NOISE PERCEPTION AND COGNITIVE LOAD IN A SIMULATED REVERBERANT LIBRARY UNDER FULL OCCUPANCY

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This paper is a revised version of the authors' submitted manuscript that was peer-reviewed by at least two anonymous reviewers.

Abstract

In recent years, libraries have evolved from silent study spaces into multifunctional environments hosting diverse activities. This shift has resulted in increasingly complex acoustic conditions. This study investigates noise perception and cognitive performance in the simulated environment of the New Central Civic Library of Torino during full occupancy. The library consists of a large space with a volume of approximately 160,000 m^3 and a mid-frequency reverberation time of around 5 s. A three-dimensional geometrical acoustics model was developed to reproduce the sound environment, including typical library sources such as traffic, HVAC systems, speech and user-generated noise. Simulated sound pressure level was in the range 50.2 – 52.0 dB(A) across two receivers, consistent with values reported for occupied libraries. An experimental session involving 20 participants was conducted in an ambisonics laboratory to assess noise sensitivity and annoyance, together with a reading-aloud cognitive task, conducted both in noise and in quiet. Results showed no statistically significant differences across receivers for subjective evaluations overall. A comparison with a previous study conducted with headphones under low occupancy, within a sound pressure level range of 45 - 47 dB(A), showed different outcomes, with a significant increase in reading errors under noise conditions compared to quiet. The different submission methods and the type of noise can explain the results of the comparison.

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Keywords: *library, acoustic environment, simulation, occupancy, cognitive tasks, annoyance*

1. Introduction

In recent years, libraries have progressively evolved from traditional silent study environments to multifunctional spaces where individual work, social interaction, and cultural activities take place simultaneously. This transition has led to increasingly complex acoustic conditions [1]. The acoustic environment of libraries is strongly influenced by room characteristics and occupancy. Sound levels are typically below 40 dB(A) in unoccupied conditions but often exceed 50 dB(A) during occupancy because of user-generated noise from activities such as conversations and movements [1–3]. Compared with historical libraries which are mostly intended for quiet study, modern multifunctional libraries are generally noisier and less reverberant due to the broader range of activities they accommodate [1,2]. Despite the importance of the acoustic environment for users' comfort and cognitive performance, few studies have investigated the impact of occupancy conditions on subjective perception and task performance in large reverberant libraries. This study investigates noise perception and cognitive performance in the large and reverberant New Central Civic Library of Torino (Italy), extending a previous investigation conducted under low-occupancy conditions [4] to a fully occupied scenario in order to simulate a more complex and typical operational library setting.

2. Methodology

2.1 Case study

The study investigates the New Central Civic Library of Torino, a multifunctional public building with a volume of approximately 160,000 m³ and a mid-frequency reverberation time of about 5 s. The predominantly open-plan layout with limited physical partitions, creates a highly interconnected acoustic environment. As shown in Fig. 1, it is distributed over three levels, including a main reading hall, an informal basement reading area ("Enchanted Garden"), and two upper balconies dedicated to reading and group study.

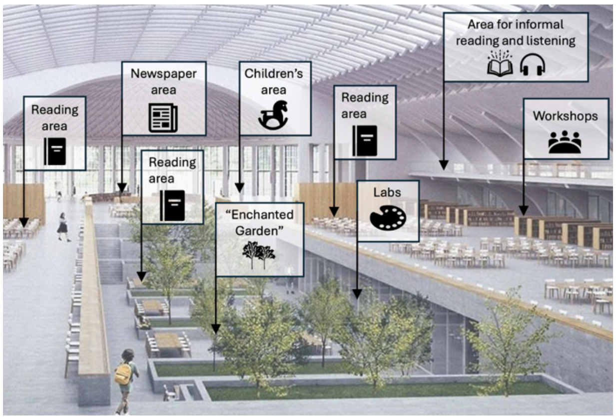

Figure 1. Render of the New Central Civic Library with the different areas.

2.2 3D geometrical acoustic model

The three-dimensional geometrical acoustic (GA) model of the New Central Civic Library of Torino was developed using Odeon 18, a specialised tool for simulating sound propagation in complex indoor environments [5]. ODEON employs a hybrid geometrical acoustics approach that combines the Image Source Method (ISM), the Early-Scattering Method (ESM), Ray-Tracing (RT), used for the early reflections, and the Ray-Radiosity Method, used for the late reflections. The geometry of the building was reconstructed from architectural drawings. To each surface were assigned the specific material properties with octave-band absorption and scattering coefficients based on the refurbishment design. Due to heritage conservation constraints, most surfaces are highly reflective, with the only absorptive treatment applied to the wall facing the apse. A worst-case scenario was considered by modeling full occupancy, i.e. approximately 1,200 people. The simulation was carried out using a transition order of 2, defining the maximum number of reflections considered, and 50,000 rays to ensure accurate sound propagation modeling.

2.3 Definition of sound sources and receivers

Once the geometric model had been completed, the sound sources and the receivers were introduced, as illustrated in Fig. 2. Their placement was defined in accordance with the expected use of the library, in order to represent realistic operating conditions. The acoustic model considers external noise, HVAC systems and indoor human-related sound sources, with particular attention to speech as one of the main noise components in a multifunctional library. Detailed information on the acquisition procedure of the sound sources, together with the corresponding anechoic tracks, is available in an open-access repository [6]. The sources considered in the simulations are the following:

- S1–S2: HVAC noise, modeled through an extended surface source covering the floor area and two linear sources representing the ceiling air diffusers;
- S3A–S3C: road traffic noise, represented by a surface source placed above the roof;
- S4: non-intelligible speech, modeled as a surface source above the desks;
- S5: intelligible conversational speech, represented by point sources simulating one or two talking people, or by equivalent sentences [7] when close to the receiver;
- S6: typical study-related sounds, such as page turning, pen clicking and notifications from personal devices, modeled as point sources;
- S7: footsteps on the staircase, represented by point sources;
- S8: indoor walking noise, modelled as point sources reproducing both slow and fast walking within the library.

The receiver positions were strategically selected to represent different acoustic conditions within the space. R1 represents a seated listener at a height of 1.2 m above the floor, located on the ground floor in the main open-plan reading area, overlooking the balcony and close to the underground courtyard. Positioned relatively far from surrounding partitions, it is primarily exposed to the direct sound field. Receiver R2 simulates a person standing 1.6 m from the floor, within the "Enchanted Garden", with his/her feet 5 m below the ground floor. This area is surrounded by parallel glass partitions, leading to a stronger contribution of reflected sound. Consequently, this receiver is more affected by the early reflections within the space.

The sound conditions at the receiver positions were determined by assigning to each source its octave-band sound power distribution together with the corresponding directivity. For the auralisation process, anechoic input tracks of each source and the original spectral content of the sources were replaced by an energetically equivalent flat spectrum. This approach was implemented by deriving a single representative sound power level for each source and redistributing it uniformly across frequency bands Subsequently, A-weighted sound pressure levels were simulated for all source - receiver combinations, as shown in Tab. 1. Each sound source was described using two different spectral approaches while keeping the total emitted power unchanged. For the auralisation process, an energetically equivalent flat spectrum was adopted to provide a spectrally neutral source rappresentation

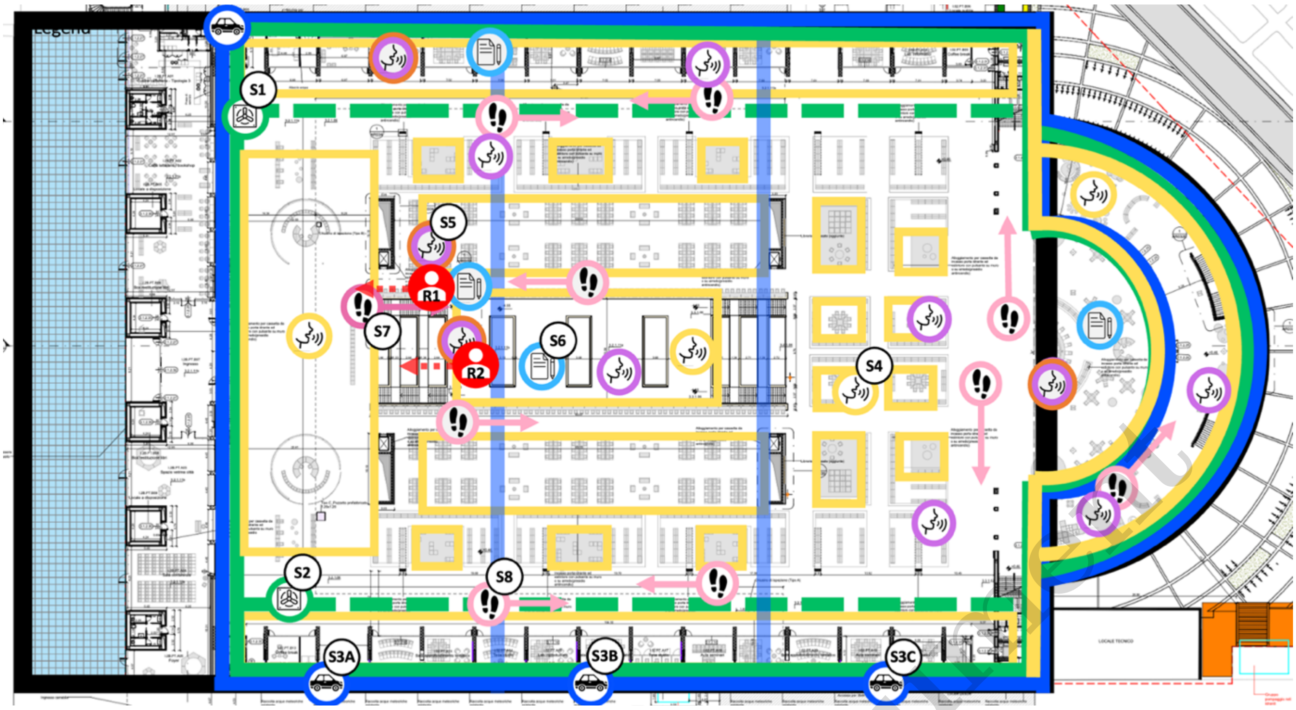

Figure 2. Plan of the main reading hall of the New Central Civic Library of Torino, showing the receiver positions and the simulated sound sources. The receivers' facing direction is indicated by the red arrows. Road traffic is represented by three blue surface sources, the HVAC system by a green surface source and two linear sources, the speech-related sources by a yellow surface source (unintelligible speech), a purple point source (intelligible speech) and orange point sources (equivalent sentences [7], activated only when located near the receiver). Indoor activities, including footsteps and study-related sounds, are represented by pink, fuchsia, and light blue point sources.

within the acoustic model. This choice avoids a potential overlap between the spectral characteristics assigned to the simulated source and those already contained in the anechoic recordings used for the convolution process [5]. Therefore, the resulting auralisation preserves the original spectral content of the source signals while reproducing the acoustic effects introduced by sound propagation in the simulated environment. In parallel, the original octave-band spectra were retained for the sound pressure level calculations. The comparison between simulations performed with the original and flattened spectra showed differences lower than 1.3 dB in the overall A-weighted levels, indicating that the adopted simplification did not significantly affect the energetic results. The resulting A-weighted levels at receivers R1 and R2 were 50.2 dB and 52.0 dB, respectively, which are consistent with the values of other fully occupied libraries reported in the literature [2-3]. The previous study in low occupancy yielded A-weighted levels at the same receivers of 44.9 dB and 46.7 dB, respectively [4].

Table 1. Source characteristics and single-source and overall sound pressure levels (dBA).

No.	Source	Source type	SPL, dB(A)	
			R1	**R2**
1	HVAC	Surface	14.3	13.1
2		Linear	15.3	14.0
3A-C	Traffic	Surface	27.9	27.2
4	Unintelligible speech	Surface	44.3	46.8
5	Intelligible speech	Point (9 distributed)	47.6	48.0
6	Equivalent sentences	Point (1 near each receiver)	41.2	45.1
7	Pages, pens, etc.	Point (1 near each receiver)	29.9	27.6
8	Footsteps (person descending the stairs)	Point (35 in a row)	36.5	41.4
9	Footsteps (people walking)	Point (14 in two rows)	37.9	37.7
-	**All sources**	-	**50.2**	**52.0**

2.4 Auralisation and calibration of the audio mixes

Auralisations were generated in Odeon 18 [5] by deriving third-order ambisonics spatial room impulse responses (SRIRs) for each source–receiver pair, which were subsequently convolved with anechoic source signals to obtain multichannel audio tracks suitable for spatial reproduction. For each receiver, six audio sequences of three minutes were created by combining the individual sources according to predefined randomization matrices. Each sequence was divided

into 20-second segments, within which different sound sources were alternated to reproduce realistic temporal variability while maintaining constant overall energy. The final auralized audio mixes for both the barely and fully occupied scenarios are available in [8].
The resulting mixes were reproduced in the Audio Space Lab (ASL), the ambisonics laboratory of the Politecnico di Torino. It is an acoustically treated listening environment compliant with ITU-R BS.1116-3 standards, characterized by low background noise and reverberation time of 0.17 s, and equipped with a 16-channel ambisonics loudspeaker array for accurate three-dimensional sound reproduction [9]. In order to ensure consistency between simulated and reproduced conditions, a calibration procedure was carried out by measuring the playback levels at the listening position with a calibrated microphone placed at the center of the array. The reproduction gain was then iteratively adjusted until the measured A-weighted sound pressure levels matched the target values obtained from the acoustic octave-band spectrum simulations.

2.5 Experimental design and procedure

Subjective tests were conducted in the ASL and involved 20 participants (11 male, 9 female) aged between 20 and 61 years. During the sessions, each participant was seated at the center of the reproduction system and was assigned an alphanumeric code to ensure anonymity. Each experimental session was conducted with 10 participants exposed to one of the simulated receiver positions and 10 to the other. The procedure followed a structured protocol organized into two main phases. In the first phase, each participant listened to a brief introduction to the study, followed by standardized questionnaires to assess noise sensitivity [10] and perceived annoyance (disturbance) [11]. Noise sensitivity was evaluated using the Italian version of the Weinstein Noise Sensitivity Scale (WNSS) [10], a six-point Likert-scale questionnaire, with higher scores indicating greater sensitivity to noise, while perceived annoyance was assessed using a discrete numerical scale ranging from 0 ("not annoying at all") to 10 ("extremely annoying") [11]. In the second phase, each participant completed a cognitive task under two acoustic conditions, silence and exposure to the simulated sound environment, allowing the comparison of cognitive performance across the two conditions. The task duration varied between conditions, with 2 min 30 s in silence and a total of 3 minutes in the noise condition, including a 30-second acclimatization period to the sound environment. No HMD or virtual reality system was used during the experimental sessions. Participants were exposed exclusively to the simulated acoustic environment reproduced through the ambisonics loudspeaker array. Before the tests, a short presentation of the case study, including renders of the library, was provided to familiarise participants with the investigated environment. The cognitive tasks were administered either on printed sheets or on a computer screen, depending on the specific task.

2.5.1 Cognitive task

The cognitive task consisted of an oral reading exercise aimed at assessing reading performance, based on established protocols for adult reading evaluation [12]. Participants were asked to read aloud short passages selected from Marcovaldo by Italo Calvino [13], chosen for their linguistic complexity and suitability for detecting subtle variations in reading ability. Reading performance was primarily quantified in terms of reading speed, expressed as correctly pronounced syllables per second, computed from the total number of syllables and the time required for completion. In addition, reading accuracy was evaluated based on the number of errors produced during the task.

2.5.2 Statistical analysis

Statistical results were first explored through box plot representations, which were used to summarize the distribution of the variables and to provide a visual comparison in terms of mean, median, spread, and possible extreme observations. Differences between independent groups were examined using the Mann–Whitney U test, with a significance level of 0.05. This test was applied to compare noise sensitivity and disturbance (annoyance) responses across receivers.
When it comes to the cognitive task analysis, the Mann–Whitney U test was first applied in order to assess whether differences between receivers were statistically significant, i.e. whether the data could be combined into a single sample. Afterwards, changes in cognitive performance between silence and noise conditions were analysed using the Wilcoxon signed-rank test for paired data, again with a significance threshold ≤ 0.05.

3. Results

Results are illustrated through box plots. The box represents the interquartile range (IQR), the blue solid line the median, the red dashed line the mean, the whiskers extend to the most extreme data points within $1.5\times$IQR from the quartiles and the circles indicate the outliers. The results are also compared to those obtained within the same library in low-occupancy conditions, with a sound pressure level of 44.9 dB(A) and 46.7 dB(A) in R1 and R2, respectively [4]. In the previous study, subjective tests were carried out in an anechoic chamber with headphones.
Figure 3 shows the results of the noise sensitivity test for the pooled sample in both the fully and barely occupied conditions. Prior to pooling, the two receiver groups for each condition were compared to verify their statistical comparability. For noise sensitivity, the Mann–Whitney test showed no significant differences between the two receiver positions, with a p-value of 0.225. Therefore, the results are presented for the pooled sample, which showed a mean noise sensitivity score of 74.2 (s.d. = 5.1). Likewise, in the barely occupied condition no significant difference between receivers was found, with a p-value of 0.199. Noise sensitivity was relatively stable, with a mean value of approximately 74.2.

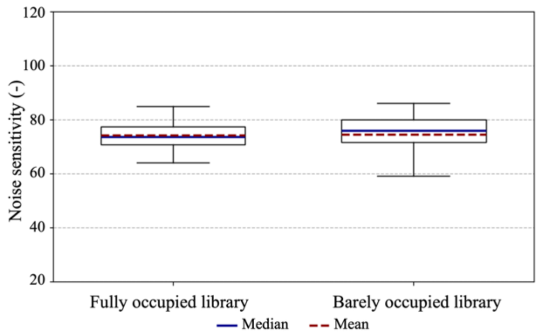

Figure 3. Box plots of the Noise sensitivity test for the two occupancy conditions.

Figure 4 shows the results of the noise disturbance (annoyance) test for the pooled sample in both the fully and barely occupied conditions. In the fully occupied scenario, the Mann–Whitney test showed no statistically significant differences between the two receiver groups, with a p-value of 0.055, supporting the pooling of the receiver groups. The pooled sample showed a mean annoyance score of 4.85 (s.d. = 2.3), indicating a moderate level of perceived disturbance. In the barely occupied scenario, a statistically significant difference between receiver positions was observed, with a p-value of 0.023, reporting higher annoyance ratings at R1 than at R2.

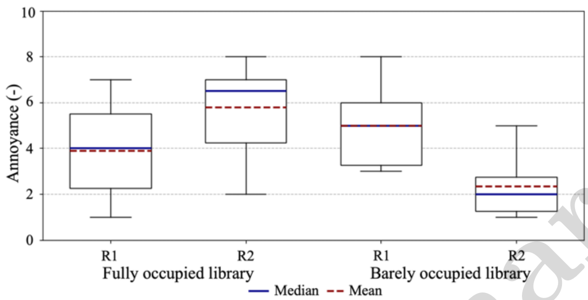

Figure 4. Box plots of the Noise disturbance (annoyance) test for the two occupancy conditions.

Figures 5-6 show the results of the cognitive task in terms of speed score and errors. In the fully occupied condition, the Mann–Whitney U test did not reveal significant differences between the two receivers, with p-values equal to 0.381 in noise and 0.128 in silence, allowing the data from the two receivers to be combined into a single sample. Speed score appears slightly higher in silence compared to noise; however, the Wilcoxon test did not show significant differences between conditions, with p-value equal to 0.227. When it comes to the number of errors, similarly, the Mann–Whitney test did not reveal significant differences between receivers, allowing the data from the two receivers to be combined into a single sample. Error rates are slightly lower in silence, although the Wilcoxon test did not reveal statistically significant differences, with a p-value of 0.080. For comparison, the figures also include the low occupancy condition [4]. In this case, the Mann–Whitney test did not reveal significant differences between receivers (p-value > 0.05), allowing the data to be combined into a single sample. No significant differences were found for reading speed between noise and silence, while errors showed a statistically significant difference between conditions, with p-value equal to 0.041, with a higher number of errors observed under noise exposure.

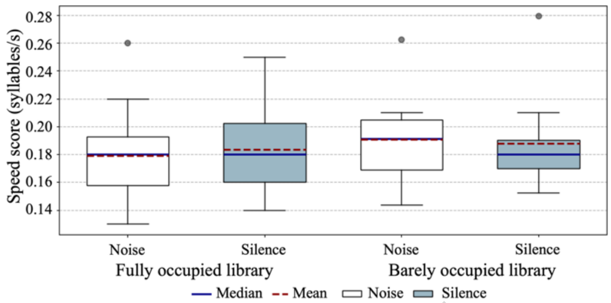

Figure 5. Box plots of the cognitive task – speed score for the two occupancy conditions.

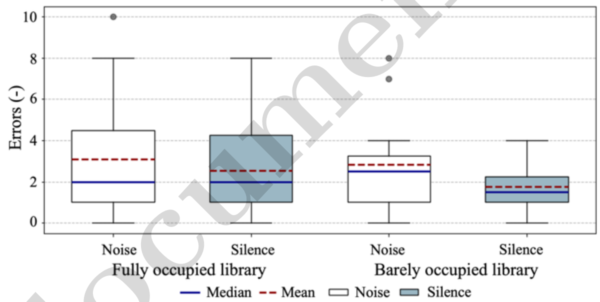

Figure 6. Box plots of the cognitive task – errors for the two occupancy conditions.

4. Discussion and Conclusions

This study investigates the noise perception and the cognitive performance in the simulated full-occupancy scenario of the New Central Civic Library of Torino, a large reverberant historical building with a volume of approximately 160,000 m³ and an estimated mid-frequency reverberation time of about 5 s. A geometrical acoustics model was developed to reproduce the acoustic environment with sound sources typical for a contemporary library, resulting in A-weighted sound pressure levels of 50.2 dB(A) and 52.0 dB(A) at the two receiver positions. To assess noise perception and cognitive effort, twenty participants, aged 20 - 61 years, completed subjective assessments of noise sensitivity and annoyance together with a reading-aloud task. No significant differences were observed between receiver positions or between noise and silence conditions in the fully occupied scenario, indicating no measurable impact of the simulated acoustic environment on cognitive performance.

Compared with the previous low-occupancy study [4], noise sensitivity was similar across both studies and conditions, whereas receiver-related differences in annoyance were observed only under low occupancy, despite the lower sound pressure levels reported at the same receiver positions, i.e. 44.9 and 46.7 dB(A) for R1 and R2, respectively. This may suggest that spatial variations become less perceptible in a more homogeneous acoustic environment. Regarding cognitive performance, unlike the previous study, which reported a significant increase in reading errors under noise exposure, no significant effects on reading speed or errors were observed in the present study. This discrepancy may be related to differences in the sound reproduction methods adopted in the two experiments. The previous study employed binaural headphone reproduction in an anechoic environment, whereas the present study used an immersive ambisonics loudspeaker-based system. According to the literature, headphone listening may reduce sound externalization and alter spatial auditory cues compared with loudspeaker reproduction which provides a more natural spatial listening experience [14, 15]. Moreover, because the cognitive task involved reading aloud, altered auditory feedback during headphone listening may have affected speech production and increased reading disfluencies [16]. Therefore, differences in the sound reproduction method may have contributed to the different cognitive outcomes observed between the two studies, although this interpretation should be considered as a possible explanation rather than evidence of a causal relationship. These findings indicate that the relationship between noise and cognitive performance in large reverberant libraries cannot be explained by sound pressure levels alone but is influenced by multiple factors, including acoustic conditions and sound reproduction characteristics, in agreement with previous studies showing that reverberation time and room acoustic characteristics can significantly affect cognitive performance under comparable sound pressure levels. Yadav et al. [17] reported significant differences in cognitive performance across room acoustic conditions with same SPL of 55 dB(A) but different reverberation times, i.e. 0.4, 0.8 and 1.1 s, showing improved task performance in environments with higher sound absorption. Similarly, Li et al. [18] found that increasing reverberation time, while maintaining a constant sound pressure level of 65 dB(A), significantly affected auditory sustained attention by increasing the number of errors and prolonging the response times. However, further research is required to better understand these relationships.

The present study has some limitations. The sample size was relatively small and included individuals with heterogeneous backgrounds. Moreover, although an immersive ambisonics reproduction was adopted, no visual virtual environment was included. Future studies should consider larger and more homogeneous samples together with longer and fully immersive audiovisual experiments.

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