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Noise perception and cognitive effort in the simulated reverberant and quiet environment of the New Central Civic Library of Torino

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ABSTRACT

In recent years, libraries have evolved from spaces dedicated exclusively to individual study into multi-functional environments, which integrate social and cultural activities. However, nowadays libraries can be experienced in two different ways, i.e., either as a traditional quiet space dedicated to individual study, or as a multifunctional environment that accommodates a wider range of noisy activities. Consequently, noise perception and its impact on users' annoyance and cognitive performance have become important research topics. This study investigates these aspects within the simulated quiet sound environment of the New Civic Central Library of Torino (Italy). With a volume of approximately 160000 m^3 and a reverberation time of about 5 s at mid frequencies, it is designed to accommodate various functions, but in this study, the primary activity of the individual study was examined. A geometrical acoustic simulation was run using Odeon 18. Four receivers were defined, exposed to various noise sources: traffic, ventilation, ambient buzz, footsteps, page-turning, pen taps, and intelligible speech. Mixed noise levels at the receivers ranged from 43 to 47 dB(A), reproducing realistic conditions of similar library environments. Listening tests were performed with 24 normal-hearing participants aged 20–55 using static headphones. Participants completed tasks reflecting typical library activities. No significant differences were revealed in most cognitive outcomes between noise and silence conditions. The only exception was a semantic processing task, such as reading aloud, which showed slight deterioration under noise exposure. These findings emphasize the importance of appropriate acoustic design even in quiet libraries to safeguard cognitive performance.

1. Introduction

In recent years, there has been a marked evolution in the function of libraries, from being exclusively designed for silent individual study to becoming multifunctional spaces that integrate social, cultural and collaborative activities [1]. However, nowadays libraries can be experienced in two different ways, i.e., either as a traditional quiet space dedicated to individual study, or as a multifunctional environment that accommodates a wider range of noisy activities. As a consequence, there is an increasing need to thoroughly examine their sound environment [2].

A multitude of noise sources determines moderate noise level in libraries, which rarely overcome 55 dB(A) in historical libraries and 60 dB(A) in contemporary libraries [3]. The sources of noise include conversations, footsteps, electrical equipment (printers and computers), HVAC systems, noise generated by opening and closing doors, electronic devices, as well as external noise such as traffic and human activities [3,4]. Reflective surfaces, including wooden floors, stone surfaces, plaster walls and ceilings, and glass windows, contribute to prolonged reverberation times, leading to significant amplification of noise.

Historical Libraries. The reading room in traditional historical libraries was conceived as a quiet place for individual study. This, e.g., occurred in the Boston Public Library, in the State Library of Victoria, Melbourne, in the Richelieu Library in Paris, etc. Looking at worldwide old libraries, the main large reading room has a high ceiling, which is often vaulted, and is mainly characterized by sound-reflecting materials. The architecture itself was designed to inspire silence and self-restraint [5]. It is interesting to notice that stillness is achieved in this space by truly relying on very high reverberation time and users are more likely to maintain a quiet behavior [6,7]. Libraries housed a relatively limited number of functions in the past (e.g., book storage, reading, study) that did not entail the presence of any particular sound

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source. A reverberation time of 5.6 s was measured by Rajagopalan et al. [4] in La Trobe Reading Room of the historical City Library of Melbourne (1854), with a volume of 32 000 m^3, matching with an A-weighted sound pressure level ranging from 47.2 to 52.2 dB. Fleming [8] also measured a mid frequencies reverberation time around 5–6 s and an overall A-weighted sound pressure level in unoccupied condition ranging from 35.6 dB and 50.1 dB, in the historical reading room Central Rotunda of the Stockholm Public Library (1925–28), with a volume of 12 000 m^3.

Contemporary Libraries. In contemporary libraries, in addition to areas dedicated to individual activities, such as reading, studying and writing, areas for more collaborative activities, as well as social relations areas, are often present. New noise sources should be considered with the proliferation of these new activities, which require a targeted acoustic design in order to guarantee acoustic comfort to the occupants [3,4]. At the Library at the Dock in Melbourne, built in 2014 and constructed from cross-laminated timber, the recorded occupied noise levels by Rajagopalan et al. [4], were between 41.5 and 48.5 dB(A). Dokmeci and Kang [3] measured 56.5 ± 1.9 dB, 51.3 ± 2.0 dB and 57.8 ± 3.7 dB, as A-weighted sound pressure level due to occupants' activity in three atria of contemporary libraries in Sheffield with volume of 1548 m^3, 1945 m^3, 2667 m^3, respectively. A positive correlation was found between the noise level and the crowd level. Brothánek et al. [9] documented acoustics in the National Library of Technology in Prague (Czech Republic), built in 2009, with 2000 daily users, finding the most common sound pressure level about 50 dB(A) and the median 47.8 dB(A). The library's central feature is a large five-story open atrium of 14 400 m^3, with reverberation times of 2–2.6 s at mid frequencies. McCaffrey and Breen [1] emphasized the significance of acoustic comfort in a university library by analyzing the impact of noise management interventions. These interventions included the introduction of noise policies, space reorganization, centralization of services, creation of quiet areas, structural interventions and zoning. A survey examined the perceptions of noise levels after the implementation of the noise-control measures and the findings demonstrated the success of the interventions.

Noise in occupied libraries, where the main task is to be concentrated, can impair the cognitive tasks of the occupants, who are mostly students [10–12]. In recent decades, increasing attention has been paid to ensure acoustic comfort in libraries, which goes beyond simply minimizing noise; it focuses on creating a sound environment that supports the function of the space, improves the well-being and productivity of its users and aligns with the activities performed [4,13,14]. Otuonuyo et al. [14] explored the acoustic comfort at the Library of Birmingham, a renowned contemporary multifunctional public library. The results show that participants seemed to expect better acoustic conditions in areas designated for 'reading and thinking' compared to those meant for 'interacting and communicating', suggesting that acoustic comfort in contemporary libraries is shaped not only by the volume but also by the spatial layout.

However, contemporary libraries are often sound proofed and their spatial layout is conceived to separate noisy and less noisy functions. The New Central Civic Library of Torino will be housed in the large volume of the historic Torino Esposizioni complex, built in 1938 and protected by the cultural heritage authorities, who do not permit any acoustic treatment on the original surfaces of the building. It is designed to combine traditional study functions with a modern concept of a digital, social, and cultural meeting space that will be hosted within the same highly reverberant space. With the aim of exploring the influence of the acoustic conditions on noise perception and cognitive performance of the occupants, the acoustic rendering of the library has been carried out and subjective tests have been conducted. A digital acoustic model of the library was created and a complex geometrical acoustics (GA) simulation was run with multiple noise sources in order to replicate realistic sound conditions. In this study, the primary activity of individual study was examined, excluding noise generated by children or adolescents, as well as noise from digital, social, and cultural gatherings. In addition, the proximity of the Department of Architecture and Design at the Politecnico di Torino suggests that the facility will be used predominantly by university students. Further studies will be carried out using these sources to assess the library's sound environment under a noisy setting. The library can, in fact, be experienced in two different ways, either as a traditional quiet space dedicated to reading and studying, or as a multifunctional environment that accommodates a wider range of noisy activities. However, it is not only a matter of decibel to perceive noise as annoying, since "*...machines cannot measure disruptions such as 'fierce whispering', which might not be loud but can be extremely annoying*" [1].

2. Methodology

2.1. Acoustic rendering of the library

The acoustic rendering of the library results from three main steps: (i) preliminary analysis of similar contexts and collection of relevant acoustic and non acoustic data; (ii) creation of the 3D model of the library with virtual receivers and consistent sources, and run of the GA simulation; (iii) auralisation of the sound sources, composition of audio mixes and comparison of the wav file with similar existing spaces. This methodology is represented with a detailed flow chart in the Supplementary Material.

2.1.1. Case study

Fig. 1 shows the 3D rendering of the large reading room of the New Central Library of Torino, with a volume of 160 000 m^3, with the intended functions. The library was designed to accommodate various usage patterns. The ground floor presents a large space with study areas; the apsidal area overlooks the Valentino park and presents an area dedicated to children; the basement, accessible by large staircases, is used as an archive area for the historical collections and presents an "Enchanted Garden", a reading area with tables and chairs among the flowerbeds and trees; the upper floor, which extends along two wings along the sides of the building, houses spaces for collaborative study.

2.1.2. One historical and one contemporary library

To study the sound environment within reading rooms with large reverberant volumes, as in the case study, the large historical Oval Room of the Richelieu Library, inaugurated in 1936 in Paris, with a volume of about 20 000 m^3, has been chosen as a reference. As shown in Fig. 2 (left), the architectural space, recently renovated, features a central skylight, sixteen round windows, mosaics and ornate arcades. The space is characterized by three levels of balconies for book access, and a ground floor with desks and armchairs for reading. The curved shelving primarily feature oak and wood finished in an aluminium-like shade. Noise level measurements were carried out in this room during autumn 2024, while it was fully occupied, primarily by students engaged in reading, studying, whispering and walking. Two 5 min recordings were made with a calibrated NTI sound level meter at two opposite sides of the hall and the results were 47.1 dB(A) and 46.5 dB(A), respectively. The estimated reverberation time of the room at mid-frequencies is about 3 s.

In Paris, acoustic measurements were also carried out with the same equipment and methodology in one of the large and low open spaces for individual study of the contemporary Bibliothèque Publique d'Information at Centre Pompidou (Bpi), shown in Fig. 2 (right). The space is very well acoustically treated, and the floor is covered with thick carpet; the ceiling is partially covered by metallic grids and false ceiling, and ducts, and the walls are glazed. Rows of desks for individual study, separated by tall metallic shelves, occupy the entire floor of the building. The two 5-min recordings at two different positions resulted in 44.5 dB(A) and 46.9 dB(A), respectively.

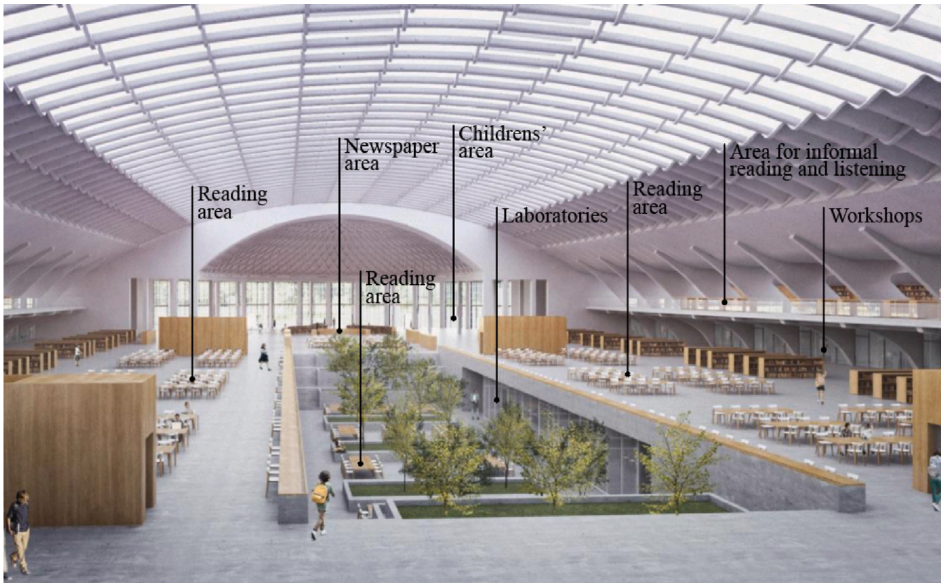

Fig. 1. 3D rendering of the New Civic Central Library of Torino with the intended functions.

Fig. 2. The Oval Room at the Richelieu library (left) and the Bibliothèque Publique d'Information at Centre Pompidou (right).

2.1.3. 3D GA model of the library

The three-dimensional model of the New Civic Central Library of Torino used for the Geometrical Acoustics (GA) simulations was developed with Odeon 18 software [15]. The model was created starting from the architectural plan, employing polygonal mesh surfaces. Once the 3D structure was complete, each surface was assigned a material and the related octave band absorption and scattering coefficients according to the renovation project.

As shown in Fig. 3, a variety of surface finishes typically found in libraries were incorporated, including plaster, glass, carpet, persons and bookshelves [16]. A PVC transparent membrane delimitates a semitoroidal space large 10 m in the exedra. The library is considered barely occupied even if the full capacity is 1200 people. The majority of surfaces remained reflective, with the exception of the vertical surface above the apse, which is covered with acoustic plaster. The scattering coefficient was set to 0.01 uniformly, despite the presence of different materials [15]. This value is inserted as a single value corresponding to 707 Hz and is then used by the algorithm to extrapolate a frequency-dependent scattering which follows the typical S-shape with higher values at high frequencies. The value of 0.01 has been considered as a valid assumption based on the state-of-the-art [17]. The vertical surfaces of the room, made of painted concrete or wood, are rather flat and smoothed, and a very low scattering coefficient can be considered appropriate [18]. The curved surfaces of the ceiling, located far from the sources and receivers, have been modeled as smaller surfaces with many boundaries, and the scattering due to diffraction over the boundaries contributes to the overall diffused reflections. Thus, a lower scattering was considered appropriate to balance the overall contribution.

Fig. 4 shows the completed 3D GA model within the Odeon 18 software, providing a detailed visualization of the space used for acoustic simulations. The simulation employed a transition order of 2, which defines the maximum number of reflections considered during the acoustic simulation. Additionally, 50,000 rays were used to ensure a high degree of accuracy in the calculation of the sound propagation.

The resulting reverberation time (T30) at different octave frequency bands was obtained as average value for the global estimate calculated considering all the main point sources. Global estimate is a software feature which calculates general reverberation for a room, rather than at a specific receiver point. The reverberation time is 8.7 s at 125 Hz,

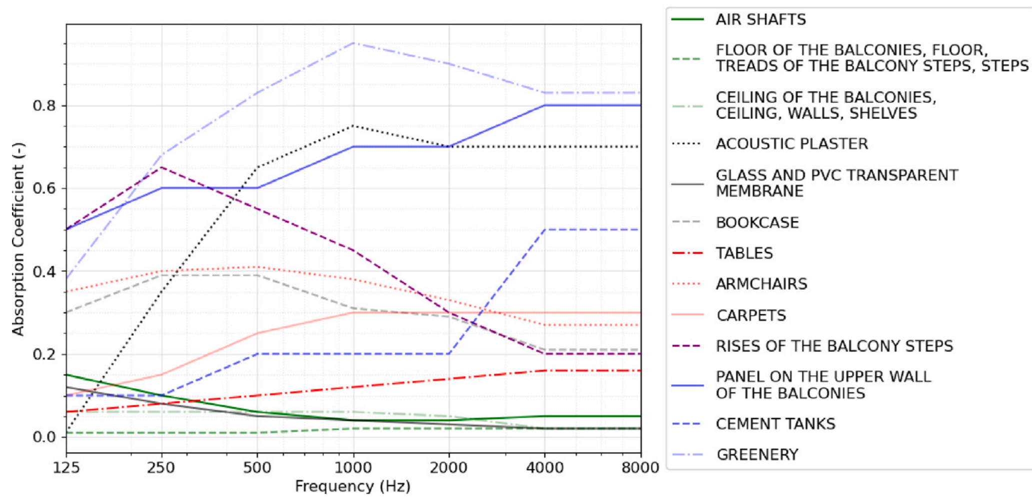

Fig. 3. Sound absorption coefficients of materials used for the 3D GA model.

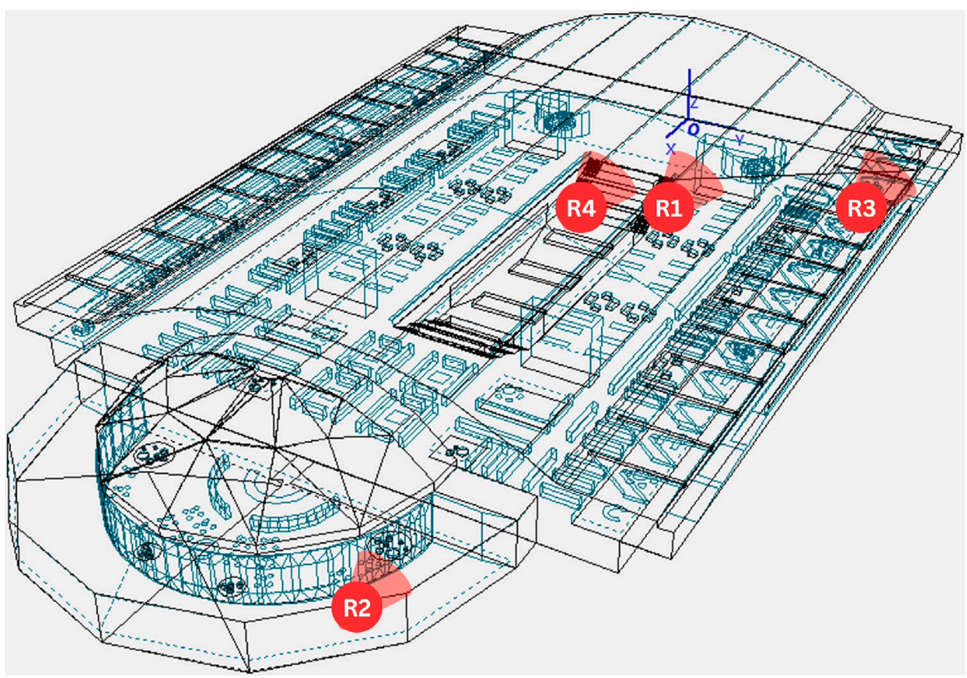

Fig. 4. 3D GA Odeon model of the Library with the position of the receivers.

5.1 s (st. dev. 0.45) as average value between 500 Hz and 2 kHz, and 3.8 s at 4 kHz. This frequency-dependent variation in reverberation time plays a crucial role in the acoustic comfort of the library, particularly in terms of speech intelligibility and the clarity of sound in different areas of the space. According to the Italian standard UNI-11532-2 [16], the optimal ratio of total equivalent absorption area to volume (A/V) for libraries is greater than or equal to 0.11 for each octave band from 250 Hz to 2 kHz, assuming a volume of about 160 000 m^3 and a height of 18.2 m. In the New Civic Central Library of Torino, the values of this ratio fall below the recommended threshold, with values of 0.02 for 250 Hz, 0.03 for 500 Hz, 0.03 for 1 kHz and 0.03 for 2 kHz. However, potential acoustic improvements are constrained by the regulations imposed by cultural heritage authorities, as the building is classified as a historical monument.

2.1.4. Sound sources and receivers

Sound sources, typical of a library, have been characterized for the simulation of the sound environment with GA algorithm according to a methodology described in [19]. Noise from traffic, HVAC, pen clicking, turning of pages and mobile phones as well as from unintelligible and intelligible speech has been registered in anechoic conditions or in situ and was assigned with an appropriate sound power level and typology in the acoustic model. The wav samples of each source have been collected and made available for future applications in similar environments where people intentionally tend to be quiet and require concentration [19]. These samples can be used for auralisation of noise mixes in which the different sources contribute to different time slots according to the desired acoustic experience.

As shown in Fig. 5, the sound sources in the Odeon 18 GA model were placed as follows:

- S1: HVAC system, represented as one surface source distributed over the entire floor area.
- S2: HVAC system, represented as two linear sources simulating the ceiling diffusers, 8.4 m high above the floor.
- S3: traffic noise, represented as a surface source divided into 3 sub-areas, 3a, 3b, 3c, on the roof of the building. S3a is close to

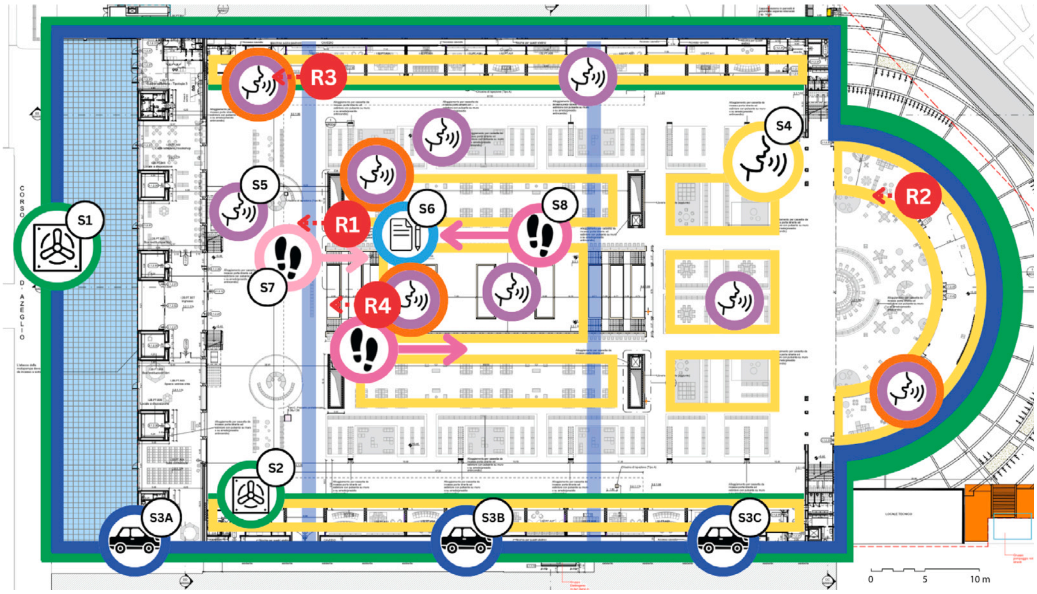

Fig. 5. Plan of the multifunctional reading room of the library with sources and receivers from R1 to R4. Receivers' feet of R3 and R4 are located 4.3 m and 5 m above and below the ground floor, respectively. The orientation of the receivers is indicated with a red arrow. Traffic is shown as blue surface source, subdivided in 3 areas. HVAC is shown both as green surface source and two multiple line sources. Unintelligible buzz is shown as yellow surface source. Intelligible buzz is shown as purple point source. Equivalent intelligible 5-words phrases from the Matrix Sentence Test [20] are shown as orange point source and are activated instead of the intelligible buzz purple source when placed close to the receivers. Footsteps are shown as multiple pink and fuchsia multiple point sources. Noise from pens and pages is shown as light blue point source. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the busy street, S3b is in the midway between the street and the river to the other side of the building, and S3c is close to the river and over the rear part of the roof and the exedra.

- S4: unintelligible buzzing considered as surface source above the tables at the level of 1.2 m above the floor in the main hall and at 1.5 m above the floor in the semitoroidal space between two parallel transparent surfaces in the exedra, that is, at the hypothetical speaker's mouth sit and standing, respectively.
- S5: omnidirectional point source representing intelligible buzzing with one person talking as in a conversation, or with one person saying equivalent intelligible phrases. Equivalent intelligible 5-words phrases from the Matrix Sentence Test [20] are activated instead of the intelligible buzz source when the source is placed close to the receivers.
- S6: omnidirectional point source of noise coming from flipping pages, click of pens and notifications from personal devices.
- S7: array of 35 omnidirectional point sources representing footsteps, that simulate a person going down the stairs quickly.
- S8: array of 14 omnidirectional point sources representing footsteps, that simulate a person walking slowly inside the library.

The receivers, sit or standing, and oriented randomly in the room, were placed at the following strategic points, as shown in Fig. 5:

- R1: sit 1.2 m high from the floor, overlooking the balcony, close to the underground courtyard named "Enchanted Garden".
- R2: standing 1.6 m from the floor, on one side of the exedra, in the semi-toroidal space between glass and the transparent PVC membrane.
- R3: sit 1.2 m high from the floor, on the balcony, in a niche, with his/her feet 4.3 m above the ground floor.
- R4: standing 1.6 m from the floor, with his/her feet 5 m below the ground floor, in the "Enchanted Garden".

The choice of these receivers' positions has been made to capture the diversity of acoustic experiences in such a large and complex volume. In particular, the receiver on the ground floor (R1) is disturbed from direct sound from different sources and does not receive early reflections from surfaces to a large extent, the receiver in the exedra (R2) receives early reflections from the exedra itself and a low contribution of direct sound, the receiver on the balcony (R3) and in the "Enchanted Garden" (R4) detect a good contribution of direct sound and early reflections from closer reflective surfaces, which are the vaulted ceiling and the parallel reflective walls of the garden, respectively. About the sound sources, R1 and R4 are more disturbed by intelligible speech, noise from flipping pages and pens' clicking, footsteps, while R3 is more disturbed by traffic and HVAC noise.

To simulate the overall sound pressure level at the receivers' positions, octave band sound power level (SWL) and directivity index (DI) have been attributed to each sound source [19]. Table 1 shows the characteristics of each source and their overall sound power level. In order to perform the auralization of the different sound source with an anechoic signal, the frequency dependent SWL has been flattered in frequency, maintaining the same overall energy.

2.1.5. Sound pressure levels

In the case of the simulations of the New Civic Central Library of Torino, A-weighted sound pressure levels have been calculated for each individual source as well as for all sources combined at each receiver location, as shown in Table 2.

2.1.6. Auralisation

Auralisation was performed in Odeon 18 using the binaural output format, as the subjective tests were conducted with headphones. Auralisation makes it possible to virtually position oneself within a specific environment and hear the resulting audio signal as it would be perceived at that location [15]. Fig. 6 shows the flowchart for the creation of the auralised tracks for the different receivers from the anechoic samples.

By selecting binaural mode, Odeon converts the spatial Room Impulse Response (RIR) into a binaural impulse response (BRIR), which results in a two-channel signal that simulates the propagation

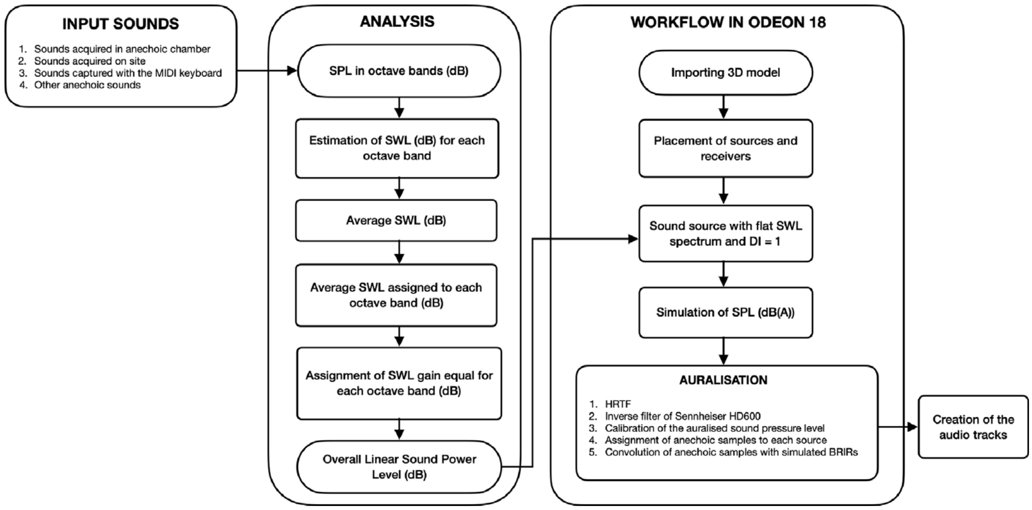

Fig. 6. Flowchart for the creation of the auralised tracks from the anechoic samples.

Table 1
Characteristics of each source, type, and overall sound power level in dB applied in the 3D GA model in Odeon 18.

Source No.	Source name	Source type	Overall power level (dB)
1	HVAC	Surface	50.7
2	HVAC	Line (2 above the balconies)	50.7
3a	Traffic	Surface	69.3
3b	Traffic	Surface	56.6
3c	Traffic	Surface	55.4
4	Unintelligible buzz	Surface	69.8
5	Intelligible buzz Equivalent sentences	Point (8 distributed) Point (1 close to each receiver)	60.2
6	Pages, pens, etc.	Point (1 close to Receiver 1)	51.2
7	Footsteps (people going down the stairs)	Point (35 in a row)	54.7
8	Footsteps (people walking)	Point (14 for two rows)	53.3

of sound in the left and right ear canals. In order to achieve this conversion, Odeon offers a set Head-Related Transfer Functions (HRTF), from which we selected the "unity_SRate44100_Apass0,50_Astop40,00_BOvrLap100_PPrHRTF1" [15]. The listener's head is oriented as indicated by the red arrows in Fig. 5.

2.1.6.1. Calibration of the auralisation system. The headphones used for the auralisation were the Sennheiser HD600 [21] because they offer a relatively flat frequency response. The equalization filter for the Sennheiser HD600 headphones provided by Odeon 18 was applied to further flatten the frequency response.

To calibrate the reproduction level of the auralization, we simulated a flat-spectrum omnidirectional source point source placed 1 meter from a receiver within the ODEON model. The simulation returned an A-weighted Sound Pressure Level (SPL) of 67 dB at the receiver position. We then used the BRIRs of that simulation to produce the auralization of a flat-spectrum continuous sound. We measured the A-weighted SPL of the auralization through a calibrated artificial head, specifically the HSU III.3 by HEAD Acoustics, wearing Sennheiser HD600 headphones. The gain of the reproduced signal was adjusted until the A-weighted SPL measured at the artificial head matched the 67 dB value obtained from the simulation.

2.1.6.2. Composition of audio mixes. To auralise each track, an anechoic signal has been associated to each source [19]. In Odeon 18, the "calibration mode" has been activated ensuring comparability in sound pressure level between the different recordings, as in Table 2. For each source-receiver pair, monaural and binaural room impulse responses were extracted from the Odeon software and convolved with the corresponding audio tracks. Monoaural RIRs were extracted from the Ambisonics export.

To create audio mixes containing all the auralized sounds from all sources for each receiver, a structured scheme was adopted in which the individual sounds were inserted at different time intervals. Specifically, six audio mixes were generated per receiver, each lasting three minutes. These three-minute tracks were divided into 20-s segments, with a different sound assigned to each segment. Each of the six mixes was composed following a time-distribution matrix, exemplified in Table 3 for Receiver 1 and Track 1. Six distinct matrices were randomly generated, ensuring that the temporal presentation of the sounds differed across mixes, while maintaining an equivalent energy content.

The equivalent A-weighted sound pressure level of the audio mixes when exported in monoaural format was arbitrarily set to 44.9 dB, 45.4 dB, 42.9 dB and 46.7 dB, for the receivers R1, R2, R3 and R4, respectively. These values correspond to the A-weighted sound pressure level in Table 2 when all the sources are activated, even if this does not occur in the audio mixes. The absolute level of the monaural wav mixes is solely intended for spectral comparison with the measurements taken in the Oval Room of the Richelieu Library and in the Bpi Library, and may therefore be considered arbitrary.

After exporting to binaural format, the equivalent A-weigthed sound pressure level for the audio mixes measured from the playback system, calibrated as described in paragraph 2.1.6.1, were 45.1 dB, 45.2 dB, 42.7 dB and 44.9 dB for the left ear R1L, R2L, R3L and R4L, respectively, and 45.7 dB, 45.8 dB, 43.4 dB and 45.6 dB, for the right ear R1R, R2R, R3R and R4R, respectively. The levels did not differ for the other five audio mixes for each receiver.

2.2. Subjective tests

Subjective tests were conducted on 24 participants aged 20–55 and normal hearing, which wore the Senneheiser HD600 headphone in the anechoic room of Politecnico di Torino, to evaluate disturbance and cognitive performance in presence of reverberant environmental noise. This study examined reading and studying, excluding social and children-related noise. As people over 55 show a high prevalence of age-related hearing loss [22], this group will be included in future research.

Table 2
A-weighted SPL for each source and for all the sources vs. each receiver obtained from the 3D GA model in Odeon 18.

Source No.	Source name	Source type	SPL dB(A)			
			R1	R2	R3	R4
1	HVAC	Surface	18.1	27.7	14.6	16.5
2	HVAC	Line (2 above the balconies)	18.4	11.4	22.6	13.5
3a, 3b, 3c	Traffic	Surface	38.9	35.6	34.4	38.0
4	Unintelligible buzz	Surface	34.6	43.9	37.4	32.5
5	Intelligible buzz	Point (8 distributed)	35.3	25.9	34.4	35.0
	Equivalent sentences	Point (1 close to each receiver)	36.1	36.9	37.1	40.5
6	Pages, pens, etc.	Point (1 close to Receiver 1)	28.2	7.1	16.2	19.0
7	Footsteps (people going down the stairs)	Point (35 in a row)	37.8	26.5	31.7	42.9
8	Footsteps (people walking)	Point (14 for the first row)	35.6	21.2	29.7	32.0
		Point (14 for the second row)	35.6	24.7	30.0	35.6
1, 2, 3a, 3b, 3c, 4, 5, 6, 7, 8	All sources	–	44.9	45.4	42.9	46.7

Table 3
Example of matrix used to create the 3 min audio files.

Track 1 - R1	Source name	20″	20″	20″	20″	20″	20″	20″	20″	20"
S1, S2 - 1 surface source and 2 line sources	HVAC	x	x	x	x	x	x	x	x	x
S3 - 3 surface sources	Traffic	x	x	x	x	x	x	x	x	x
S4 - 9 surface sources	Unintelligible buzz	x	x	x	x	x	x	x	x	x
S5 - 8 distributed point sources	Intelligible buzz	x	x	x	x	x	x	x	x	x
S5 - 1 point source close to each receiver	Equivalent sentences	x			x			x		
S6 - 1 point source close to Receiver 1	Pages, pens, etc.	x	x	x	x	x	x	x	x	x
S7 - 35 point sources in a row	Footsteps (people going down the stairs)			x			x			x
S8 - 14 point sources of first row	Footsteps (people walking)	x			x			x		
S8 - 14 point sources of the second row	Footsteps (people walking)		x			x			x	

A noise sensitivity test was previously administrated to the subjects in order to discriminate between low and high sensitive categories. To maintain the anonymity, each participant was assigned a code, e.g., S1, T1, Z1, etc. The tests were preceded by an introduction, consisting of a presentation narrating the genesis of the project of the Library.

2.2.1. Noise sensitivity test

Noise sensitivity test was assessed using the Weinstein Noise Sensitivity Scale (WNSS), a psychometric questionnaire, initially developed in English by Marvin Weinstein in 1978, then translated in Italian by Senese et al. [23] in accordance with a systematic process to ensure that the translated version retained the validity and reliability of the original, that involved not only linguistic adaptation but also cultural adaptation. During the test, participants rated their agreement with statements about their relationship with sound on a six-level scale (1 = "strongly disagree" to 6 = "strongly agree"). The final score is obtained by summing the answers, thus, a higher score reflects greater sensitivity to noise.

2.2.2. Noise disturbance test

The noise disturbance test [24] measured the impact caused by noise simulating the library environment. Participants rated the disturbance of the reproduced noise on a discrete scale of 0 ('not annoying') to 10 ('extremely annoying').

2.2.3. Cognitive tests

The cognitive tests, aimed at assessing different cognitive abilities typically involved in library-related activities, were administered under both noise and silence conditions. The session included the following tasks:

- Task A: Silent reading a 15-word list of the "Rey's 15-Word Test" [25].
- Task B: Reading aloud a passage from a book; in this task, reading speed was calculated by dividing the total time (in seconds) required to read the passage by the number of syllables it contained. In addition, errors were also recorded [26–31].
- Task C: Trail Making Test (TMT), a task in which randomly arranged numbers or letters are printed on a sheet, and the participant is required to connect them in ascending order; in this case, the completion time was measured to assess processing speed [32].
- Task D: Semantic Verbal Fluency (SVF) Test, where the participant is asked to produce as many words as possible belonging to a given category (e.g., birds or furniture) [33].
- Task E: Open source Open-access Reaction Time Test (OORTT) carried out using the OpenSesame software [34], in which participants have to press a button as quickly as possible when they see a visual stimulus.
- Task F: Verbally recall the words presented during Task A.

2.2.4. Administration of the tests

The tests were administered in the anechoic chamber of the Politecnico di Torino, a dead room with a background noise level less than 20 dB(A). Nine male and fifteen females, with a mean age of 33.5 years, participated to the survey, wearing the headphone. Each participant listened six audio files reproducing the sound environment from the perspective of one of the four receivers. The six files maintained an equivalent energy content but a different temporal presentation of the various sounds. The survey was divided into different phases: the initial phase, which was aimed to acquire personal information, to perform the noise sensitivity test and the noise disturbance test, was followed by other six tasks which corresponded to the six cognitive tasks. The cognitive tests were carried out both in noise and in silence by the same participant, using different equivalent tests (A and B), in a counterbalanced order between the participants. Each task lasted 2.5 min. After each task, participants took a 5–10 min break. A one-minute training session was given before the cognitive tests, to let the subjects to familiarize with the tasks. In the noise condition, an initial 30-s noise period was included to allow the participant to acclimate to the sound environment, after which the test commenced. Table 4 shows an example of test schedule for one subject. Overall, each subject completed the survey in one hour.

Table 4
Example of test schedule for one subject.

Step no.	Description	Training [min]		Noise immersion [min]	Test [min]		Duration [min]
1	Introduction	–	–	–	–	–	2.0
2	Personal questionnaire	–	–	–	2.0	Quietness	2.0
3	Noise sensitivity test	–	–	–	2.0	Quietness	2.0
4	Noise disturbance test	1.0	Noise	–	2.0	Noise	3.0
Break							5.0
5	(A) Silent reading of a list of 15 words (version A)	–	–	0.5	2.5	Noise	3.0
6	(B) Reading a piece aloud (version A)	–	–	0.5	2.5	Noise	3.0
7	(C) Trail Making Test - test A1 and B1	1.0	Quietness	0.5	2.5	Noise	4.0
8	(D) SVF Test on a category version A	1.0	Quietness	0.5	2.5	Noise	4.0
9	(E) OORTT	1.0	Quietness	0.5	2.5	Noise	4.0
10	(F) Recall as many words as possible of Task A	–	–	0.5	2.5	Noise	3.0
Break							10.0
11	(A) Silent reading of a list of 15 words (version B)	–	–	–	2.5	Quietness	2.5
12	(B) Reading a piece aloud (version B)	–	–	–	2.5	Quietness	2.5
13	(C) Trail Making Test - test A2 and B2	–	–	–	2.5	Quietness	2.5
14	(D) SVF Test on a category version B	–	–	–	2.5	Quietness	2.5
15	(E) OORTT	–	–	–	2.5	Quietness	2.5
16	(F) Recall as many words as possible of Task A	–	–	–	2.5	Quietness	2.5
							60.0

2.2.5. Statistical analysis

Box plots were generated to visually represent the distribution of data and to compare variables, highlighting the mean, median, dispersion and the presence of outliers. Quartile analysis allowed outliers to be identified and to describe better the variability of the results. Correlation analysis was carried out to search dependence among variables.

The Kruskal–Wallis test [35] was applied to verify differences among the outcomes of each task both in noise and in quiet condition across receivers. It is a nonparametric statistical test that assesses differences among three or more independently sampled groups on a single, non-normally distributed continuous variable. The Wilcoxon signed-rank test for paired samples [36] is a non-parametric statistical test used to compare two sets of paired data. In particular, the test was applied to compare data in noise and in quiet from the same list of subjects. Significance was assessed with a p-value threshold of 0.05 . If the result was significant, the one-tailed right Wilcoxon signed-rank test was used to determine whether the noise condition produced greater effects than the quiet condition. The null hypothesis states that the median difference between noise and quiet samples is ≤ 0, while the alternative hypothesis is >0. A p-value ≤ 0.05 indicates rejection of the null hypothesis and supports the finding that scores are higher in noise than in quiet.

To quantify the effect sizes of the tests and hence indicate whether the difference in the responses collected in noise and in quiet conditions is practically important, Cohen's d for paired samples was applied [37, 38].

3. Results

3.1. Comparison with the Oval Room at the Richelieu library and the Bibliothèque Publique d'Information at Centre Pompidou

Fig. 7 shows the octave band SPLs obtained after the auralisation of one audio mix for each receiver in the monoaural format and measured in the Oval Room at the Richelieu library and in the Bibliothèque Publique d'Information at Centre Pompidou (Bpi). The equivalent overall A-weighted sound pressure level was set at 44.9 dB, 45.4 dB, 42.9 dB, 46.7 dB for the audio mix at the receivers R1, R2, R3 and R4, respectively, as described in paragraph 2.1.6.2, and at 46.5 dB and 44.5 dB, as measured in the Oval Room and at the Bpi, respectively.

The spectra are very similar among receivers, apart from R2 in the semitoroidal space between two parallel surfaces in the exedra, i.e., the glass and the PVC transparent membrane, which absorbs at low frequencies the unintelligible buzz surface source, at 1.5 m above the floor.

The spectrum of the Richelieu Library closely resembles those simulated for the New Civic Central Library of Torino, with key differences observed at higher frequencies. These differences are primarily due to sounds associated with higher occupancy in the Richelieu Library, such as typing on keyboards, rustling papers and pen clicking, whereas the Torino library, considered to be sparsely occupied, lacks these additional sound elements. The audio recordings illustrating these differences can be found in the Supplementary Material. The spectrum measured in the large and low open space of Bpi is similar to the one measured in the Oval Room at high frequencies, and it was essentially of the same type, while at low frequencies it is characterized by slightly lower sound pressure levels, probably due to the high absorption of the metallic false ceiling, shelves and ducts and of the large, glazed walls.

3.2. Noise sensitivity test

As shown in Fig. 8 and Table 5, the noise sensitivity test revealed a range of similar sensitivity level across receivers. The average value is 72.2 (s.d. = 7.7), 72.7 (s.d. = 3.7), 73.2 (s.d.= 7.7) and 76.7 (s.d. = 8.5) for receiver R1, R2, R3, R4, respectively. The Kruskal–Wallis test reveals no significant differences among the receivers, with a p-value of 025.

3.3. Noise disturbance test

Fig. 9 shows the results of the noise disturbance test. Average annoyance scores of 5.0 (s.d. = 2.0), 4.0 (s.d.= 2.7), 3.0 (s.d. = 2.1), 2.3 (sd = 1.5), on a scale from 1 to 10, have been found for receivers from R1 to R4, suggesting a slight perception of disturbance for R1, while a low disturbance is experienced for the other receivers. The Kruskal–Wallis test did not reveal differences among the receivers (p-value = 0.08). Correlation analysis showed no relationship between noise sensitivity and noise disturbance (r = 0.04).

3.4. Cognitive tasks

Figs. 10–15 show the boxplots related to the distributions of the answers for the 6 participants in Tasks from A to F, respectively, for each of the four receivers from R1 to R4, related to the two conditions of noise and silence. The sample size per receiver is small, but as the noise level across positions is similar, if the Kruskal–Wallis test showed no significant differences ($p > 0.05$), the data were pooled, treating the groups as homogeneous under comparable acoustic conditions. The rationale for this choice is detailed below:

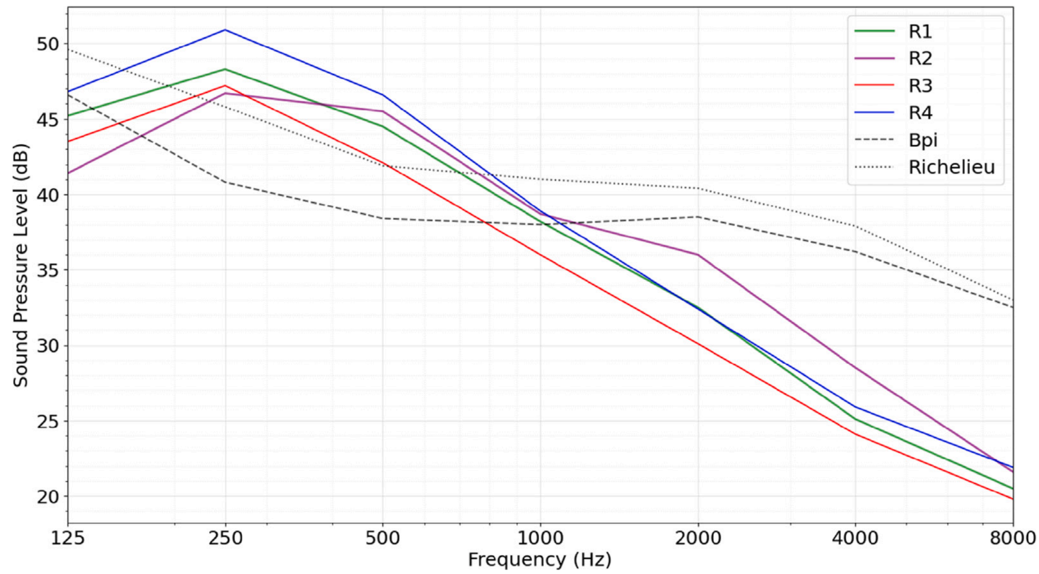

Fig. 7. Sound pressure level in octave bands for each receiver in the Torino library, in the Oval Room at the Richelieu library and at Bpi.

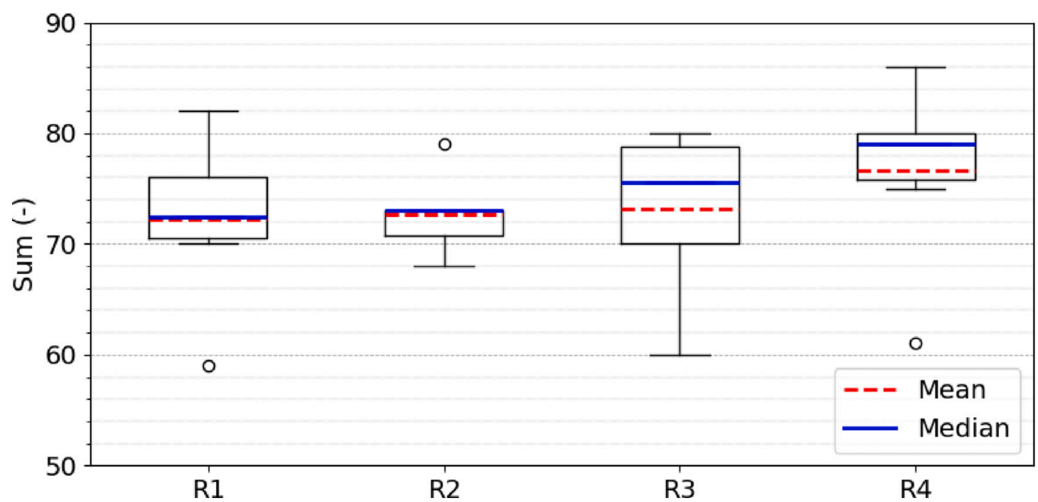

Fig. 8. Scores of the noise sensitivity test.

- The Kruskal–Wallis test did not reveal differences among the receivers in the noise sensitivity and the noise disturbance tests.
- The participants were exposed to the same experimental protocol and their average age in the groups was homogeneous, that is 32.0, 31.2, 32.2, and 38.5 years, respectively.
- The level differences across receivers ranged from a maximum of 3.8 dB to a minimum of 0.5 dB. According to the literature, the just noticeable level difference (JNLD) for stationary signals is approximately 1 dB [39]. Nevertheless, higher thresholds have been observed for short-duration stimuli, low-pass or low-level noises, as well as for just-noticeable amplitude modulation [40] and click-intensity discrimination [41], with values reaching approximately 2–3 dB. This is consistent with the nature of our audio mixes, which included stationary HVAC noise, modulated traffic and speech sounds, and intermittent stimuli such as footsteps, pen clicks, and phone rings. Moreover, since our audio mixes combined reverberant background noise with speech signals at very low signal-to-noise ratios (SNR), it is relevant that previous research has shown an SNR JND of around 3 dB under such conditions [41].

In light of these factors, pooling the listener groups can be considered perceptually justified. Having 24 subjects is consistent with several previous experimental studies which investigated the effects of noise on cognitive performance, many of which have relied on similar or even smaller samples [42–45]. In addition, our study employed a within-subject design, meaning that each participant experienced both experimental conditions (noise and silence), thereby serving as their own control. This substantially reduces the influence of inter-individual variability and increases the sensitivity to detect reliable noise effects, even with small samples [46].

3.4.0.1. Task A and F. As shown in 10, the results highlight that the number of recalled words slightly increased in quiet conditions for all the receivers. Kruskal–Wallis test showed no significant difference between the receivers both in the noise and quiet conditions, with p-values equal to 0.058 and 0.373, respectively. On the other hand, a Wilcoxon test for paired samples, performed considering all the receivers, does not assign a strongly significant difference between the noise and quiet condition, being the p-value equal to 0.106.

3.4.0.2. Task B. Figs. 11 and 12 show the results obtained for Task B, related to the speed scores and the errors made in reading the passage, respectively. For the speed scores, Kruskal–Wallis test showed

Table 5
Mean score (m), median (M) and standard deviation (sd) for the cognitive tasks.

A–F															
Noise R1		Quiet R1		Noise R2		Quiet R2		Noise R3		Quiet R3		Noise R4		Quiet R4	
m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd
7.3	3.9	9.7	3.3	11.2	1.7	12.5	2.4	12.8	2.4	11.8	3.4	11.3	4.9	12.8	3.0
Noise - pooled sample								Quiet - pooled sample							
m			M			sd		m			M			sd	
10.7			11.0			3.8		11.7			13.0			3.1	
B - errors															
Noise R1		Quiet R1		Noise R2		Quiet R2		Noise R3		Quiet R3		Noise R4		Quiet R4	
m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd
3.2	2.2	1.8	1.5	1.3	1.5	1.0	1.5	4.8	1.9	3.0	2.0	2.5	2.9	1.7	1.4
Noise - pooled sample								Quiet - pooled sample							
m			M			sd		m			M			sd	
3.0			2.4			2.4		1.9			1.7			1.7	
B - speed score															
Noise R1		Quiet R1		Noise R2		Quiet R2		Noise R3		Quiet R3		Noise R4		Quiet R4	
m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd
0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.0
Noise - pooled sample								Quiet - pooled sample							
m			M			sd		m			M			sd	
0.2			0.2			0.03		0.2			0.2			0.03	
C - TMT-A															
Noise R1		Quiet R1		Noise R2		Quiet R2		Noise R3		Quiet R3		Noise R4		Quiet R4	
m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd
31.2	7.9	25.5	5.0	29.7	10.8	27.5	9.7	25.2	3.6	22.8	6.1	26.5	5.5	28.0	5.7
Noise - pooled sample								Quiet - pooled sample							
m			M			sd		m			M			sd	
28.1			28.0			7.4		26.0			23.5			6.7	
C - TMT-B															
Noise R1		Quiet R1		Noise R2		Quiet R2		Noise R3		Quiet R3		Noise R4		Quiet R4	
m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd
58.3	11.6	55.8	17.3	49.3	16.8	41.2	14.6	47.0	16.2	50.0	26.6	63.3	10.7	47.8	5.3
Noise - pooled sample								Quiet - pooled sample							
m			M			sd		m			M			sd	
54.5			14.0			14.8		48.7			17.3			17.3	
D															
Noise R1		Quiet R1		Noise R2		Quiet R2		Noise R3		Quiet R3		Noise R4		Quiet R4	
m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd
17.3	4.0	21.5	4.7	21.2	3.1	22.8	12.2	19.5	6.0	20.8	6.4	22.3	6.5	24.3	7.8
Noise - pooled sample								Quiet - pooled sample							
m			M			sd		m			M			sd	
20.1			21.0			5.1		22.4			22.5			7.8	
E															
Noise R1		Quiet R1		Noise R2		Quiet R2		Noise R3		Quiet R3		Noise R4		Quiet R4	
m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd	m	sd
318.8	54.9	308.8	73.2	282.2	32.5	266.7	25.9	278.5	39.1	271.9	36.4	325.3	111.6	324.4	103.5
Noise - pooled sample								Quiet - pooled sample							
m			M			sd		m			M			sd	
301.2			296.9			66.2		293.0			285.6			67.4	

no significant difference between the receivers both in the noise and quiet conditions, with p-values equal to 0.432 and 0.470, respectively, and from the Wilcoxon statistical tests carried out on the pooled sample of 24 subjects, no significant differences between the conditions noise and quiet emerged, being the p-value equal to 0.090. About the errors made reading a text, the Kruskal–Wallis test yielded a p-value of 0.053 in noise and of 0.208 in quiet. The former does not reach statistical significance, but suggests a trend toward differences among the four receivers that could become clearer with a larger sample size. However, with the pooling of the data among receivers in both noise and quiet, a significant difference between the two conditions emerged from the Wilcoxon signed rank test, with a p-value equal to 0.002. The one-tailed

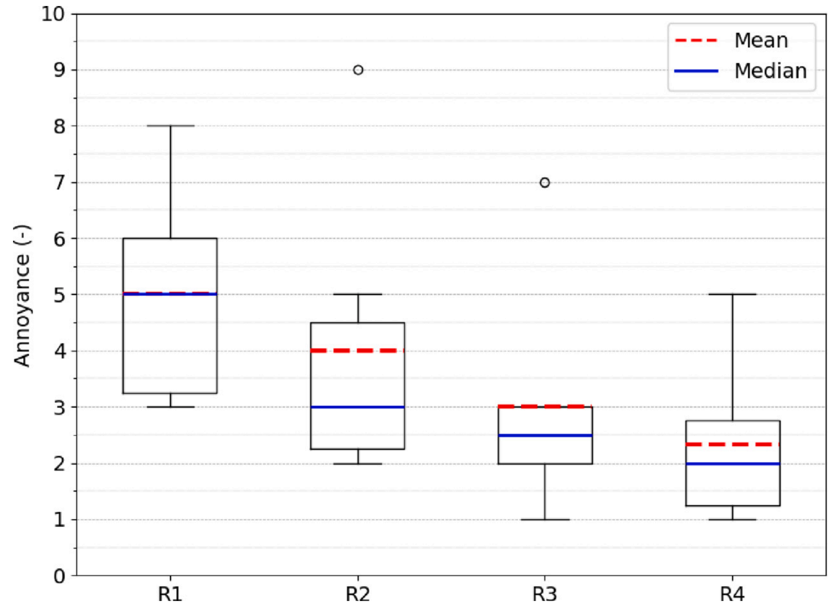

Fig. 9. Scores of the noise disturbance test - annoyance.

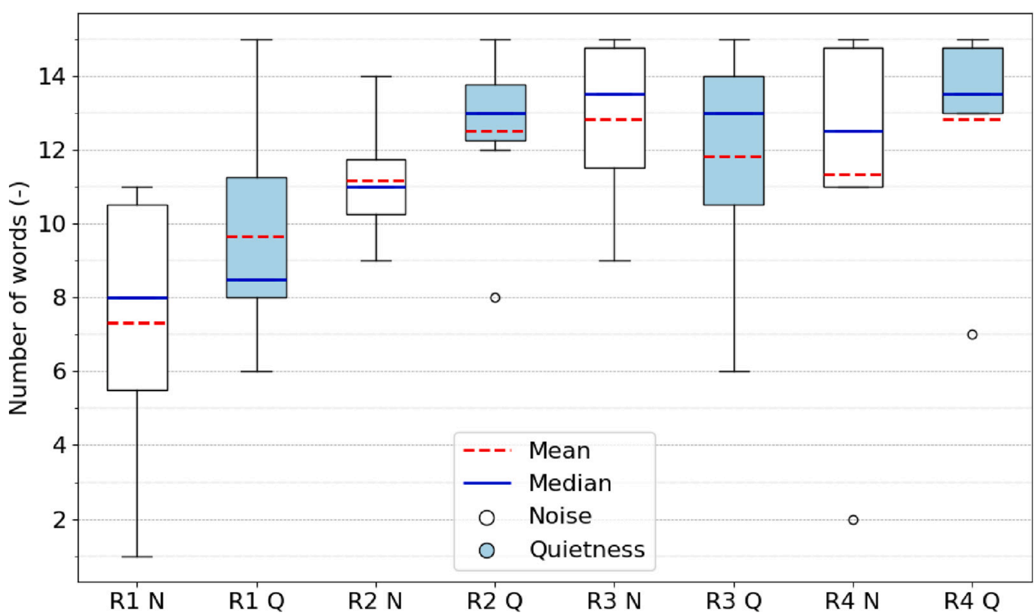

Fig. 10. Number of words recalled in Task F connected with Task A.

right Wilcoxon test, with p-value equal to 0.0009, supports the finding that outcomes are higher in noise than in quiet. A "large" effect size with Cohen's d for paired samples equal to 0.80 has also been found for Task B related to the errors in reading a passage, which proves a detrimental impact under noise exposure.

To ensure that the sample size was adequate, a post hoc power analysis using the statistical software G*Power 3.1 [38,47] was conducted. Assuming a within-subject design with matched pairs, a one-tailed condition, an effect size of 0.5, 24 participants, and a significance level set at 0.05, the statistical power is 0.71. This confirms that, with 24 participants included in the experiment, the study had sufficient statistical power. We nevertheless acknowledge that future studies with larger and more diverse samples would be valuable to enhance generalizability.

3.4.0.3. Task C. Fig. 13 shows the boxplots of the distribution of the time required to complete Task C. The results indicate that in the TMT-A version the completion times remained relatively stable across conditions, whereas in the TMT-B version greater variability and longer times of completion were observed. From the results obtained with the Kruskal–Wallis statistical test, no significant differences emerged between the four receivers in the analysis of the completion time for the two conditions. In particular, for the version A of this task the p-value in the noise condition was equal to 0.378 and in the quiet condition was equal to 0.460, whereas for the version B the p-values in the noise and quiet conditions were 0.253 and 0.467, respectively. The Wilcoxon test showed no significant differences between the two conditions, being the p-value for TMT-A equal to 0.069 and for TMT-B equal to 0.095. Therefore, neither noise nor location appears to have influenced the speed score in the completion of task C.

3.4.0.4. Task D. Fig. 14 shows the boxplot for Task D. It shows that participants produced more words in the Semantic Verbal Fluency test in the quiet condition. This difference can be seen particularly in

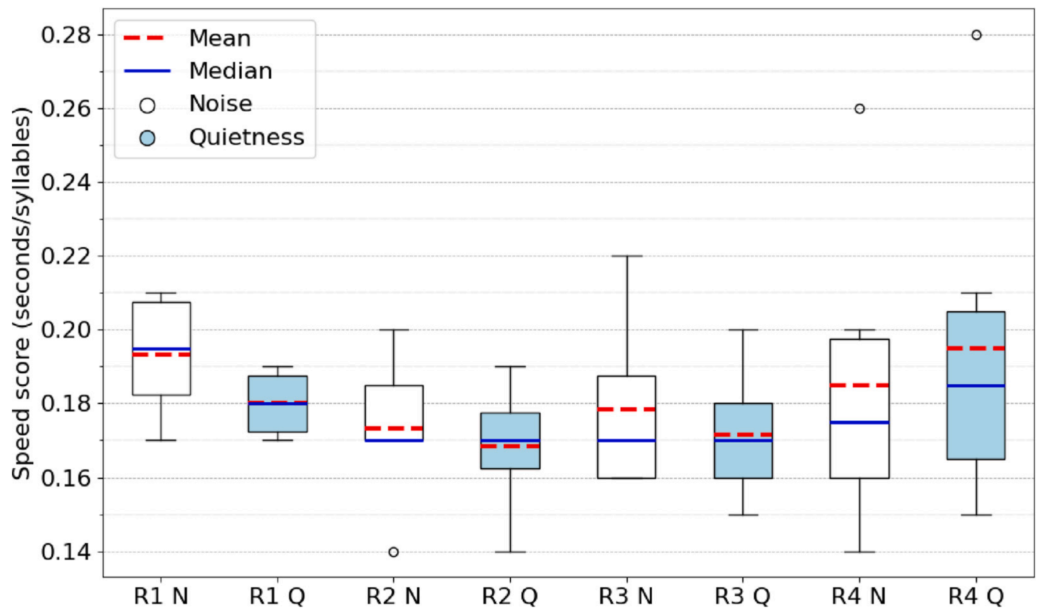

Fig. 11. Speed scores obtained in reading a text aloud during Task B.

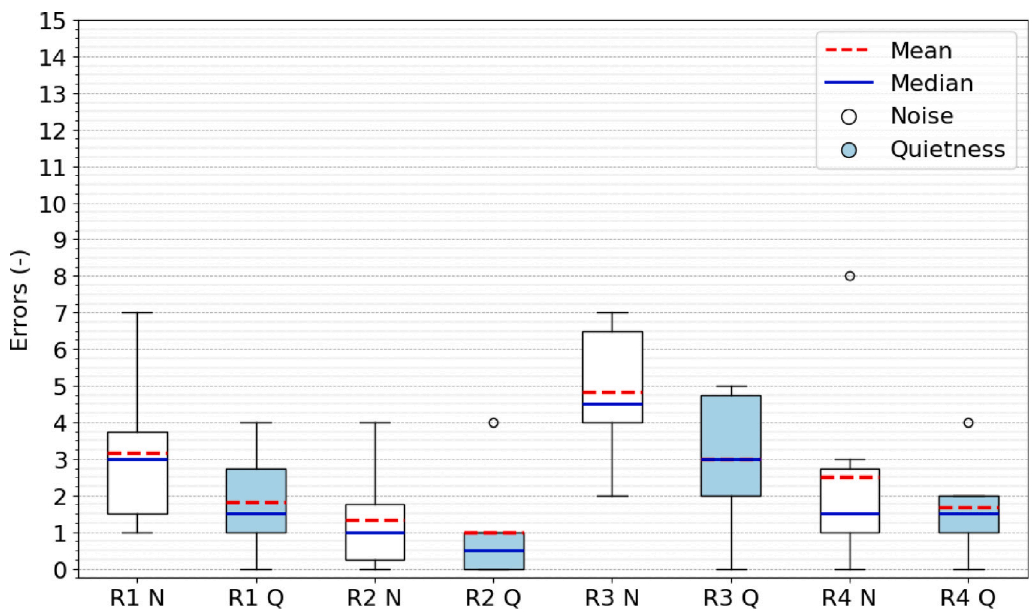

Fig. 12. Number of errors depicted in reading a text aloud during Task B.

R2, where the performance showed the highest variability. From the results obtained with the Kruskal–Wallis tests, no significant differences emerged between the receivers in noise and quiet conditions, being the p-values equal to 0.335 and 0.845, respectively. After data pooling, the Wilcoxon test showed no significant differences between the noise and quiet conditions, being the p-value equal to 0.241. Therefore, neither noise nor location has influenced the speed score in the completion of task D.

3.4.0.5. Task E. Fig. 15 shows the boxplots of the distribution of the reaction time in Task E. The difference between the results obtained in noise and in quiet is negligible, and in some cases, as can be seen from the wide distribution of R4's results, the exercise completion times were longer in the quiet condition. From the results obtained with the Kruskal–Wallis statistical test, no significant differences emerged between the four receivers in the analysis of the reaction time in the OORTT for the two conditions, being the p-value in the noise condition equal to 0.613 and the p-value in the quiet condition equal to 0.690. Analyzing the results with the Wilcoxon test for a pooled sample of 24 subjects, the obtained p-value is 0.086, which states a non-statistical difference between noise and quiet conditions. Thus, neither noise nor location appears to have strongly influenced the speed score in the completion of Task E.

4. Discussion

4.1. Sound environment in the New Civic Central Library of Torino and in other similar libraries

The New Civic Central Library of Torino offers a relevant example of a historical library designed for silent study. With a reverberation time

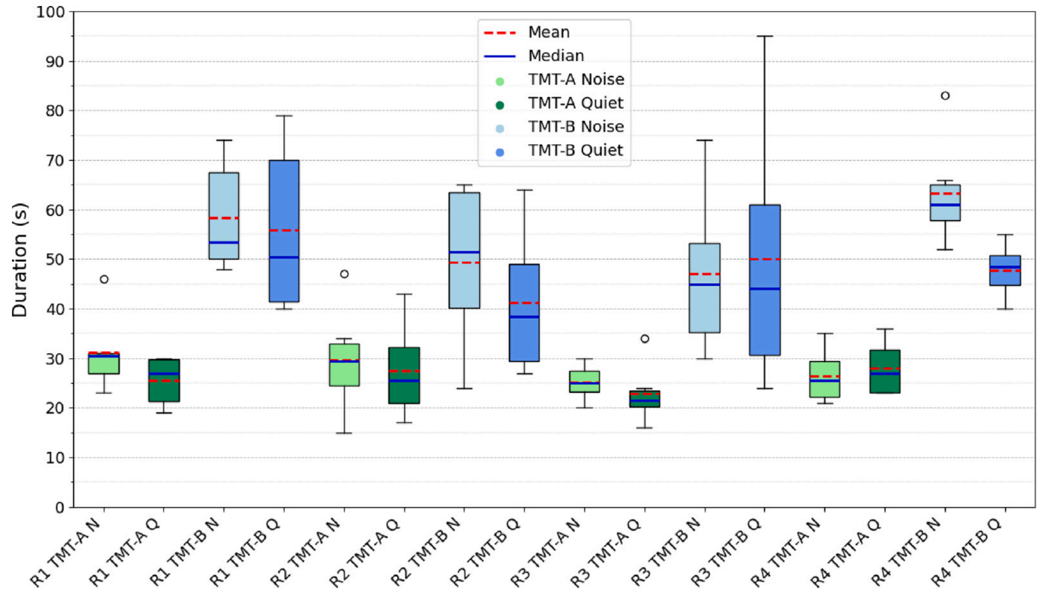

Fig. 13. Time taken to complete the Trail Making Test version A and B during Task C.

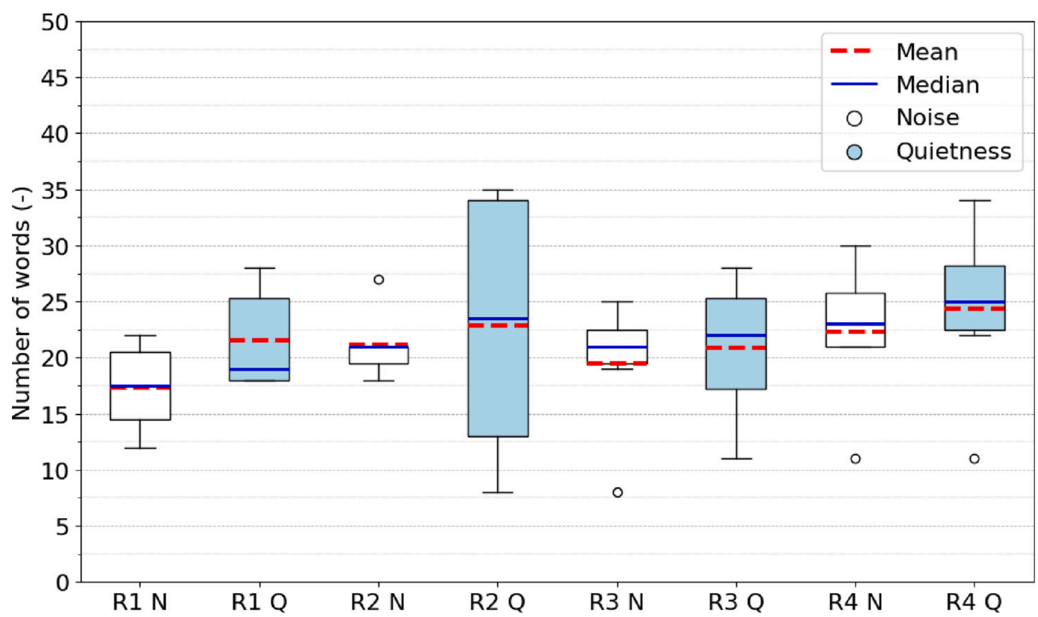

Fig. 14. Number of words collected in Semantic Verbal Fluency test during Task D.

of around 5 s at mid frequencies and simulated noise levels from 43 to 47 dB (A), it shares acoustic similarities with other monumental libraries, such as the historical La Trobe Reading Room in Melbourne [4] or the Oval Room at the Richelieu Library, and the contemporary Library at the Dock in Melbourne [4] and the Bibliothèque Publique D'Information at Centre Pompidou (Bpi) in Paris. As cited libraries, the Library of Torino is primarily used for individual study, but could accommodate silent collaborative work, as well. In the current study the sound pressure levels were simulated to be moderate, presuming Sabine's effect, according to which in environments with long reverberation, people spontaneously tend to lower their voices, contributing to the maintenance of silence [7]. However, keeping silence in a library could depend on the normative behavior. Aarts and Dijksterhuis [48] demonstrated that viewing a picture of a library causes people to lower their voice, but only if they also have the goal of going to the library, suggesting environmental priming works when a behavioral goal is active. They found that well-established situational norms (like the norm for silence in a library) activate both mental representations of the norm and actual behavior.

In literature, higher values of sound pressure levels appear in spaces with shared connections and main areas that cross or surround others. This highlights that acoustic quality depends not only on reverberation time but also on spatial design, zoning strategies and allowed activities [5]. Gordon-Hickey et al. [49] found that students are adept at judging the amount of background noise they can tolerate while reading or listening, and these "noise acceptance" levels correlate with the types of study environments they prefer. Their results suggest libraries should offer a variety of spaces to match users' different acoustic preferences. Future studies will consider additional activities taking place in different zones of the library, with the aim of increasing noise levels to better reflect the architectural features of a multifunctional space.

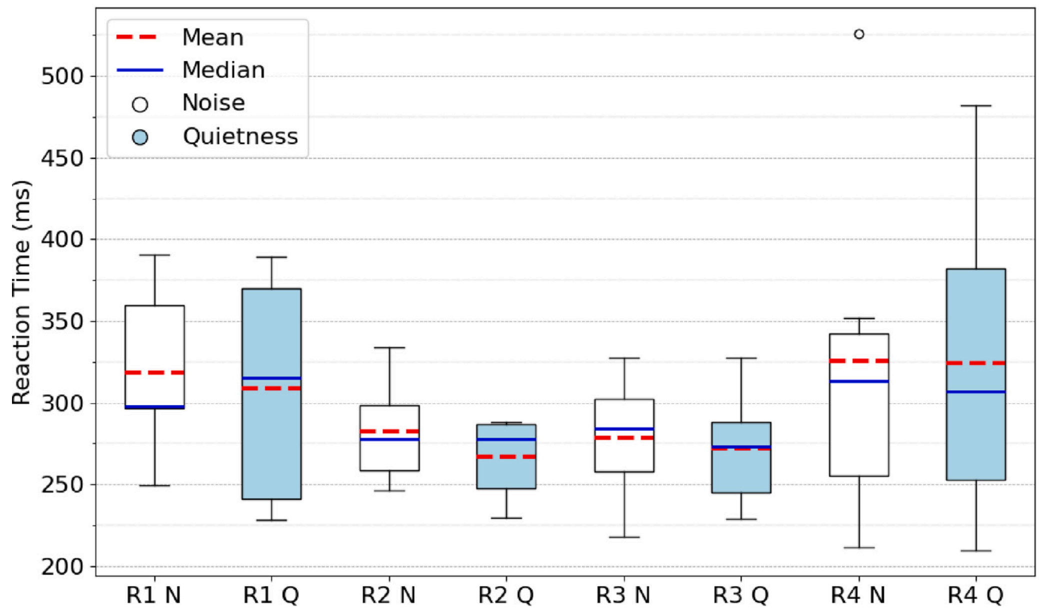

Fig. 15. Time taken to complete the Open-source Open-access Reaction Time Test during Task E.

4.2. Cognitive outcomes in the presence of moderate multi-source background noise

Literature shows that almost all types of background noise, including traffic noise, ventilation noise, intelligible and non-intelligible speech, generally harm cognitive performance, especially during verbal or memory-related tasks, even at moderate levels [50–52]. However, no definitive conclusions have yet been established. Liebl et al. [50] found that clearly intelligible background speech at a low volume of 40 dB(A) can impair short-term memory and reasoning abilities; however, it does not appear to affect text comprehension or the ability to maintain attention over time. Zhou et al. [52] reviewed the effects of moderate broadband noise on various cognitive tests and found little or no impact on reaction time, attention, long-term memory, tasks that involved multiple information processing, and higher-order tasks. Short-term memory impairments emerged only under high cognitive load, such as when more items had to be recalled. Some tasks even showed improved performance in noise. For higher-order cognition tasks, individuals may adopt strategies to redistribute load, while other factors such as emotional response, effort, and coping strategies also play a role [53]. In the case of Irrelevant Sound Effect (ISE), Schlittmeier et al. [51] examined the effects of intelligible background speech at 35 and 55 dB(A) on verbal serial recall and mental arithmetic. They found that disturbance was significantly reduced only when both level and intelligibility were lowered, whereas simply decreasing the SPL from 55 to 35 dB(A), maintaining high intelligibility, did not improve performance. This highlights the limited effectiveness of reducing sound levels alone. The current study shows that, although average sound levels were moderate, Task B, which involved reading aloud a passage from a book, was negatively impacted under mixed noise, which includes meaningful speech, HVAC noise, traffic noise, footsteps, and other sources typical of a library. This partly aligns with the Irrelevant Sound Effect (ISE), which shows that meaningful speech determines stronger impairments than meaningless speech in verbal tasks involving reading [54–56]. Moreover, serial recall is disrupted by any speech-like sound [57, 58], whereas proofreading was impaired only by meaningful speech, regardless of its intensity [58]. Reading comprehension and reading speed are also negatively affected by traffic noise [59]. In contrast, tasks involving executive function, reaction time, or visual tracking (e.g., Task C - TMT, Task E - OORTT) were less affected [60].

4.3. Audio reproduction system

The current setup, which delivers cognitive tests with static binaural playback with headphones, cannot fully replicate authentic library conditions, lacking the immersive experience provided by large-scale loudspeaker auralisation. Nonetheless, static headphone playback and loudspeaker reproduction each present specific advantages and drawbacks. Loudspeakers permit natural head movements but require acoustically treated spaces and a sufficiently dense speaker array to achieve high-quality reproduction [61]. Conversely, headphone playback in static conditions limits head movements and can lead to front–back confusions and in-head localizations, potentially altering the spatial impression of the sound field [62]. At the same time, it is independent of room acoustics and offers strong experimental control, ensuring consistency in presentation level, spectral content, and signal-to-noise ratio, thereby removing variability due to the listening environment and guaranteeing uniform calibrated sound exposure for all participants.

Delivering auditory stimuli through headphones is a well-established standard in noise and cognition research [63–65]. In [66], speech intelligibility was tested in simulated room acoustics using static headphones as well as small- and large-scale loudspeaker arrays, with no substantial differences observed under most conditions. Headphone-based simulations also ensured consistent intelligibility across both real and virtual rooms. In soundscape evaluation studies, with or without visual rendering, it is emphasized that the fidelity of acoustic reproduction should match the research goals: static binaural reproduction is adequate for assessing overall soundscape quality, whereas speaker arrays are required to capture spatial aspects and improve localization when combined with video [67]. Future investigations will employ High-Order Ambisonics in the Audio Space Lab at Politecnico di Torino, a sound-treated listening room equipped with a 3rd-order Ambisonics system synchronized with the Meta Quest 2 headset to enable immersive 3D AV environments [68].

4.4. Design guidelines

Design guidelines based on the results of this study have potential implications for librarians and architects. This study's outcome proved that even low-level multi-source background noise impairs cognitive abilities during individual study in a library. The adoption of detailed acoustic zoning and careful material design is thus recommended where the spatial conditions affect users' cognitive experience [69]. Quiet zones can be dedicated to reading and study, while other areas can host children's activities or school workshops, especially in large libraries that allow functional separation. It is essential to note that even minor interventions can significantly alter the sound environment perceptually. Luyben et al. [70] showed that separating three types of furniture, such as chairs, tables, and carrels, in a library, which were placed adjacent to each other, did not reduce noise but significantly reduced subjective ratings of noise. Thus, the proposed interventions aim at improving sound quality near occupants:

- Transit areas with sound-absorbing runners to mitigate footstep noise, complemented by acoustic pads on chairs and tables, and the use of silent carts.
- Quiet zones delineated by panels, glass booths, or tall bookshelves, supported by acoustic signage [71] or "sound traffic lights" that encourage users to lower the intensity of their voices [72].
- Buffers and filters to reduce sound transfer between spaces, and "sonic niches" carved out in larger volumes for individual or special uses [7].
- Visual elements, including patterns and softly colored acoustic materials on walls, partitions, floors, and ceilings, which can positively shape psychological responses to noise [73,74].
- Children's area with installation of acoustic curtains and sound-absorbing furniture designed in the form of small "houses" where children can play, thereby containing noise and reducing reverberation and sound pressure levels.

5. Limitations and future studies

This study presents several limitations that should be acknowledged. The analysis was conducted under conditions of low occupancy and low background noise, excluding children, adolescents, and cultural or social events. This methodological choice reflected the focus on the library as a silent space dedicated to individual study. Future work will extend the investigation to noisier scenarios, more typical of contemporary libraries.

The participant sample ($n = 24$) was limited to adults aged 20–55 years, thus excluding two key groups of users: younger students (<20 years) and older adults (>55 years), the latter often experiencing age-related hearing loss. Individuals with hearing impairments were also not included. Upcoming studies will broaden the sample to these populations, providing a more comprehensive understanding of user responses.

The study examined only two libraries dedicated to individual study, namely the historical Richelieu Oval Room with its large volume and the acoustically treated contemporary Bpi, thus limiting generalizability. This choice was motivated by the scarcity of documented libraries with very low background noise, and future research will expand to other case studies with different functions and activities.

Another limitation concerns the use of static headphones for auralisation. While this method ensured reproducibility and control, it did not capture the fully immersive spatial experience of being physically present in the library. Future studies will employ higher-order ambisonics in immersive audio-visual environments to overcome this issue.

Exposure to irrelevant speech and environmental noise in settings that demand concentration and cognitive engagement, such as offices and schools, undermines both performance and well-being, while fostering annoyance, fatigue, and negative emotional states [50,75–78]. These results underscore the importance of considering well-being as a central factor in future evaluations of indoor sound environments for cognitive activities, including those occurring in libraries. The cognitive tasks may even show improved performance in noise, as noted in the literature [52]. For higher-order cognition, compensatory strategies and factors such as emotion, effort, and coping also play a role, which future studies will examine using biometric stress monitoring.

The number of participants per receiver was relatively small, and the Kruskal-Wallis test showed no significant differences among the four receivers, except in Task B (text reading), where a non-significant trend with p-value close to 0.05 suggested that differences between positions might emerge with a larger sample. These results and the small difference in sound pressure level justified pooling the data among receivers to have a larger sample of 24 subjects, which is consistent with several previous similar studies. However, the distribution of the subjects across the receivers is a limitation of the study that can be addressed by hiring more subjects for only one experimental condition in forthcoming experiments.

Finally, although disturbance ratings were complemented with cognitive performance measures, the study did not collect qualitative feedback such as open-ended reflections on realism, comfort, or coping strategies. These aspects will be integrated into future investigations to enrich the interpretation of the findings.

Overall, this research represents one of the first attempts to investigate the sound environment of a library, a topic that, to the Author's knowledge, has received little attention to date.

6. Conclusions

This study examines the noise perception and the cognitive effort in the quiet historical New Civic Central Library of Torino (Italy) dedicated to individual study. A geometrical acoustic simulation was performed using Odeon 18 at four receiver positions, accounting for various noise sources. The library, with a volume of about 160 000 m^3 and a mid-frequency reverberation time of approximately 5 s, is protected by cultural heritage authorities. Simulated noise sources included traffic (ceiling), ventilation (floor and balconies), ambient buzz from occupied areas, footsteps, page-turning, pens, and syntactically correct but semantically meaningless sentences. Noise levels at receivers ranged between 43–47 dB(A). The sound pressure levels were simulated to be moderate presuming the Sabine's effect according to which in environments with long reverberation people spontaneously tend to lower their voices, contributing to the maintenance of silence. Subjective tests were conducted on 24 participants (aged 20–55, normal hearing) to evaluate noise sensitivity, disturbance, and cognitive performance. No significant differences across receivers for noise sensitivity and disturbance were obtained. No significant differences in cognitive performance were observed between noise and silence conditions for simple tasks that did not involve semantics processing. On the other hand, the more complex task that included semantic processing such as reading aloud, showed a slight deterioration in the presence of noise.

CRediT authorship contribution statement

Mariasole Modica: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ioana Grozeva:** Writing – review & editing, Writing – original draft, Visualization. **Davide Cetani:** Visualization, Software, Resources, Methodology. **Lorenzo Lavagna:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Louena Shtrepi:** Visualization, Validation, Supervision, Project administration, Methodology, Conceptualization. **Massimiliano Zampini:** Visualization, Validation, Resources, Conceptualization. **Arianna Astolfi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Arianna Astolfi reports financial support was provided by Onleco s.r.l. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.buildenv.2025.113810.

Data availability

Data will be made available on request.

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