reflected by the 95 percent confidence interval, which does not cross zero. The interpretation suggests a modest but reliable difference between the two versions of the memory task, potentially due to differences in word familiarity, semantic clustering, or order effects, despite efforts to match difficulty across versions. All other factors, such as age, gender, sensitivity to noise, and fluctuation strength, did not show significant effects in the model. This suggests that verbal memory performance in this task was not meaningfully shaped by demographic or perceptual characteristics, at least within the range represented in the sample. In conclusion, while the receiver position and acoustic environment did not significantly impact performance on the verbal memory task, the specific version of the test did play a small but meaningful role, highlighting the importance of controlling for version-related differences in experimental design.

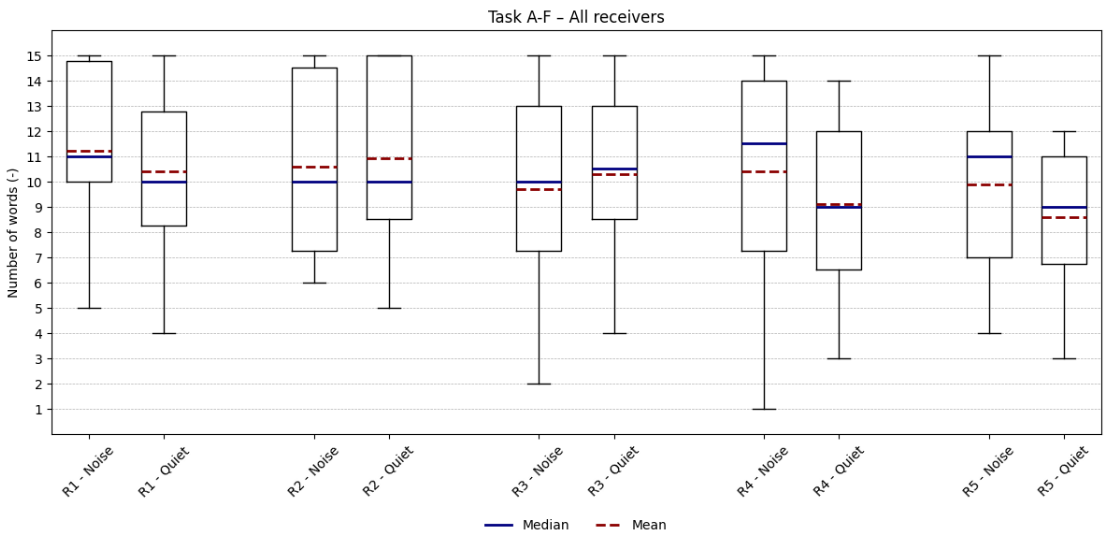


Figure 6.13: Box plots of the results of Task A-F for all receivers.

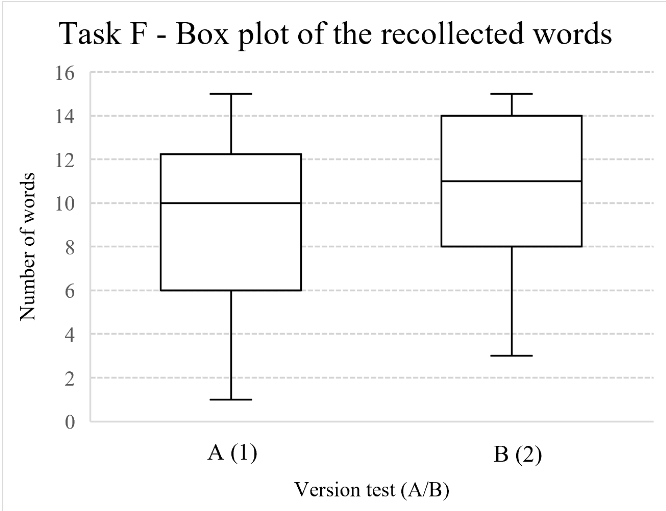


Figure 6.14: Box plot of the correlation between the number of recollected words and the version of the test for the Task A-F.

6.4.2 Task B

Receiver 1

Figure 6.15 and Figure 6.16 present the box plots of participants' performance at Receiver 1 in the Reading Aloud task, under the two acoustic conditions, i.e. background noise and quietness. Two outcome measures were analyzed simultaneously, the speed score, reflecting the fluency of reading, and the number of errors, indicating accuracy. With regard to speed score, descriptive statistics revealed virtually identical results between the two conditions. Both the mean and median values were almost the same (around 0.19), and the range of performance showed minimal variation. While the lower quartile was slightly elevated in the quiet condition, the overall distribution, including the maximum and 75th percentile, remained very similar. The box plots confirmed this visual pattern, with overlapping interquartile ranges and closely aligned central tendencies. A Wilcoxon Signed-Rank Test was conducted to assess whether the small observed differences were statistically significant. The resulting p-value was 0.102, indicating no significant difference in reading speed between noise and quiet conditions.

Regarding the number of errors, participants made slightly more errors in the noise condition (mean = 3.40) than in quietness (mean = 2.70), with the median showing a modest improvement under quiet as well. Although the maximum values were identical, the entire distribution in the quiet condition shifted downward, with lower values at the 25th and 75th percentiles. However, the variability remained high in both conditions, as reflected in the similar standard deviations. A Wilcoxon

Signed-Rank Test was again applied to test for statistical significance. The resulting p-value of 0.185 indicates that the observed reduction in errors under quietness, while descriptively present, did not reach statistical significance. Taken together, these findings suggest that background noise did not significantly affect either the speed or accuracy of reading aloud for participants at Receiver 1. While there was a slight trend toward improved accuracy in the quiet condition, the effect was not strong or consistent enough to be considered statistically meaningful. The stability of the speed score across conditions further supports the interpretation that the reading fluency was resistant to the moderate noise levels simulated in this setting.

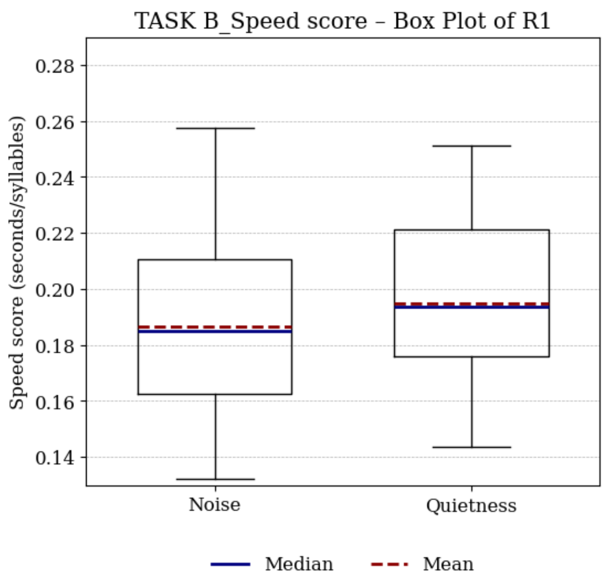


Figure 6.15: Box plot of the results of Task B - Speed score for Receiver 1.

Table 6.10: Statistical parameters for Task B - Speed score for Receiver 1.

	Noise	**Quietness**
Mean	0.19	0.19
SD	0.03	0.04
Min	0.13	0.14
25th perc.	0.16	0.18
Median	0.19	0.19
75th perc.	0.21	0.22
Max	0.25	0.25

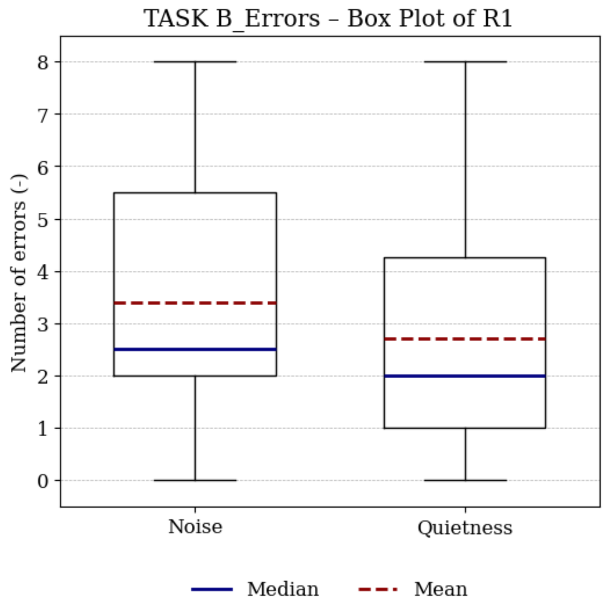


Figure 6.16: Box plot of the results of Task B - Errors for Receiver 1.

Table 6.11: Statistical parameters for Task B - Errors for Receiver 1.

	Noise	Quietness
Mean	3.40	2.70
SD	2.55	2.50
Min	0.00	0.00
25th perc.	2.00	1.00
Median	2.50	2.00
75th perc.	5.50	4.25
Max	8.00	8.00

Receiver 2

Figure 6.17 and Figure 6.18 present the box plots illustrating participants' performance in the Reading aloud task at Receiver 2, under both noise and quiet conditions. As in the previous analysis, two performance metrics were considered: the speed score, representing fluency, and the number of errors, indicating accuracy. In terms of speed score, the data show a high degree of consistency between conditions. Both the mean and median values were approximately 0.17 in both noise and quiet (rounded values), with minimal variation in dispersion. According to the descriptive statistics, the interquartile range remained narrow and virtually identical across the two environments: the 25th percentile was around 0.16 and the 75th percentile about 0.18. These observations are well represented in the boxplot, which shows overlapping boxes and whiskers with only a slightly more compact shape in the quiet condition, suggesting a minor reduction in variability. However, the overall central tendency remains unchanged. This impression is confirmed by the Wilcoxon Signed-Rank Test, which yielded a non-significant result (p-value = 0.646), indicating no statistically detectable difference in fluency between the two acoustic conditions.

The analysis of errors, on the other hand, reveals a more distinct trend. Participants made fewer mistakes on average in quiet: the mean error count decreased from approximately 3.00 in noise to 1.90 in quiet, with the median shifting from 3.00 to 2.00, based on rounded values. The box plot visually reinforces this trend, showing a noticeable downward shift in the entire distribution. The upper quartile dropped from about 5.5 to 3.0, and the maximum number of errors fell from 6 to 3, suggesting that participants not only improved on average but also made fewer extreme errors under quiet conditions. Additionally, the spread of the data was more compressed in quiet, with a smaller interquartile range and shorter whiskers, indicating increased performance consistency. Despite these descriptive improvements, the Wilcoxon Signed-Rank Test produced a p-value of 0.136, which is above the conventional threshold for significance, thus preventing firm statistical conclusions.

In summary, for Receiver 2, reading fluency remained stable regardless of the acoustic environment, as confirmed by both visual analysis and statistical testing. However, reading accuracy showed a notable descriptive improvement in the quiet condition, with fewer errors and reduced variability across participants. Although this effect did not reach statistical significance, the consistency of the trend across multiple indicators suggests that background noise may have introduced subtle interference in reading accuracy. It is important to note that the numerical values reported here are rounded for clarity and do not capture the full precision of the underlying dataset, which is better represented by the box plots.

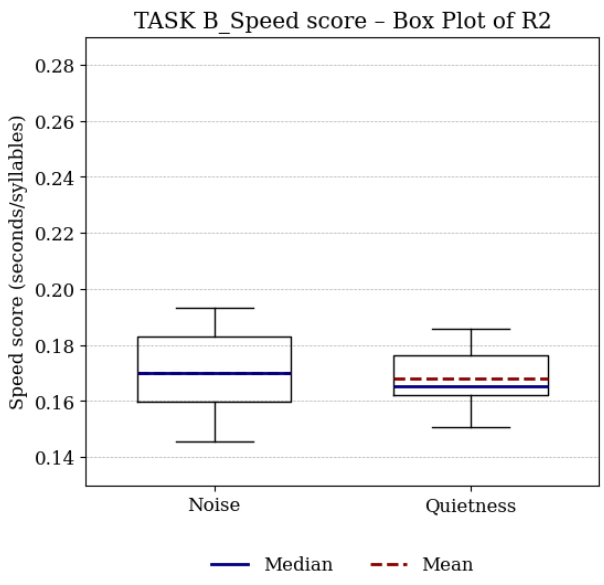


Figure 6.17: Box plot of the results of Task B - Speed score for Receiver 2.

Table 6.12: Statistical parameters for Task B - Speed score for Receiver 2.

	Noise	**Quietness**
Mean	0.17	0.17
SD	0.02	0.01
Min	0.14	0.15
25th perc.	0.16	0.16
Median	0.17	0.17
75th perc.	0.18	0.18
Max	0.19	0.19

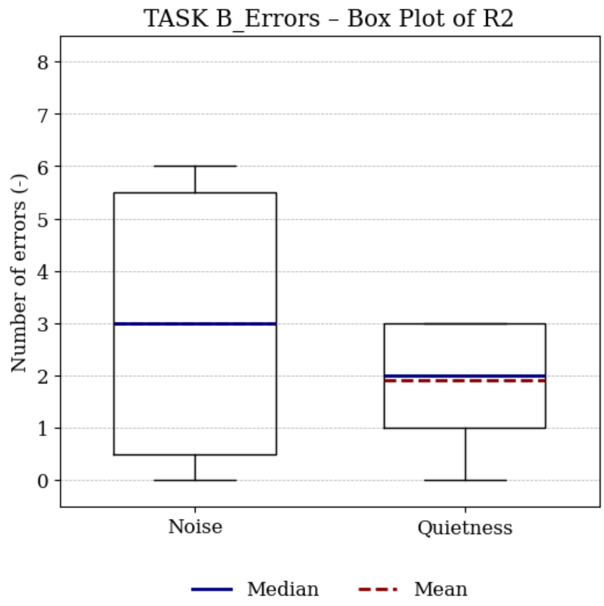


Figure 6.18: Box plot of the results of Task B - Errors for Receiver 2.

Table 6.13: Statistical parameters for Task B - Errors for Receiver 2.

	Noise	Quietness
Mean	3.00	1.90
SD	2.50	1.10
Min	0.00	0.00
25th perc.	0.50	1.00
Median	3.00	2.00
75th perc.	5.50	3.00
Max	6.00	3.00

Receiver 3

Figure 6.19 and Figure 6.20 present the box plots illustrating participants' performance in the Reading aloud task at Receiver 3, under both noise and quiet conditions. As in the previous cases, both speed score and number of errors were analyzed to assess reading fluency and accuracy, respectively. Starting with the speed score, the box plot reveals only minimal variation between the two conditions. Although the median appears slightly lower in quiet (around 0.18) compared to noise (approximately 0.19), the overall ranges and interquartile intervals are largely overlapping. The data also exhibit a relatively symmetric and narrow distribution in both environments. Descriptive statistics confirm this impression: the mean values are identical (0.19), and dispersion metrics (e.g., standard deviation and percentile spread) differ only marginally. Notably, in the quiet condition the upper quartile is slightly compressed, but a mild outlier is present. The Wilcoxon Signed-Rank Test supports the lack of statistical differentiation between conditions (p-value = 0.838), confirming that this slight shift in the median is not significant.

The trend is more nuanced when considering the number of errors. Descriptively, one might expect an advantage for the noise condition: the mean number of errors increased from 2.9 in noise to 3.3 in quiet, and the maximum observed value under quiet reached 10, compared to 7 in noise. Despite this, the median dropped from

3.0 to 2.0, and the distribution under quiet became noticeably more dispersed, with a broader range and multiple outliers. This increased variability suggests that, while most participants performed similarly or better, a few individuals made substantially more errors in quiet, skewing the overall statistics. The box plot highlights this duality: central tendency improves slightly under quiet, but the spread increases. The Wilcoxon test for this variable also did not yield statistical significance (p-value = 0.618), reinforcing that these descriptive differences are not strong or consistent enough to be considered reliable effects.

Overall, the data from Receiver 3 suggest that reading fluency was unchanged across acoustic conditions, as supported by nearly identical means and medians and a non-significant test result. In terms of accuracy, the quiet condition was associated with greater variability and a slightly higher average error count, although the median actually improved. These mixed results, coupled with non-significant statistics, point to individual differences in sensitivity to noise rather than a systematic effect. The values discussed in this section are rounded for clarity, and the box plots offer a more precise view of the underlying data distributions.

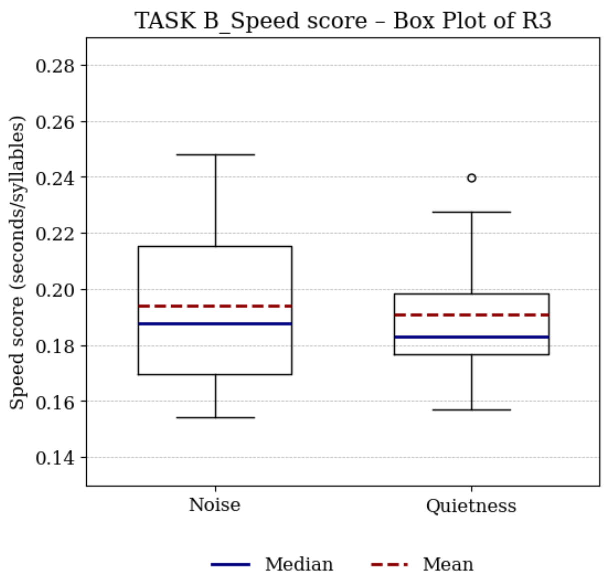


Figure 6.19: Box plot of the results of Task B - Speed score for Receiver 3.

Table 6.14: Statistical parameters for Task B - Speed score for Receiver 3.

	Noise	**Quietness**
Mean	0.19	0.19
SD	0.03	0.03
Min	0.15	0.16
25th perc.	0.17	0.18
Median	0.19	0.18
75th perc.	0.22	0.20
Max	0.25	0.24

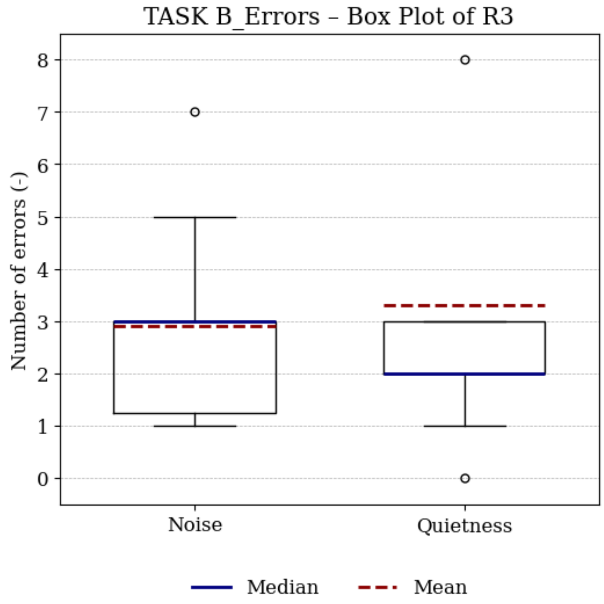


Figure 6.20: Box plot of the results of Task B - Errors for Receiver 3.

Table 6.15: Statistical parameters for Task B - Errors for Receiver 3.

	Noise	Quietness
Mean	2.90	3.30
SD	1.91	3.16
Min	1.00	0.00
25th perc.	1.25	2.00
Median	3.00	2.00
75th perc.	3.00	3.00
Max	7.00	10.00

Receiver 4

Figure 6.21 and Figure 6.22 present the box plots illustrating participants' performance in the Reading aloud task at Receiver 3, under both noise and quiet conditions. Starting with the speed score, the descriptive statistics revealed identical mean and median values across the two conditions (mean = 0.17; median = 0.17). The range of values was comparable: in noise, scores ranged from 0.14 to 0.20, while in quietness they ranged from 0.14 to 0.21. Minor shifts were observed in the quartiles, with the 75th percentile slightly higher in noise (0.19) than in quiet (0.18), suggesting a slightly wider spread in the presence of background noise. However, these small differences were not reflected in the statistical analysis. The Wilcoxon Signed-Rank Test did not indicate any significant difference between the two conditions (p-value = 0.683), suggesting that background noise did not affect the reading speed in a consistent way for this participant.

Looking at the number of errors, a slightly more variable pattern emerged. On average, Receiver 4 made more errors in the noise condition (mean = 2.80) than in quietness (mean = 2.40), although the medians went in the opposite direction (1.5 in noise vs 2.0 in quiet). The distribution of errors in noise was more dispersed (SD = 3.16), likely influenced by an outlier at the upper extreme (10 errors). In the quiet condition, the maximum value was notably lower (5 errors), and the overall dispersion was more contained (SD = 1.84). This suggests that performance in noise may have been more erratic, though not necessarily worse. The Wilcoxon test again did not show a statistically significant difference between the two conditions (p-value = 0.670).

Taken together, these results indicate that Receiver 4 maintained a relatively stable performance across both environments. Neither the speed nor the accuracy of reading appeared to be systematically influenced by the presence of noise, as confirmed by the lack of significant effects in the inferential tests. While minor descriptive variations were observed, particularly in the dispersion of error scores, these did not translate into meaningful changes in performance from a statistical perspective.

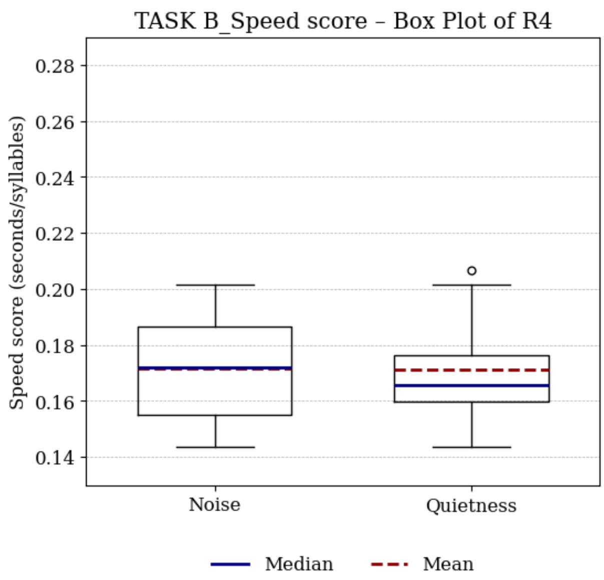


Figure 6.21: Box plot of the results of Task B - Speed score for Receiver 4.

Table 6.16: Statistical parameters for Task B - Speed score for Receiver 4.

	Noise	**Quietness**
Mean	0.17	0.17
SD	0.02	0.02
Min	0.14	0.14
25th perc.	0.16	0.16
Median	0.17	0.17
75th perc.	0.19	0.18
Max	0.20	0.21

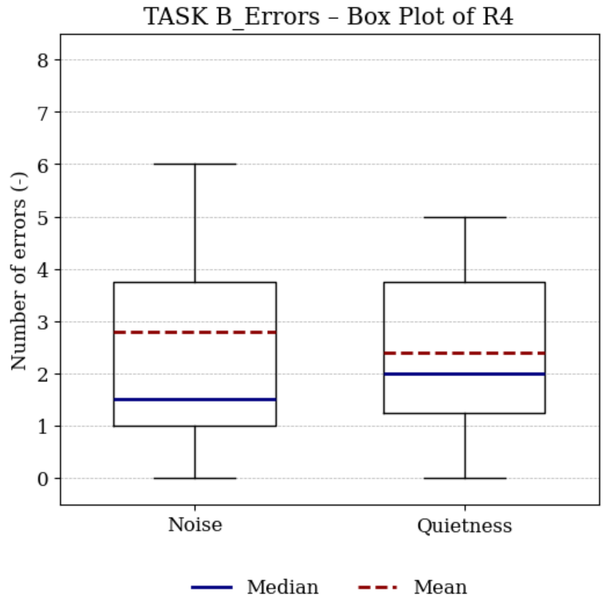


Figure 6.22: Box plot of the results of Task B - Errors for Receiver 4.

Table 6.17: Statistical parameters for Task B - Errors for Receiver 4.

	Noise	**Quietness**
Mean	2.80	2.40
SD	3.16	1.84
Min	0.00	0.00
25th perc.	1.00	1.25
Median	1.50	2.00
75th perc.	3.75	3.75
Max	10.00	5.00

Receiver 5

Figure 6.23 and Figure 6.28 present the box plots illustrating participants' performance in the Reading aloud task at Receiver 3, under both noise and quiet conditions. For the speed score, the box plots revealed highly similar distributions between the two conditions, with almost complete overlap. Both the median and the mean were identical (0.18), as also shown by the horizontal lines on the boxes. The interquartile range was very narrow, ranging from 0.17 to 0.19 in both cases. The maximum values differed only slightly (0.21 in noise, 0.20 in quietness), while the minimum was slightly lower in the noise condition (0.15 vs 0.16). The distributions appeared symmetric and compact in both conditions, and the difference in performance between noise and quietness was minimal. The Wilcoxon Signed-Rank Test confirmed the lack of statistically significant differences as the p-value was 0.646. The balance between positive ($n = 6$) and negative ($n = 4$) ranks further supports the absence of a consistent trend in favor of either condition.

Regarding the number of errors, the descriptive statistics indicated slightly higher variability in the noise condition, where the standard deviation reached 1.55 compared to 2.01 in quietness, though the mean number of errors was slightly higher in noise (1.8 vs 1.6). Interestingly, the median was actually lower in noise (1.5) than in quietness (1.0), but this may reflect the influence of a few higher values in quietness, as visible in the box plots. In both conditions, the maximum number of errors reached the same value (5), while the lower quartile in quietness dropped to 0.0, suggesting better performance in at least a subset of trials. The Wilcoxon test for errors also yielded no statistically significant difference ($p = 0.733$). There was a near balance between negative ($n = 4$) and positive ($n = 3$) ranks, with 3 ties, suggesting individual variability rather than a systematic effect of condition.

In summary, R5 showed consistent performance across noise and quiet conditions for both parameters. Neither speed nor accuracy appeared to be significantly influenced by background noise, and the statistical tests support this conclusion.

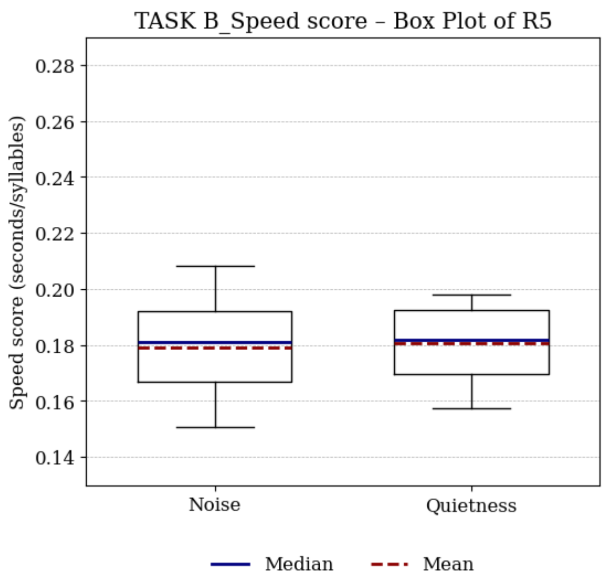


Figure 6.23: Box plot of the results of Task B - Speed score for Receiver 5.

Table 6.18: Statistical parameters for Task B - Speed score for Receiver 5.

	Noise	**Quietness**
Mean	0.18	0.18
SD	0.02	0.01
Min	0.15	0.16
25th perc.	0.17	0.17
Median	0.18	0.18
75th perc.	0.19	0.19
Max	0.21	0.20

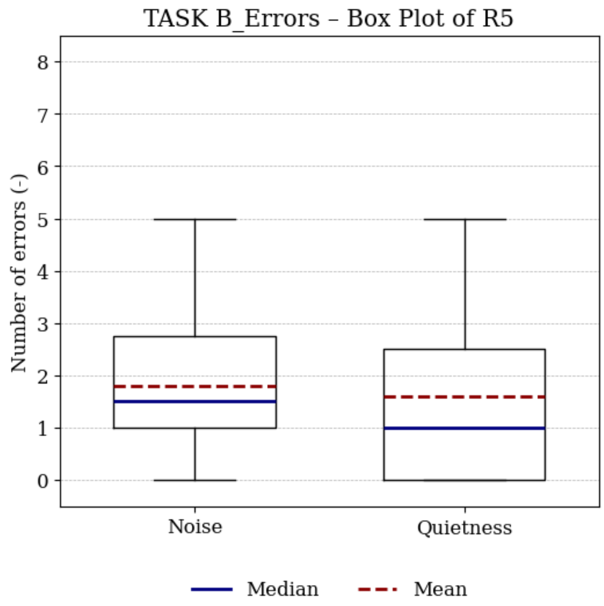


Figure 6.24: Box plot of the results of Task B - Errors for Receiver 5.

Table 6.19: Statistical parameters for Task B - Errors for Receiver 5.

	Noise	Quietness
Mean	1.80	1.60
SD	1.55	2.01
Min	0.00	0.00
25th perc.	1.00	0.00
Median	1.50	1.00
75th perc.	2.75	2.50
Max	5.00	5.00

All receivers

To evaluate whether the spatial position of the receivers had an impact on participants' performance in the Reading Aloud task, both reading fluency, measured by the speed score (where higher values indicate slower reading), and accuracy, measured by the number of errors, were analyzed. As a first step, a Kruskal-Wallis Test was conducted to determine whether the five receivers could be treated as a homogeneous group for subsequent analyses. This non-parametric test was applied separately to each of the measured parameters, under both acoustic conditions. For the speed score, no statistically significant differences were found among the five receivers, either in the noise condition ($p = 0.433$) or in the quiet condition (p-value = 0.085). Although the result for quietness approached significance, it remained above conventional thresholds. Similarly, for the number of errors, the Kruskal-Wallis test revealed no significant group differences in either the noise (p-value = 0.591) or quiet condition (p-value = 0.537). These findings suggest that receiver location did not systematically affect participants' fluency or accuracy, thus justifying the aggregation of data across spatial positions for further statistical comparisons. Following this validation, Wilcoxon Signed-Rank Tests were used to assess the effect of the acoustic environment on participants' performance. Regarding the speed score, the mean value was slightly higher in quiet than in noise, suggesting a small improvement in reading speed when background noise was absent. However, this difference was not statistically significant (p-value = 0.398), indicating stable fluency across both conditions. As for accuracy, the number of reading errors decreased in the quiet condition. While this descriptive trend favored the quiet condition, the Wilcoxon test yielded a non-significant result (p-value = 0.138), suggesting that the effect of noise on reading accuracy was not robust at the group level.

To further explore the influence of individual differences, Linear Mixed Models (LMMs) were applied separately for each dependent measure. For reading speed, noise sensitivity emerged as a statistically significant predictor (p = 0.004). Specifically, participants with higher noise sensitivity exhibited higher speed scores—indicating slower reading, compared to less sensitive individuals. This suggests that personal sensitivity to environmental noise can negatively impact reading fluency, even when the group-level effect of noise is minimal. In the case of reading accuracy, two factors were found to significantly influence performance: age and test version. Age was negatively associated with error rate (p-value = 0.032), with older participants making slightly fewer errors. This may reflect a more cautious reading style or more developed compensatory mechanisms in older adults. Additionally, test version played a significant role (p-value = 0.013), i.e. participants who completed Version B of the reading task made, on average, 0.70 more errors than those who received Version A. This suggests that the content or structure of Version B may have been more demanding or less accessible to some participants.

In summary, both fluency and accuracy measures showed no significant differences across receiver positions or acoustic conditions at the group level. However, the LMM analysis revealed that individual factors such as noise sensitivity, age, and test version contributed significantly to performance variation. These findings underscore the importance of accounting for personal and task-related variables when assessing cognitive performance in complex acoustic environments.

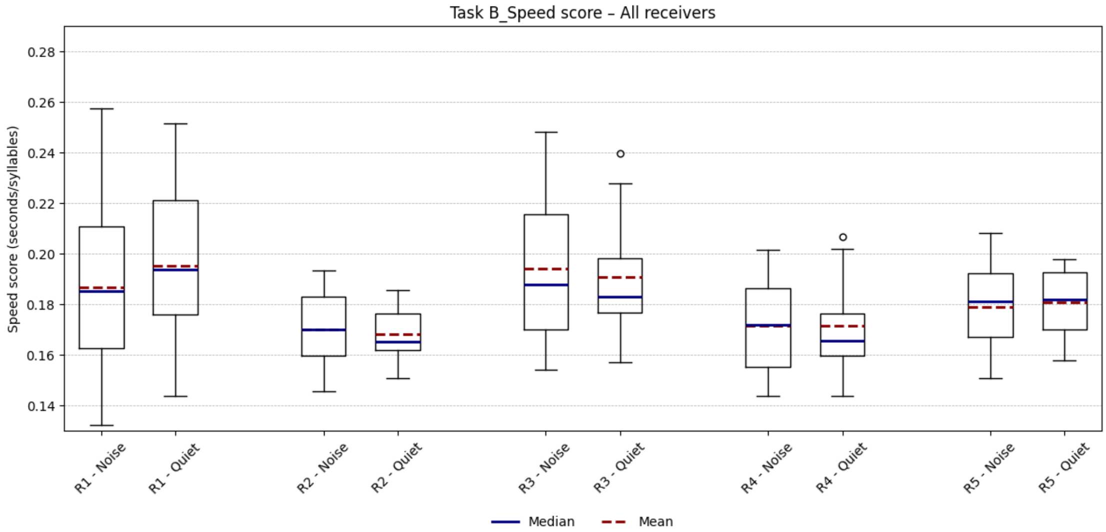


Figure 6.25: Box plots of the results of Task B for all receivers.

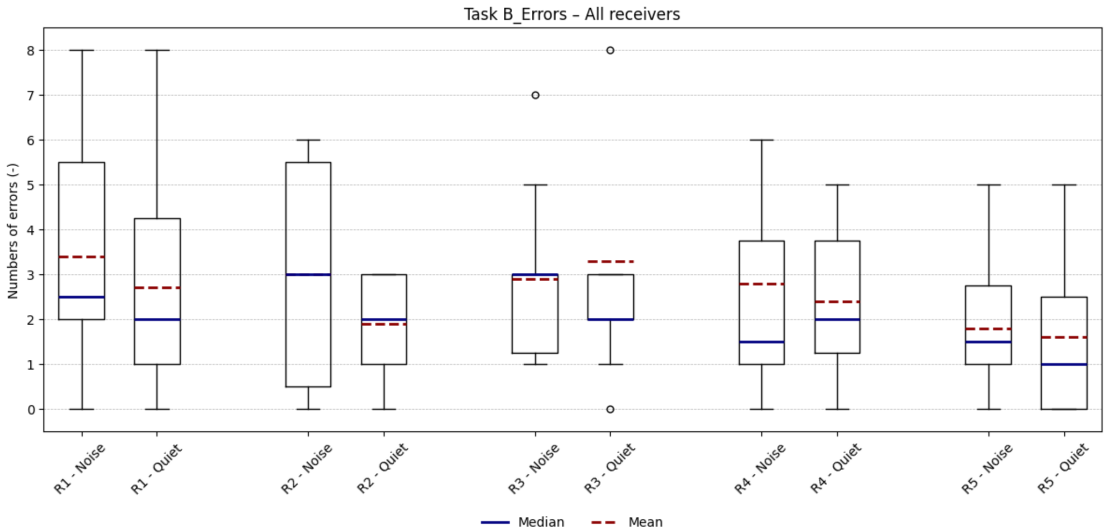


Figure 6.26: Box plots of the results of Task B for all receivers.

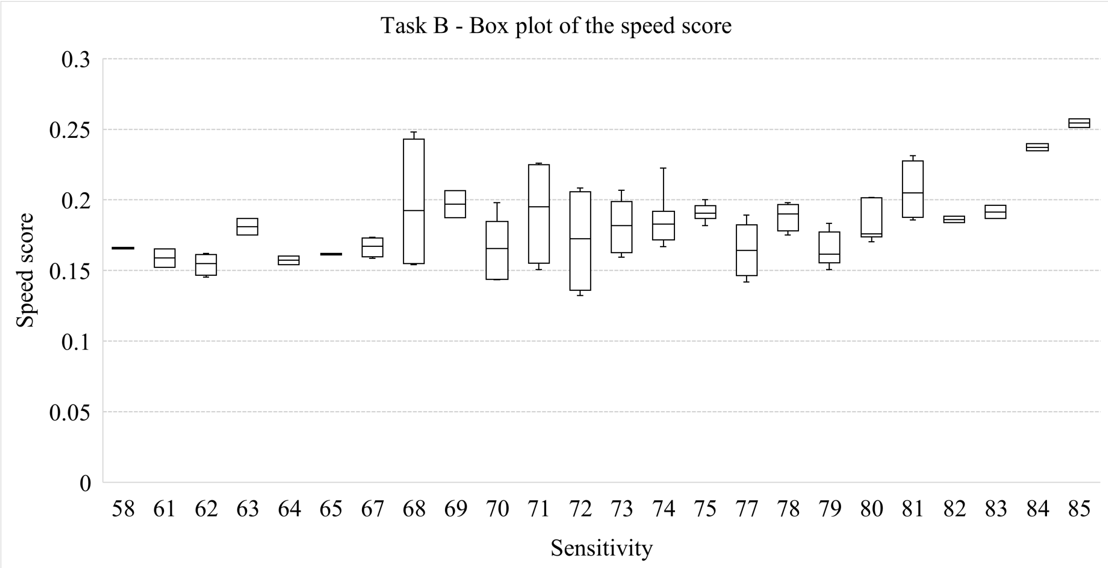


Figure 6.27: Box plot of the correlation between the speed score and the noise sensitivity for the Task B.

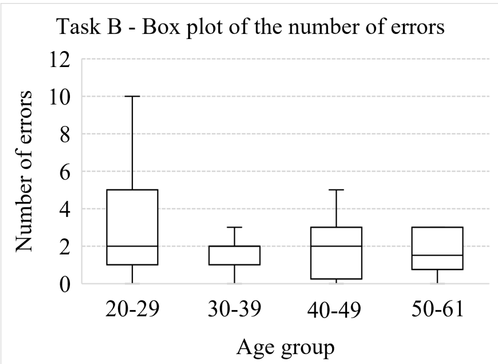


Figure 6.28: Box plot of the correlation between the number of errors and the age for the Task B.

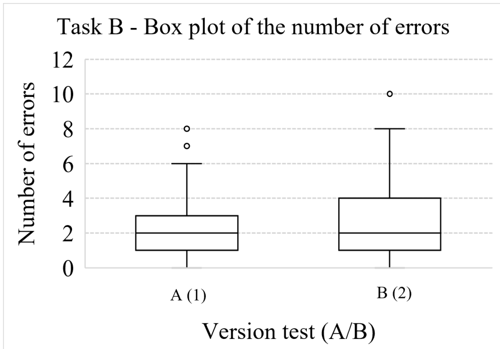


Figure 6.29: Box plot of the correlation between the number of errors and the version of the test for the Task B.

6.4.3 Task C

Receiver 1

Figure 6.30 and Figure 6.31 display the box plots of participants' performance at Receiver 1 in the Trail Making Test (TMT), under the two acoustic conditions, background noise and quietness. Both versions of the task, TMT-A, which involved connecting numbers in ascending order, and TMT-B, requiring alternation between numbers and letters, were analyzed to assess cognitive processing speed and flexibility. In both versions, shorter execution times indicate better performance. Starting with TMT-A, descriptive statistics indicate comparable performance across the two conditions. In noise, participants had a mean execution time of 31.60 seconds and a median of 33.00 seconds. In quiet, these values were slightly higher, with a mean of 32.40 and a median of 32.00. The range of performance, however, differed as the maximum time dropped from 66.00 in noise to 50.00 in quietness, while the 75th percentile rose from 34.00 to 41.25, suggesting a broader distribution under quiet. The box plot visually confirms these differences, with a more compressed lower range in noise but wider spread in quietness, particularly in the upper quartile. The Wilcoxon Signed-Rank Test resulted with a p-value of 0.358, indicating that the observed variations were not statistically significant. Turning to TMT-B, the descriptive statistics revealed a moderate increase in execution time under quietness. The mean increased from 52.60 seconds in noise to 59.90 in quiet, and the median increased from 50.00 to 55.50. The 25th percentile was also higher in quiet (45.25) compared to noise (38.00), indicating that most participants took longer in the quiet condition. Moreover, the maximum time rose from 110.00 to 129.00, suggesting that outliers performed more slowly in the absence of background noise. The box plot reinforces this impression, showing an upward shift of the entire distribution under quietness. Nonetheless, the Wilcoxon Signed-Rank Test returned a p-value of 0.285, again indicating that the differences in execution time between noise and quiet conditions were not statistically significant.

Taken together, these results suggest that for Receiver 1, background noise did not significantly impair performance on either version of the Trail Making Test. While participants showed a slight trend toward faster execution in the noise condition, particularly in TMT-B, these differences were not statistically reliable. Therefore, the data do not support a consistent influence of acoustic condition on cognitive performance in this context. Minor variations in mean and percentile values likely reflect individual variability rather than a systematic effect of noise.

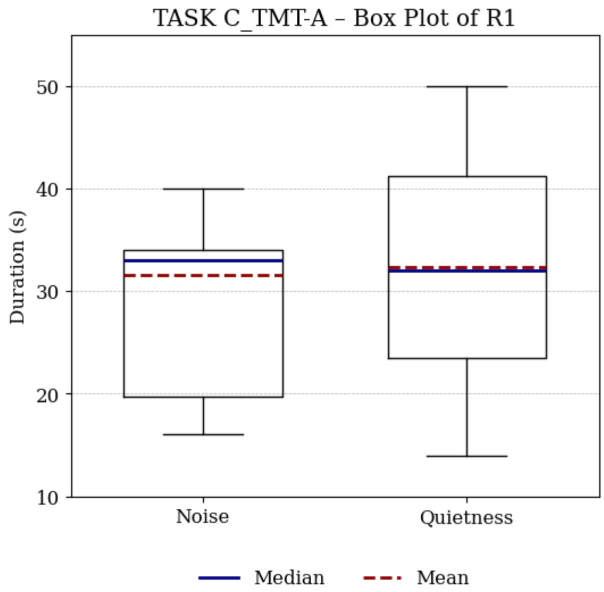


Figure 6.30: Box plot of the results of Task C - TMT-A for Receiver 1.

Table 6.20: Statistical parameters for Task C - TMT-A for Receiver 1.

	Noise	Quietness
Mean	31.60	32.40
SD	14.74	11.61
Min	16.00	14.00
25th perc.	19.75	23.50
Median	33.00	32.00
75th perc.	34.00	41.25
Max	66.00	50.00

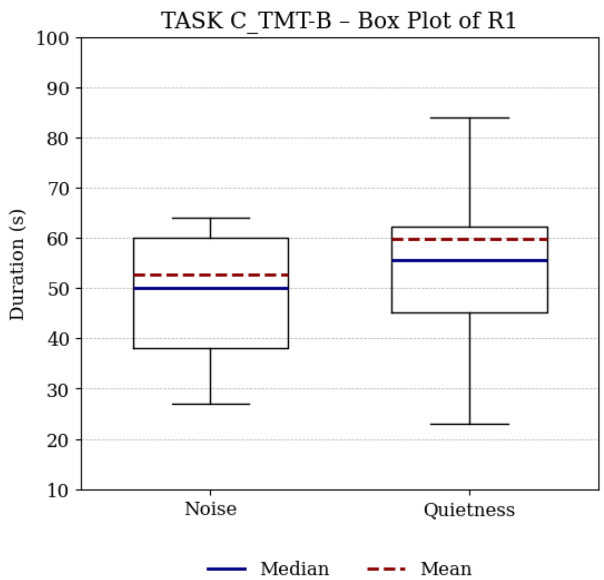


Figure 6.31: Box plot of the results of Task C - TMT-B for Receiver 1.

Table 6.21: Statistical parameters for Task C - TMT-B for Receiver 1.

	Noise	Quietness
Mean	52.60	59.90
SD	23.85	29.22
Min	27.00	23.00
25th perc.	38.00	45.25
Median	50.00	55.50
75th perc.	60.00	62.25
Max	110.00	129.00

Receiver 2

Figure 6.32 and Figure 6.33 display the box plots of participants' performance at Receiver 2 in the Trail Making Test (TMT) with its two versions, TMT-A and TMT-B, under the two acoustic conditions, background noise and quietness. Starting with TMT-A, a difference in central tendency is noticeable between the two conditions. In the noise condition, participants completed the task with a mean time of 29.50 seconds and a median of 28.00 seconds, whereas under quietness the mean increased to 35.50 seconds and the median to 32.50 seconds. Similarly, the upper quartile rose from 33.75 to 44.00, and the maximum execution time shifted from 47.00 to 58.00 seconds. These results suggest a general tendency toward slower task execution in quiet conditions. However, a Wilcoxon Signed-Rank Test yielded a p-value of 0.057, which borders on statistical significance but does not fall below the conventional threshold of 0.05. This result points to a potential trend, yet it is not sufficient to confirm a meaningful difference between the two acoustic environments. When it comes to TMT-B, performance showed a different pattern. Although the mean time increased from 47.70 seconds in noise to 51.60 in quiet, the median value also rose considerably from 45.50 to 55.50 seconds. Interestingly, while the minimum value was lower in quiet (32.00 vs. 37.00), the maximum was actually higher under noise (86.00 vs. 72.00), indicating greater variability in that condition. Despite the apparent shifts in central tendency and dispersion, the Wilcoxon test revealed a p-value of 0.575, indicating no statistically significant difference between the two conditions.

In summary, for Receiver 2, there appears to be a modest descriptive increase in execution time under quiet conditions for both TMT-A and TMT-B. While TMT-A almost approached statistical significance, particularly in its consistent shift across all distributional metrics, TMT-B results were more mixed and showed less consistency. These findings suggest that noise may have facilitated slightly faster performance on the simpler task, i.e. TMT-A, though this effect did not consistently extend to more complex task such as the TMT-B version or reach statistical reliability.

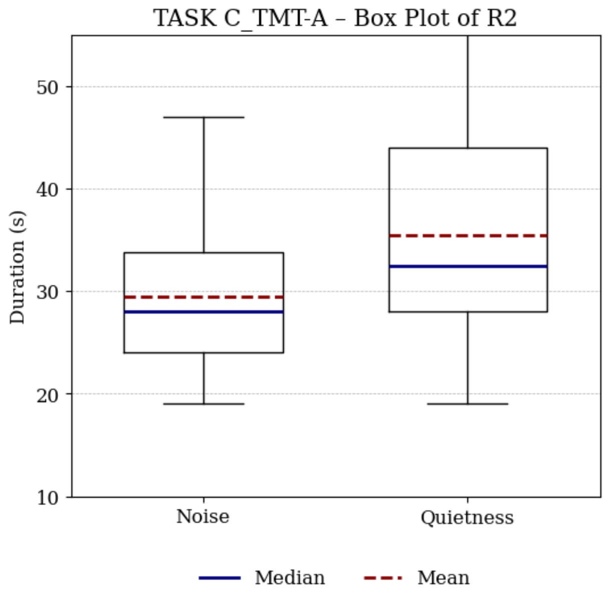


Figure 6.32: Box plot of the results of Task C - TMT-A for Receiver 2.

Table 6.22: Statistical parameters for Task C - TMT-A for Receiver 2.

	Noise	Quietness
Mean	29.50	35.50
SD	8.50	11.75
Min	19.00	19.00
25th perc.	24.00	28.00
Median	28.00	32.50
75th perc.	33.75	44.00
Max	47.00	58.00

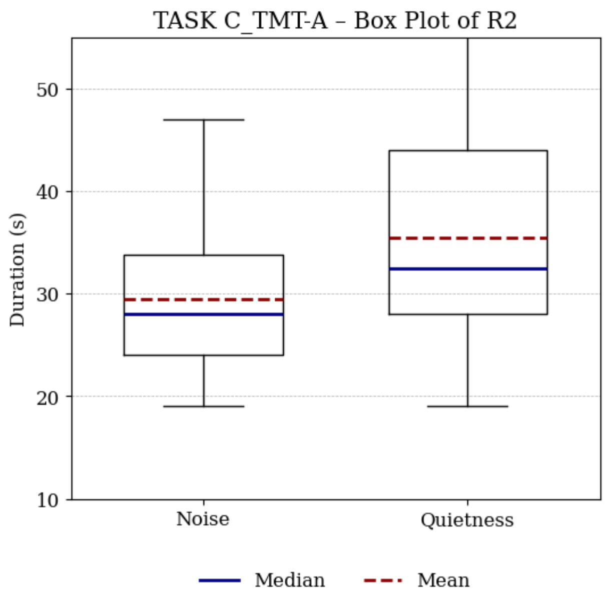


Figure 6.33: Box plot of the results of Task C - TMT-B for Receiver 2.

Table 6.23: Statistical parameters for Task C - TMT-B for Receiver 2.

	Noise	Quietness
Mean	47.70	51.60
SD	13.98	13.21
Min	37.00	32.00
25th perc.	42.50	45.25
Median	45.50	55.50
75th perc.	46.00	60.25
Max	86.00	72.00

Receiver 3

Figure 6.34 and Figure 6.35 illustrate the execution times of participants at Receiver 3 during the Trail Making Test under two acoustic conditions, background noise and quietness, for both TMT-A and TMT-B versions. In TMT-A, participants generally performed more efficiently in the quiet condition. The mean execution time was slightly lower in quietness (29.90 s) compared to noise (32.20 s), and the median followed the same trend (29.00 s vs. 33.00 s). Variability was also reduced in the quiet condition, with a standard deviation of 5.80 compared to 10.12 in noise. The quiet condition exhibited a narrower interquartile range (25.00 to 35.25) and a lower maximum execution time (38.00 s vs. 46.00 s). Despite this descriptive advantage for quietness, the Wilcoxon Signed-Rank Test yielded a p-value of 0.721, indicating no statistically significant difference between the two conditions for this version of the task. For TMT-B, which introduces increased cognitive demands by requiring alternating connections between numbers and letters, the pattern shifted. Participants completed the task more quickly under noise (mean = 50.60 s; median = 51.00 s) than in quietness (mean = 61.60 s; median = 55.00 s). The quiet condition was associated with a greater range and variability, as shown by a higher standard deviation (19.24 vs. 9.37), and a maximum completion time of 94.00 s compared to 66.00 s in noise. This suggests that, for some participants, quietness may have resulted in less consistent or less focused performance. However, the Wilcoxon test again indicated that the difference was not statistically significant ($p = 0.110$).

Taken together, the data suggest no significant effect of acoustic condition on task performance for Receiver 3 in either TMT-A or TMT-B. Nonetheless, the descriptive patterns point toward potentially interesting interactions between task complexity and environmental noise. While performance in the simpler TMT-A appeared slightly better in quietness, the opposite trend was observed in TMT-B, where noise may have had a mildly facilitative effect. Although these trends did not reach statistical significance, they hint at individual differences in sensitivity to background noise, particularly under varying cognitive loads.

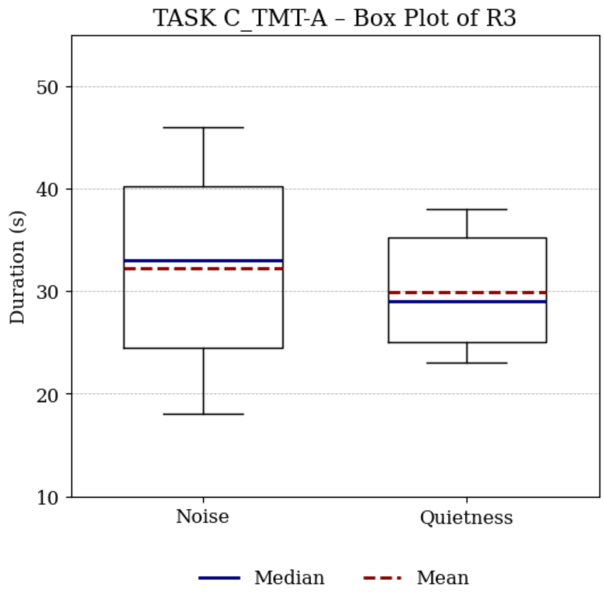


Figure 6.34: Box plot of the results of Task C - TMT-A for Receiver 3.

Table 6.24: Statistical parameters for Task C - TMT-A for Receiver 3.

	Noise	Quietness
Mean	32.30	29.90
SD	10.12	5.80
Min	18.00	23.00
25th perc.	24.50	25.00
Median	33.00	29.00
75th perc.	40.25	35.25
Max	46.00	38.00

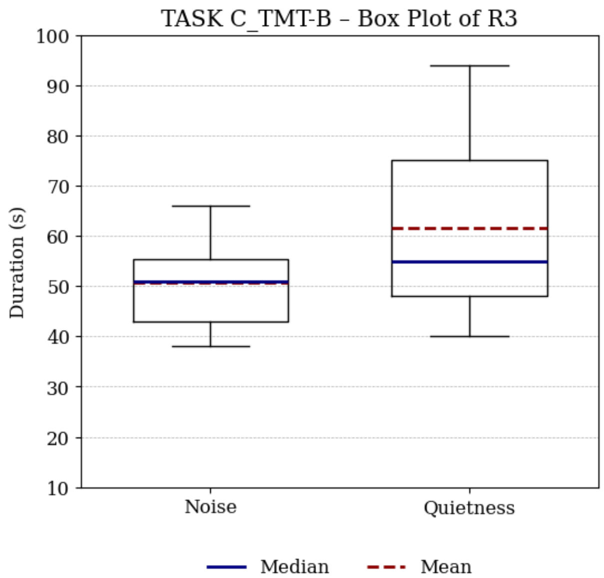


Figure 6.35: Box plot of the results of Task C - TMT-B for Receiver 3.

Table 6.25: Statistical parameters for Task B - TMT-A for Receiver 3.

	Noise	Quietness
Mean	50.60	61.60
SD	9.37	19.24
Min	38.00	40.00
25th perc.	43.00	48.00
Median	51.00	55.00
75th perc.	55.25	75.00
Max	66.00	94.00

Receiver 4

Figure 6.36 and Figure 6.37 illustrate the box plots for Receiver 4 in both TMT-A and TMT-B showing the execution times across the two acoustic conditions. For TMT-A, participants at R4 showed slightly faster execution times under noise compared to quietness. The mean execution time was lower in the noise condition (31.20 seconds) relative to the quiet condition (35.60 seconds). The median times followed a similar pattern, i.e. 31.50 seconds (noise) versus 33.50 seconds (quietness). Furthermore, the lower and upper quartiles were also marginally lower in the presence of noise (27.75 and 34.50 seconds) than in silence (30.25 and 39.75 seconds), suggesting a general trend of faster performance during noise exposure. Nevertheless, there was greater variability in the quiet condition, as shown by a higher standard deviation (SD = 9.35) compared to noise (SD = 7.02). Despite these descriptive differences, the Wilcoxon Signed-Rank Test did not reveal a statistically significant effect of acoustic condition (p-value = 0.125), indicating that the differences in TMT-A execution times were not robust enough to reject the null hypothesis. In TMT-B, the same general pattern was observed. Participants appeared to perform better in the noise condition (mean = 54.00 seconds, median = 49.50) than in the quiet condition (mean = 58.80, median = 60.50), suggesting that noise may have facilitated performance even in this more demanding task. Execution times under noise ranged from 29.00 to 80.00 seconds, while in quietness the range was from 35.00 to 73.00 seconds. The 25th percentile was lower under noise (46.75) than in quietness (52.75), and similarly for the 75th percentile (65.50 in noise vs. 66.25 in quietness), indicating faster and more efficient performance in the presence of background noise. However, variability was greater in the noise condition (SD = 15.03) compared to quietness (SD = 11.13), suggesting less consistent performance under distraction. Once again, the Wilcoxon Signed-Rank Test did not reveal a statistically significant difference between conditions (p-value = 0.260), indicating that the observed trends should be interpreted cautiously.

Overall, participants at Receiver 4 tended to complete both TMT-A and TMT-B more quickly under background noise. Although none of the differences reached statistical significance, the descriptive results suggest that moderate background noise might enhance cognitive efficiency, possibly by increasing arousal or alertness. However, the greater variability observed—particularly in TMT-B—also indicates that noise may not benefit all individuals equally, and that the effect may depend on individual differences in cognitive control or susceptibility to distraction.

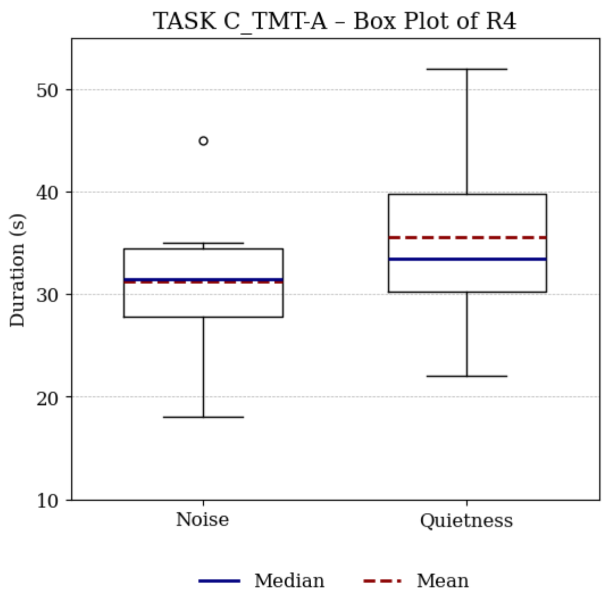


Figure 6.36: Box plot of the results of Task C - TMT-A for Receiver 4.

Table 6.26: Statistical parameters for Task C - TMT-A for Receiver 4.

	Noise	**Quietness**
Mean	31.20	35.60
SD	7.02	9.35
Min	18.00	22.00
25th perc.	27.75	30.25
Median	31.50	33.50
75th perc.	34.50	39.75
Max	45.00	52.00

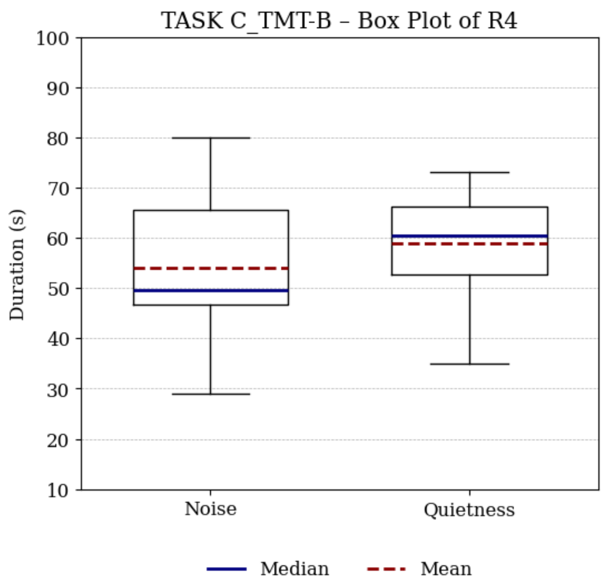


Figure 6.37: Box plot of the results of Task C - TMT-B for Receiver 4.

Table 6.27: Statistical parameters for Task C - TMT-B for Receiver 4.

	Noise	**Quietness**
Mean	54.00	58.80
SD	15.03	11.13
Min	29.00	35.00
25th perc.	46.75	52.75
Median	49.50	60.50
75th perc.	65.50	66.25
Max	80.00	73.00

Receiver 5

Figure 6.38 and Figure 6.39 show the box plots for Receiver 5, illustrating execution times in both TMT-A and TMT-B under the two acoustic conditions: background noise and quietness. Beginning with TMT-A, the descriptive statistics indicate a modest increase in execution times under quiet conditions. Specifically, the mean execution time was 36.80 seconds under noise and 39.80 seconds in quietness, while the median rose from 34.00 to 40.00 seconds. The interquartile range remained fairly similar across conditions, with the 25th percentile at 30.75 (noise) versus 30.25 (quiet), and the 75th percentile slightly lower in quietness (43.75) than in noise (44.75). The minimum execution time was identical at 22.00 seconds in both conditions, but the maximum increased under quietness (69.00) compared to noise (59.00), suggesting slightly greater variability. The standard deviation also reflected this trend, rising from 11.36 (noise) to 13.75 (quiet). Despite this general descriptive tendency toward slower performance in quietness, the Wilcoxon Signed-Rank Test resulted in a p-value of 0.758, indicating no statistically significant difference between the two acoustic conditions. For TMT-B, a similar pattern emerged. Participants exhibited a higher mean execution time under quietness (63.60 seconds) than in the noise condition (60.30 seconds). The median remained relatively stable across the two environments (61.50 in quiet vs. 61.00 in noise), suggesting consistency in central tendency. However, variability increased under quietness, as reflected in the higher standard deviation (26.91 vs. 20.08), and a wider range (maximum of 123.00 vs. 97.00). Interestingly, the lower quartile was actually lower in quietness (45.50) than in noise (48.50), indicating that some participants may have performed faster in silence, although the overall trend pointed in the opposite direction. The Wilcoxon Signed-Rank Test returned a p-value of 0.307, again not reaching statistical significance.

In summary, for Receiver 5 the execution times in both TMT-A and TMT-B were descriptively longer in the quiet condition, with greater variability particularly evident in TMT-B. Nevertheless, none of these differences were statistically significant. The findings suggest a subtle trend in which background noise may have offered a mild facilitative effect, though this was not strong or consistent enough to be deemed statistically reliable. As with other receivers, individual differences may play a role in modulating sensitivity to environmental noise.

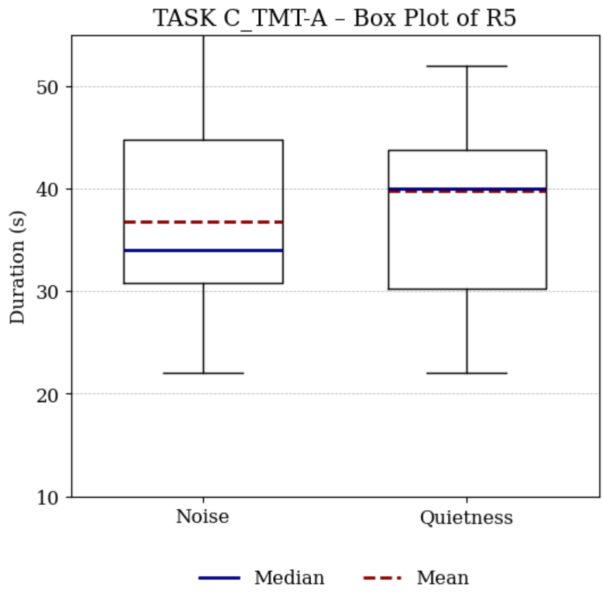


Figure 6.38: Box plot of the results of Task C - TMT-A for Receiver 5.

Table 6.28: Statistical parameters for Task C - TMT-A for Receiver 5.

	Noise	Quietness
Mean	36.80	39.80
SD	11.36	13.75
Min	22.00	22.00
25th perc.	30.75	30.25
Median	34.00	40.00
75th perc.	44.75	43.75
Max	59.00	69.00

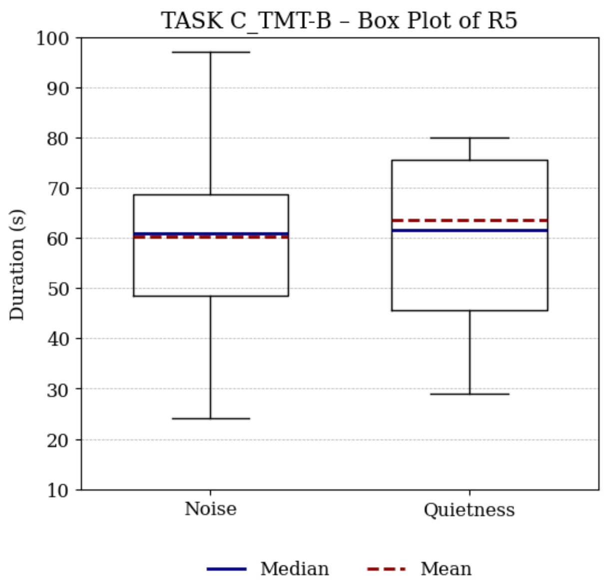


Figure 6.39: Box plot of the results of Task C - TMT-B for Receiver 5.

Table 6.29: Statistical parameters for Task C - TMT-B for Receiver 5.

	Noise	Quietness
Mean	60.30	63.60
SD	20.08	26.91
Min	24.00	29.00
25th perc.	48.50	45.50
Median	61.00	61.50
75th perc.	68.75	75.50
Max	97.00	123.00

All receivers

To examine whether the spatial position of the receivers influenced participants' performance on the Trail Making Test (TMT), Kruskal-Wallis tests were first conducted for both versions of the task, TMT-A and TMT-B, under the two acoustic conditions. No statistically significant differences emerged among the five receivers. In particular, for TMT-A, p-value = 0.611 (noise) and p-value = 0.457 (quiet) were calculated, whereas for TMT-B, the p-values were 0.275 in noise and 0.707 in quietness. These results indicate that the different spatial locations did not produce systematic variability in performance, justifying the aggregation of data across receivers. Subsequently, Wilcoxon Signed-Rank Tests were conducted on the full sample (N = 50) to assess the overall impact of acoustic condition. While no significant difference was observed for TMT-A (p-value = 0.080), results for TMT-B revealed a statistically significant advantage in the noise condition with a p-value of 0.021, suggesting improved cognitive flexibility and speed under background noise. Box plots and descriptive statistics across receivers further clarify local trends. For TMT-A, Receiver 2 showed the fastest mean execution time in the noise condition compared to the silent one. Receiver 1,4 and 5 also performed better under quiet, whereas Receiver 3 displayed shorter times in noise than in silence. For TMT-B, Receiver 1 showed a mean of 52.60 s in noise, increasing to 59.90 s in quiet. Receiver 2's times also rose slightly (47.70 vs. 51.60), while Receiver 3 displayed a clearer contrast (mean = 50.60 noise, 61.60 quiet). Receiver 4 maintained this pattern (54.00 vs. 58.80), and Receiver 5 showed similar results (60.30 vs. 63.60). Notably, the median times for TMT-B were also generally higher under quiet, particularly at Receivers 2, 3, and 4.

To further investigate potential sources of individual variability in TMT performance, linear mixed-effects models were constructed separately for TMT-A and TMT-B. For both tasks, the only significant fixed effect was the factor When, indicating the session in which the test was administered (Session 1 vs. Session 1). Specifically, participants completed TMT-A approximately 4.48 seconds faster when it was administered during the second session (Estimate = -4.480, p-value < 0.001). Similarly, for TMT-B, completion time decreased by an average of 8.3 seconds when the test was performed in the second session (Estimate = -8.300, p-value = 0.002). These findings suggest a learning or familiarization effect across sessions, with participants performing both TMT-A and TMT-B more efficiently upon repeated exposure. Notably, no other individual-level variables, such as age, noise sensitivity, or gender, were found to significantly affect performance in either task within the LMM framework. Taken together, these findings suggest that while small variations across receivers exist, such as descriptively faster performance at Receiver 2 for TMT-A under noise, or at Receiver 3 under quiet, none of these differences reached statistical significance individually. The only statistically robust environmental effect was the overall improvement in TMT-B performance under noise, suggesting that moderate background noise may have enhanced executive functioning under higher cognitive load. Moreover, the significant session effect found in both LMM analyses emphasizes the importance of considering test repetition and order effects in cognitive performance assessments.

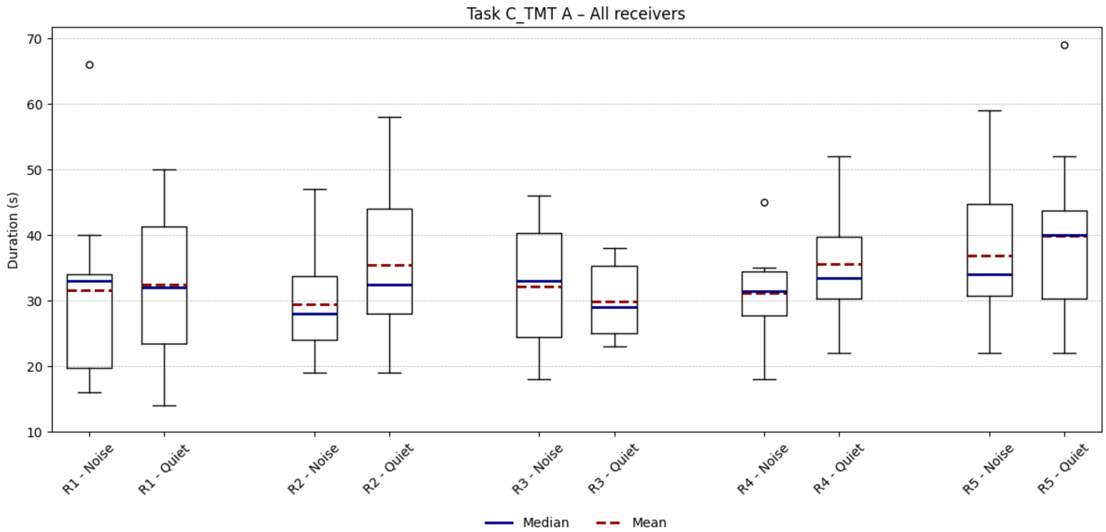


Figure 6.40: Box plots of the results of Task C - TMT-A for all receivers.

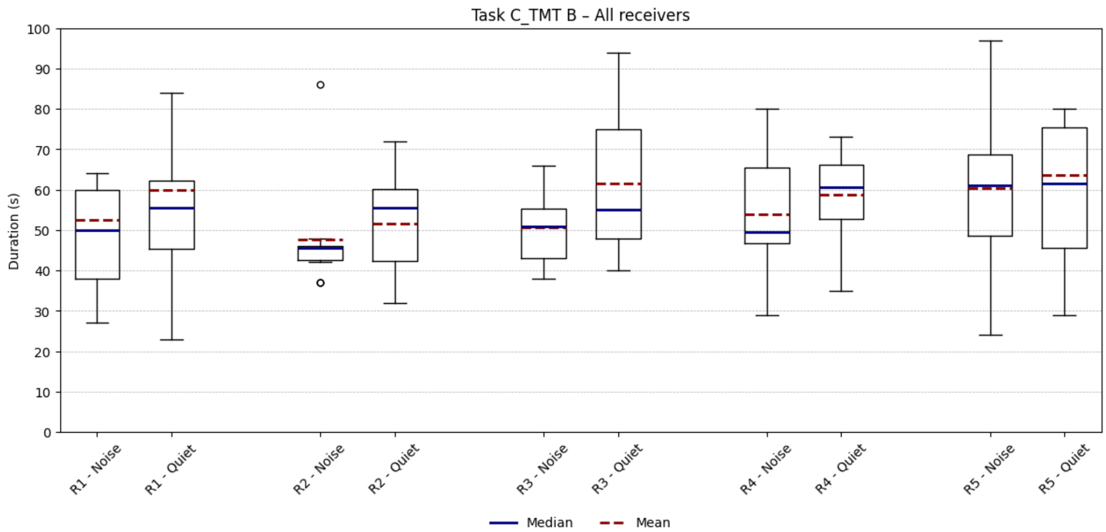


Figure 6.41: Box plots of the results of Task C - TMT-B for all receivers.

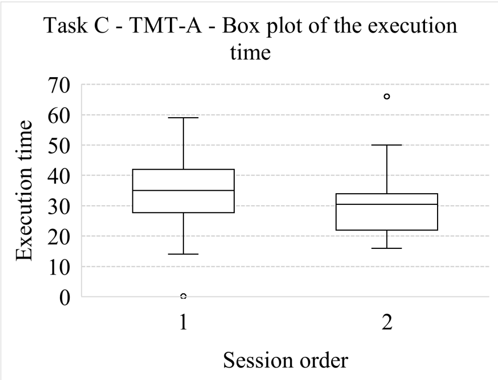


Figure 6.42: Box plot of the correlation between the execution time and the session order for the Task C - TMT-A.

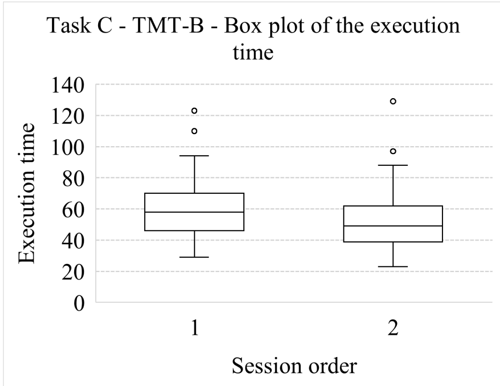


Figure 6.43: Box plot of the correlation between the execution time and the session order for the Task C - TMT-B.

6.4.4 Task D

Receiver 1

Figure 6.44 displays the box plots of participants' performance at Receiver 1 in the Semantic Verbal Fluency Task (SVFT), under two acoustic conditions: background noise and quietness. This task assessed verbal retrieval by asking participants to generate as many words as possible within a given category in a fixed time. Higher word counts indicate better performance. Descriptive statistics showed a trend toward improved performance in the presence of background noise. The mean number of words generated under noise was 29.70 compared to 26.30 in quietness. Median values followed a similar pattern (29.50 in noise vs. 25.00 in quiet), while the 25th percentile was roughly equivalent (22.00 in noise, 22.50 in quiet), indicating that the middle of the distribution slightly favored the noise condition. The upper quartile was notably higher in noise (36.50 vs. 28.75), suggesting that participants with better performance tended to do particularly well in the noisy environment. Interestingly, although the maximum score was slightly higher under quietness (42.00) than in noise (40.00), this appears to be due to a single outlier, as reflected in the box plot. Despite these descriptive differences, the Wilcoxon Signed-Rank Test did not yield a statistically significant difference between the two conditions (p-value = 0.192), suggesting that the apparent advantage under noise may be attributable to random variability. The majority of participants (6 out of 10) performed better under noise, with a mean rank of 5.58, while 3 performed better in quietness, and 1 participant showed no difference between conditions.

In summary, although participants at Receiver 1 displayed a slight descriptive advantage under noise, particularly visible in mean, median, and upper-quartile values, this trend was not statistically significant. The findings suggest that background noise may have had a minor facilitative effect on semantic fluency for some individuals, but the results do not provide strong evidence for a consistent acoustic influence on verbal retrieval performance.

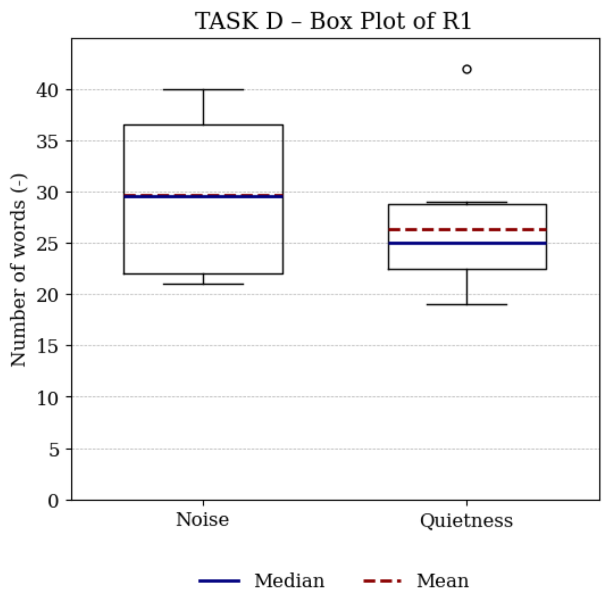


Figure 6.44: Box plot of the results of Task D for Receiver 1.

Table 6.30: Statistical parameters for Task D for Receiver 1.

	Noise	Quietness
Mean	29.70	26.30
SD	7.53	6.53
Min	21.00	19.00
25th perc.	22.00	22.50
Median	29.50	25.00
75th perc.	36.50	28.75
Max	40.00	42.00

Receiver 2

Figure 6.45 displays the box plots of participants' performance at Receiver 2 during the Semantic Verbal Fluency Task (SVFT). Descriptive statistics indicate that participants generated slightly more words in the noise condition. Specifically, the mean number of words was 32.30 in noise versus 30.30 in quietness, and the median followed a similar trend (32.00 vs. 29.50). Additionally, the 75th percentile was higher under noise (38.25 compared to 34.00), while the lower quartile showed a slight advantage in quiet (24.75 vs. 26.00), suggesting more consistent upper-range performance in the presence of background noise. Although these patterns suggest that participants tended to perform marginally better under noise, the difference was not statistically significant. The Wilcoxon Signed-Rank Test returned a p-value of 0.646, indicating that the variation in performance across acoustic conditions was not robust enough to reject the null hypothesis. Interestingly, performance distributions were also more dispersed in noise, with a higher standard deviation (SD = 11.68) compared to quietness (SD = 7.62), and a broader range (14.00 – 49.00 in noise vs. 21.00 – 45.00 in quiet, respectively), implying greater variability among participants under the noisy condition.

Overall, these results suggest that at Receiver 2, background noise did not significantly influence performance in the verbal fluency task. While there was a slight descriptive trend favoring noise, particularly among higher-performing individuals, the lack of statistical significance and the increased variability under noise imply that the acoustic environment had no systematic or consistent effect on word retrieval in this setting.

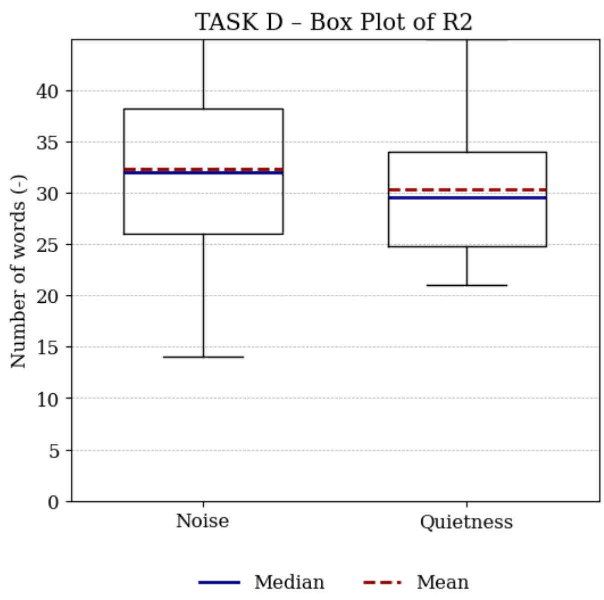


Figure 6.45: Box plot of the results of Task D for Receiver 2.

Table 6.31: Statistical parameters for Task D for Receiver 2.

	Noise	**Quietness**
Mean	32.30	30.30
SD	11.68	7.62
Min	14.00	21.00
25th perc.	26.00	24.75
Median	32.00	29.50
75th perc.	38.25	34.00
Max	49.00	45.00

Receiver 3

Figure 6.46 displays participants' performance at Receiver 3 on the Semantic Verbal Fluency Test (SVFT), administered under both background noise and quiet conditions. Descriptive statistics reveal nearly identical mean scores between the two conditions, i.e. 27.50 words in noise and 27.30 in quiet. The medians are also comparable, 29.00 in noise and 28.00 in quiet, suggesting little difference in central tendency. However, the distributions differ in variability. Under noise, the interquartile range is relatively narrow (27.50 to 29.75), reflecting a more concentrated performance. In contrast, the quiet condition shows a broader interquartile spread (20.50 to 35.00), indicating greater individual variability. The box plot also highlights a few outliers in the noise condition, whereas the quiet condition, although more dispersed, appears more consistent in shape. The Wilcoxon Signed-Rank Test yielded a p-value of 0.646, indicating no statistically significant difference between the two acoustic environments. The number of participants who performed better in noise (N = 6) was slightly higher than those who improved in quiet (N = 4), but this difference was not sufficient to suggest a systematic effect.

In summary, the results at Receiver 3 show that background noise did not significantly affect semantic verbal fluency. Although variability was somewhat greater in quiet, overall performance remained stable across conditions, pointing to the absence of a clear environmental influence at this spatial location.

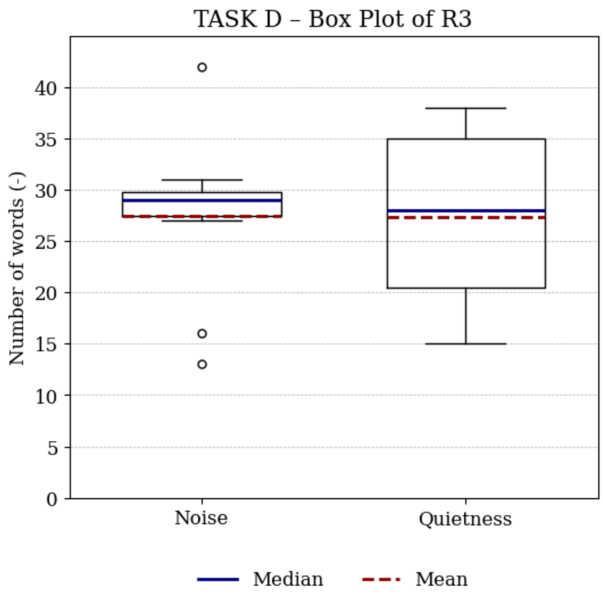


Figure 6.46: Box plot of the results of Task D for Receiver 3.

Table 6.32: Statistical parameters for Task D for Receiver 3.

	Noise	**Quietness**
Mean	27.50	27.30
SD	8.03	8.49
Min	13.00	15.00
25th perc.	27.50	20.50
Median	29.00	28.00
75th perc.	29.75	35.00
Max	42.00	38.00

Receiver 4

Figure 6.47 presents participants' performance at Receiver 4 on the semantic verbal fluency task (SVFT), under both background noise and quiet conditions. Descriptive statistics suggest a notable improvement in performance under quiet conditions. The mean number of words recalled increased from 25.80 in noise to 30.50 in quietness, and the median rose from 23.00 to 32.00. Similarly, the interquartile range shifted upward, with the 25th percentile moving from 20.00 to 22.25, and the 75th percentile from 29.25 to 38.00. The maximum number of words increased slightly from 41.00 to 43.00, while the minimum remained constant at 17.00 in both conditions. These data suggest not only an overall improvement in central tendency, but also a broader upper spread in the quiet condition, potentially indicating better performance among high scorers. The box plot reinforces these trends, showing a clear upward shift in the distribution of scores under quietness. Participants' outputs in quiet conditions were more widely distributed with higher median and mean values, suggesting improved verbal fluency for most individuals. However, the standard deviation also increased (from 8.22 in noise to 9.40 in quiet), reflecting greater variability, which may point to individual differences in sensitivity to the acoustic environment. Despite these positive descriptive trends, the Wilcoxon Signed-Rank Test did not yield a statistically significant result (p-value = 0.169). This indicates that the observed increase in performance under quiet conditions cannot be conclusively attributed to the absence of background noise, at least not at the group level.

In summary, while the data at Receiver 4 show a consistent pattern favoring the quiet condition in terms of central tendency and range, the lack of statistical significance advises caution. The results may reflect subtle cognitive benefits of quietness on verbal access for some individuals, but further research with larger samples would be needed to confirm these effects.

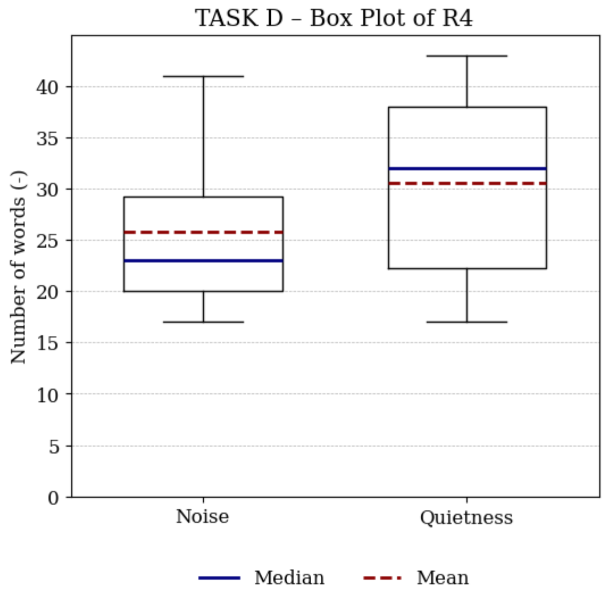


Figure 6.47: Box plot of the results of Task D for Receiver 4.

Table 6.33: Statistical parameters for Task D for Receiver 4.

	Noise	Quietness
Mean	25.80	30.50
SD	8.22	9.40
Min	17.00	17.00
25th perc.	20.00	22.25
Median	23.00	32.00
75th perc.	29.25	38.00
Max	41.00	43.00

Receiver 5

To evaluate whether acoustic conditions influenced semantic verbal fluency at Receiver 5, participants' performance in the Semantic Verbal Fluency Task (SVFT) was compared across noise and quiet settings. At this location, participants showed a moderate decline in word production under quietness compared to background noise. As shown in the box plot in Figure 6.48, the average number of words produced dropped from a mean of 30.00 in noise to 25.70 in quiet. The median followed a similar trend, decreasing from 28.50 to 25.00. This suggests that, descriptively, background noise may have had a slightly facilitating effect on verbal retrieval in this location. Examining the distribution more closely, the interquartile range shifted lower in quietness: the 25th percentile fell from 26.25 in noise to 20.75 in quiet, while the 75th percentile decreased from 35.75 to 30.25. Interestingly, although the maximum number of words was slightly higher in noise (44.00 vs. 38.00), the minimum value improved marginally in quiet (16.00 vs. 13.00), indicating less extreme under-performance in the absence of noise. However, the overall spread of scores appeared more compressed in quiet, suggesting a narrower performance range. Despite these trends, the Wilcoxon Signed-Rank Test revealed that the observed difference was not statistically significant (p-value = 0.221). Of the ten participants, seven produced more words under noise, three under quiet, and none showed equal performance. While the direction of ranks favors the noise condition, the evidence does not reach the conventional threshold for significance.

In conclusion, participants at R5 tended to perform slightly better under background noise in the SVFT, with higher mean and median scores as well as a wider performance range. Nonetheless, this trend did not achieve statistical significance, and thus may reflect individual variation rather than a systematic effect of the acoustic condition.

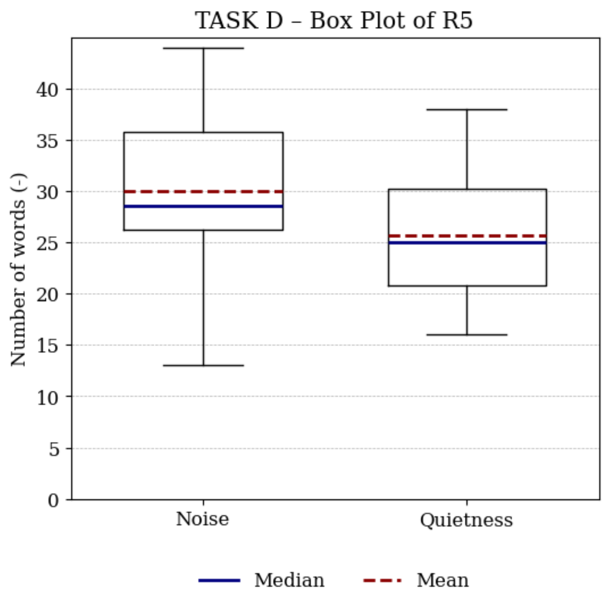


Figure 6.48: Box plot of the results of Task D for Receiver 5.

Table 6.34: Statistical parameters for Task D for Receiver 5.

	Noise	**Quietness**
Mean	30.00	25.70
SD	8.84	6.99
Min	13.00	16.00
25th perc.	26.25	20.75
Median	28.50	25.00
75th perc.	35.75	30.25
Max	44.00	38.00

All receivers

To investigate whether the spatial location of the receivers influenced participants' performance on the Semantic Verbal Fluency Test (SVFT), a Kruskal-Wallis test was conducted separately for the noise and quiet conditions. The results revealed no statistically significant differences across the five receiver positions in either condition (p-value = 0.580 for noise; p-value = 0.521 for quiet), suggesting that participants' physical location within the space did not systematically affect word retrieval. This supports the comparability of receiver positions and justifies pooling data across locations for further analysis. A Wilcoxon Signed-Rank Test was then conducted on the full sample (N = 50) to assess the overall impact of the acoustic condition. Although 27 out of 50 participants produced more words in noise than in quiet, the difference was not statistically significant (p-value = 0.508), indicating that, at the group level, background noise did not reliably influence semantic fluency. The mean rank scores for the two conditions were nearly identical (noise = 25.15; quiet = 24.82), confirming the absence of a consistent effect. Descriptive statistics by receiver provide a more nuanced picture. Receivers 1, 2, and 5 showed higher mean word counts under noise compared to quiet, with Receiver 2 yielding the highest mean (32.30) and widest range. Receiver 5 also followed this trend (30.00 noise vs. 25.70 quiet), while Receiver 3 showed comparable means across conditions. Receiver 4 was the only location where performance was descriptively better in quietness compared to noise (mean = 30.50 vs. 25.80, respectively), though none of these local effects reached statistical significance.

To explore the role of other factors, a Linear Mixed Model was run with task version (A vs. B) and perceived acoustic roughness as predictors. Results showed that Version B (furniture items) led to significantly poorer performance than Version A (fruits and vegetables), with an estimated decrease of 8.4 words (p-value < 0.001), confirming that Version B was cognitively more demanding. Interestingly, roughness was positively associated with word production: for each unit increase in perceived roughness, participants produced on average 1.760 more words (p-value = 0.003). While the effect size was modest, this finding may reflect a mild arousal-based facilitation of lexical access under conditions of greater sensory stimulation. Taken together, the data suggest that neither spatial location within the environment nor the presence of background noise had a strong or systematic effect on semantic verbal fluency. However, task difficulty and subjective auditory experience, particularly perceived roughness, did influence performance, pointing to the relevance of internal, perceptual variables over external spatial ones.

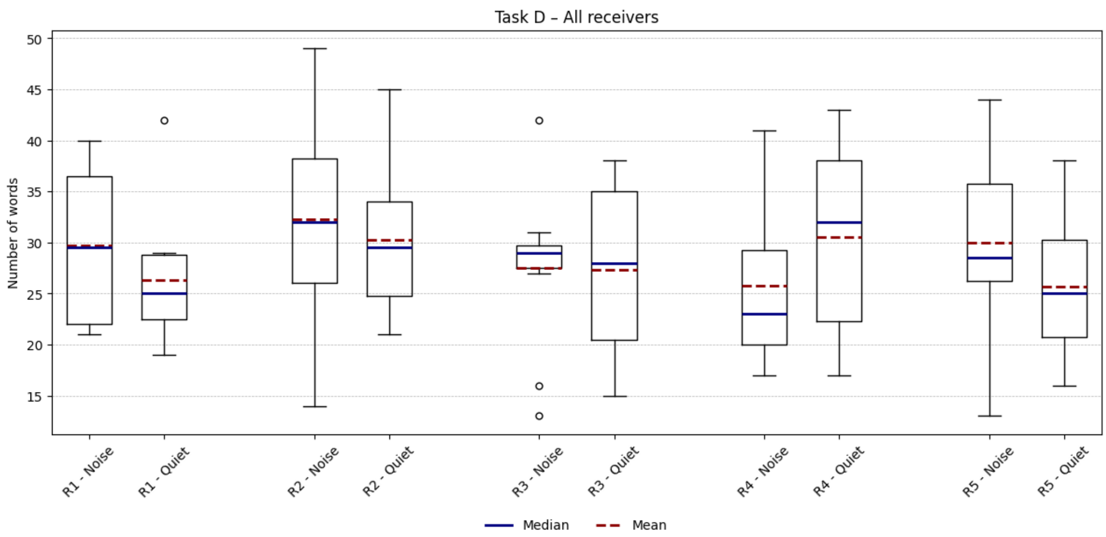


Figure 6.49: Box plots of the results of Task D for all receivers.

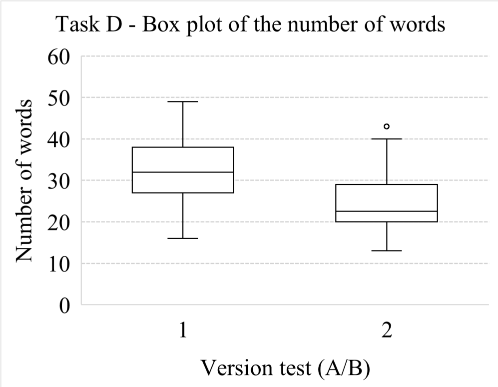


Figure 6.50: Box plot of the correlation between the number fo words and the version of the test for the Task D.

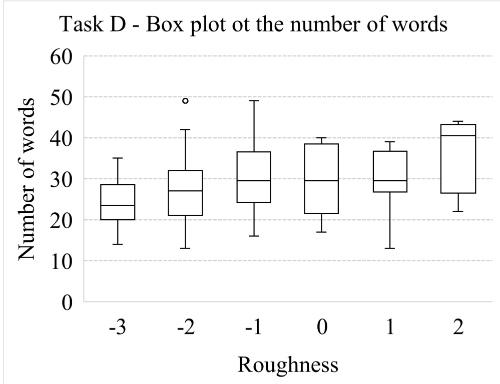


Figure 6.51: Box plot of the correlation between the number of words and the roughness for the Task D.

6.4.5 Task E

Receiver 1

Figure 6.52 and Figure 6.53 show participants' performance at Receiver 1 in the Reaction Time task, evaluated under both background noise and quiet conditions. Two key metrics were assessed: average reaction time (RT), which captures overall speed, and the standard deviation (SD), which reflects response consistency. Lower values for both indicators suggest better and more stable performance. Descriptive statistics for reaction time indicate a slight improvement in the quiet condition. Specifically, the mean RT decreased from 299.74 ms under noise to 288.92 ms in quiet, with median values following a similar trend (291.53 vs. 283.76, respectively). The interquartile ranges were nearly identical, but the lower quartile dropped under quiet (249.28 ms) compared to noise (266.97 ms), suggesting faster responses among quicker participants. Similarly, the maximum RT declined from 401.25 ms in noise to 358.76 ms in quietness, reinforcing the trend toward improved performance in quiet. The Wilcoxon Signed-Rank Test, however, yielded a p-value of 0.799, indicating that this difference was not statistically significant. In terms of response variability, standard deviation values also favored quietness. The average SD dropped from 79.91 ms in noise to 69.59 ms in quiet, and the interquartile spread narrowed. Notably, the SD was less dispersed under quiet conditions (SD = 25.39) compared to noise (SD = 51.57), as visible in the box plot, which also highlights more extreme outliers in the noisy environment. These results suggest more consistent reaction times in quiet. Nevertheless, the Wilcoxon test for SD differences returned a p-value of 0.959, providing no evidence of a significant effect of the acoustic environment. In summary, while Receiver 1 showed a descriptive trend toward faster and more consistent responses in the quiet condition, neither reaction time nor variability reached statistical significance. These findings imply that background noise did not significantly impair or enhance performance at this receiver position, though individual response patterns may have contributed to the observed numerical differences.

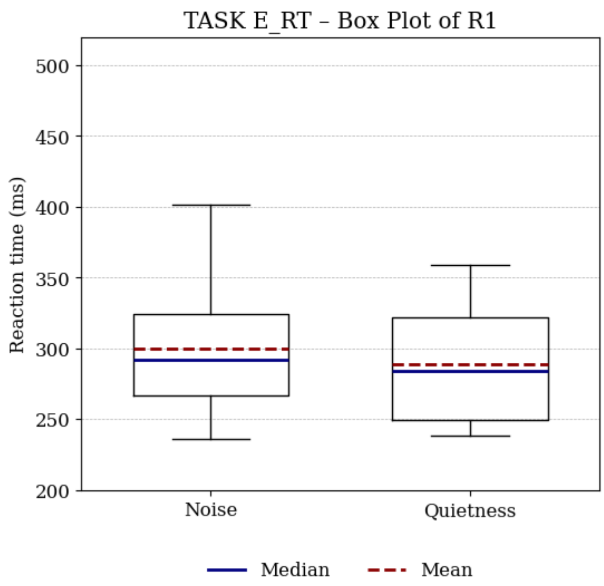


Figure 6.52: Box plot of the results of Task E - RT for Receiver 1.

Table 6.35: Statistical parameters for Task E - RT for Receiver 1.

	Noise	Quietness
Mean	287.50	308.71
SD	39.66	62.44
Min	222.08	222.89
25th perc.	270.86	272.69
Median	283.03	304.69
75th perc.	318.89	324.80
Max	351.21	458.51

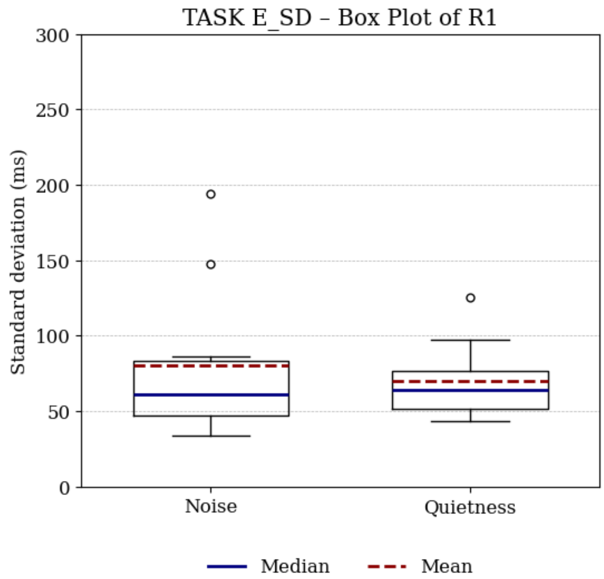


Figure 6.53: Box plot of the results of Task E - SD for Receiver 1.

Table 6.36: Statistical parameters for Task E - RT for Receiver 1.

	Noise	**Quietness**
Mean	79.91	69.59
SD	51.57	25.39
Min	33.65	43.06
25th perc.	46.70	51.57
Median	60.79	63.93
75th perc.	83.16	76.63
Max	194.05	125.16

Receiver 2

Figure 6.54 and Figure 6.55 show participants' performance at Receiver 2 in the reaction time task, under the two acoustic conditions of background noise and quietness. Two indicators were analyzed: average reaction time (RT) in milliseconds, and the standard deviation (SD) of those reaction times as a measure of response consistency. Starting with RT, descriptive statistics indicate slower responses under quietness. The mean reaction time increased from 287.50 ms in noise to 308.71 ms in quiet, and the median rose from 283.03 to 304.69 ms. This trend is further supported by higher values at the upper end of the distribution, with the 75th percentile shifting from 318.89 to 324.80 ms, and the maximum value increasing substantially from 351.21 ms in noise to 458.51 ms in quiet. The box plot confirms a noticeable upward shift under quietness, suggesting overall slower performance. However, the Wilcoxon Signed-Rank Test did not reveal a statistically significant difference between the two conditions (p-value = 0.114). Although eight out of ten participants showed faster responses in noise, this was not enough to reject the null hypothesis. Turning to intra-individual variability, as captured by the SD of reaction times, results were more mixed. The mean SD was slightly lower in quietness (70.54 ms) than in noise (75.04 ms), while the median increased slightly (63.06 vs. 60.70 ms). The interquartile range narrowed under quiet conditions, and extreme values—such as the maximum SD—were reduced from 157.08 ms in noise to 104.72 ms in quiet. This suggests a modest reduction in variability for most participants when noise was absent. Nonetheless, as with RT, the Wilcoxon Signed-Rank Test found no statistically significant difference between the two conditions (p-value = 0.333), with seven participants exhibiting lower variability in quietness and three in noise. In summary, participants at Receiver 2 tended to respond more quickly under noise and slightly more consistently in quietness, as shown by mean and percentile values. However, neither effect reached statistical significance, indicating that the observed patterns may be due to chance rather than a consistent influence of the acoustic environment.

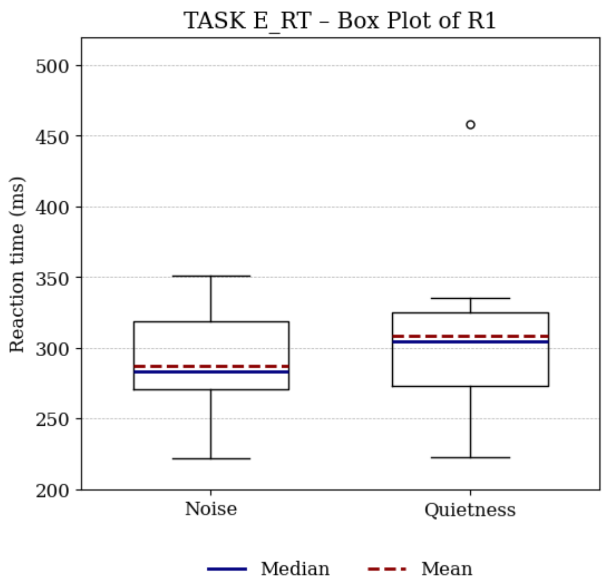


Figure 6.54: Box plot of the results of Task E - RT for Receiver 2.

Table 6.37: Statistical parameters for Task E - RT for Receiver 2.

	Noise	Quietness
Mean	287.50	308.71
SD	39.66	62.44
Min	222.08	222.89
25th perc.	270.86	272.69
Median	283.03	304.69
75th perc.	318.89	324.80
Max	351.21	458.51

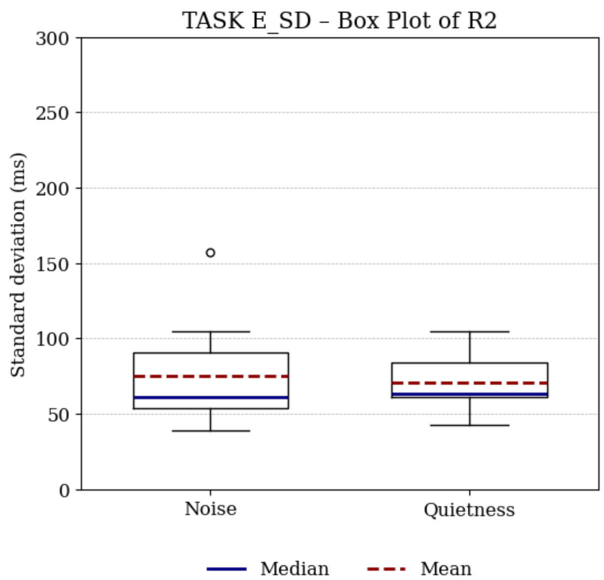


Figure 6.55: Box plot of the results of Task E - SD for Receiver 2.

Table 6.38: Statistical parameters for Task E - RT for Receiver 2.

	Noise	**Quietness**
Mean	75.04	70.54
SD	35.45	18.24
Min	38.75	42.85
25th perc.	53.95	61.02
Median	60.70	63.06
75th perc.	90.70	83.75
Max	157.08	104.72

Receiver 3

Figure 6.56 and Figure 6.57 show participants' performance at Receiver 3 during the reaction time task, considering both Reaction Time (RT) and intra-individual variability (Standard Deviation, SD) under two acoustic conditions: background noise and quietness. Starting with Reaction Time, descriptive statistics indicate faster responses under quiet conditions. The mean RT dropped from 305.22 ms in noise to 277.05 ms in quietness, while the median followed a similar trend, decreasing from 291.01 to 274.12 ms. The lower quartile shifted from 277.09 to 239.28 ms, and the upper quartile from 327.94 to 294.13 ms, suggesting a general compression of the distribution under quiet conditions. Furthermore, both the minimum and maximum values were slightly lower in quiet (231.89–371.29 ms) compared to noise (260.91–385.69 ms). These patterns suggest improved reaction speed in a quieter environment. Despite this descriptive improvement, the Wilcoxon Signed-Rank Test yielded a non-significant result (p-value = 0.114), indicating that the observed differences in RT were not statistically reliable. Nonetheless, 7 out of 10 participants showed faster reaction times under quietness. Turning to standard deviation (SD), participants again showed a more favorable pattern in the quiet condition. The mean SD was 82.39 ms under noise and decreased to 58.60 ms in quietness. The median SD dropped from 76.78 to 59.55 ms, and the interquartile range narrowed from 64.45 – 87.43 in noise to 46.23 – 71.89 in quiet, respectively, indicating not only a lower average variability but also more consistent performance among participants. The presence of a strong outlier in the noise condition is reflected in the maximum SD (152.39 ms), compared to 92.17 ms in quiet. These findings point to greater temporal stability in participants' reactions when background noise was absent. The Wilcoxon Signed-Rank Test for SD values also did not reach statistical significance (p-value = 0.093), although 7 participants showed reduced variability in quietness, suggesting a potentially meaningful trend. In conclusion, participants at Receiver 3 tended to perform better in the quiet condition both in terms of faster reaction times and more stable responses. While these differences did not reach statistical significance, the direction and consistency of the descriptive data, particularly the lower means, medians, and compressed ranges in quiet, suggest that the absence of noise may have positively influenced both processing speed and response consistency for most individuals.

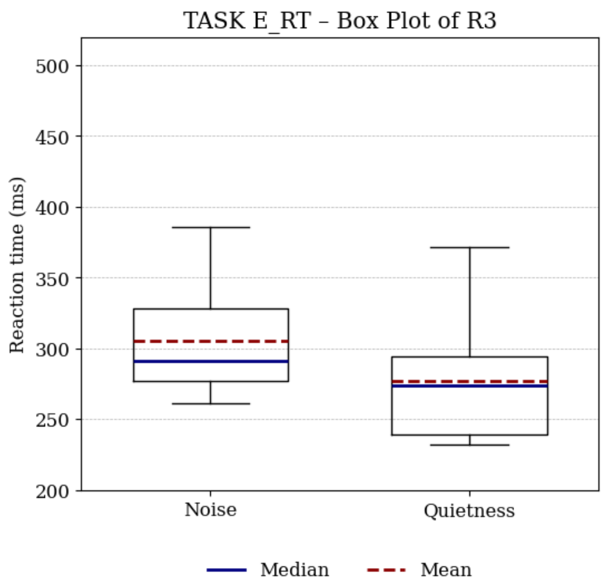


Figure 6.56: Box plot of the results of Task E - RT for Receiver 3.

Table 6.39: Statistical parameters for Task E - RT for Receiver 3.

	Noise	**Quietness**
Mean	305.22	277.05
SD	40.34	44.36
Min	260.91	231.89
25th perc.	277.09	239.28
Median	291.01	274.12
75th perc.	327.94	294.13
Max	385.69	371.29

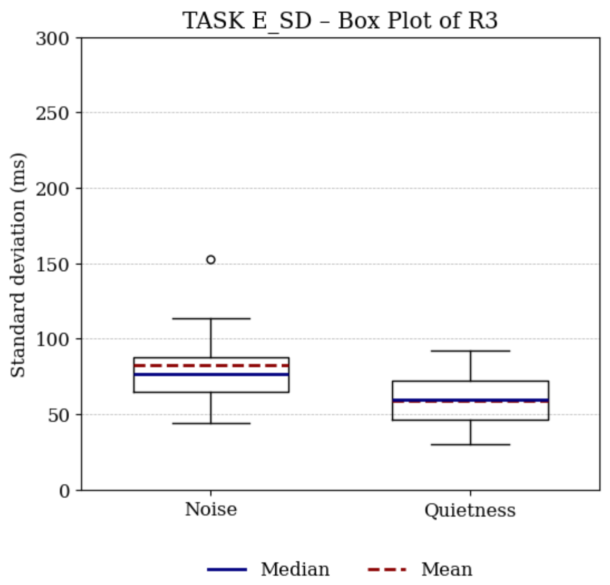


Figure 6.57: Box plot of the results of Task E - SD for Receiver 3.

Table 6.40: Statistical parameters for Task E - RT for Receiver 3.

	Noise	**Quietness**
Mean	82.39	58.60
SD	30.95	20.09
Min	44.30	30.24
25th perc.	64.45	46.23
Median	76.78	59.55
75th perc.	87.43	71.89
Max	152.39	92.17

Receiver 4

Figure 6.58 and Figure 6.59 illustrate the distribution of reaction time and its variability, i.e. standard deviation, for Receiver 4, under the two acoustic conditions, background noise and quietness. These measures provide insights into both the speed and consistency of responses during the task. Starting with reaction time, descriptive statistics show slightly faster responses under quietness. The mean reaction time decreased from 274.53 ms in noise to 266.38 ms in quiet, and the median dropped from 274.05 to 270.03. Similarly, the 25th and 75th percentiles shifted slightly lower under quietness (258.88 and 290.92 in noise vs. 243.63 and 285.04 in quiet). The minimum value decreased from 189.24 to 163.20, and the maximum from 377.91 to 348.59, suggesting a generally lower and more compressed distribution in quietness. The box plot confirms this pattern, showing a downward shift in central tendency and a reduced spread, despite the presence of outliers in both conditions. However, the Wilcoxon Signed-Rank Test yielded a p-value of 0.241, indicating that the difference in reaction time between the two conditions was not statistically significant. Turning to the standard deviation, which captures response variability, participants showed lower variability under quietness. The mean standard deviation dropped from 74.84 ms in noise to 57.64 ms in quiet, and the median followed a similar trend, declining from 66.87 to 56.93. Percentile values also decreased, with the 25th percentile shifting from 55.86 to 50.96 and the

75th from 88.59 to 67.61. These results suggest a more consistent performance in quiet conditions. The corresponding box plot visually reinforces this interpretation, revealing a narrower interquartile range and a reduced upper bound in quietness. Nevertheless, the Wilcoxon Signed-Rank Test for standard deviation returned a p-value of 0.203, showing that the reduction in variability was not statistically significant. Overall, for Receiver 4, both the average reaction speed and the consistency of responses appeared to improve slightly under quiet conditions. Yet, these differences were not strong enough to reach statistical significance, implying that the presence or absence of background noise had a limited impact on performance in this task.

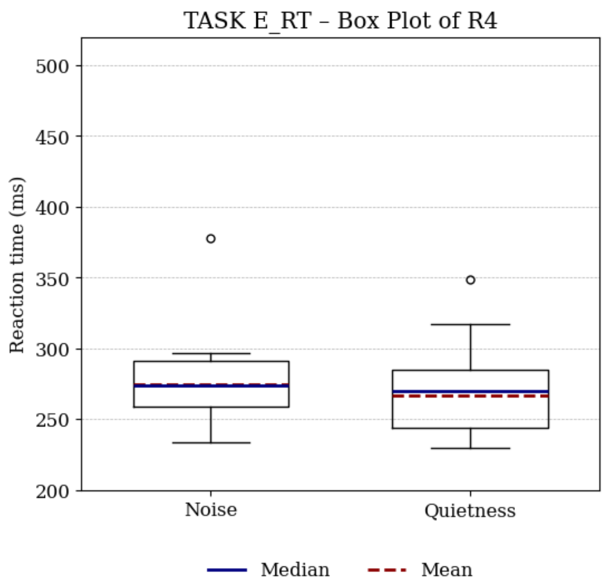


Figure 6.58: Box plot of the results of Task E - RT for Receiver 4.

Table 6.41: Statistical parameters for Task E - RT for Receiver 4.

	Noise	Quietness
Mean	274.53	266.38
SD	48.35	50.46
Min	189.24	163.20
25th perc.	258.88	243.63
Median	274.05	270.03
75th perc.	290.92	285.04
Max	377.91	348.59

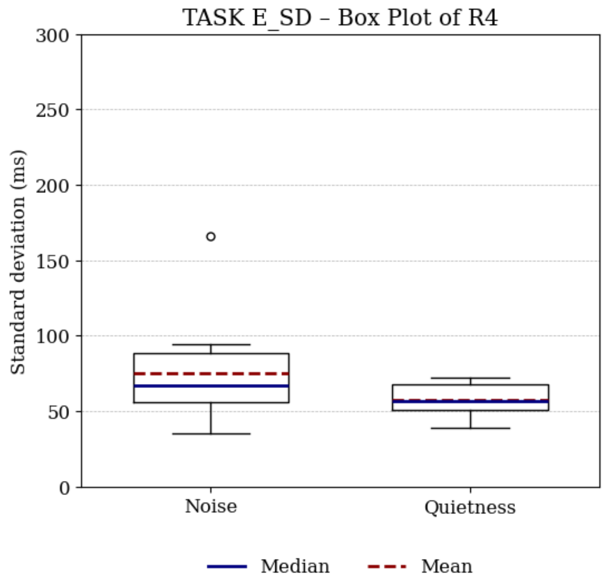


Figure 6.59: Box plot of the results of Task E - SD for Receiver 4.

Table 6.42: Statistical parameters for Task E - RT for Receiver 4.

	Noise	Quietness
Mean	74.84	57.64
SD	37.98	11.72
Min	35.45	38.66
25th perc.	55.86	50.96
Median	66.87	56.93
75th perc.	88.59	67.61
Max	166.16	72.40

Receiver 5

Figure 6.60 and Figure 6.61 show participants' performance at Receiver 3 during the reaction time task, considering both Reaction Time (RT) and intra-individual variability (Standard Deviation, SD) under two acoustic conditions, background noise and quietness. The analysis of reaction time (RT) indicates comparable performance between the noise and quietness conditions. The mean RT was 293.59 ms under noise and 294.46 ms in quietness, suggesting no substantial difference in average response speed. Interestingly, the median was slightly lower in quietness (266.56 ms) compared to noise (276.43 ms), which might reflect a tendency toward faster responses in a quieter environment. The interquartile range also shifted slightly: in noise, it ranged from 250.54 to 312.35 ms, while in quietness, it was narrower (258.90 to 294.46 ms), possibly indicating slightly more consistent performance when noise was absent. Nevertheless, both conditions exhibited a wide spread in values, as shown by the maximum RTs, i.e. 423.55 ms in noise and 433.59 ms in quietness, and similar standard deviations (60.70 ms and 61.21 ms, respectively), highlighting the presence of some variability and outliers. These observations were supported by the Wilcoxon Signed Ranks Test, which showed no statistically significant difference between conditions (p-value = 0.878), confirming that noise had no significant effect on R5's reaction speed. Regarding the standard deviation of reaction time (SD), results again showed minimal differences between the two conditions. The mean SD was 79.27 ms in noise and 78.50 ms in quietness, with medians of 51.30 ms and 51.14 ms, respectively, values that are virtually identical. Despite similar central tendencies, there was noticeable variability in performance, particularly in the noise condition, which recorded a maximum SD of 305.62 ms compared to 274.77 ms in quietness. The interquartile range was slightly broader in noise (44.46 to 66.55 ms) than in quietness (44.05 to 63.26 ms), again hinting at marginally higher variability with background noise. However, the Wilcoxon test did not reveal a significant difference between conditions (p-value = 0.721), suggesting that the presence of noise did not significantly influence the consistency of the responses. Overall, R5 showed stable performance across both conditions, with only minimal fluctuations that did not reach statistical significance.

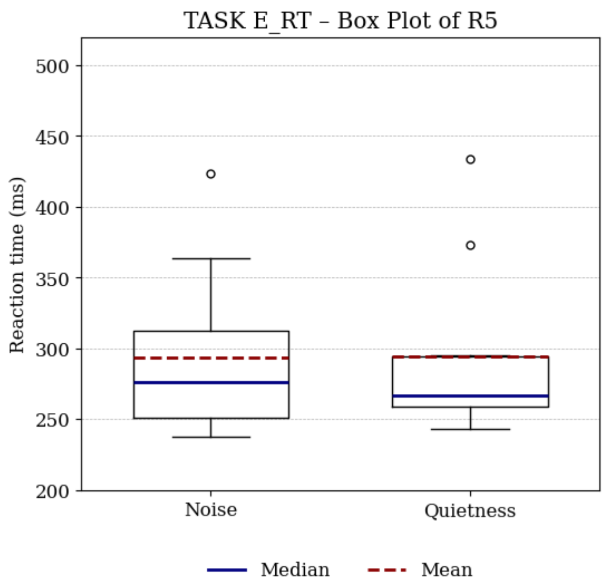


Figure 6.60: Box plot of the results of Task E - RT for Receiver 5.

Table 6.43: Statistical parameters for Task E - RT for Receiver 5.

	Noise	Quietness
Mean	293.59	294.46
SD	60.70	61.21
Min	237.29	243.11
25th perc.	250.54	258.90
Median	276.43	266.56
75th perc.	312.35	294.46
Max	423.55	433.59

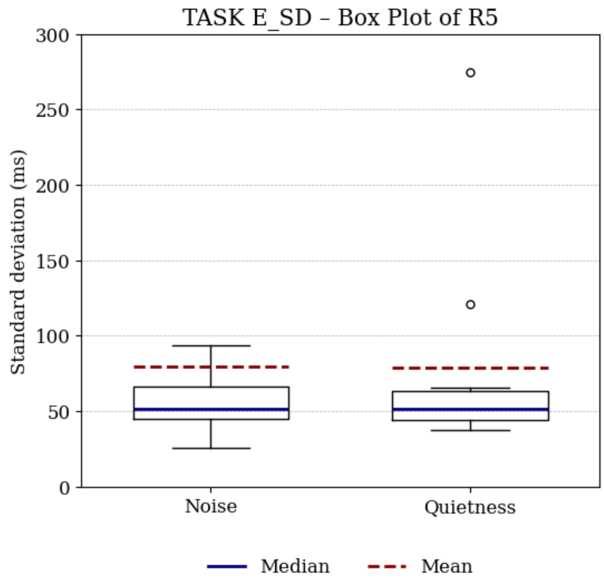


Figure 6.61: Box plot of the results of Task E - SD for Receiver 5.

Table 6.44: Statistical parameters for Task E - RT for Receiver 5.

	Noise	**Quietness**
Mean	79.27	78.50
SD	81.56	73.08
Min	25.47	37.03
25th perc.	44.46	44.05
Median	51.30	51.14
75th perc.	66.55	63.26
Max	305.62	274.77

All receivers

To assess whether the spatial position of receivers influenced participants' reaction time performance under different acoustic conditions, a Kruskal-Wallis test was performed separately for background noise and quiet. No significant differences emerged across the five receiver locations in either condition (p = 0.641 for noise; p = 0.557 for quiet), suggesting that spatial position did not systematically affect participants' response speed. Similarly, an analysis of response consistency, measured by the standard deviation (SD) of reaction times, revealed no significant differences across receiver locations (p-value = 0.516 for noise; p-value = 0.445 for quiet), indicating that the consistency of responses was also unaffected by spatial position. A Wilcoxon Signed-Rank Test conducted on the full sample (N = 50) revealed no significant overall effect of acoustic condition on mean reaction time (p-value = 0.449), with participants nearly evenly split between performing faster in quiet (n = 24) versus noise (n = 26). A similar null result was found for SD (p-value = 0.237), with 27 participants showing less variability in quiet and 23 in noise. These findings suggest that background noise did not reliably influence either reaction speed or response stability at the group level. Despite the absence of statistically significant effects, descriptive data and individual receiver analyses showed interesting patterns. Receivers 1, 3, and 4 exhibited faster average and median reaction times in quiet, while Receiver 2 showed slower reaction times in quiet compared to noise, i.e. the participants assigned to this position performed better under noise exposure. Receiver 5 presented nearly identical average RT values across conditions, though slightly faster median responses in quiet. In terms of response variability, given by the standard deviation (SD), Receivers 1, 3, and 4 also showed lower SD scores in quiet, while Receivers 2 and 5 displayed more ambiguous or minimal differences. Variability tended to decrease under quiet conditions, as reflected in lower interquartile ranges and maximum SDs in most receiver positions.

These descriptive trends were further explored using a Linear Mixed Model with age as a predictor of average reaction time. The model revealed a significant positive effect of age (p-value < 0.001), with an estimate of 2.406 ms per year. This means that for each additional year of age, participants' reaction times increased by approximately 2.41 milliseconds. This age-related slowing is consistent with established findings on processing speed decline with aging. However, when SD of reaction times was modeled as the dependent variable, none of the predictors reached statistical significance, including age (p-value $= 0.793$), condition (p-value $= 0.088$), spatial position, or perceptual sound attributes such as roughness, sharpness, or tonality. Although the effect of condition approached significance, the overall model indicates that response variability was not systematically modulated by any of the tested variables. In summary, while no robust group-level effects were detected for spatial position or background noise on reaction time or response variability, the significant age effect on mean RT suggests an expected decline in speed with age. Additionally, subtle trends at the descriptive level point to slightly faster and more stable responses in quiet conditions for certain receiver positions, though these patterns did not reach statistical significance.

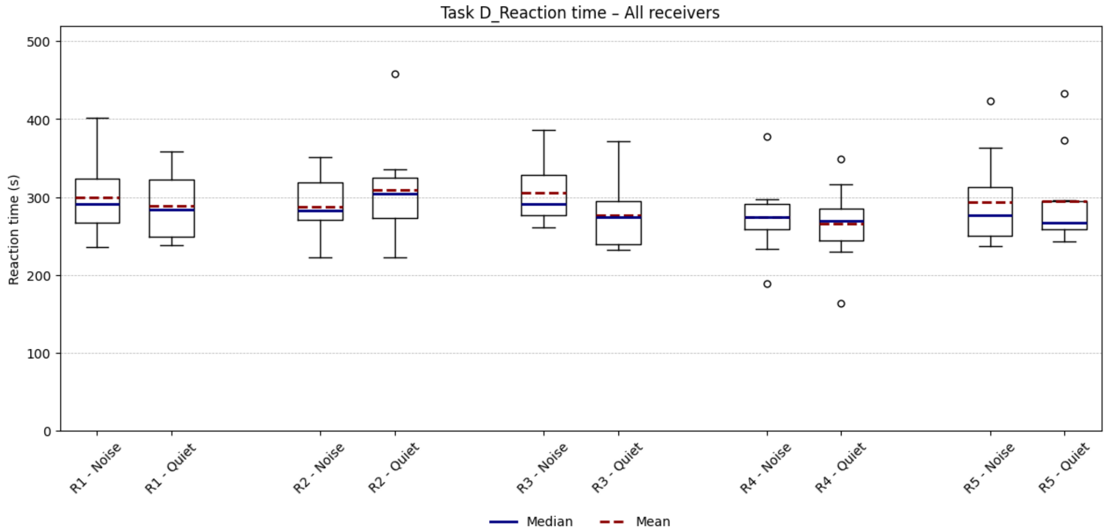


Figure 6.62: Box plots of the results of Task E - RT for all receivers.

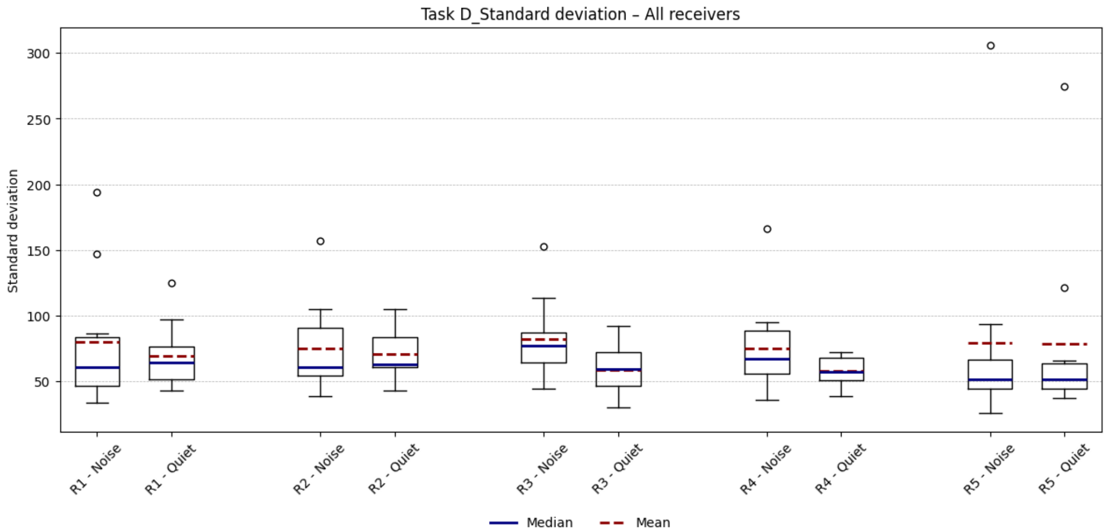


Figure 6.63: Box plots of the results of Task E - SD for all receivers.

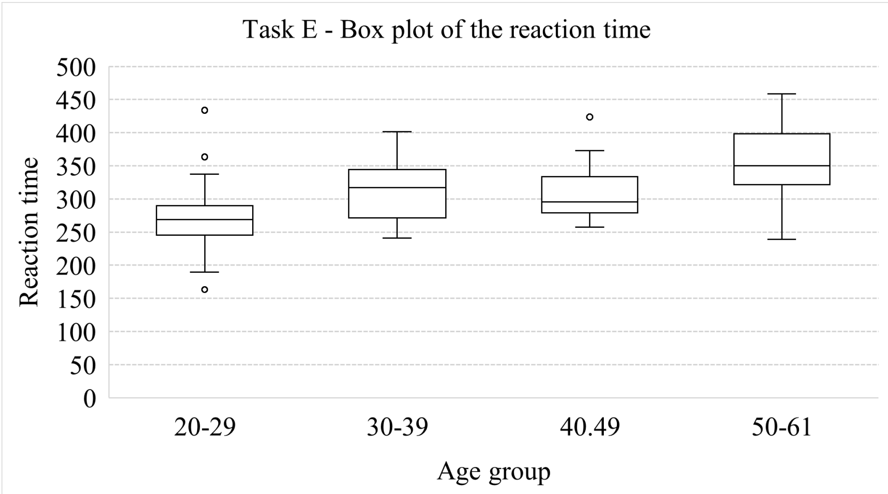


Figure 6.64: Box plot of the correlation between the the reaction time and the age for the Task E.

Chapter 7

Conclusions

This study aimed to explore how environmental noise influences cognitive performance and subjective experience across a range of tasks and acoustic parameters. A combination of descriptive statistics, non-parametric tests, and Linear Mixed Models (LMMs) was used to evaluate the effects of noise exposure on cognitive outcomes, as well as to assess the roles of individual differences such as noise sensitivity, psychoacoustic perception, and demographic factors. The conclusions are organized around the three main dimensions assessed: subjective sensitivity and disturbance, task performance, and individual variability.

7.1 Cognitive performance in the different tasks

Each cognitive task responded differently to the acoustic conditions, reflecting a task-dependent sensitivity to noise:

- In the Word memorisation task (Task A), no significant differences were observed across noise and quiet conditions or across receiver positions. However, a systematic advantage was found for one version of the test, suggesting that internal task characteristics (e.g., semantic structure or word familiarity) had a stronger influence than acoustic context.
- In the Reading aloud task (Task B), both reading speed and accuracy remained statistically unaffected by noise at the group level. Nonetheless, subtle trends emerged: noise-sensitive individuals showed slower reading, and age and test version significantly influenced error rates. These findings suggest that individual traits rather than noise per se shaped reading outcomes.
- In the Trail Making Test (Task C), distinct patterns were observed between TMT-A and TMT-B. While TMT-A did not show significant differences across

conditions, performance on TMT-B improved under noise. This suggests that background noise might enhance certain aspects of executive functioning, such as mental flexibility, especially when cognitive demand is high.

- The Semantic Verbal Fluency Task (Task D) also showed no main effect of noise; however, performance was significantly affected by task version and perceived roughness. These internal factors appeared to shape lexical access more than the external auditory environment.
- In the Reaction Time Task (Task E), results revealed no significant effect of noise on either average response speed or response variability. Yet, consistent with existing literature, age significantly predicted slower reaction times.

Taken together, the impact of noise on cognition was not uniform. Tasks involving higher cognitive load or executive functioning—such as TMT-B—appeared more sensitive to the presence of noise, sometimes benefiting from it. Tasks relying on automatic or overlearned processes, like reading aloud or simple reaction time, showed greater resilience to acoustic variation. This variability underscores the importance of considering the nature and complexity of cognitive tasks when assessing environmental effects.

7.2 Performance across receiver locations

Although the main statistical analyses justified treating the five receiver positions as a unified sample for most tasks, descriptive trends across locations still provide valuable insights into the spatial dynamics of performance and perception. These trends suggest that while differences were not always statistically significant, certain receiver positions tended to perform better or worse across specific tasks or perceptual evaluations. In particular:

- Receiver 1 emerged as a particularly distinctive location in several respects. In the noise sensitivity analysis, participants assigned to Receiver 1 exhibited higher sensitivity scores, indicating a greater reactivity to noise. Similarly, in the Noise Disturbance Test, Receiver 1 was perceived as less loud than others, a finding supported by both descriptive statistics and pairwise comparisons, possibly due to specific acoustic shielding or spatial characteristics at that location. In particular, this receiver was placed in a relatively central position at the main floor, therefore far from reverberant surfaces. In cognitive tasks, Receiver 1 showed stronger performance trends under noise in the Verbal memory task, the TMT-B, the Semantic Verbal Fluency Test and the Reaction time test (Task F), although these were not statistically significant. Overall, Receiver 1 stood out as a unique position, with heightened sensitivity and perceptual contrast, but also with moments of relatively better cognitive performance under noise exposure than the other positions.

- Receiver 2 demonstrated high verbal fluency, especially in the Semantic Verbal Fluency Test, and performed relatively well in TMT-A under noise condition. However, it was also associated with lower noise sensitivity and higher loudness ratings in the disturbance test, suggesting a complex balance between acoustic exposure and performance outcomes. This receiver may reflect a condition of greater arousal or alertness, potentially beneficial in tasks involving lexical access.

- Receiver 3 was marked by intermediate sensitivity and performance, with no extreme results in either direction. In some tasks, such as reaction time and TMT-B, this receiver showed moderate values that mirrored the sample average, suggesting a relatively neutral acoustic and cognitive profile.

- Receiver 4 displayed inconsistent patterns, with slightly better performance in the Verbal memory task and Reading aloud task in terms of number of errors, particularly under noise. Yet, in the SVFT, this location was the only one where performance was descriptively better in quiet, suggesting that acoustic features here may have influenced cognitive engagement differently depending on task demands.

- Receiver 5, while not significantly impaired in any specific task, tended to show lower fluency and poorer performance in several tasks. For example, in the Reading Aloud task, this receiver exhibited more errors and in the Reaction Time task (Task E), it presented more ambiguous trends. Despite being among the positions with higher perceived loudness due to the higher sound pressure level, this did not translate into clear performance advantages or disadvantages, suggesting either desensitization or variability in individual coping strategies.

In summary, although most performance differences across receiver positions did not reach statistical significance, qualitative trends suggest that Receiver 1 and Receiver 2 were the most distinctive: the former for its high sensitivity and perceptual contrast, and the latter for its lexical performance and arousal-related characteristics. These observations support the idea that spatial acoustic variability, even when not statistically conclusive, can subtly influence perception and task execution.

7.3 Noise sensitivity and Noise disturbance

Noise sensitivity, as measured through a 20-item standardized questionnaire, revealed relatively homogeneous distributions across the sample, with no significant differences across receiver locations. This justified the use of a unified participant pool for subsequent analyses. Perceptions of noise disturbance were captured using a separate scale evaluating annoyance and various psychoacoustic attributes. Most attributes—fluctuation, roughness, sharpness, and tonality, did not vary significantly across receiver groups. However, loudness showed meaningful spatial differences, with Receiver 1 perceived as significantly less loud. Annoyance ratings were moderate on average, suggesting that the acoustic stimulus was neither trivial nor overwhelmingly disruptive. Interestingly, fluctuation was the only positively perceived attribute, hinting at a nuanced auditory experience.

7.4 Individual differences and predictive factors

Throughout the study, Linear Mixed Models (LMMs) provided valuable insights into how individual factors shaped task performance beyond environmental conditions. Predictors such as age, gender, noise sensitivity, psychoacoustic evaluations (e.g., roughness, fluctuation), test version, and session order significantly contributed to explaining performance variance in specific tasks. In particular:

- Age consistently predicted slower reaction times.
- Test version influenced outcomes in memory, reading, and fluency tasks, revealing the importance of controlling for test content.
- Perceived roughness was associated with improved performance in the verbal fluency task, suggesting a subjective arousal-based effect.
- Session order predicted faster completion of the TMT tasks when administered in the second session, possibly indicating a learning or familiarity effect.

These findings highlight that individual characteristics, both stable (e.g., age, sensitivity) and contextual (e.g., test version), significantly shaped responses and should be accounted for in future designs.

7.5 Final considerations: arousal and the role of noise

A crucial interpretive lens for these findings is the arousal theory, previously introduced in this study. This theory suggests that moderate noise levels can increase physiological and cognitive arousal, which, under certain conditions, can enhance performance. In the present work, this was particularly evident in the TMT-B task, where noise was associated with better performance, likely due to increased engagement and cognitive activation under challenging conditions. Additionally, subtler traces of arousal effects were detected in the verbal fluency task, where perceived roughness—a parameter often associated with higher auditory stimulation—was positively correlated with word production. These results suggest that noise may not universally hinder cognition; rather, its effect is contingent upon the interaction between task demands and individual sensitivity. For tasks requiring sustained attention or higher cognitive flexibility, moderate background noise may actually serve as a stimulant, improving efficiency and focus. This perspective challenges the simplistic assumption of noise as purely detrimental, instead supporting a context-sensitive model where arousal modulation plays a key role in shaping cognitive performance.

Chapter 8

Limitations

While the present study offers valuable insights into the interplay between noise and cognitive performance, several limitations must be acknowledged to contextualize the findings and guide future research:

- Small sample size: The number of participants involved was relatively limited. Although statistical methods suited for small samples were employed (e.g., non-parametric tests and LMMs), a larger sample would increase applicability to broader populations and statistical power, particularly for detecting subtle effects.

- Noise disturbance test comprehension: In the Noise Disturbance Test, terms such as fluctuating and rough were verbally explained to participants, as they were considered the most abstract or technically complex. However, no auditory examples were provided. This lack of concrete reference may have hindered accurate self-reporting, especially among participants without a background in acoustics, potentially affecting the validity of the psychoacoustic ratings.

- Unequal task difficulty across versions: In at least one task, a discrepancy in difficulty was identified between the two versions administered. For example, participants who were asked to recall items from categories like fruits and vegetables performed better than those assigned to less familiar or cognitively demanding categories, such as furniture. This imbalance was confirmed by the LMM analysis and likely influenced cognitive outcomes independently of the acoustic condition, limiting the ability to isolate the effect of noise.

- Session order effects: Some participants reported feeling more prepared or confident during the second testing session, regardless of the condition. This subjective feedback aligns with the LMM results, which identified session order as a significant predictor in multiple tasks. Familiarity with the experimental setup and reduced anxiety may have contributed to improved performance in the second session, independently of acoustic condition.

These limitations highlight important methodological considerations and suggest caution in interpreting specific effects. Nonetheless, the analytical framework employed was robust enough to detect meaningful patterns and lay the groundwork for more controlled investigations in future studies.

Chapter 9

Potential directions for future implementations

In light of the results and methodological framework adopted in this study, several future developments can be envisioned to expand the scope and depth of similar research. Two particularly promising directions are discussed below: the integration of physiological monitoring through wearable technology and the implementation of a soundscape-focused experimental protocol.

9.1 Investigating the effect of environmental noise on physiological and emotional responses measured through wearable sensors

One future development involves the integration of wearable physiological sensing devices, such as EmotiBit, into experimental paradigms assessing the relationship between noise exposure and cognitive performance. While the present study focused on behavioral and subjective measures, future research could benefit greatly from the addition of real-time physiological data to investigate the psychophysiological correlates of environmental noise. In particular, there is an sensor, called EmotiBit, which offers the opportunity to monitor emotional arousal and stress-related responses by capturing signals such as electrodermal activity (EDA), heart rate variability (HRV), and body temperature. These indicators can reveal the activation of the autonomic nervous system in response to noise and task demands, providing a direct link between physiological states and cognitive outcomes. By implementing this tool in future studies, it would be possible to identify individual patterns of arousal and stress that may explain variability in performance, beyond what can be inferred from self-reports or task accuracy alone. This kind of integration would allow researchers to investigate, in a more holistic manner, how internal bodily states mediate or moderate the effects of acoustic environments on cognition. Such multidimensional data collection could help delineate which noise conditions are experienced as cognitively stimulating versus disruptive, and how these perceptions are reflected in the body's emotional and physiological responses.

9.2 Exploring soundscape perception

Another significant avenue for future implementation concerns the design of a study specifically centered on the perception of soundscapes. While the current research examined noise as an acoustic factor influencing cognition, further exploration of how individuals subjectively experience different acoustic environments could enrich the interpretation of the acoustic impact. A proposed future project would involve administering validated soundscape perception questionnaires present in the scientific literature, while participants listen to a series of environmental sound recordings. This would allow for a structured comparison of different libraries, including the one investigated in this study and others for which calibrated recordings already exist. One notable reference is the Saint Geneviève Library, for which immersive 360-degree video recordings with spatial audio have been created.

In this context, virtual reality (VR) technology could be employed to simulate environmental immersion. Participants could evaluate the same soundscape both with and without the use of VR headsets, allowing researchers to assess whether immersive visual input influences the perception of the acoustic environment. This methodology would provide insights into the integration of auditory and visual stimuli and how it shapes subjective soundscape assessments. Moreover, this experimental design would enable a comparative analysis of how the newly designed library is perceived relative to real existing libraries. Such insights could guide architectural and acoustic decisions during the design and implementation phases of new public spaces, ensuring that soundscape quality is aligned with user expectations and functional demands.

Bibliography

[1] J. Xiao and F. Aletta. «A soundscape approach to exploring design strategies for acoustic comfort in modern public libraries: A case study of the Library of Birmingham». In: *Noise Mapping* 3 (2016), pp. 264–273. https://doi.org/10.1515/noise-2016-0018.

[2] S. Torresin, F. Aletta, F. Babich, E. Bourdeau, J. Harvie-Clark, J. Kang, L. Lavia, A. Raddichi, and R. Albatici. «Acoustics for supportive and healthy buildings: Emerging themes on indoor soundscape research». In: *Sustainability* 12 (2020), p. 6054. https://doi.org/10.3390/su12156054.

[3] A. Laurìa, S. Secchi, and L. Vessella. «Acoustic comfort as a salutogenic resource in learning environments—A proposal for the design of a system to improve the acoustic quality of classrooms». In: *Sustainability* 12 (2020), p. 9733. https://doi.org/10.3390/su12229733.

[4] ISO 12913-1:2014. «Acoustics–Soundscape – Part 1: Definition and conceptual framework». International Organization for Standardization, Geneva, Switzerland, 2014. https://www.iso.org/standard/52161.html. (Last viewed July 31, 2023).

[5] ISO 12913-3:2019. «Acoustics–Soundscape – Part 3: Data analysis». International Organization for Standardization, Geneva, Switzerland, 2019. https://www.iso.org/standard/69864.html. (Last viewed July 31, 2023).

[6] Ö. Axelsson, M. E. Nilsson, and B. Berglund. «A principal components model of soundscape perception». In: *Journal of the Acoustical Society of America* 128 (2010), pp. 2836–2846.

[7] F. Aletta and A. Astolfi. «Soundscapes of buildings and built environments». In: *Building Acoustics* 25 (2018), pp. 195–197.

[8] P. Dokmeci Yorukoglu and J. Kang. «Analysing sound environment and architectural characteristics of libraries through indoor soundscape framework». In: *Archives of Acoustics* 41 (2016). DOI: https://doi.org/10.1515/aoa-2016-0020.

[9] P. Rajagopalan, H. T. H. Nguyen, and A. Carre. «Acoustic performance of contemporary public libraries: An evaluation of public libraries in Melbourne, Australia». In: *Architectural Science Review* 60(2) (2016), pp. 104–115. https:

//doi.org/10.1080/00038628.2016.1265483.

[10] J. Mu, T. Wang, and Z. Zhang. «Research on the acoustic environment of heritage buildings: A systematic review». In: *Buildings* 12(11) (2022), p. 1963. https://doi.org/10.3390/buildings12111963.

[11] P. H. Fleming. «The historical building and room acoustics of the Stockholm Public Library (1925–28, 1931–32)». In: *Acoustics* 6 (2024), pp. 754–771. https://doi.org/10.3390/acoustics6030041.

[12] J. Zhang, L. Pang, C. Yang, Y. Fan, B. Zhao, and X. Cao. «Experimental Evaluation of Noise Exposure Effects on Subjective Perceptions and Cognitive Performance». In: *Buildings* 14 (2024), p. 1100. https://doi.org/10.3390/buildings14041100.

[13] C. Song, H. Li, H. Ma, T. Han, and J. Wu. «Effects of noise type and noise sensitivity on working memory and noise annoyance». In: *Noise Health* 24 (2022), pp. 173–181. https://doi.org/10.4103/nah.NAH_50_22.

[14] F. Gheller, G. Spicciarelli, P. Scimemi, and B. Arfé. «The effects of noise on children's cognitive performance: A systematic review». In: *Environment and Behavior* 55(8–10) (2024), pp. 698–734. https://doi.org/10.1177/00139165241245823.

[15] C. Liu, Q. Zang, J. Li, X. Pan, H. Dai, and W. Gao. «The effect of the acoustic environment of learning spaces on students' learning efficiency: A review». In: *Journal of Building Engineering* 79 (2023), p. 107911. https://doi.org/10.1016/j.jobe.2023.107911.

[16] H. Liu, H. He, and J. Qin. «Does background sounds distort concentration and verbal reasoning performance in open-plan office?». In: *Applied Acoustics* 172 (2021), p. 107577. https://doi.org/10.1016/j.apacoust.2020.107577.

[17] K. Kostallari, E. Parizet, P. Chevret, J.-N. Amato, and E. Galy. «Irrelevant speech effect in open plan offices: Comparison of two models explaining the decrease in performance by speech intelligibility and attempt to reduce interindividual differences of the mental workload by task customisation». In: *Applied Acoustics* 161 (2020), p. 107180. https://doi.org/10.1016/j.apacoust.2019.107180.

[18] G. Guerra, J. Tijms, A. Vaessen, A. Tierney, F. Dick, and M. Bonte. «Loudness and intelligibility of irrelevant background speech differentially hinder children's short story reading». In: *Mind, Brain, and Education* 15 (2021), pp. 77–87. https://doi.org/10.1111/mbe.12264.

[19] M. Pellegatti, S. Torresin, C. Visentin, F. Babich, and N. Prodi. «Indoor soundscape, speech perception, and cognition in classrooms: A systematic review on the effects of ventilation-related sounds on students». In: *Building and Environment* 236 (2023), p. 110194. https://doi.org/10.1016/j.buildenv.2023.110194.

[20] D. Fernández-Quezada, D. E. Martínez-Fernández, I. Fuentes, J. García-Estrada, and S. Luquin. «The influence of noise exposure on cognitive function in children and adolescents: A meta-analysis». In: *NeuroSci* 6 (2025), p. 22. https://doi.org/10.3390/neurosci6010022.

[21] W. Yang and J. Y. Jeon. «Effects of lighting and sound factors on environmental sensation, perception, and cognitive performance in a classroom». In: *Journal of Building Engineering* 76 (2023), p. 107063. https://doi.org/10.1016/j.jobe.2023.107063.

[22] H. Sukowski. «Effects of noise on employees during a concentration task: Results from performance and subjective assessments and a critical view of the chosen performance test». In: *Applied Acoustics* 231 (2025), p. 110533. https://doi.org/10.1016/j.apacoust.2025.110533.

[23] J. Radun, H. Maula, I.-K. Tervahartiala, V. Rajala, S. Schlittmeier, and V. Hongisto. «The effects of irrelevant speech on physiological stress, cognitive performance, and subjective experience – Focus on heart rate variability». In: *International Journal of Psychophysiology* 200 (2024), p. 112352. https://doi.org/10.1016/j.ijpsycho.2024.112352.

[24] L. Zhang and H. Ma. «The effects of environmental noise on children's cognitive performance and annoyance». In: *Applied Acoustics* 198 (2022), p. 108995. https://doi.org/10.1016/j.apacoust.2022.108995.

[25] K. Teigen. «Yerkes-Dodson: A law for all seasons». In: *Theory Psychology* 4 (1994), pp. 525–547. https://doi.org/10.1177/0959354394044004.

[26] A. Kjellberg. «[Titolo dell'articolo mancante – inseriscilo qui se disponibile]». In: *Scandinavian Journal of Work, Environment Health* 16(1) (1990). https://doi.org/10.5271/sjweh.1825.

[27] G. R. J. Hockey. «Effects of loud noise on attentional selectivity». In: *Quarterly Journal of Experimental Psychology* 22(1) (1970), pp. 28–36.

[28] P. A. Hancock and J. S. Warm. «A dynamic model of stress and sustained attention». In: *Human Factors* 31(5) (1989), pp. 519–537. https://doi.org/10.1177/001872088903100503.

[29] E. C. Poulton. «Arousing environmental stresses can improve performance, whatever people say». In: *Aviation, Space, and Environmental Medicine* 49(5) (1978), pp. 719–729.

[30] C. Song, H. Li, H. Ma, T. Han, and J. Wu. «Effects of noise type and noise sensitivity on working memory and noise annoyance». In: *Noise Health* 24 (2022), pp. 173–181.

[31] C. Cognigni and M. Bodonio. «La nuova Biblioteca centrale di Torino e il ridisegno del sistema bibliotecario urbano». In: *Presentazione PowerPoint al Convegno delle Stelline*, Milano, Italia, 31 marzo 2023. https://bct.comune.torino.it/sites/default/files/2023-06/REV%20Presentazione%20Convegno%20Stelline%2031%20marzo.pdf.

[32] ODEON Room Acoustics Software. *User's Manual, Version 18*. Published in November 2023, Odeon A/S, DTU Science Park, Diplomvej, building 381, DK-2800 Kgs. Lyngby, Denmark. Tel: +45 8870 8845, Fax: +45 8870 8090. https://odeon.dk/download/Version18/OdeonManual.pdf.

[33] Tovusound. *Edward Foley Artist Instrument*. Available at: https://tovusound.com/shop/edward-foley-artist-instrument/. (Last viewed July 3, 2025).

[34] Tovusound Instruments. «Instrument sample libraries and Foley-style expansions». In: *Tovusound.com*, 2025. https://tovusound.com/instruments/.

[35] Native Instruments. *Virtual Studio Tool (VST) – NI Kontakt*. Available at: https://www.native-instruments.com/en/products/komplete/samplers/kontakt-7/. (Last viewed July 3, 2025).

[36] Avid Technology. *Pro Tools – Digital Audio Workstation*, 2023. Available at: https://www.avid.com/pro-tools. (Last viewed July 3, 2025).

[37] ISO 1996-2:2017. «Acoustics – Description, measurement and assessment of environmental noise – Part 2: Determination of sound pressure levels». International Organization for Standardization, Geneva, Switzerland, 2017. https://www.iso.org/standard/59765.html. (Last viewed July 3, 2025).

[38] R. Lacqua. *Physical acoustical validation of the Audio Space Lab at the Polytechnic of Turin*. Tesi di laurea magistrale, rel. A. Astolfi, A. Guastamacchia, L. Shtrepi. Politecnico di Torino, Corso di Laurea Magistrale in Ingegneria del Cinema e dei Mezzi di Comunicazione, 2024.

[39] A. Guastamacchia et al. «Set up and preliminary validation of a small spatial sound reproduction system for clinical purposes». In: (Jan. 2022), pp. 4991–4998. https://doi.org/10.61782/fa.2023.0698.

[40] A. Guastamacchia, R. G. Rosso, G. E. Puglisi, F. Riente, L. Shtrepi, and A. Astolfi. «Real and virtual lecture rooms: Validation of a virtual reality system for the perceptual assessment of room acoustical quality». In: *Acoustics* 6 (2024), pp. 933–965. https://doi.org/10.3390/acoustics6040052.

[41] V. P. Senese, F. Ruotolo, G. Ruggiero, and T. Iachini. «The Italian version of the Weinstein Noise Sensitivity Scale: Measurement invariance across age, sex, and context». In: *European Journal of Psychological Assessment* 28 (2011), pp. 118–124. https://doi.org/10.1027/1015-5759/a000099.

[42] J. Zhang, K. Chen, H. Li, X. Chen, and N. Dong, *The effects of rating scales and individual characteristics on perceived annoyance in laboratory listening tests*, Applied Acoustics, vol. 202, 2023, Art. no. 109137.

[43] A. Rey. *L'examen clinique en psychologie*. Presses Universitaires de France, Paris, 1958.

[44] A. Cornoldi, A. Pra Baldi, and G. Friso. *Prove MT avanzate di lettura e matematica 2 per il biennio della scuola superiore di II grado*. Giunti O.S. Organizzazioni Speciali, Firenze, 2010.

[45] A. Cornoldi and M. Candela. *Prove di lettura e scrittura MT 16-19: Batteria per la verifica degli apprendimenti e la diagnosi di dislessia e disortografia.* Erickson, Trento, 2015.

[46] M. Spinelli, M. De Luca, G. Di Filippo, M. Mancini, M. Martelli, and P. Zoccolotti. «Length effect in word naming latencies: Role of reading experience and reading deficit». In: *Developmental Neuropsychology* 27 (2005), pp. 217–235.

[47] I. Calvino. *Marcovaldo.* Palomar S.r.l. e Arnoldo Mondadori Editore, Milano, 1993.

[48] D. Bindelli, D. Depretis, A. Fasola, K. Folisi, D. Marzorati, E. Profumo, R. Serafino, and F. Torcellini. «La comorbidità tra dislessia, disortografia, disgrafia, discalculia nella scuola secondaria di secondo grado». In: *Dislessia* 6(1) (2009), pp. 59–76.

[49] M. De Luca et al. *Prove di velocità di lettura brani.* [Editore e anno non specificati].

[50] S. Wagner, I. Helmreich, N. Dahmen, K. Lieb, and A. Tadić. «Reliability of three alternate forms of the Trail Making Tests A and B». In: *Archives of Clinical Neuropsychology* 26(4) (2011), pp. 314–321. `https://doi.org/10.1093/arclin/acr024`.

[51] D. Quaranta et al. «Standardization, clinical validation, and typicality norms of a new test assessing semantic verbal fluency». In: *Archives of Clinical Neuropsychology* 31(5) (2016), pp. 434–445.

[52] M. Rigoli, A. Facchin, D. Cardile, N. Beschin, and C. Luzzatti. «Open-source open-access reaction time test (OORTT): An easy tool to assess reaction times». In: *Neurological Sciences* 42 (2021), pp. 2461–2469.