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Preliminary study of a University Hospital outdoor noise environment based on monitoring and soundscape

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ABSTRACT

Noise in hospital wards can significantly impact patients and healthcare staff, disrupting physiological processes and contributing to stress and annoyance. In this context, outdoor healthcare spaces are essential in creating a healing environment that positively affects human well-being. While indoor hospital acoustics have been widely studied, research on outdoor hospital soundscapes remains limited. Within a two-year project, the study presented in this paper features a soundscape alongside noise monitoring techniques, focusing on the external area of the Sant' Orsola University Hospital in Bologna. By integrating these methods, the analysis uncovered aspects of the hospital's acoustic environment that conventional approaches might miss. A pilot soundwalk was conducted with 21 participants according to Method A of ISO 12913-2. Binaural audio recordings were measured to assess psychoacoustic parameters, e.g., loudness and psychoacoustic annoyance. Preliminary findings reveal elevated noise levels near a hospital pavilion, with values exceeding Italian legal limits by 8.5 dB during the day and 11.5 dB at night. The study identified a highly variable acoustic environment, distinguishing between quiet, active and traffic-dominated areas. The results show a strong correlation between traditional sound level measurements and soundscape analysis, highlighting the importance of a holistic approach to noise assessment in hospitals.

Keywords: *noise in hospitals; soundscape; soundwalk; psychoacoustics; annoyance.*

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1. INTRODUCTION

The acoustic environment is crucial to people's health and general well-being [1]. Numerous studies have shown that exposure to excessive noise can lead to serious health problems, including cardiovascular disease, annoyance, sleep disturbance and mental health status [2]. Highly sensitive environments, such as hospitals, require careful consideration, as noise can aggravate patients' health conditions and impair the performance of healthcare professionals. According to the World Health Organisation (WHO), hospitalized individuals represent a vulnerable subgroup with heightened sensitivity to noise exposure, where the combined effect of multiple noise sources may further compromise their health and recovery. Studies in the healthcare sector have enhanced the benefits of outdoor spaces and associated them with the comfort, safety, and well-being of occupants in hospital environments[3].
Worldwide research and policy on sound have focused mainly on noise pollution and its negative effects on individuals and communities. In contrast, soundscape studies suggest that managing sound environments can promote health benefits. In a systematic review, Aletta et al. [4] identified associations between health and well-being, including stress recovery and positive urban soundscape, e.g. natural sounds. Furthermore, using a systems thinking approach, Aletta et al. [5] explored the complex relationships between soundscape quality and public health, finding that soundscape design and sound source diversity positively affect soundscape quality, while noise pollution negatively impacts public health. According to ISO 12913-1[6], the soundscape is “the acoustic environment as perceived or experienced and/or understood by a person or in context,” emphasizing acoustic perception's subjective and contextual dimensions. Consequently, ISO 12913-2 [7] recommends integrating acoustic and psychoacoustic indicators in soundscape assessment. Kang et al. [8]

emphasise that the evaluation of acoustic comfort is strongly influenced by the type of sound sources present, underlining the psychological significance of soundscapes. Indeed, perceived acoustic comfort and loudness were found to be highly correlated with annoyance [9].
To the best of the authors' knowledge, existing research on hospital facilities has predominantly concentrated on indoor acoustics soundscape [10–13] and comfort [14, 15]. There has been relatively less focus on evaluating soundscapes in the outdoor areas of healthcare facilities. In addition, many studies have investigated hospital acoustic environments using conventional noise metrics [16], which do not provide the human perception point of view and many details of the hospital's sound context without a deeper analysis [17].
This pilot study aims to characterize the outdoor hospital's current acoustic environment through noise monitoring and soundscape analysis and is part of a wider project on the urban regeneration of the hospital area using an interdisciplinary method. It combines design insights from acoustics, road paving, landscaping, and urban microclimate improvements in outdoor spaces. The work was carried out at the Sant' Orsola University Hospital, Bologna, Italy. The healthcare facility is located in Class 1, according to Italian legislation (D.P.C.M. 14/11/1997), classified as the most noise-sensitive area.

2. METHOD

The method used in this study combines soundscape and psychoacoustic parameters analysis with acoustic indicators. Initially, two points in the hospital's area were selected to monitor the environmental noise: point A is near the gynaecology pavilion, and point B is near two high-speed roads inside the hospital (see **Figure 1**). Then, seven key soundwalk locations were chosen to capture the area's spatial and acoustic diversity (see **Figure 1**). Moreover, these locations were chosen based on the best combination of minimum interference with staff activities and the best and most representative evaluation of critical and quiet areas of the hospital.

2.1 The study area

This pilot study focuses on a real-world scenario: the Sant' Orsola University Hospital in Bologna. The latter covers an area of 2 km², bordering Bologna's historic centre and belongs to the most noise-sensitive class (D.P.C.M. 14/11/1997). It is a complex of 30 pavilions that serve as hospital wards, outpatient clinics, and University campus classrooms. Nowadays, the hospital is situated within the city's urban infrastructure, but it was originally composed of two monasteries isolated in the countryside. The northern side, near Via Massarenti, and the western one, via Ercolani, experience heavy traffic congestion from private cars, ambulances, and public transport. The internal road system is primarily for emergency and logistical traffic, with restricted access for authorized vehicles only. Public transport does not enter the hospital but runs along its perimeter. The green spaces within the hospital are poorly organized, mainly serving as corridors rather than accessible areas for patients, staff, students and visitors.

Figure 1 A geographical overview of the Sant' Orsola University Hospital in Bologna. Routes and listening stations during the soundwalk and noise monitoring sites are shown in red (S1-S7) and blue (A, B), respectively. Instead, yellow is highlighted via Massarenti, and green is highlighted via Ercolani.

2.2 *N*oise monitoring data

The monitoring was performed using a sound spectrum analyser with an interval of 100 ms (see **Table 1**). Continuous Sound Pressure Level (SPL) measurements were carried out from 12:00 am on Wednesday, the 5th of March, to approximately 4:00 pm on Tuesday, the 6th of March, 2025 (point A, see **Figure 1**). Moreover, on the 5th of March, a second sound spectrum analyser was used to record SPL data at another point for approximately 1-hour of measurement (point B, see **Figure 1**). Due to the complexity of the dynamic activities in the hospital environment, these monitoring activities were aimed at having a minimal impact.
The equivalent continuous level L_{Aeq} and the percentile difference between the source event and the overall background (L_{10} - L_{90}) were analysed from the long-term monitoring data of 24 hours in point A and 1 hour in point B. The percentile difference (L_{10} - L_{90}) is a representative descriptor of the energetic increase

produced by a source or in the context of mixed source exposure. The Italian law states that for hospitals, L_{Aeq} of outdoor noise must not exceed 50 dB(A) in the daytime (h 6–22) and 40 dB(A) at night-time (h 22–6). In this preliminary study of the area, the calculation of L_{day}, L_{night} and L_{den} is reported to have a comparison with Italian limits and European indications [18].

2.3 Soundscape survey analysis

Twenty-one people participated in the soundwalk, divided into two subgroups with different walking orders to reduce the systematic influence of order effects on the assessment. The soundwalk took place on the 28th of November 2024 from 10:00 to 11.30 am for the 1st group and from 11.30 to 13:00 am for the 2nd group. Each group of participants was guided through the study area and made consecutive stops at seven selected sites within the hospital borders (**Figure 1**). According to Method A of Annex C [7], the participants were asked to listen to the acoustic environment for three minutes and to complete a structured questionnaire.

Table 1 Equipment used for acoustic measurement during soundwalk.

Equipment	Specification	Factors collected	Measurement duration
Sound spectrum analyser	01 dB DUO, class 1	100 ms log. period L_{Aeq}, L_{AFmax}, 1/3rd octave band	3 min per each location
Binaural rec. system	Binaural Head	.wav audio rec.	3 min per each location
Audio rec.	Portable Tascam HD-P2	44.1 kHz, 24 bit resolution	
Data rec.	Data Logger RS PRO	Temp. (°C), Rel. Humidity (RH)	Approx 3-4 hours
Windshield	-	Used for SLM	-
Tripod stands	-	Used for SLM and Binaural Head	-

Throughout the soundwalk for each site's listening part, a three-minute acoustic recording was simultaneously collected through a binaural recording system and a calibrated sound spectrum analyser. In addition, an environmental meter collected temperature and humidity data at each of the seven selected locations. The equipment used in the soundwalk is reported in **Table 1**, following most of the SSID protocol's recommendations [19]. The environmental metrics are not reported in this study, but they were necessary for monitoring the environment's state during the measurements.

The soundwalk participants (48% female F and 52% male M, average age Mage=30.5 years) were all native Italian speakers. The questionnaire was set in Italian according to the International recognised translation [20]. The group was composed of external guests in the area (43%), workers in the hospital (33%), patients (10%), residents in the neighbourhood (5%), and others (5%). Furthermore, 81% of the participants live in an urban setting (city or town, close to busy roads) and not in independent residences, while the remaining 19% were in rural settings and independent residences. According to ISO 12913 part 2 [7], the questionnaire is divided into four sections, and the 1st part (Q1) refers to sound source identification. The next question (Q2) concerns the perceived affective quality with a list of eight scales which make up the circumplex model [21]. The last two questions (Q3, Q4) investigate the overall assessment and appropriateness of the surrounding sound environment. The sound spectrum analyser recordings computed the following acoustic parameters, and the arithmetic average was presented. The difference between the 10th and 90th percentile levels (L_{10} - L_{90}) was used as an indicator of soundscape variability [22].In addition, artificial head recordings were collected to describe and analyse the current state of the hospital area through psychoacoustic parameters. Loudness (N) was calculated using the free software package according to ISO 532-1 standard [23] for time-varying sounds in a free field. To avoid the underestimation of evaluated loudness seen when using the arithmetic mean of the loudness curve, the N_5 and N_{95} values (the 5th and 95th percentile of the time-varying loudness curve) were reported as a single loudness value. Zwicker's model [24] defines the Psychoacoustic Annoyance (PA) as a multicomponent parameter, depending on the combination of four psychoacoustic metrics: loudness, sharpness, roughness and fluctuation strength, as follows.

$$PA = N_5 \left(1 + \sqrt{{w_S}^2 + {w_{FR}}^2}\right) \quad (1)$$

Where w_S represents the influence of the sharpness (S) and w_{FR} is the effect of fluctuation strength (FR).

$$w_S = \begin{cases} (S - 1.75)0.25lg(N_5 + 10) & S > 1.75\ acum \\ 0 & S < 1.75\ acum \end{cases}$$

$$w_{FR} = \frac{2.18}{{N_5}^{0.4}}(0.4F + 0.6R)$$

Psychoacoustic parameters and PA were calculated in Matlab. The analyses are therefore based on the maximum value between the two channels (left and right) of the binaural recordings.

3. RESULTS AND DISCUSSION

This section reports the main findings from the analysis of the acoustic data collected and the responses to the questionnaires submitted during the soundwalk around the hospital grounds. All the following noise levels reported are A-weighted.

3.1 Noise Monitoring Assessment Data

The selected points for noise monitoring are expected to be exposed to external and internal traffic noise. **Figure 2** analyses the time history of the complete day measurement, highlighting a scenario affected by the frequent passage of civil and emergency vehicles both day and night. The selected point for noise monitoring, indicated as A in **Figure 1**, is influenced by Via Massarenti's proximity (about 60 m distance) and the hospital's internal traffic noises. The measured L_{day} and L_{night} values are 58.5 dB and 51.5 dB, respectively, and the percentile levels are in the range of 49.6-59.4 dB for the day (6-22) and 44.6-54.2 dB for the night period (22-6). Moreover, a very slight decrease in the SPL is noticeable during the night, with a reduction that does not fall below 44 dB. Compared to Italian law, the results exceed the daily limit of 8.5 dB and the night limit of 11.5 dB. In addition, the noise indicator L_{den} equal to 60.3 dB is reported to assess the overall annoyance, as indicated in the European Union Directive 2002 [18].

Figure 3 shows the distributions of L_{Aeq}, L_{90} and L_{10} mean values of 1-hour recordings in the same daytime period and in two locations inside the hospital's area (A and B, see **Figure 1**). The point identified as B is located at the intersection of two arterial roads within the hospital complex, experiencing the effects of internal traffic noise. In the box plot, the outlier points (related to the sirens' sound of ambulance passing) come from point A, near Via Massarenti. Despite this, the mean values of the parameters at point B are approximately 3 dB higher than those at point A. Therefore, traffic noise within the hospital also needs to be considered as a dominant source in the characterization of the site. The internal areas facing the main circulation path are highly subject to the passage of internal logistic vehicles. This issue was repeatedly raised by stakeholders involved in the project as a problem felt by frequent users of the hospital spaces. Long-term noise monitoring is extremely useful for studying environmental noise levels and for assessing noise effects. However, their narrow focus exclusively on noise levels limits the potential to detect noise's health and psychological effects.

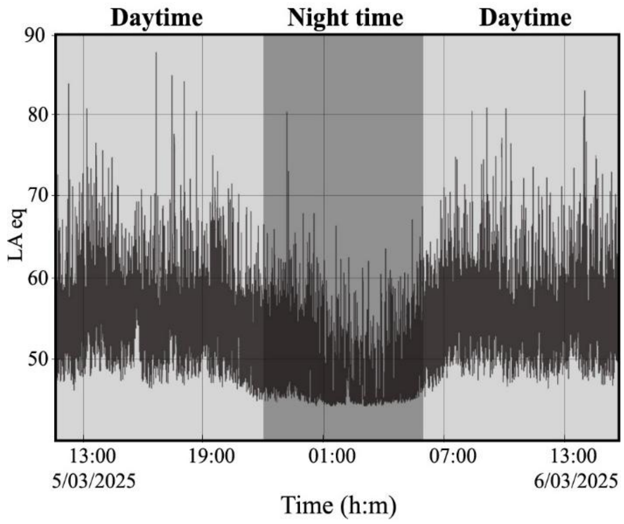

Figure 2 24-hour long-time monitoring time history, located near the gynaecology pavilion (point A in **Figure 1**).

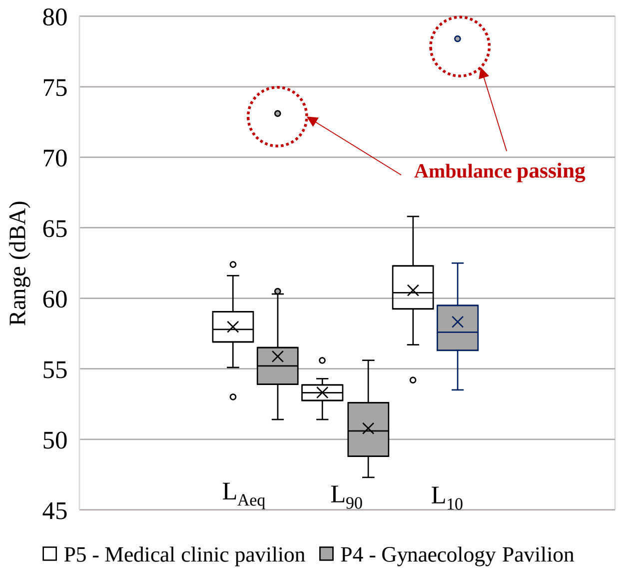

Figure 3 Box-whisker plot of 1-hour noise monitoring results comparing 2 locations within the hospital' area (points A and B in **Figure 1**).

3.2 Subjective Assessment Data

Figure 4 and **Figure 5** report the assessment of the questionnaire, which is composed of four parts (Q1-Q4). **Figure 4** shows the distribution of source identification throughout the seven soundwalk locations. As recommended by Brown et al. [25], the sources' taxonomy of the study area was analysed, highlighting that "traffic noise" was by far the most dominant sound source, especially in (S1) and (S5), which were directly exposed to the traffic flows. Whereas stations (S3), (S6) and (S7) were mainly characterized by "other noise", except (S7), described as having dominant "natural sounds". The sites (S2) and (S4) are in the hospital's internal areas, and fewer dominant sources were identified here.

Figure 5 highlights how the stations are spread in the opposed graph's quadrants, following the diagonal "Chaotic-Calm" distribution in the circumplex model, according to ISO 12913 part 3 [26]. The locations (S2) and (S4) are found in the "Pleasant-Calm-Uneventful", while the rest of the sites tend to converge towards the "Eventful-Chaotic-Annoying" graph's area. Results indicate that the perception between two groups who repeated the soundwalk from an hour away has less variation in those stations dominated by traffic and other noise sources. Otherwise, human and nature-dominated locations shifted toward eventful soundscapes compared to the 1st and 2nd groups of soundwalks. It is worth noting that these previous results confirm the conclusions of studies highlighting how contextual information is important for predicting pleasantness, unlike eventfulness [27].

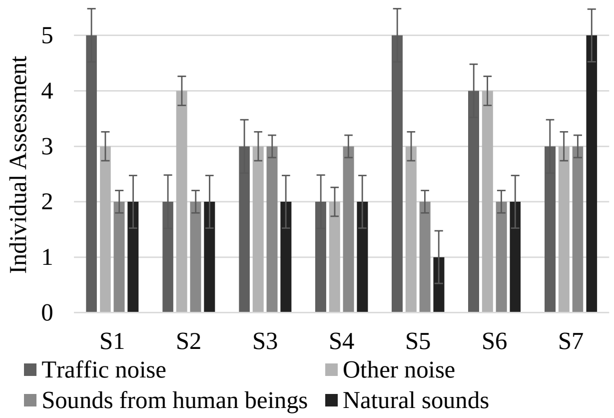

Figure 4 Median values for the individual responses of Q1: perceived sound dominance at each station. Assessment is given on a Likert scale of 1-5. The error bars show a deviation of standard error from the respective mean.

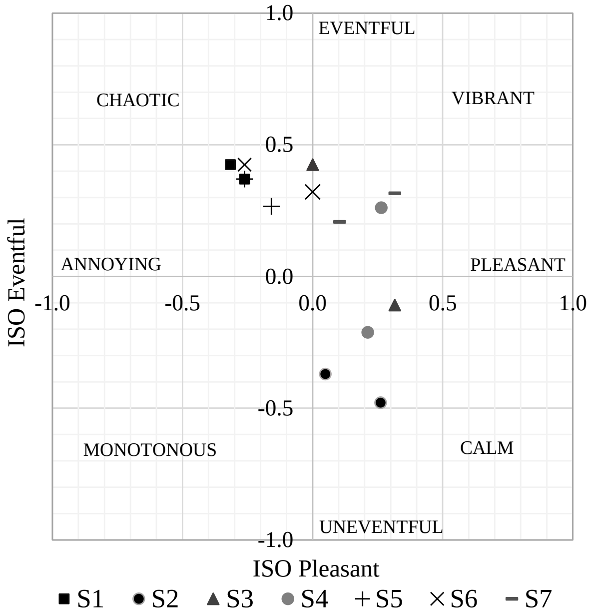

Figure 5 The scatter plot of the Q2 question shows assessment for both the 1st and 2nd groups on the soundscape circumplex.

Figure 6 illustrates SPL recorded during the soundwalk and the responses given for the last two questions of the questionnaire: (Q3) *'Overall, how would you describe the present surrounding sound environment?'* and (Q4) *'Overall, to what extent is the present surrounding sound environment appropriate to the present place?'*. The graph shows that higher sound pressure levels correspond to a lower individual assessment of the sound environment and the appropriateness of the location. It should be noted that people who often experience the hospital environment (for need or work) may have very different ideas of what is appropriate compared to other outdoor spaces. Hence, the concept of appropriateness needs to be judged by the context [28] and is affected by the interaction with visual elements [29]. In particular, station (S7) reverses the trend because it has a high site appreciation value despite the high sound pressure levels. The acoustic environment in site 7 is dominated by a water feature that could have a masking effect on the other sources [9]. Similarly, station S6 has been identified as an outlier due to its considerably appropriateness score despite elevated SPL values. This discrepancy may be attributed to the presence of green areas and birdsong, as outlined by the authors from the analysis of the recorded audio file. These elements could enhance the visual-audio experience and influence the perception of appropriateness within this specific environmental context [30]. In the overall assessment, (S6) remains in the

"Eventful-Chaotic-Annoying" area of the circumplex model, probably because it is mainly characterised by traffic and "other noise" over the recording time (**Figure 4Figure 5**). Based on the preliminary characterization of the hospital areas, an identification of quiet zones (S2, S4), active zones (S3, S6, S7), and traffic-dominated zones (S1, S5) was established. This categorization underlines the different acoustic environments present within the hospital facility, which were identified through a comprehensive analysis of measured sound levels and soundscape metrics.

Finally, **Figure 7** presents the evaluation of acoustic and psychoacoustic parameters across these representative areas, highlighting significant differences in noise exposure and perceptual attributes. Overall, data showed that the 5th percentile Loudness N_5 is significantly correlated ($r = 0.78$, $p < 0.05$) with the difference between the 10th and 90th percentile level L_{10} - L_{90}. The soundscape metrics ISO Pleasantness (ISO_{Pl}) and ISO Eventfulness (ISO_{Ev}) were considered among the intercorrelations. The results revealed a good correlation with PA (see **Equation 1**) for ISO_{Ev} ($r = 0.73$, $p < 0.01$) and, respectively, a negative correlation with ISO_{Pl} ($r = -0.84$, $p < 0.01$). Comparable results were observed in the correlations between percentile levels L_{10} - L_{90} and ISO_{Ev} ($r = 0.67$, $p < 0.01$), and ISO_{Pl} ($r = -0.86$, $p < 0.01$). Overall, the (L_{10} - L_{90}) parameter describes the variability of the soundscape (ISO_{Pl}, ISO_{Ev}) and shows some correspondence with the PA parameter. This suggests that higher fluctuations in noise levels are associated with an increased perception of disturbance. However, hospital areas exhibit unique acoustic characteristics, wherein psychoacoustic factors and the contextual influence of noise sources play a crucial role in achieving human affective responses and extra-auditory effects. For instance, subjective metrics such as the acoustic environment's eventfulness, pleasantness, and appropriateness cannot be effectively derived from standard acoustic measurements alone. These findings emphasize the necessity for a multi-factorial approach to assessing hospital noise, integrating both traditional acoustic metrics with psychoacoustic and soundscape indicators to achieve a holistic understanding of its effects.

4. CONCLUSION (AND FUTURE WORK)

This paper investigated a case study in Sant' Orsola Hospital, near Bologna's city centre, surrounded by urban roads and heavy traffic. Originally consisting of two monasteries isolated in the open countryside, the healthcare facility became increasingly exposed to urban noise due to the expansion of the city, highlighting the need for a thorough assessment of the soundscape in healthcare environments. This preliminary study highlights the considerable variability in the acoustic conditions of Sant' Orsola Hospital. Based on the results, the area under study can be categorized into three main source-dominated areas: traffic-exposed, active, and quiet. Traffic-exposed areas face major urban roads, where noise levels are primarily influenced by continuous vehicular flow. Active areas are characterized by exposure to internal traffic, construction sites, and natural sounds due to green spaces and

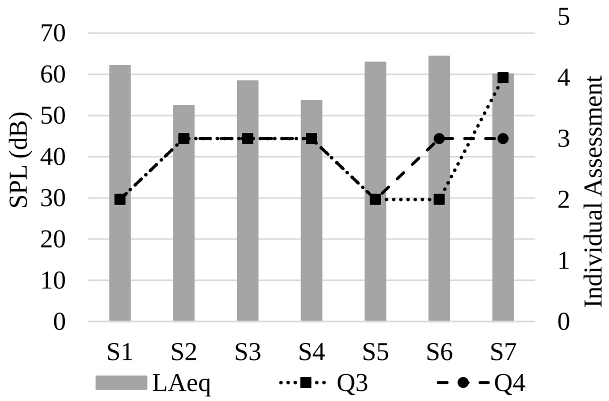

Figure 6 Mean individual rating for Q3 and Q4 questions of the in-person questionnaire. Assessment is given on a Likert scale of 1-5.

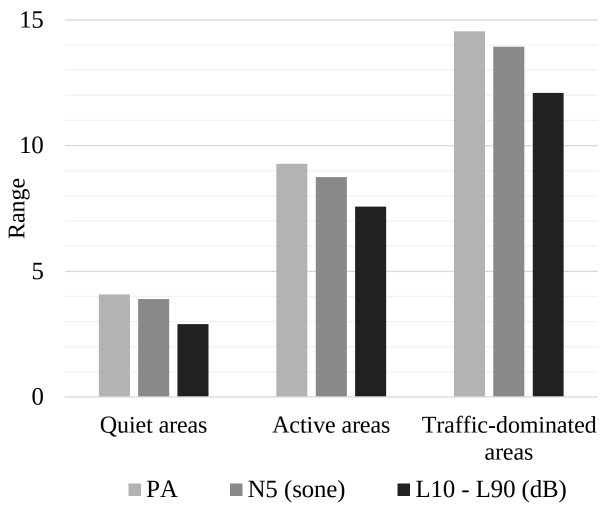

Figure 7 The mean rating of psychoacoustic and acoustic parameters in different hospital areas: quiet, active, and traffic-dominated.

a water feature. In contrast, quiet areas are located within internal courtyards, where the surrounding buildings help reduce exposure to both external urban noise and internal hospital-related traffic.
The findings confirm a strong correlation between traditional sound level measurements, soundscape evaluation and psychoacoustic analysis, reinforcing the need for a multidimensional approach to hospital noise assessment. Further long-term monitoring is necessary for a more comprehensive understanding of the acoustic scenario, particularly for noise sources such as internal transport systems. In addition, more soundwalks will be conducted to increase data robustness for future evaluations of the hospital soundscape. These findings will provide a valuable basis for developing targeted noise mitigation strategies, ultimately improving the well-being of patients and medical staff.

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