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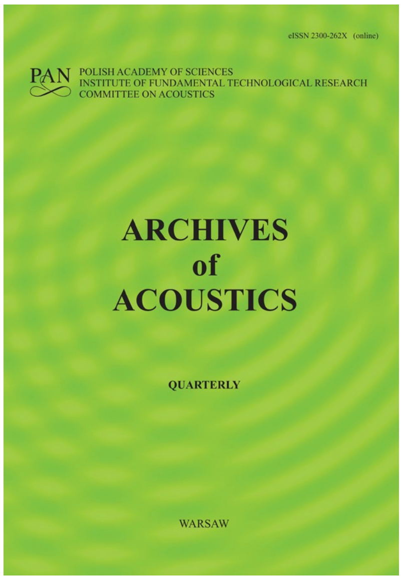

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Beyond Decibels: Spectral and Perceptual Dichotomy of Noise in a Busy Emergency Department (ED)

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Abstract

This study investigates the acoustic environment of a high-volume emergency department in a Chinese tertiary hospital and its differentiated perceptual impacts on occupants. Continuous 24-h monitoring was conducted for 20 consecutive days in four representative areas: triage, waiting area, treatment rooms, and bridge. Daily 24-h L_{Amin}, L_{Aeq}, and L_{Amax} were analyzed, and one-third-octave band sound pressure levels were used to identify dominant frequency components. Structured questionnaires were administered to healthcare staff, patients, and visitors to assess subjective noise perception and psychological responses. Objective measurements showed severe and persistent noise pollution. Mean L_{Aeq} ranged from 62.2 dB(A) in treatment rooms to 67.0 dB(A) on the bridge. The triage showed the highest background noise (L_{Amin} = 52.8 dB(A)), whereas the bridge exhibited the highest peak level (L_{Amax} = 82.3 dB(A)). Diurnal analysis revealed a sustained daytime high-noise plateau in all areas, and nighttime levels remained well above recommended limits. Spectral analysis showed a pronounced peak around 500 Hz, indicating that human speech was strongly associated with the ED soundscape. Perceptual results revealed a clear dichotomy: healthcare staff showed signs of cognitive adaptation, whereas patients and visitors responded more strongly through emotion-driven stress and communication-related discomfort. Piercing call bells and speech masking emerged as salient sources of disturbance for the public, while healthcare staff appeared more tolerant of routine operational sounds. These findings position noise in the ED as not only an acoustic burden but a human-factors challenge, underscoring the need for integrated interventions to improve communication, reduce stress, and advance safer, more patient-centered emergency care.

Keywords: Hospital noise; Noise perception; Cognitive adaptation; Healthcare environment; Acoustic measurements; Emergency department (ED).

1. Introduction

Modern hospitals, as core facilities for providing healthcare and promoting health, play a crucial role in patient recovery and healthcare staff efficiency. Among these factors, acoustic environment quality—specifically, noise levels within hospital premises—is increasingly recognized as a key determinant of both medical quality and staff well-being (Shetty et al., 2024; Dwairi et al., 2025). The World Health Organization (WHO) has long emphasized that the equivalent continuous A-weighted sound pressure level (L_{Aeq}) in hospital ward areas should not exceed 35 dB(A) during the day and 30 dB(A) at night to ensure patients have a conducive environment for rest and recovery. However, extensive empirical research indicates that significant noise pollution issues are prevalent in hospitals worldwide, with sound pressure levels far exceeding recommended standards, particularly in high-activity areas such as intensive care units (ICUs), outpatient departments, emergency department (ED), and ward corridors (Eijkelenboom, 2021; Filus et al., 2015; Jung et al., 2020; Tahvili et al., 2025). China also has standards limiting noise levels in sensitive areas of hospitals (GB 50118-2010), with background noise levels in patient rooms restricted to 40 dB(A) during the day and 35 dB(A) at night (GB 50118-2010, 2010; T/CECS 669-2020, 2020). However, according to extensive research, noise levels in hospital wards worldwide have not been reduced to the levels recommended by the World Health Organization (WHO) or relevant national standards (Jonescu et al., 2024). Different medical facilities and hospitals in various countries have reported that since 1960, noise levels in hospitals worldwide have been steadily increasing by 0.4 dB(A) annually, with environmental noise levels exceeding WHO recommendations by 15–20 dB(A) (Lima Andrade et al., 2021).

Excessive hospital noise is not merely an unpleasant background sound. For patients, persistent noise interference has been proven to be closely associated with multiple adverse health outcomes, including sleep disorders, elevated stress levels, heightened pain perception, blood pressure fluctuations, communication difficulties, and delayed recovery processes, severely compromising the environment that should be conducive to "peaceful healing" (Loupa, 2020; Cunha and Silva, 2015; Imbriaco et al., 2024). For healthcare staff, prolonged exposure to high-intensity, unpredictable hospital noise can lead to auditory fatigue, distracted attention, reduced communication efficiency, and decreased job satisfaction (Themann and Masterson, 2019; Padmakumar et al., 2017). It may also trigger chronic stress responses, increase the risk of occupational burnout, and potentially elevate the incidence of medical errors, thereby threatening patient safety (Joseph and Joseph, 2016). On the one hand, the sources of hospital noise are quite complex (Abbasi et al., 2024). Allaouchiche et al. found that staff conversations accounted for 56% of sounds greater than 65 decibels, while other sources of noise (call bells, telephones) were 10% lower than conversations (Allaouchiche et al., 2002). Lo Castro et al. collected self-assessment reports from staff at a Roman hospital regarding their working environment (Lo Castro et al., 2022). The conclusions indicated that background noise in the hospital exceeded 50 dB(A) and affected speech intelligibility. Noise disturbance is a key factor in increasing stress and reducing work efficiency. Ruettgers et al. assessed healthcare staff perceptions of noise levels and related sound sources in their work environments in Germany, Switzerland, and Austria. 69.3% of healthcare staff considered noise levels in ICUs to be too high, with short bursts of human voices, equipment and call bells, and short bursts of object sounds considered to be the most disturbing sounds. Hospital floors, walls, and ceilings are typically hard and smooth surfaces that reflect sound rather than absorb it (Ruettgers et al., 2022). Deng et al. indicated that previous studies mainly considered the impact of sound absorption treatment on the acoustic environment of hospital rooms and public areas, while there has been little research on the need to enhance the sound insulation between hospital rooms and the external environment (Deng et al., 2023a). Patients often perceive better care during quieter periods, underscoring the importance of reducing noise levels in healthcare facilities (Song et al., 2022). Therefore, reducing noise levels in healthcare facilities is very important. Healthcare providers should provide a quiet environment for patients and staff, as unnecessary noise can have a negative impact on patient outcomes and the efficiency of healthcare professionals (Nyembwe et al., 2023; Deng et al., 2023b).

Although the objective existence of hospital noise pollution and its potential hazards have been widely recognized, existing research still has some areas worthy of further exploration: on the one hand, there is a need for more detailed sound pressure level monitoring data specific to hospital environments, particularly those that provide a detailed description of noise time distribution characteristics (such as diurnal variations and peak noise levels). On the other hand, research on the differentiated effects of noise on the subjective perception, psychological responses, and behavioral coping mechanisms of the two core groups in hospitals—healthcare staff and patients—remains relatively insufficient. Understanding how healthcare staff maintain professional efficacy in noisy environments and how patients experience and cope with noise is crucial for developing more targeted noise control strategies.

Therefore, this study aims to: (1) measure the sound pressure levels in representative functional areas of the hospital ED to quantify the intensity and temporal characteristics of noise exposure;

(2) design and distribute structured questionnaires to explore the differentiated effects of noise on the subjective perceptions, psychological responses, and behavioral coping mechanisms of healthcare staff, patients, and visitors; (3) based on a comprehensive analysis of objective and subjective data, provide targeted acoustic recommendations.

The anticipated outcomes of this study will provide a solid objective data foundation for gaining a deeper understanding of the actual acoustic environment conditions in the target hospital, and will reveal the differentiated mechanisms by which noise pollution impacts the work efficiency and occupational health of healthcare staff, as well as patients' treatment experiences and perceptions. The findings may also inform the development of more evidence-based and human-centered strategies for hospital noise control and acoustic-environment optimization, with potential implications for service quality, patient safety, and staff well-being.

2. Materials and Methods

2.1. Hospital Samples

A tertiary Grade A hospital—the highest-tier medical institution in China's hospital classification system, characterized by large scale, comprehensive services, and high patient volume—was selected in the eastern coastal region of China. The hospital is located between two administrative districts near the city's central business district, in a densely populated area with substantial traffic-noise exposure. The first floor of the emergency building was selected as the study area. The emergency building has a single-corridor layout with waiting areas on both sides, PVC flooring, and no sound-absorbing ceiling treatment. Glass curtain walls account for approximately 70% of the façade, and the indoor acoustic environment is therefore substantially influenced by external traffic. Although basic noise-management measures had been implemented in the study area, the high volume of visitors and the non-optimized grading of equipment call bells contributed to a persistently poor acoustic environment, making this setting a representative case for the present study.

2.2. Data Measurement

To systematically quantify the acoustic environment and address the operational complexities of the ED, noise measurements were conducted across four typical areas: the triage, waiting area, treatment rooms, and the bridge. Based on acoustic monitoring guidelines and to capture the full diurnal acoustic dynamics, continuous noise monitoring was conducted over a 24-hour cycle for 20 consecutive days. To provide a clear temporal acoustic profile in line with national standards, the measurement timeframe was stratified into the Daytime period (06:00–22:00) and the Nighttime period (22:00–06:00) according to GB 50118-2010 (GB 50118-2010, 2010).

Objective noise levels were measured using Class 1 integrated sound level meters (SLM) AWA6228+ compliant with national GB/T 3785-2010 standards (GB/T 3785-2010, 2010). The devices were equipped with AWA 14421 prepolarized free-field microphones operating within a frequency range of 20 Hz to 12.5 kHz and a measurement range of 30 dB(A) to 130 dB(A). Prior to and following each 24-hour measurement cycle, the SLMs were rigorously calibrated using a multi-frequency calibrator AWA6223 F at a 94.0 dB nominal sound pressure level at 1 kHz, ensuring an error margin of strictly within ±0.5 dB(A). If this threshold was exceeded, the SLM was readjusted in accordance with the instrument manual and recalibrated before further measurements were taken. The entire measurement process adhered to the principles outlined in ISO 1996-2:2017 and GB 3096-2008 (ISO 1996-2:2017, 2017; GB 3096-2008, 2008).

For acoustic parameter analysis, three complementary A-weighted noise indicators were used: L_{Amin}, L_{Aeq}, and L_{Amax}. L_{Aeq} denotes the equivalent continuous A-weighted sound pressure level, that is, the constant sound level containing the same total acoustic energy as the time-varying sound over a given measurement period. In the present study, daily L_{Aeq} values refer to the 24-h equivalent continuous A-weighted sound pressure level calculated for each monitoring day. L_{Amax} and L_{Amin} denote, respectively, the maximum and minimum A-weighted sound pressure levels recorded during the same 24-h period. Because the sound level meter was operated using A-weighting and a Fast time response (125 ms), these indicators represent A-weighted Fast-response measurements. For each monitoring location, daily 24-h L_{Amin}, L_{Aeq}, and L_{Amax} values were obtained for 20 consecutive days, and the mean values with 95% confidence intervals were then calculated across days for statistical comparison. Simultaneously, one-third-octave band sound pressure levels from 20 Hz to 10 kHz were obtained using Z-weighting. Z-weighting provides a flat frequency response and was therefore used for spectral analysis to avoid the frequency-dependent attenuation introduced by A-weighting, especially at low frequencies, and to preserve the sound pressure levels in individual frequency bands for subsequent analysis (IEC 61672-1:2013, 2013; Leventhall, 2004).

Continuous 24-hour long-term (LT) noise monitoring was conducted for 20 consecutive days to capture typical fluctuations in noise levels during peak patient and visitor hours. The placement strategy for the sound level meters was tailored to the geometry and circulation characteristics of the ED. In the large and acoustically complex triage area, microphones were arranged in a three-point asymmetric configuration to ensure comprehensive spatial sampling. For waiting areas with regular shapes, a two-point diagonal arrangement was used to effectively cover the space. On the bridge, microphones were positioned along the central axis to minimize the impact of boundary reflections. Finally, a representative sampling strategy was applied to numerous similar treatment rooms, with a single sampling point placed at the approximate geometric center of two selected rooms (Figure 1). This method proved sufficient to characterize the sound field in these small rooms. At each indoor point, microphones were placed at heights of 1.2 m and 1.6 m above the floor, corresponding to the ear levels of seated and standing individuals, respectively. They were positioned at least 1 meter away from walls and other reflective surfaces, and approximately 1.6 meters from windows (ISO 3382-1:2009, 2009). The SLM was configured with A-weighting and a Fast time response (125 ms), recording data every 15 minutes. Noise measurements were performed using one-third-octave band sound pressure levels within the 20 Hz to 10 kHz frequency range. This method allows the collected data to characterize noise distributions at different frequencies, particularly those sensitive to human hearing. To quantify the traffic-noise component, an external weatherproof microphone was installed outside the ED main entrance. It was placed 2 meters from the building's glass curtain wall, with the microphone mounted outdoors at an elevation 1.5 meters above the indoor finished-floor level taken as the reference datum, in order to reduce reflection bias (ISO 16283-3:2016, 2016). It continuously recorded outdoor traffic and ambient noise synchronously with the indoor measurements over the 20-day, 24-hour period. The SLM integrates an internal Bluetooth module that transmits measurement results to the dedicated “AWA Monitor” app v2.3.1, supporting remote monitoring, data visualization, and export. The app serves solely as a tool for remote monitoring and data retrieval; it does not perform any calculations or modifications on the raw data collected by the SLM.

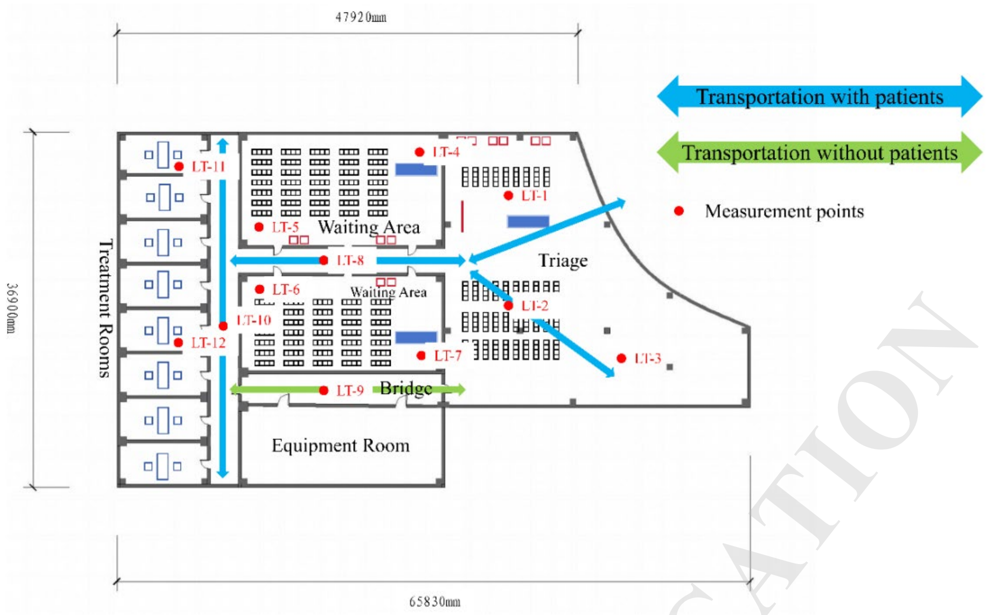

Fig. 1. Floor plan of the ED, 1st floor.

2.3. Questionnaire Survey

A structured questionnaire was developed, and a mixed-method survey approach was used to collect perception data separately from healthcare staff and from patients and visitors. The questionnaire included questions about the respondents' identity and sociodemographic information (age, educational background, occupation), but the three independent variables—position, shift, and work experience—applied only to healthcare staff. The dependent variable section for healthcare staff included thirty-two questions divided into seven parts: (a) overall perception (Part 1, two questions, addressing the sources and impact of noise); (b) the impact of noise on work efficiency (Part 2: three questions, addressing annoyance caused by environmental noise, lack of concentration, and equipment-related disturbance); (c) the impact of noise on negative emotions (Section 3, three questions: irritability, increased stress, and communication difficulties caused by noise); (d) the impact of noise on physical and mental health (Section 4, three questions: tinnitus, headaches, and accelerated or irregular heart rate caused by prolonged exposure to noise); (e) the attitude toward ambient noise (Part 5, four questions: subjective perception of noise levels, tolerance of noise, whether to report to hospital authorities, and whether to take noise reduction measures independently); (f) knowledge of noise pollution improvement (Part 6, two questions: hospital noise control standards and knowledge of noise reduction measures); (g) sensitivity to ambient noise (Part 7, one question: sensitivity to noise). The dependent variables for patients and visitors comprised nineteen questions divided into seven sections. Except for sections 2 and 6, the questions in the remaining sections are consistent with those for healthcare staff. (b) primarily addresses issues related to the efficiency of patient care, including the efficiency of medical consultations, recovery speed, and the overall experience of diagnosis and treatment. (f) includes improving patients' knowledge of noise prevention and enhancing family members' understanding of noise prevention measures (Zhang et al., 2025). For both questionnaires, each dimension score was obtained by summing the relevant items. Responses were recorded on a 5-point Likert scale, with 1 indicating “strongly disagree” and 5 indicating “strongly agree.” Higher scores indicate stronger perceived impact, more negative attitudes, or greater knowledge/sensitivity as appropriate to each dimension. Table 1 provides the full wording of each item, the scale construction method (total score/mean, percentile range), and reliability results. The complete questionnaires are provided in Appendix A. The questionnaire was administered to respondents via a WeChat-based survey platform. This program facilitated efficient and effective data collection through embedded controls, such as mandatory-response settings, and automatically stored responses for subsequent analysis.

Table 1. Full wording of questionnaire items, scale construction, and reliability by dimension

Dimension (code)	Description	Scoring method	Theoretical range	Cronbach’s α
A. Healthcare staff questionnaire				
Overall perception	The source of noise and the feeling of the overall acoustic environment	Sum of 2 items	——	——
F1: The impact of noise on work efficiency	Perceived interference of noise with work tasks	Sum of 3 items	3–15	0.945
F2: The impact of noise on negative emotions	Noise-induced emotional responses	Sum of 3 items	3–15	0.896
F3: The impact of noise on physical and mental health	Self-reported health effects from noise exposure	Sum of 3 items	3–15	0.955
F4: The attitude toward ambient noise	Overall perception and coping behaviors	Sum of 4 items	4–20	0.941
F5: Knowledge of noise pollution improvement	Awareness of noise standards and mitigation	Sum of 2 items	2–10	0.808
F6: Sensitivity to ambient noise	Personal sensitivity to acoustic environment	Single item	1–5	——

B. Patients and visitors questionnaire				
Overall perception	The source of noise and the feeling of the overall acoustic environment	Sum of 2 items	——	——
F1: The efficiency of patient care	Perceived interference with care experience	Sum of 3 items	3–15	0.878
F2: The impact of noise on negative emotions	Noise-induced emotional responses	Sum of 3 items	3–15	0.973
F3: The impact of noise on physical and mental health	Self-reported health effects from noise exposure	Sum of 3 items	3–15	0.947
F4: The attitude toward ambient noise	Overall perception and coping behaviors	Sum of 4 items	4–20	0.941
F5: Knowledge and prevention	Awareness of noise prevention	Sum of 2 items	2–10	0.824
F6: Sensitivity to ambient noise	Personal sensitivity to acoustic environment	Single item	1–5	——

Note: Since F6 (Sensitivity) consists of a single item, calculating Cronbach's α is not applicable.

2.4. Statistical Analysis

Except for Part 1, each question in all other parts uses a 5-point Likert scale (1 = strongly disagree; 2 = disagree; 3 = neutral; 4 = agree; 5 = strongly agree). The formal survey was conducted from February to April 2025. The recruitment criteria were: clinical healthcare staff who had been employed for over three months and conscious patients who had been hospitalized for over 48 hours, as well as their family members. Stratified quota sampling was used, with the healthcare staff group stratified by department and shift ($n = 102$) and the patient group stratified by disease type and age ($n = 107$). Healthcare staff completed an electronic questionnaire via QR code scanning (average completion time: 15 minutes), while patients and visitors were interviewed by trained investigators (average duration: 25 minutes). All procedures were conducted in an independent, low-noise environment (<50 dB(A)). The study was approved by the hospital's ethics committee, and all participants signed informed consent forms. 190 valid questionnaires were collected, including 99 from healthcare staff and 91 from patients and visitors.

Prior to statistical analysis, data were meticulously screened for completeness and consistency.

Missing data were handled using mean imputation, and outliers were identified and addressed via winsorization (Sharifnia et al., 2025). Descriptive statistics, including means, standard deviations, and frequencies, were calculated for all demographic and noise perception variables to summarize the characteristics of the study population and key variables. One-way Analysis of Variance (ANOVA) was employed to assess statistically significant differences in noise perception scores (F1-F6) across various demographic categories. Assumptions of normality were assessed using the Shapiro-Wilk test, and homogeneity of variances using Levene's test (González-Estrada et al., 2022). For significant ANOVA results, post-hoc analyses with Bonferroni correction were conducted to identify specific group differences. Pearson product-moment correlation coefficients were calculated to examine the linear relationships among the six scored noise-perception dimensions (F1-F6) in each group. The strength and direction of the correlations were interpreted. All statistical analyses were performed using SPSS software, version 14.0 (IBM Corp., Armonk, NY, USA). A two-tailed p-value of less than 0.05 was considered statistically significant for all tests.

3. Results

3.1. Sound Levels and Temporal Characteristics in the ED

Table 2 presents the daily 24-h L_{Amin}, L_{Aeq}, and L_{Amax} values for the four ED measurement locations over 20 consecutive monitoring days, while Figure 2 summarizes their mean values with 95% confidence intervals. Clear spatial differences were observed among the four areas. The triage exhibited the highest L_{Amin} (52.8 ± 0.6 dB(A)), indicating a persistently elevated background noise floor. In contrast, the treatment rooms and bridge showed the lowest L_{Amin} values (both 43.1 dB(A), with 95% CIs of ±1.3 and ±1.4 dB(A), respectively), suggesting relatively quieter minimum conditions. The bridge had the highest mean value (67.0 ± 0.5 dB(A)), followed by the triage (66.1 ± 0.5 dB(A)) and the waiting area (65.6 ± 0.4 dB(A)), whereas the treatment rooms showed the lowest mean L_{Aeq} (62.2 ± 0.6 dB(A)). These findings indicate that the bridge, triage, and waiting area were characterized by consistently high overall noise exposure. For L_{Amax}, the bridge again showed the highest value (82.3 ± 2.0 dB(A)), followed by the waiting area (79.2 ± 0.5 dB(A)), while the triage (76.2 ± 1.0 dB(A)) and treatment rooms (76.3 ± 1.1 dB(A)) showed slightly lower peak levels. Overall, the triage was characterized by the highest background noise, the bridge by the highest average and peak noise levels, and the treatment rooms by the lowest overall noise exposure despite occasional high-level events.

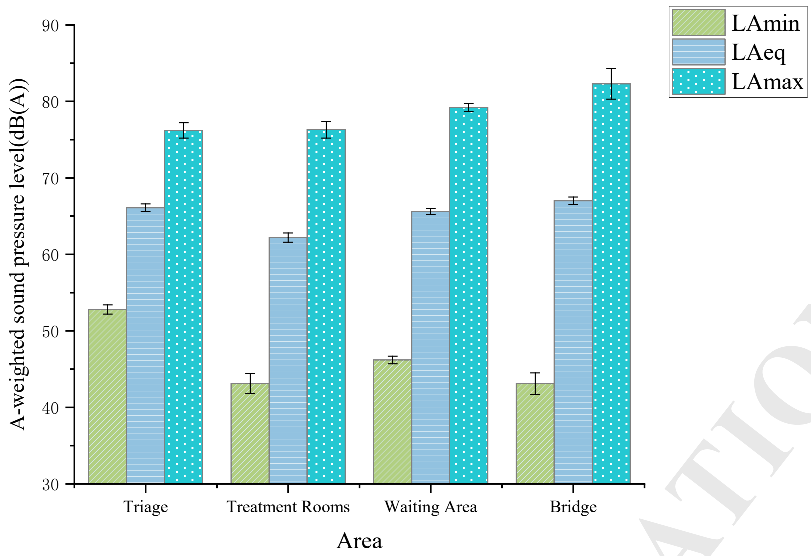

Fig. 2. Comparison of L_{Amin}, L_{Aeq}, and L_{Amax} across ED areas. Error bars indicate 95% confidence intervals.

Table 2. Daily 24-h L_{Amin}, L_{Aeq}, and L_{Amax} values for the four ED locations over 20 consecutive monitoring days; the bottom row shows the mean ± 95% CI across days.

Date	Triage			Treatment Rooms			Waiting Area			Bridge		
	L_{Amin}	L_{Aeq}	L_{Amax}	L_{Amin}	L_{Aeq}	L_{Amax}	L_{Amin}	L_{Aeq}	L_{Amax}	L_{Amin}	L_{Aeq}	L_{Amax}
Day1	51.0	64.3	73.8	41.4	62.4	76.8	45.0	65.6	77.8	40.4	65.5	82.0
Day2	53.9	66.9	76.4	41.1	62.1	76.5	47.3	66.2	80.1	41.7	66.3	82.5
Day3	53.4	66.4	75.9	40.6	62.0	76.2	46.6	66.0	79.8	44.8	69.2	85.5
Day4	51.8	64.9	74.3	38.6	60.2	74.0	45.3	64.7	78.5	41.8	66.4	82.6
Day5	50.8	65.5	77.5	38.6	60.5	74.2	44.8	64.2	78.0	41.0	65.6	81.8
Day6	53.7	67.2	76.5	39.0	60.8	74.4	47.7	66.6	80.5	42.9	67.2	83.5
Day7	55.3	67.3	81.9	38.9	61.3	84.5	45.1	65.8	78.5	41.6	67.2	82.4
Day8	53.4	66.8	76.2	42.0	63.0	77.4	45.5	64.4	78.3	55.9	65.2	63.7
Day9	54.2	65.6	76.7	46.3	63.5	76.9	45.0	64.4	78.2	43.7	68.3	84.5
Day10	53.7	66.8	76.2	46.0	63.3	76.6	46.9	66.3	80.1	43.3	67.9	84.1
Day11	51.7	64.8	74.2	43.7	61.1	74.1	45.0	64.4	78.2	41.5	66.1	82.3
Day12	51.6	64.7	74.1	43.7	61.2	74.3	44.8	64.2	78.0	41.1	65.7	81.9
Day13	52.7	67.4	79.4	43.8	61.3	74.4	47.4	66.8	80.6	43.9	68.2	84.5
Day14	53.7	68.6	80.4	43.9	61.4	74.5	48.2	67.1	81.0	43.4	68.0	84.2
Day15	52.8	65.9	75.3	44.7	62.2	75.3	46.1	65.5	79.3	42.3	66.9	83.1
Day16	54.0	66.8	76.5	46.2	63.7	76.8	47.2	66.6	80.4	43.5	68.1	84.3
Day17	51.4	64.9	74.2	45.7	63.2	76.3	46.7	66.1	79.9	43.0	67.6	83.8
Day18	51.8	64.9	74.3	47.0	64.7	81.1	45.1	64.5	78.3	41.4	66.0	82.2
Day19	51.5	64.6	74.0	43.7	61.2	74.3	45.9	65.0	77.1	40.7	66.0	82.5
Day20	54.3	67.1	76.8	46.6	64.1	77.2	47.6	67.0	80.8	44.0	68.6	84.8
95%	52.8	66.1	76.2	43.1	62.2	76.3	46.2	65.6	79.2	43.1	67.0	82.3
CI	±0.6	±0.5	±1.0	±1.3	±0.6	±1.1	±0.5	±0.4	±0.5	±1.4	±0.5	±2.0

Analysis of the 20-day continuous monitoring data reveals persistent noise pollution across all ED functional zones (Figure 3). The L_{Aeq} fluctuated between 39.8 dB(A) and 72.1 dB(A), exhibiting a clear diurnal pattern aligned with hospital operation cycles. The triage and waiting area remained the most noise-intensive, characterized by a high-level "plateau" (65.4–72.1 dB(A)) from 06:00 to 22:00. Even during nighttime, noise levels in these zones hovered between 52.9 and 58.2 dB(A), consistently exceeding the WHO and national (GB 50118-2010) nighttime limit of 35 dB(A) (GB 50118-2010, 2010). In contrast, the treatment rooms and bridge showed more pronounced fluctuations, with minimum levels recorded around 03:00. However, peak-hour noise in treatment rooms still frequently exceeded 60 dB(A) due to medical activities and alarms. These results suggest that opportunities for an "acoustic recovery window" were limited in the ED, which may help explain the noise-related fatigue reported in the subjective surveys.

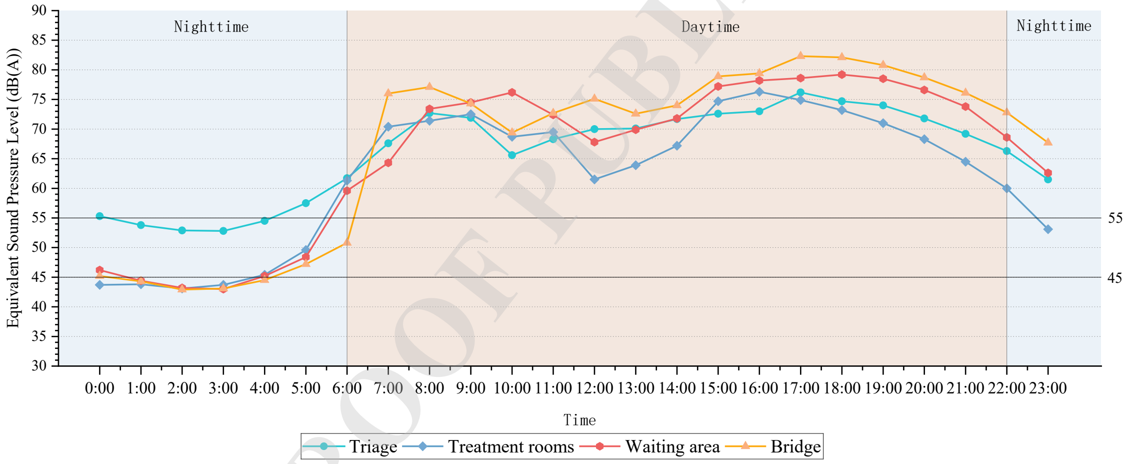

Fig. 3. Average diurnal profile of L_{Aeq} in four typical areas.

Unweighted sound pressure levels in the 20 to 31.5 Hz low-frequency range exceeded 45 dB SPL, indicating significant low-frequency equipment operational noise. The curve shown in Figure 4 has a mountain-shaped profile with a distinct peak around 500 Hz, suggesting that human speech was strongly associated with the dominant spectral peak in the ED. However, this spectral pattern alone does not establish speech as the sole source of disturbance. Additional source-specific analyses would be needed to quantify the contribution of different sound sources in each area. The time during which noise levels exceeded 50 dB(A) accounted for 50% of the total time in all four measurement areas. The time during which noise levels exceeded the lower limit standard of GB 50118-2010 (45 dB) accounted for 90% of the total time in each measurement area. This finding provides objective frequency data to support the communication difficulties commonly reported in subsequent subjective perception questionnaires, while also identifying specific targets for targeted acoustic modifications.

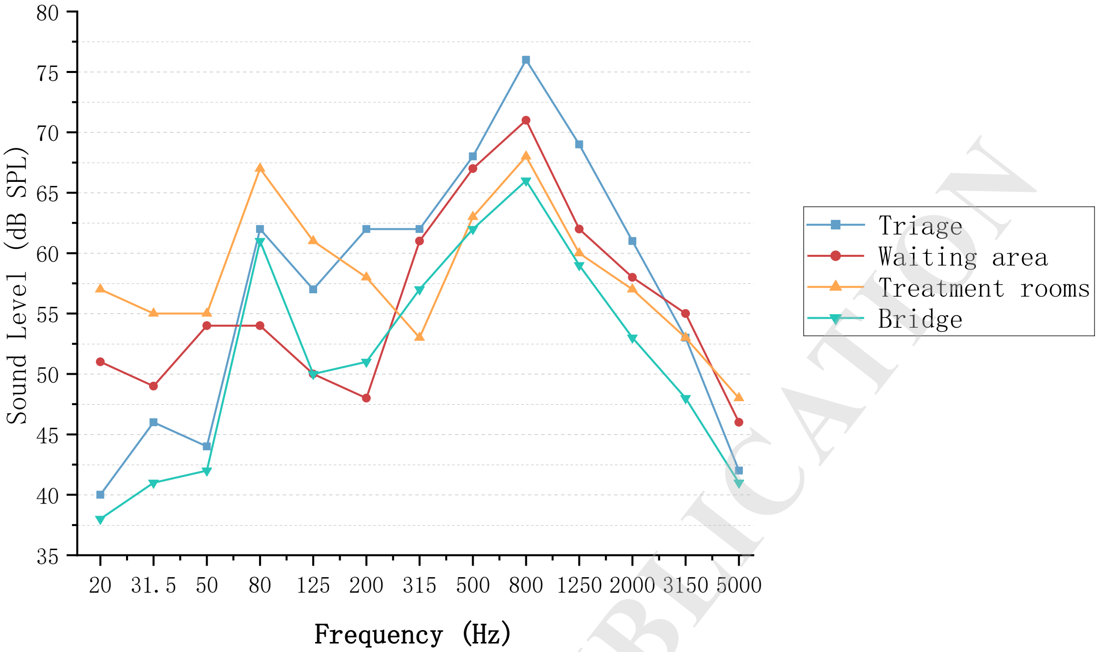

Fig. 4. One-third-octave-band sound pressure levels in the ED.

3.2 Effects of External Traffic and ED Occupancy on Zonal Noise Levels

To elucidate the specific drivers of the ED acoustic environment and address the potential influence of the building's large glass glazing, continuous 24-hour monitoring was conducted. Figure 5 illustrates the diurnal acoustic profile overlaid with hourly ED occupancy. External traffic noise maintained a consistently high baseline throughout the daytime, peaking at approximately 77 dB(A) during rush hours. Even during nighttime, external levels rarely dropped below 71 dB(A), reflecting the persistent nocturnal influx of emergency vehicles typical of a city-center tertiary hospital. Notably, indoor noise levels broadly tracked fluctuations in ED occupancy. During daytime and evening peak hours, indoor noise levels consistently exceeded the external traffic noise. This temporal co-variation suggests that indoor-noise fluctuations were associated with the combined influence of the external acoustic environment and internal ED activity intensity.

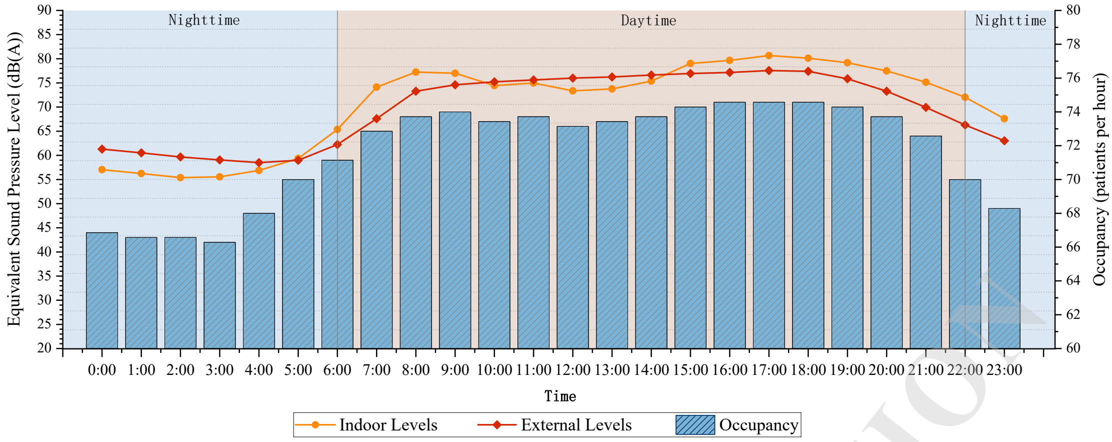

Fig. 5. Hourly profiles of outdoor noise, indoor noise, and ED patient flow.

The correlation analysis provided quantitative support for this pattern. Outdoor L_{Aeq} was strongly and positively associated with indoor noise levels in all monitored areas, including the overall indoor L_{Aeq} (r = 0.993), triage (r = 0.883), treatment rooms (r = 0.835), waiting area (r = 0.857), and bridge (r = 0.817), with statistically significant correlations according to the significance markers reported in Table 3. ED patient flow also showed consistent positive associations with noise levels across all indoor areas. The correlation coefficients between hourly patients per hour and noise levels were 0.667 for the overall indoor L_{Aeq}, 0.776 for triage, 0.765 for treatment rooms, 0.814 for the waiting area, and 0.738 for the bridge. Among these, the waiting area showed the strongest association with patient flow, followed by triage and treatment rooms. This pattern is acoustically plausible, because these areas are the most directly affected by patient conversations, broadcast, rolling of trolley wheels, doors opening or closing and children frolicking. In contrast, the somewhat lower coefficient observed for the bridge suggests that although this space remained sensitive to occupancy-related activity, it may have been less directly exposed to the most intense patient-centered noise-generating processes.

Table 3. Spearman correlation coefficient between external noise, patient occupancy, and indoor sound levels across specific ED zones

Variable	Indoor L_{Aeq}	Triage L_{Aeq}	Treatment rooms L_{Aeq}	Waiting area L_{Aeq}	Bridge L_{Aeq}
Outdoor L_{Aeq}	0.993**	0.883**	0.835**	0.857**	0.817*

Variable	Indoor L_{Aeq}	Triage L_{Aeq}	Treatment rooms L_{Aeq}	Waiting area L_{Aeq}	Bridge L_{Aeq}
Patients per hour	0.667**	0.776**	0.765**	0.814**	0.738*

3.3. Noise Source Perception

There was a significant discrepancy between healthcare staff and patients/visitors in their perception of dominant noise sources (Table 4). 87.9% of healthcare staff identified patient conversations as the primary noise source, followed by air conditioning operation and children frolicking, at 68.7% and 64.6%, respectively. Over half of healthcare staff identified broadcast as a primary noise source. Healthcare staff did not perceive call bells at nursing stations and rolling of trolley wheels as significant, at 21.2% and 19.2%, respectively. Follow-up interviews revealed they had become accustomed to such noises.

Among patients and visitors, 84.6% identified call bells at nursing stations as a primary noise source, and many described the sound as extremely piercing (data not shown). Over 60% of patients listed broadcasts, shouting between doctors and nurses, television sets, rolling of trolley wheels, and doors opening or closing as primary noise sources. This perceptual gap highlights a critical management issue: sounds essential for clinical operation (call bells, staff communication) are perceived as intrusive noise by patients, suggesting that the current design and management of these auditory signals may not adequately balance operational needs and user comfort.

Table 4. Views of healthcare staff and patients on the main sources of noise from ED

Noise Sources	Healthcare Staff	Patients and Visitors
	Number (percentage)	Number (percentage)
Patient conversations	87 (87.9%)	54 (59.3%)
Shouting between doctors and nurses	37 (37.4%)	65 (71.4%)
Call bells at nursing stations	21 (21.2%)	77 (84.6%)
Rolling of trolley wheels	19 (19.2%)	61 (67.0%)
Doors opening or closing	23 (23.2%)	55 (60.4%)
Broadcast	51 (51.5%)	69 (75.8%)
Phone ringing	34 (34.3%)	14 (15.4%)

Seat movement	28 (28.3%)	42 (46.2%)
Children frolicking	64 (64.6%)	37 (40.7%)
Television sets	39 (39.4%)	63 (69.2%)
Air conditioning operation	68 (68.7%)	26 (28.6%)
Footsteps	25 (25.3%)	8 (8.8%)
Others	7 (7.1%)	13 (14.3%)

3.4. Noise Perception Analysis of Healthcare Staff

An in-depth analysis of healthcare staff reveals that their subjective perception of noise is influenced by a complex interplay of job attributes and individual factors (Table 5). One of the most significant findings is the pronounced effect of work shifts: Graveyard shift workers reported significantly higher intensity across all negative dimensions—including impaired work efficiency ($p = 0.007$), worsened emotional state ($p < 0.001$), and compromised physical and mental health ($p < 0.001$)—compared to day shift workers. This indicates that the disruptive effects of noise are amplified during the inherently sensitive nighttime period, suggesting that graveyard shift staff may be more vulnerable to noise-related disturbance and therefore warrant particular attention. Occupational role also proved a significant factor: nurses reported substantially higher noise-induced negative emotions and work efficiency disruption than physicians ($p = 0.045$). This likely stems from nurses' more stationary work positions, proximity to primary noise sources, and higher communication frequency, highlighting the unique challenges faced by frontline nursing staff. A particularly insightful finding concerns cognitive adaptation: data indicate that employees with over five years of experience, while reporting higher levels of noise management knowledge ($p < 0.001$), perceive lower impacts on physical and mental health compared to the mid-career group. This suggests that prolonged exposure may foster psychological compensation or habituation mechanisms, providing a crucial entry point for designing employee support and training programs.

Table 5. Statistical analysis of subjective perception of environmental noise by healthcare staff

Factor & Subgroup	n	F1	F2	F3	F4	F5	F6
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
Educational background							
Below-college	21	7.67 ± 0.84	9.89 ± 0.85	9.52 ± 0.38	4.48 ± 0.22	4.86 ± 0.49	1.90 ± 0.36
Undergraduate	43	7.84 ± 0.54	7.84 ± 0.55	8.35 ± 0.55	8.79 ± 0.20	5.51 ± 0.34	2.88 ± 0.27
Master's+	35	8.23 ± 0.59	6.86 ± 0.55	8.80 ± 0.54	14.40 ± 0.30	5.80 ± 0.36	3.00 ± 0.30
p-value		<0.001	0.002	0.003	<0.001	0.001	0.164
Work position							
Doctor	44	6.89 ± 0.52	6.44 ± 0.54	10.56 ± 0.46	6.66 ± 0.21	2.50 ± 0.08	0.83 ± 0.19

Factor & Subgroup	n	F1	F2	F3	F4	F5	F6
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
Nurse	36	8.45 ± 0.51	9.72 ± 0.55	8.21 ± 0.42	11.67 ± 0.22	5.50 ± 0.08	1.97 ± 0.15
Administration	7	9.29 ± 1.08	8.38 ± 0.72	8.71 ± 1.39	15.86 ± 0.34	8.43 ± 0.20	3.00 ± 0.14
Others	12	9.28 ± 0.92	9.89 ± 1.08	6.50 ± 1.28	17.00 ± 0.25	9.42 ± 0.19	3.89 ± 0.21
p-value		0.016	0.045	<0.001	0.359	<0.001	0.036
Work experience (years)							
< 1	18	9.56 ± 0.60	5.17 ± 0.51	7.03 ± 0.93	10.39 ± 1.06	4.50 ± 0.12	1.98 ± 0.23
1-3	29	10.48 ± 0.48	8.62 ± 0.52	10.44 ± 0.55	11.41 ± 0.79	6.48 ± 0.09	1.81 ± 0.22
3-5	34	11.12 ± 0.39	8.94 ± 0.66	8.32 ± 0.58	11.65 ± 0.69	8.32 ± 0.15	1.86 ± 0.67
> 5	18	11.89 ± 0.49	8.94 ± 0.86	6.56 ± 1.01	11.78 ± 0.98	8.78 ± 0.30	3.83 ± 0.32
p-value		0.004	0.003	0.001	0.001	<0.001	<0.001
Work shift							
Day shift	35	7.00 ± 0.41	6.02 ± 0.35	7.19 ± 0.56	4.69 ± 0.20	3.84 ± 0.29	2.14 ± 0.20
Graveyard shift	64	9.06 ± 0.61	9.00 ± 0.48	9.46 ± 0.44	9.40 ± 0.35	6.26 ± 0.21	2.89 ± 0.23
p-value		0.007	<0.001	<0.001	<0.001	0.146	0.016

Figure 6 reveals the systematic correlation between the various dimensions of healthcare staff's noise perception. The results show that noise interference with work efficiency is highly positively correlated with improved cognitive levels, and is also significantly positively correlated with noise tolerance, indicating that individuals with a more systematic understanding of acoustic environment management are more sensitive to the substantial impact of noise on work processes. Noise tolerance, as a core hub dimension, is not only strongly correlated with improved cognitive function but also significantly linked to noise sensitivity, confirming that a reduced tolerance threshold simultaneously enhances the ability to perceive changes in the acoustic environment. Notably, physical and mental health damage is negatively correlated with noise sensitivity, reflecting that long-term health damage leads to a decline in perceptual adaptability. The negative emotion dimension maintains relative independence, showing only weak correlations with other indicators, highlighting its characteristic of being dominated by individual psychological regulatory mechanisms. Improved cognition plays a core pivotal role: it maintains moderate to high positive correlations with work efficiency, tolerance, and sensitivity, indicating that enhancing management cognition can simultaneously optimize multi-dimensional noise experiences. These findings suggest that healthcare institutions should prioritize strengthening healthcare staff's cognitive levels through noise management training, with a focus on establishing a three-tier prevention and control system comprising “cognitive intervention-health monitoring-psychological support.”

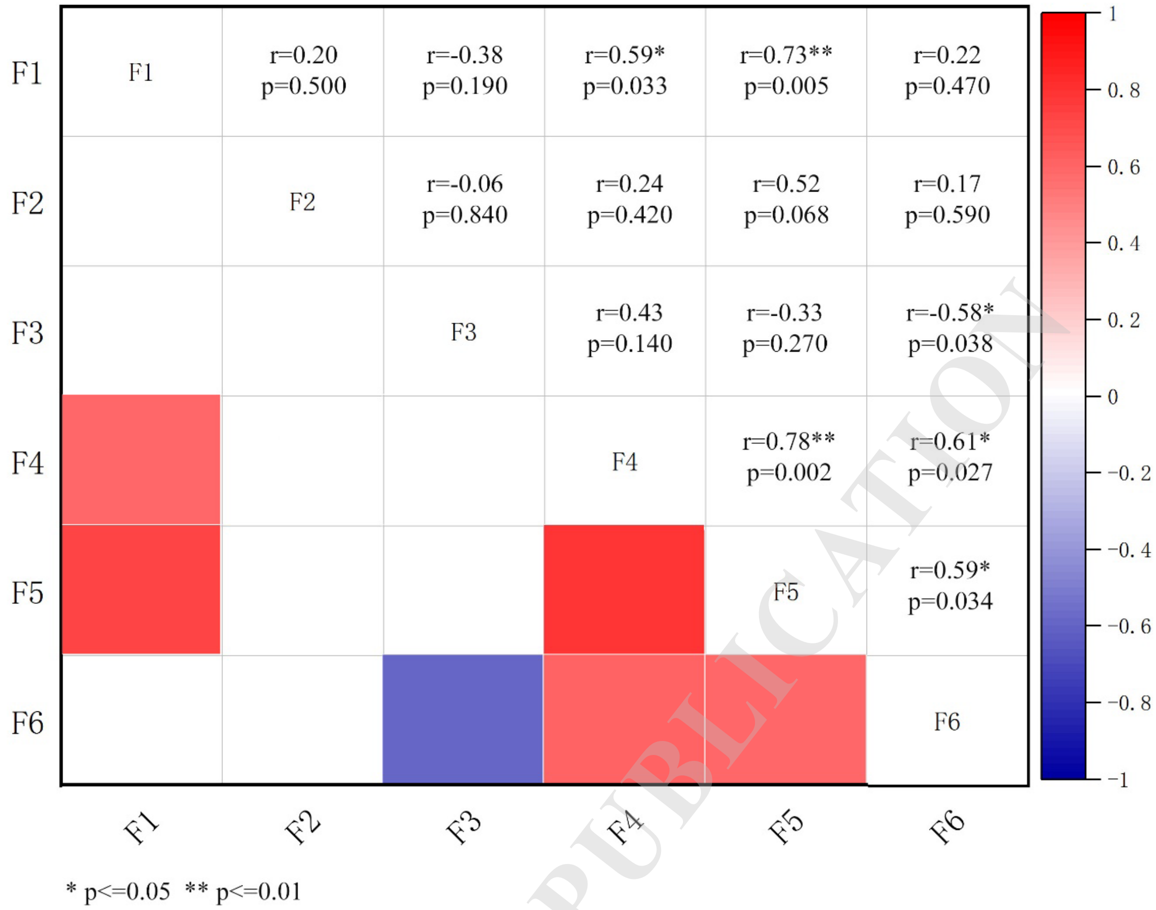

Fig. 6. Correlation matrix of noise perception dimensions for healthcare staff (n = 99).

Upper triangle shows Pearson's correlation coefficient (r) and corresponding p-values.

Only correlations significant after Bonferroni correction are marked (* $p \leq 0.05$, ** $p \leq 0.01$).

* F1-The impact of noise on work efficiency; F2-The impact of noise on negative emotions; F3-The impact of noise on physical and mental health; F4-The attitude toward ambient noise; F5-Knowledge of noise pollution improvement; F6-Sensitivity to ambient noise.

3.5. Noise Perception Analysis of Patients and Visitors

Analysis of patient and visitor groups reveals that noise perception is an emotion-driven psychological response heavily modulated by identity and background (Table 6). Data analysis indicates that identity attributes are the most critical influencing factor. Visitors scored significantly higher than patients across all negative dimensions (all $p < 0.01$). They reported more severe work efficiency disruption, stronger negative emotions (such as anxiety and irritability), higher perceived health risks, and greater noise sensitivity. This disparity stems from their fundamentally different psychological states: patients exhibit a degree of "patient tolerance" due to physical discomfort and role expectations; whereas visitors, caught in a state of waiting and uncertainty, experience heightened helplessness and concern for patients, significantly amplifying the negative impact of noise and making it a major environmental stressor. Educational background emerged as another critical factor. Individuals with bachelor's degrees or higher demonstrated significantly greater work efficiency disruption and noise sensitivity ($p < 0.001$). This likely stems from their greater familiarity with quiet, controlled work environments, lower adaptation thresholds to chaotic soundscapes, and cognitive functions more susceptible to noise disruption. Age similarly modulates noise effects. Middle-aged and older respondents aged 41 and above reported greater physical and mental health impacts than younger individuals ($p = 0.008$). This may relate to declining physiological noise tolerance with age or heightened sensitivity to environmental stressors due to underlying health conditions. The findings indicate that noise responses among patients and visitors result from the interplay of psychological states, social identities, and physical environments. Understanding these differentiated response patterns is crucial for designing precise, human-centered noise management strategies.

Table 6. Statistical analysis of subjective perception of environmental noise by patients and visitors

Factor & Subgroup	n	F1	F2	F3	F4	F5	F6
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
Educational background							
Below-college	59	4.68 ± 0.19	8.88 ± 0.44	9.15 ± 0.48	8.97 ± 0.47	8.25 ± 0.46	6.34 ± 0.38
Undergraduate	28	8.79 ± 0.30	9.14 ± 0.70	9.46 ± 0.68	7.14 ± 0.69	10.29 ± 0.76	9.86 ± 0.67
Master's+	4	13.00 ± 0.91	13.25 ± 0.63	8.25 ± 2.78	7.75 ± 1.03	11.50 ± 2.53	10.75 ± 1.65
p-value		<0.001	0.191	0.893	0.029	0.008	<0.001
Occupation							
Company employee	29	4.97 ± 0.47	3.52 ± 0.35	5.66 ± 0.51	6.52 ± 0.45	6.34 ± 0.47	4.48 ± 0.42
Government-affiliated	21	6.20 ± 0.63	5.65 ± 0.36	5.85 ± 0.51	5.20 ± 0.46	5.10 ± 0.57	5.25 ± 0.55
Liberal professions	38	6.28 ± 0.42	4.95 ± 0.38	6.28 ± 0.40	5.54 ± 0.36	6.92 ± 0.38	5.82 ± 0.42
Others	3	9.00 ± 0.58	9.00 ± 0.58	7.67 ± 1.20	7.67 ± 1.20	7.00 ± 1.73	6.67 ± 1.76
p-value		0.037	0.006	0.086	0.649	0.045	0.042
Age (years)							
< 20	17	4.41 ± 0.61	5.35 ± 0.66	4.12 ± 0.52	4.35 ± 0.45	4.82 ± 0.51	5.00 ± 0.68
21-40	47	5.81 ± 0.42	5.94 ± 0.36	5.23 ± 0.35	5.09 ± 0.34	5.00 ± 0.33	6.11 ± 0.40

Factor & Subgroup	n	F1	F2	F3	F4	F5	F6
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
41-60	25	6.68 ± 0.58	6.28 ± 0.46	6.00 ± 0.54	6.92 ± 0.47	7.12 ± 0.51	6.76 ± 0.46
> 60	2	7.50 ± 1.50	5.00 ± 3.00	8.00 ± 2.00	10.00 ± 0.00	9.00 ± 1.00	8.50 ± 0.50
p-value		0.009	0.359	0.008	<0.001	<0.001	0.020
Identity							
Patients	26	5.92 ± 0.32	5.65 ± 0.28	6.23 ± 0.39	5.50 ± 0.25	11.54 ± 0.83	7.12 ± 0.75
Visitors	65	11.00 ± 0.67	11.85 ± 0.66	11.46 ± 0.65	12.71 ± 0.61	12.46 ± 0.62	11.65 ± 0.60
p-value		<0.001	0.006	<0.001	<0.001	0.237	0.001

Figure 7 reveals the unique association patterns among the various dimensions of noise perception in patients and their families. Negative emotions are highly positively correlated with physical and mental health damage, and both are significantly positively correlated with noise tolerance, forming a core association cluster of “emotion-health-tolerance,” showing that emotional distress exacerbates perceived health risks and significantly lowers noise tolerance thresholds. Notably, work efficiency interference shows a moderate positive correlation with negative emotions but weak associations with other dimensions, suggesting that work efficiency impacts are primarily mediated through emotional pathways. Noise sensitivity exhibits a unique isolation, showing no significant associations with any dimensions and reflecting its perceptual independence. Improved cognition exhibits a dual-pathway influence: it is significantly positively correlated with physical and mental health and negative emotions, but has no substantial association with tolerance, showing that while cognitive enhancement cannot directly improve tolerance, it can indirectly optimize sound environment experiences by alleviating health damage. The aforementioned association patterns reveal that noise perception in patient populations centers on emotional health, forming a stark contrast to the association structure centered on cognitive management among healthcare staff.

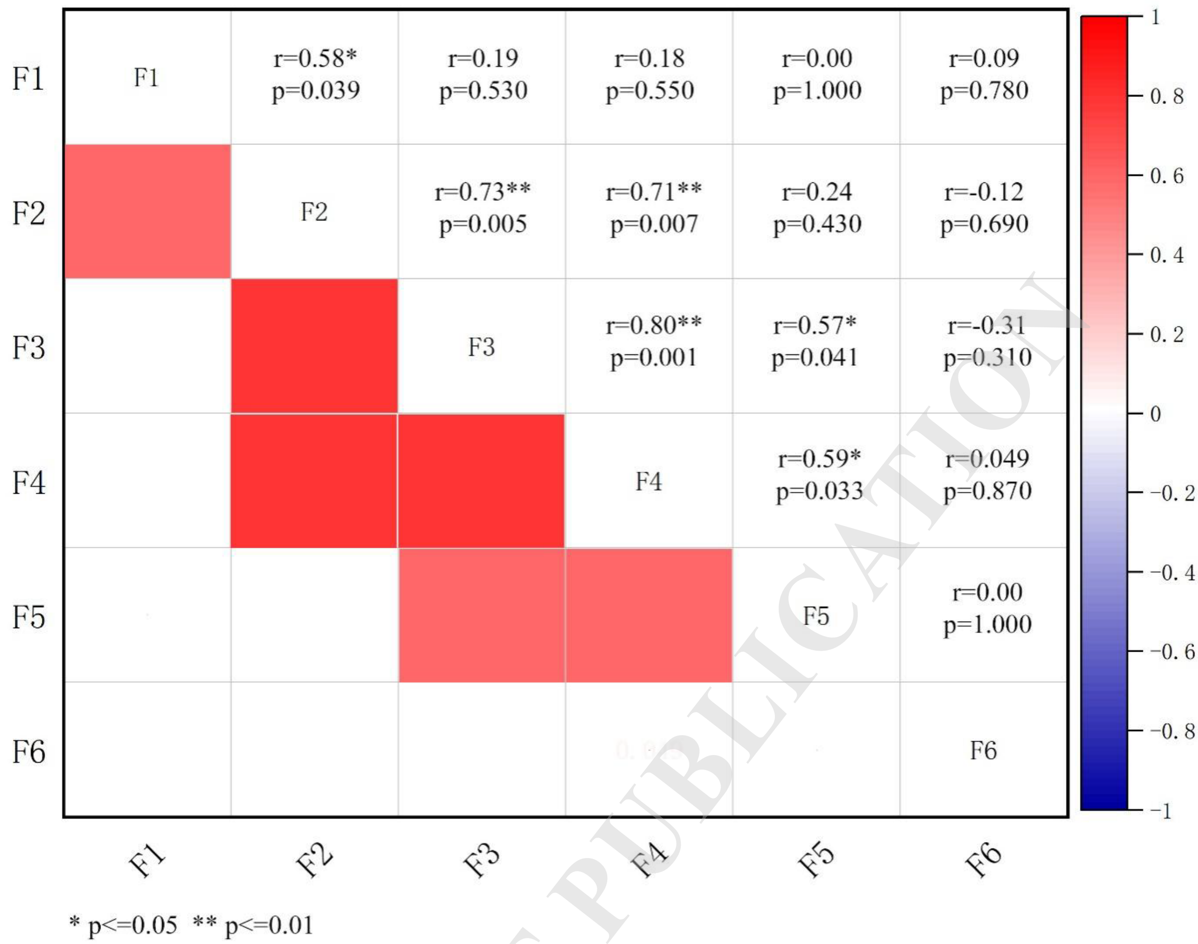

Fig. 7. Correlation matrix of noise perception dimensions for patients and visitors (n = 91).

Upper triangle shows Pearson's correlation coefficient (r) and corresponding p-values.

Only correlations significant after Bonferroni correction are marked (* p ≤ 0.05, ** p ≤ 0.01).

* F1-The impact of noise on work efficiency; F2-The impact of noise on negative emotions; F3-The impact of noise on physical and mental health; F4-The attitude toward ambient noise; F5-Knowledge of noise pollution improvement; F6-Sensitivity to ambient noise.

4. Discussion

This study conducted a comprehensive, multi-method analysis of noise pollution in the ED of a large tertiary hospital in China, yielding two key findings: First, objective acoustic measurements suggested severe and persistent noise pollution, with levels far exceeding international and national guidelines. Second, and more importantly, we identified a fundamental dichotomy in noise perception mechanisms: healthcare staff develop cognitive adaptation, while patients and visitors exhibit emotion-driven responses. This separation not only explains the differing priorities of noise sources among these groups but also provides a novel theoretical lens for developing targeted, evidence-based noise mitigation strategies.

4.1. Interpretation of Key Findings

Our objective measurements confirmed severe and persistent noise pollution across all monitored ED areas. Based on the 20-day monitoring dataset, mean daily 24-h L_{Aeq} values ranged from 62.2 ± 0.6 dB(A) in the treatment rooms to 67.0 ± 0.5 dB(A) on the bridge, with similarly elevated values at the triage (66.1 ± 0.5 dB(A)) and in the waiting area (65.6 ± 0.4 dB(A)). These values consistently exceeded the relevant WHO and national guideline levels, indicating that excessive noise was not confined to isolated events but represented a persistent feature of the ED acoustic environment. This overall pattern is consistent with the well-documented global trend of excessive hospital noise (Hampton et al., 2023; Song et al., 2023; Hendriks et al., 2024). Spectral analysis focusing on 500 Hz human speech as the primary noise source is important, aligning with studies identifying staff and patient conversations as major contributors (Kumar, 2024; Latif et al., 2021). However, our frequency-specific evidence demonstrates a strong association between staff-reported communication failures and elevated noise levels at 500 Hz, rather than a definitive causal relationship. The perceived intrusiveness of call bells was the most prominent concern among visitors (84.6%), which may mask or interfere with speech intelligibility within this critical frequency range, potentially creating a vicious cycle where poor acoustic performance may cause louder communication, further increasing noise levels.

The most striking finding lies in the profound perceptual gap between the two core groups. Healthcare staff, through prolonged and inevitable exposure, appear to have undergone a process of professional habituation or cognitive adaptation. This is evidenced by their reports of equipment-related noise encountered daily (call bells: 21.2%, carts: 19.2%), and more importantly, statistical relationships suggest that knowledge of noise management may be associated with lower perceived work-efficiency impacts. This suggests that, for staff, noise is to some extent a controllable cognitive load rather than an uncontrollable stressor. This finding refines the widely held view that noise is a pervasive negative stressor for healthcare staff, introducing the concept of adaptive resilience (Obeng and Atan, 2024; Mrklas et al., 2020; Cao et al., 2023). In contrast, for patients and visitors, the hospital soundscape is a novel, unpredictable, and often threatening environment. Their perceptions are primarily emotional and emotionally loaded. The strong correlation between negative emotions and perceived health risks suggests that, for this group, noise may be perceived as threatening to well-being and may be related to variation in perceived health risks. This pattern may reflect the difficulty of seeking rest and peace while recovering or supporting loved ones in a noisy hospital environment (Lin et al., 2022; Wadhwa, 2023).

4.2. Theoretical and Practical Implications

This study challenges the homogenized focus on hospital residents in acoustic research. By describing the cognitive-emotional dichotomy in noise assessment, we provide a more nuanced framework for understanding environmental stress in healthcare settings (Gao et al., 2021). Staff adaptation mechanisms align with the theory of learned helplessness transforming into habit under extreme conditions, while visitor responses align with the environmental stress model, where lack of control and uncertainty exacerbate negative outcomes (Marmo and Hirsch, 2022; Huang et al., 2025). From a practical perspective, our findings advocate a shift from generic quiet campaigns to precise acoustic interventions. First, architectural interventions must target the 500 Hz frequency with specific sound-absorbing materials on ceilings and walls, particularly in triage and waiting area. Second, addressing the high-pitched auditory call bells is hypothesized to be beneficial. Replacing them with softer, melodic, localized signals could potentially mitigate visitor distress. However, we clearly state that this is a hypothesis requiring future empirical testing. Subsequent studies must employ Speech Transmission Index (STI) or Modulation Transfer Function (MTF) analyses in simulated ED backgrounds to ensure that redesigning these alerts does not compromise clinical functionality and speech intelligibility. Third, visitor flow management through scheduled visit times, clear zoning, and real-time noise level displays can directly reduce conversation noise from primary sources. Finally, employee training and support must be tiered; mandatory noise management modules should be incorporated into onboarding training, and specialized support such as stress management techniques and ergonomically designed break times should be provided, particularly for graveyard shift workers and nurses.

4.3. Limitations and Future Research

This study has several limitations. First, it was conducted in the ED of a regional hospital, which may limit the generalizability of the findings. Future studies should include multiple ED across different geographic and cultural contexts. Second, the cross-sectional design captured perceptions at a single point in time; longitudinal studies are needed to track how noise perceptions evolve over extended hospital stays or career spans. Third, while our questionnaires were validated, they rely on self-reported data, which may be biased. Future studies could incorporate objective physiological measures to triangulate subjective reports of stress and health impacts. Finally, the effectiveness of interventions proposed based on our cognitive-emotional model should be tested through randomized controlled trials in real-world clinical settings.

5. Conclusion

This study documented severe and persistent noise pollution in the investigated ED. Across the four monitored areas, mean daily 24-h L_{Aeq} values ranged from 62.2 to 67.0 dB(A), exceeding the World Health Organization (WHO) guideline value and the Chinese GB 50118-2010 standard value. Spectral analysis suggested that the dominant spectral peak around 500 Hz was strongly associated with human speech and was also associated with staff-reported communication difficulties and visitor complaints about piercing call bells. Althahab et al. reached similar conclusions through deep learning and provided a starting point for further research in this field (Althahab et al., 2024). Crucially, the perceptual results suggest that healthcare staff may develop cognitive adaptation mechanisms, suggesting that knowledge of noise management may be associated with lower perceived work-efficiency impacts, while graveyard shift workers face significantly higher health risks. In contrast, patients and visitors exhibit emotion-driven responses, with negative emotions mediating the variability of health risks, and higher-educated individuals reporting significantly higher levels of work interruption than those with lower education.

This study's findings necessitate comprehensive noise control strategies targeting the identified spectral, behavioral, and cognitive vulnerabilities. Visitor management programs should be prioritized to reduce conversational noise—identified by 87.9% of healthcare staff as a primary source—through scheduled visiting hours and designated quiet zones, particularly in triage and waiting area. Concurrently, auditory alert redesign is critical to minimize spectral masking of human speech, addressing visitors' pervasive distress over piercing call bells while maintaining clinical functionality. Architectural interventions must integrate frequency-specific absorption materials (>500 Hz) in high-traffic spaces, complemented by prominent bilingual signage illustrating real-time noise levels to enhance environmental awareness.

For healthcare staff, shift-adapted training modules leveraging their demonstrated cognitive adaptation capacity should be implemented, equipping graveyard shift personnel—who endure higher health risks—with evidence-based coping techniques for noise-mediated stress. Patient-centered interventions require emotion-focused acoustic interventions incorporating nature-based masking sounds, especially for highly educated visitors. As demonstrated by the strong correlation between noise exposure, subjective perception, and self-reported health impacts, this comprehensive approach addresses the core issue of acoustic environmental mismatch in clinical spaces, advancing the World Health Organization (WHO) goal of "making hospitals safer" through precise acoustic design.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS' CONTRIBUTION

Guangxing Wang made the primary contribution to the investigation, data collection, formal analysis, figure preparation, original draft preparation, and manuscript revision. Nuowei Zhang contributed to the conceptualization, research design, supervision, project administration, and funding acquisition. Houlai Lin contributed to data interpretation and critical review and editing of the manuscript. All authors reviewed and approved the final version of the manuscript.

ETHICAL APPROVAL

The study was conducted in accordance with the Declaration of Helsinki and was approved by the ethics committee of the study hospital and Ruison Lean Construction Co., Ltd. Informed consent was obtained from all participants. All data were anonymized prior to analysis.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A: Hospital Noise Perception Questionnaire

Survey Instructions

Please evaluate each statement based on your actual experience in the hospital. Thank you for participating in this study on noise perception in emergency department (ED). Your answer is completely anonymous and confidential, and is only used for academic research purposes. There is no right or wrong answer. Please answer based on your own experience. For the scoring sections, please tick the box that best represents your level of agreement:

(1) Strongly Disagree, (2) Disagree, (3) Neutral, (4) Agree, (5) Strongly Agree.

Part I: Sociodemographic Information

1. What is your current role in the hospital?

[ ] Healthcare Staff [ ] Patient [ ] Visitor/Family Member

2. Age: [ ] < 25 [ ] 25–35 [ ] 36–45 [ ] 46–55 [ ] > 55

3. Educational Background:

[ ] High School or below [ ] Associate Degree [ ] Bachelor's Degree [ ] Master's or above

[Healthcare Staff Only]

4. Position: [ ] Doctor [ ] Nurse [ ] Technician [ ] Admin

5. Shift: [ ] Day shift [ ] Graveyard shift

6. Work Experience: [ ] < 1yr [ ] 1–5yrs [ ] 6–10yrs [ ] > 10yrs

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Part II: Perception Assessment (Healthcare Staff)

Section 1: Overall Perception
7. What do you perceive as the primary sources of noise in the ED? (Select all that apply) [ ] Patient conversations [ ] Shouting between doctors and nurses [ ] Call bells at nursing stations [ ] Rolling of trolley wheels [ ] Doors opening or closing [ ] Broadcast/PA system [ ] Phone ringing [ ] Seat movement [ ] Children frolicking [ ] Television sets [ ] Air conditioning operation [ ] Footsteps [ ] Others: __________
8. How would you describe the overall impact of the noise on your experience in the ED? [ ] No impact [ ] Mild impact [ ] Moderate impact [ ] Severe impact

Section 2: The impact of noise on work efficiency	1	2	3	4	5
9. I frequently feel annoyed by environmental noise while working.	[ ]	[ ]	[ ]	[ ]	[ ]
10. Environmental noise causes a lack of concentration.	[ ]	[ ]	[ ]	[ ]	[ ]
11. Noise from office/medical equipment interferes with efficiency.	[ ]	[ ]	[ ]	[ ]	[ ]

Section 3: The impact of noise on mood	1	2	3	4	5
12. Hospital noise makes me feel irritable.	[ ]	[ ]	[ ]	[ ]	[ ]
13. Noise significantly increases my work-related stress.	[ ]	[ ]	[ ]	[ ]	[ ]
14. Background noise causes communication difficulties.	[ ]	[ ]	[ ]	[ ]	[ ]

Section 4: The impact of noise on physical and mental health	1	2	3	4	5
15. Prolonged exposure causes me to experience tinnitus.	[ ]	[ ]	[ ]	[ ]	[ ]
16. The noise environment triggers or exacerbates my headaches.	[ ]	[ ]	[ ]	[ ]	[ ]
17. I experience accelerated heart rate due to noise exposure.	[ ]	[ ]	[ ]	[ ]	[ ]

Section 5: The attitude toward ambient noise	1	2	3	4	5
18. I perceive the noise level in my environment as excessively high.	[ ]	[ ]	[ ]	[ ]	[ ]
19. I have a very low tolerance for noise in this hospital.	[ ]	[ ]	[ ]	[ ]	[ ]
20. I am willing to report noise issues to management.	[ ]	[ ]	[ ]	[ ]	[ ]
21. I take independent measures (e.g., closing doors) to reduce noise.	[ ]	[ ]	[ ]	[ ]	[ ]

Section 6: Knowledge of noise pollution improvement	1	2	3	4	5
22. I am familiar with hospital noise control standards.	[ ]	[ ]	[ ]	[ ]	[ ]
23. I have adequate knowledge of noise reduction measures.	[ ]	[ ]	[ ]	[ ]	[ ]

Section 7: Sensitivity to ambient noise	1	2	3	4	5
24. In general, I consider myself highly sensitive to noise.	[ ]	[ ]	[ ]	[ ]	[ ]

Part III: Perception Assessment (Patients & Visitors)

Section 1: Overall Perception
7. What do you perceive as the primary sources of noise in the ED? (Select all that apply) [ ] Patient conversations [ ] Shouting between doctors and nurses [ ] Call bells at nursing stations [ ] Rolling of trolley wheels [ ] Doors opening or closing [ ] Broadcast/PA system [ ] Phone ringing [ ] Seat movement [ ] Children frolicking [ ] Television sets [ ] Air conditioning operation [ ] Footsteps [ ] Others: ___________
8. How would you describe the overall impact of the noise on your experience in the ED? [ ] No impact [ ] Mild impact [ ] Moderate impact [ ] Severe impact

Section 2: The efficiency of Patient Care	1	2	3	4	5
6. Noise negatively affects the efficiency of my medical visits.	[ ]	[ ]	[ ]	[ ]	[ ]
7. I believe noisy environments hinder the speed of recovery.	[ ]	[ ]	[ ]	[ ]	[ ]
8. Noise levels negatively impact my overall diagnosis experience.	[ ]	[ ]	[ ]	[ ]	[ ]

Section 3: The impact of noise on negative emotions	1	2	3	4	5

12. Hospital noise makes me feel irritable.	[ ]	[ ]	[ ]	[ ]	[ ]
13. Noise significantly increases my work-related stress.	[ ]	[ ]	[ ]	[ ]	[ ]
14. Background noise causes communication difficulties.	[ ]	[ ]	[ ]	[ ]	[ ]
Section 4: The impact of noise on physical and mental health	**1**	**2**	**3**	**4**	**5**
15. Prolonged exposure causes me to experience tinnitus.	[ ]	[ ]	[ ]	[ ]	[ ]
16. The noise environment triggers or exacerbates my headaches.	[ ]	[ ]	[ ]	[ ]	[ ]
17. I experience accelerated heart rate due to noise exposure.	[ ]	[ ]	[ ]	[ ]	[ ]
Section 5: The attitude toward ambient noise	**1**	**2**	**3**	**4**	**5**
18. I perceive the noise level in my environment as excessively high.	[ ]	[ ]	[ ]	[ ]	[ ]
19. I have a very low tolerance for noise in this hospital.	[ ]	[ ]	[ ]	[ ]	[ ]
20. I am willing to report noise issues to management.	[ ]	[ ]	[ ]	[ ]	[ ]
21. I take independent measures (e.g., closing doors) to reduce noise.	[ ]	[ ]	[ ]	[ ]	[ ]
Section 6: Knowledge and Prevention	**1**	**2**	**3**	**4**	**5**
19. I believe it is necessary to improve my noise prevention knowledge.	[ ]	[ ]	[ ]	[ ]	[ ]
20. Enhancing family members' understanding of noise is important.	[ ]	[ ]	[ ]	[ ]	[ ]
Section 7: Sensitivity to ambient noise	**1**	**2**	**3**	**4**	**5**
24. In general, I consider myself highly sensitive to noise.	[ ]	[ ]	[ ]	[ ]	[ ]

Part IV: Qualitative Feedback

A. What is the most disruptive source of noise you encountered?

B. Do you have suggestions for improving the acoustic environment?