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Research on the Performance, Measurement, and Influencing Factors of the Acoustic Environment in Hospital Buildings

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Abstract: In this study, the current noise situation in eight hospitals in central and northern Taiwan was investigated and analyzed. Recording equipment was utilized to measure environmental noise levels at the busiest points in the hospital lobby, specifically the pricing and medicine waiting areas. Furthermore, the acoustic data of the recorded audio samples were analyzed to determine the psychoacoustic parameter, namely, loudness. Subsequently, correlation analysis was performed between the analyzed data spectrum and the subjective psychological noise value. Ultimately, it was found that the mid-frequency band (MF) had a greater impact on the subjects compared to the other two frequency bands. When comparing the correlation coefficient analysis with the prior factor analysis, the primary sources of intrusive noise affecting the subjects were identified. The mid-frequency band is predominantly attributed to footsteps and conversations, and the high-frequency band is predominantly attributed to broadcast sound.

Keywords: hospital lobby; noisiness; noise recording and analysis; spatial attribute analysis; correlation; factor analysis; loudness; mid-frequency band

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1. Introduction

1.1. Background

Noise ranks among the environmental stressors with the greatest impact on public health [1]. Unlike several other environmental stressors, noise pollution is increasing, especially in the urban environment [2,3]. It is evident that in a public space such as a hospital, noise levels can hinder patient recovery. Patients require a more tranquil environment than that commonly found in their everyday surroundings. Noise in hospitals can also distract hospital staff and increase the risk of medical incidents [4]. Verbal communication in the hospital lobby is necessary at the registration desk, pharmacy counter, and outpatient service counter. In Taiwan, the duration of patient stays in hospital lobbies typically exceeds 20–30 min, which can often result in an uncomfortable experience [5]. Noise in hospital lobbies, characterized by the din of conversation, has been identified as a major stressor for patients, staff, and visitors, yet there are only a limited number of studies on this issue [4].

This study continues the research of Chen [5,6], aiming to investigate and analyze the current noise situation of eight hospitals in central and northern Taiwan, and presents in-depth discussions based on previous research. First, the hospitals under study were grouped for discussion. Given the unique characteristics of each hospital lobby, the tested lobbies were categorized based on their functions, and those with similar functional attributes were grouped together. Second, starting from its acoustic properties, the loudness in the hall was analyzed and summarized to verify the feasibility of the previous attribute grouping. In this study, recording equipment was used to record environmental noise at two measurement points in the sample hospital lobby where the crowds are most dense, namely, the areas designated for pricing and waiting for medicine. The focus was on various types of noise present in the lobby, such as crowd noise, equipment noise, noise from traffic entering the lobby, and noise from the emergency department. Moreover, the acoustic data of the recorded audio samples were analyzed. Our aim was to record the comprehensive acoustic environment inside and outside the hospital lobby, that is, the loudness. Subsequently, a correlation analysis between the analyzed data spectrum and noise was performed; lastly, a group discussion was conducted with regard to the correlation analysis of the eight hospital samples. The goal was to ascertain the factors affecting these data and to determine the impact on the patients in the hospital lobby in addition to the main noise frequency bands and noise sources.

1.2. Literature Review

Through listening experiments conducted in the laboratory using typical road traffic noise, Antonio J. Torija et al. [7] demonstrated that changes in different parts of the spectrum exert different effects, and their final experimental results showed that while low-frequency noise (LFN) was predominant in physical measurements, it did not always correlate with subjective perception. The authors of this study delved into the correlation between users' annoyance with environmental noise in indoor settings and the impact of different frequency bands from this perspective. However, this study was conducted in a laboratory. This study distinguishes itself from other simulation methods by focusing on on-site measurements to collect fundamental acoustic data for analysis, with the authors acknowledging that data from acoustic simulation software or laboratory-scale models might slightly deviate from real-world soundscape data.

According to Sandrock et al. [8] and ABo-Oudais and ABuOdais [9], the effects of noise on patients and staff are a major concern in hospital lobbies; however, the authors of most previous studies have focused only on the noise levels of individual hospital units or have detailed the acoustic properties of medical equipment. The authors of a few studies, in fact, have only provided information about annoyance and noise perceptions in terms of road-traffic composition. The authors of such studies concluded that annoyance is highly dependent on the actual noise sources in complex traffic scenarios; however, they provided only limited evaluations regarding the complicated hospital noise disturbances in the lobbies studied. In this study, we comprehensively analyzed the acoustic conditions of the halls of multiple hospitals with the aim of locating the main sources of noise annoyance in the hospital lobbies studied.

ISO1996-1-2016 [10] specifies methods for assessing environmental noise and provides guidance for predicting the potential annoyance responses of communities to long-term exposure to various types of environmental noise. Sound sources may occur in isolation or in various combinations. Based on these rating levels, the long-term response of the community can be estimated. Sounds are evaluated individually or in combination, taking into account, if necessary, their special characteristics of tonality and low-frequency content, in addition to road traffic noise, other forms of traffic noise with different characteristics (e.g., aircraft noise), and industrial noise. In this study, the aim was to study the correlation between the subjects' annoyance levels and noise in the hospital lobby.

Bush-Vishniac et al. [11] reviewed the extensive literature on hospital noise levels over the past 40–50 years. They found that sound pressure level measurements in hospitals significantly exceeded the maximum noise levels allowed under World Health Organization (WHO) guidelines [12]. In fact, the authors of a considerable number of studies have confirmed a link between higher levels of ambient noise and various adverse health effects, such as cardiovascular disease [13], sleep quality issues [14–16], other issues [17–19], and the cognitive development of vulnerable groups such as children [16,20]. It has also been observed that long-term exposure to noisy environments has adverse health effects on individuals' memory and expression ability [21–25].

Bayo et al. [26] conducted a survey on 295 staff members on the ward of a large teaching hospital, and the average noise level spanned between 52 and 75 dB (A). In addition, 15–20% of respondents stated that noise within the hospital had a negative impact on their professional performance and quality of work. As indicated by Ryherd et al. in their study [27], 43% of surveyed neurological intensive care unit (ICU) nurses believed that noise in the work environment leads to distraction. Persson Waine K. et al. [28] conducted an experiment involving 51 medical and surgical ICU nurses and found that noise annoyance was associated with self-reported mental fatigue (tiredness, headache, lack of concentration, irritability, etc.) and auditory fatigue (such as sound sensitivity, hearing fatigue, and tinnitus).

Hearing loss associated with a critical illness may be worsened by noise. In particular, for patients with hearing impairments, noise may significantly impede their communication abilities and, as a result, their understanding of the environment. This impact is more pronounced among the elderly, as their speech processing is highly sensitive to noise. Hearing impairment is associated with a greater prevalence of psychotic symptoms in both general and psychiatric populations. Moreover, the acoustic environment in an ICU can influence the likelihood of delirium in patients, characterized by acute and fluctuating consciousness and cognitive impairment, a condition linked to increased hospital mortality risk [29].

Collectively, the impact of noise in hospitals is significant, necessitating attention to its control. Through factor analysis of the questionnaire results, we were able to identify the types of noise that have the greatest impact in the lobby. A correlation analysis was conducted between the subject's noise perception and the spectrum (20 Hz–4 kHz) of the field recording analysis to determine the main frequency bands that affect the level of noise in the hospital lobby. Next, the samples were taken and analyzed over time. The loudness and frequency bands were reviewed to determine the reliability of previous analyses. Lastly, the audio data were manually listened to in order to determine the specific noise source. The findings of this study could effectively assist in identifying the primary sources of noise in hospital lobbies, enabling the mitigation of noise-related disturbances.

2. Methods

2.1. Research Objects

In this study, on-site recordings of the acoustic environment in eight hospitals in north–central Taiwan (Table 1) were taken for subsequent experiments and analyses. The selection of the eight hospitals was strategic, encompassing both public and private institutions, to ensure a more comprehensive study of the hospital lobby under study.

Table 1. Names of the hospitals under study.

No.	Name	Affiliation	Area
A.	Jen-Ai Hospital Dali	Private	Taichung
B.	Ching-Chyuan Hospital, Daya	Private	Taichung
C.	Cheng-Ching Hospital Chung, Kang Branch	Private	Taichung
D.	Feng-Yuan Hospital, Ministry of Health and Welfare	Public	Fengyuan
E.	Chang-Hua Hospital, Ministry of Health and Welfare	Public	Changhua
F.	Tao-Yuan Hospital, Ministry of Health and Welfare	Public	Taoyuan
G	Taipei Hospital, Ministry of Health and Welfare	Public	Taipei
H	New Taipei City Hospital, Government	Public	New Taipei

2.2. Inclusion Criteria

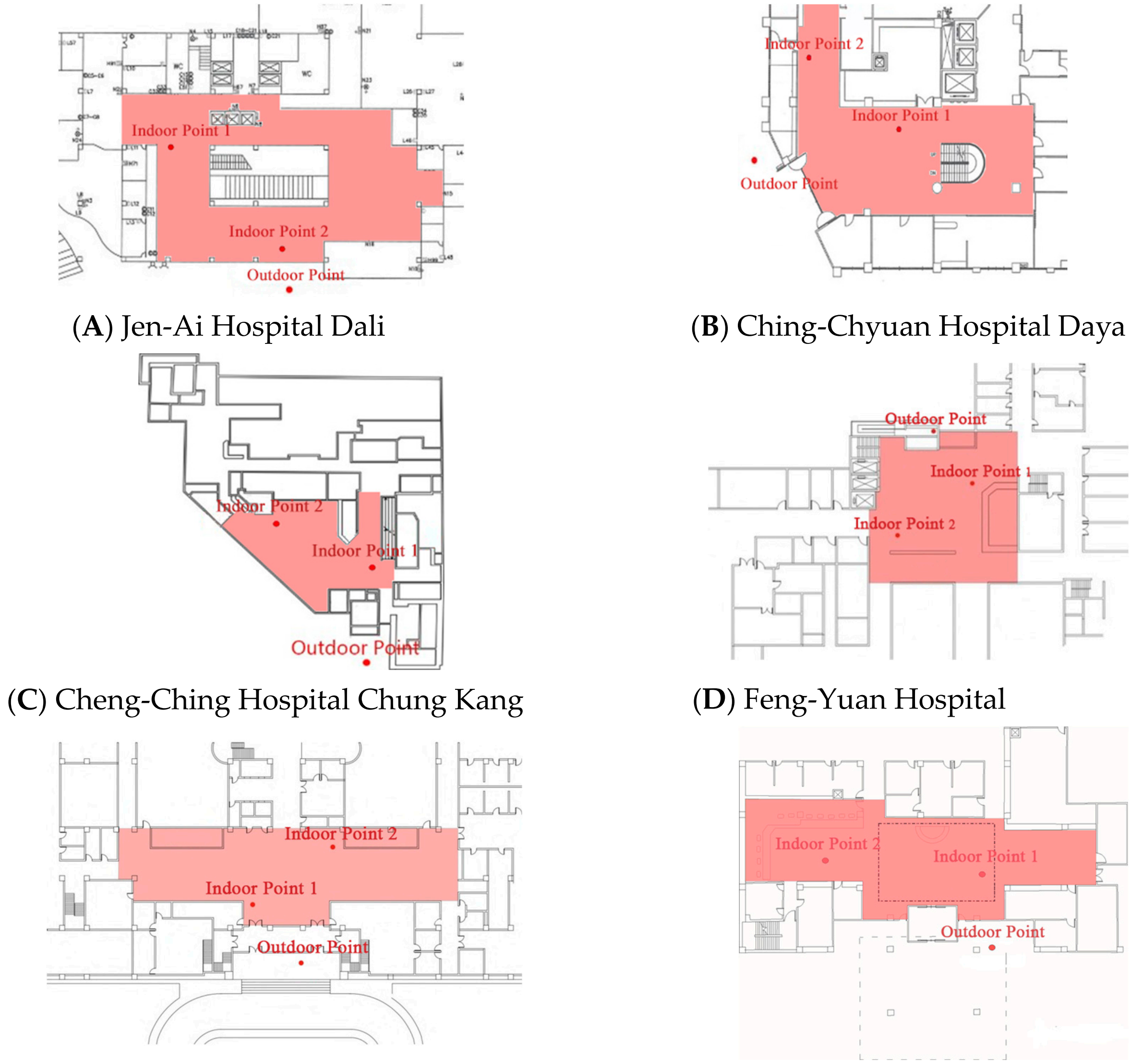
The sound source records in this study were based on testing standards proposed by Chen (2015) [5]. The main reference used was ISO 1006-1, "Description and measurement of acoustic environmental noise, Part 1: Basic quantities and measurement methods" [24]. The standards for measuring and setting measuring points can be listed as follows:

Measurements were conducted on normal working days from 9:00 a.m. to 5:00 p.m. and from Monday to Friday. This format was chosen to avoid specific impact noise when the hospital opens in the morning, such as the noise of opening iron gates, air conditioning, and the trial operation of mechanical equipment.

The layout of measurement points must meet the following conditions:

(1) The height between the measuring point and the ground must be 1.2–1.6 m.
(2) The distance between the measuring point and each radiation surface in space must be greater than 1.0 m.
(3) The distance between each measuring point must be greater than 1.5 m.
(4) The distance between the measuring point and the noise source in space must be greater than 1.5 m.

The floor plans of the major hospitals under study are shown in Figure 1.

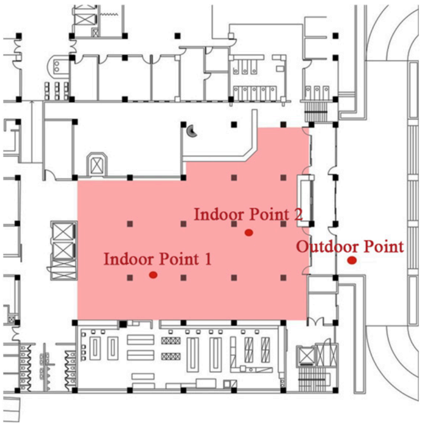


(**A**) Jen-Ai Hospital Dali (**B**) Ching-Chyuan Hospital Daya

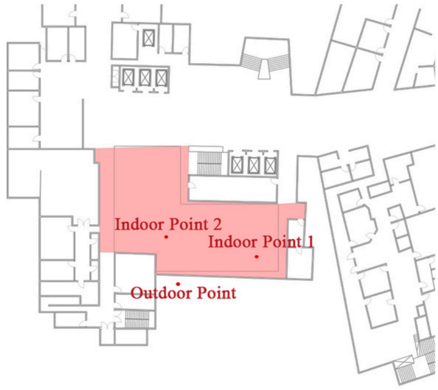
(**C**) Cheng-Ching Hospital Chung Kang (**D**) Feng-Yuan Hospital

(**E**) Chang-Hua Hospital (**F**) Tao-Yuan Hospital

Figure 1. *Cont.*



(**G**) Taipei Hospital



(**H**) New-Taipei, City Hospital, Government

Figure 1. Floor plans of the first-floor lobby of the 8 hospitals under study.

2.3. Methodology

Our research methodology involved four research phases, as follows:

1. The first stage involved the establishment of the research motivation and purpose in addition to the research objects.
2. In the second stage, the design of the psychological questionnaire began, in addition to on-site inspection of the research objects, to determine the main attributes of the hall functional area and the recording of audio data. Lastly, the data from the questionnaire results, the distribution of hall functional attributes, and the audio recordings were compiled for analysis.
3. In the third stage, after organizing the data obtained above, the psychological noise parameters of the subjects in each hospital were first calculated based on the data from the questionnaire. Subsequently, SPSS was employed to conduct factor analysis on the noise events listed in the questionnaire to identify the main noise events affecting the subjects. Subsequently, the audio data were analyzed to obtain the 20 Hz–4 kHz spectrum and loudness parameters of the major hospitals, that is, the Sone (MAX) data. Lastly, the functional attributes of each tested hospital lobby were analyzed, and the eight hospitals under study were grouped based on their functional attributes and Sone's (MAX) data.
4. The fourth stage involved the final data acquisition. Following the third stage of grouping, the correlation between the noise parameters and the data of each frequency band of the two groups of hospitals under study were compared to detect the frequency band with psychological noise correlation (David Nettleton [30] believes that the correlation value between the two variables is 0.7, indicating a significant positive correlation between the two variables). Next, the highly correlated frequency bands were compared with the noise events identified during factor analysis. An analysis was subsequently conducted to determine the consistency between these frequency bands and the noise events. Lastly, combined with the previous factor analysis and correlation analysis results, time-varying loudness and time-varying frequency analysis and manual listening and reading of audio samples were used to determine the main noise events affecting the hospital lobbies, ensuring the reliability of the experimental results and thereby facilitating the formulation of conclusions and recommendations.

2.4. Data Acquisition

According to the study by Feng H et al. [31] and Vecchiotti A et al. [32], the experimental conditions to be tested are similar to those of this experiment, involving multiple measurement points and the need for simultaneous multi-point and multi-track audio recording using multiple recorders. The final processing and analysis of the recorded audio files will also be conducted with analysis instruments in an anechoic room. Therefore, this study will follow a similar experimental process, including multi-point and multi-track simultaneous recording in the hospital hall, as well as audio recording of segments and post-processing in an anechoic chamber.

On-site data acquisition was performed from 25 March 2024 to 24 April 2024. The temperature was 25.1 ± 0.12 °C and the humidity was 50% ± 4% onsite. Two SONY PCM-A10 (SONY, Tokyo, Japan) recording units were used. The sampling frequency is 44.1 kHz, which allows for accurate recording of sound in the hall, with a resolution of 16 bits. And the sample acquisition procedure involved setting up two measuring points in the lobby of the hospital under study. The location of the measuring point is shown in Figure 1. (Since there are two measurement points at the site, multi-track digital recording equipment is required to capture audio data simultaneously. Consequently, this study utilized multiple recorders to collect data, ensuring it can be effectively analyzed in subsequent research).

The subsequent processing of the recordings is conducted in an anechoic room. (The anechoic chamber's physical conditions include a clear space of 5 m in height, 4 m in width, and 3 m in depth. The cut-off frequency is below 100 Hz, the average sound absorption rate exceeds 0.99, and the background noise level is lower than NC-15). After the recorder captured on-site acoustic data, and then, pink noise was recorded in an anechoic chamber at a frequency and decibel level that matched the live audio files, ensuring volume consistency. The corrected audio data were then saved as a wav file for subsequent analysis and to measure the loudness in the hospital lobby. And last, an Nor140 sound analyzer (Norsonic, Tranby, Norway) was employed to process these live recordings, generating spectral files for analysis (the equipment parameters of the PCM-A10 recording pen and Nor140 sound analyzer can be found in Appendix B).

2.5. Questionnaire Summary

The questionnaire used in this study was developed using a five-point Likert scale, and the content of the questionnaire was set with reference to Chen's study (2015) [5]. Research shows that nurses show a higher degree of annoyance in response to noisiness than inpatients [33]; therefore, research involving the use of questionnaires for noise evaluation should avoid seeking answers from hospital personnel. Consequently, responses regarding individual perceptions of noisiness in this study were restricted to the visitors and their companions (i.e., any persons above 13 years of age) in the hospital lobby. The noise situation in the hall of the hospital under study was summarized, and the subjects were instructed to fill in the information according to their personal feelings. The results are shown in Appendix A regarding the questionnaire content and detailed data.

3. Results

3.1. Hospital Lobbies' Property Summary

Upon sample establishment, the floor plan data of the eight hospitals and the geographical data obtained from field surveys were summarized and integrated. The results are shown in Table 2. The table below systematically compiles information on the dimensions of the hospital lobbies from the sample and the characteristics of adjacent spaces. The presence of green vegetation around the facility was evaluated to gauge its effectiveness in reducing road noise, and we identified whether the lobby entrance was fitted with an airlock chamber.

Table 2. Sizes of the lobbies and the nature of adjacent spaces in the hospitals surveyed.

	A	B	C	D	E	F	G	H
NP	28	44	39	35	49	44	41	40
AR (m^2)	357	300	300	295	168	197	300	276
VO (m^3)	964	900	900	1033	588	788	2250	828
CH (m)	2.7	3.0	3.0	3.5	3.5	4.0	7.5	3.0
NS	70	60	140	80	50	60	72	75
NE	3	2	3	3	5	2	3	5
NB	444 (5) *	243 (3)	237 (3) *	396 (7) *	638 (2)	235 (9) *	560 (10) *	258 (7) *
EV OR ES	y	y	y	y	y	y	y	y
MRI	1 T			1.5 T	1 T		1.5 T	1.5 T
CT	64			64	64	64	64	64
DC	13.7 m	7.36 m	17.4 m	28.79 m	24.67 m	50.15 m	31.83 m	38.79 m
PL				Y	Y	y	y	y
DE				Y	Y	y	y	y

NP—number of participants for the subjective noisiness survey. **AR**—area of lobby hall but with the hallway, stores, elevator facilities, etc., excluded. **VO**—volume of the lobby hall but with the hallway, stores, elevator facilities, etc., excluded. **CH**—the ceiling height of the lobby hall. **NS**—number of seats in the lobby. **NE**—number of entrances. **NB**—number of inpatient beds and the amount of flooring of the lobby hall in round brackets. **EV**—elevator. **ES**—escalator. **MRI**—quantity of the magnetic field (Tesla), magnetic resonance imaging. **CT**—slices of X-ray images, computerized tomography. **DC**—the distance from the entrance to the road. **PL**—plant coating. **DE**—De-ventilated room. *—wards were located on higher floors above the lobby in the same building.

3.2. Subjective Response Acquisition

Once the questionnaire results from the major hospitals under study had been sorted, the noise perceptions of the subjects in the eight hospitals were calculated for subsequent analysis of the correlation coefficient. The results are shown in Figure 2.

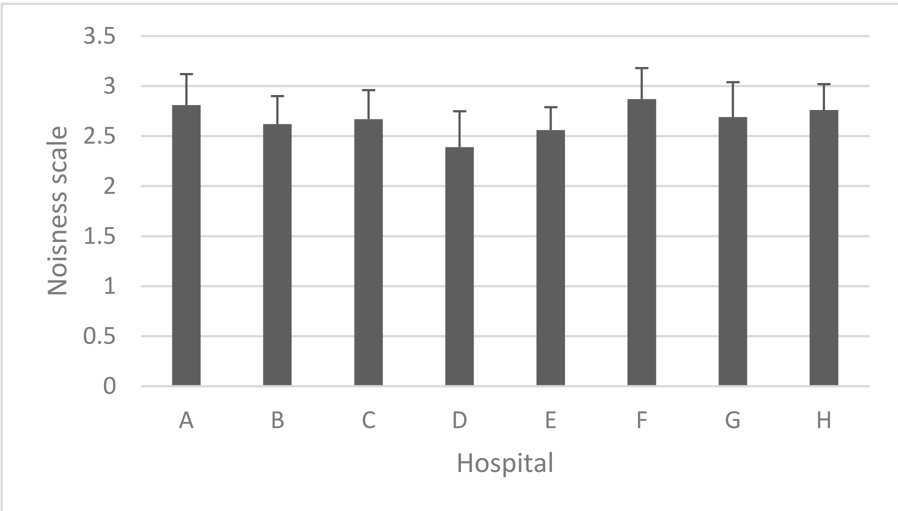


Figure 2. Noisiness with the standard deviation of each hospital according to the questionnaire responses of subjects.

3.3. Review of Possible Noise Sources in the Lobby

In the study by Park et al. [34], a total of 67 h (3 days) of continuous recording was conducted from Thursday to Sunday. In the hospital in their study, there are 14 single-bed wards surrounded by a central open nursing station. Except for patients who require isolation, the door to the room is usually left open to allow observation of the patient. Recordings were conducted in a non-isolated room (14.3 m^2). The authors focused on analyzing the characteristics of noise sources in the ICU, identical to the research method used in this study, using manual listening and recordings of various noise sources present in the hall and analyzing the main noise events, summarized as shown in Figure 3. During the listening process, we found that noise events such as crowd conversations, footsteps, medical carts, and radio broadcasts occurred very frequently in the halls of major hospitals. These findings also confirmed the problem we found of high mid-frequency susceptibility, corresponding to the sound of conversations, footsteps, and medical carts; high-frequency noise events correspond to the sound of broadcasts.

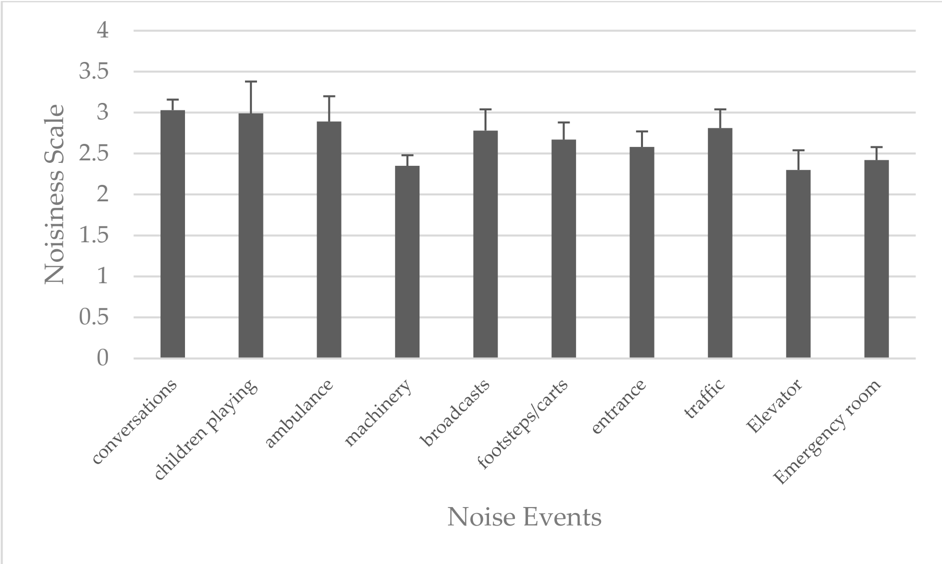


Figure 3. Noisiness events with standard deviations between noise levels in hospital lobbies compiled based on questionnaire results and observation.

3.4. Sample Grouping

The lobby functions of the eight hospitals surveyed on site were summarized, as shown in Table 3, which were then grouped to determine the functional attributes of the lobbies in each hospital to allow subsequent group attributes to be clarified for correlation coefficient analysis.

Table 3. Analysis of functional attributes and grouping of hospital lobbies.

Team	Name	Attributes
Team α Fully functional	Hospital (A) Hospital (B) Hospital (C)	■ The main entrance hall of the affiliated hospital □ The entrance to the hall is ≥20 m from the road □ The de-ventilated room is at the entrance of the hall ■ Direct connection to emergency department space ■ Includes a registration counter and pharmacy ■ Directly connected to some outpatient clinic spaces ■ Elevators and escalators running through the upper area □ Includes a medical supply store or supermarket
Team β Fully functional	Hospital (D) Hospital (E) Hospital (F) Hospital (G) Hospital (H)	■ The main entrance hall of the affiliated hospital ■ The entrance to the hall is ≥20 m from the road ■ The de-ventilated room is at the entrance of the hall ■ Direct connection to emergency department space ■ Includes a registration counter and pharmacy ■ Directly connected to some outpatient clinic spaces ■ Elevators and escalators running through the upper area ■ Includes a medical supply store or supermarket

3.5. Reverberation Times

In the study by Busch-Vishniac et al. [11], the authors' analysis focuses on the reverberation time (T30) in each lobby. The results of the measurements showed that the T30 at

0.5 kHz and 1.0 kHz ranged from 0.5 s to 2.26 s, as shown in Figure 4. Correlation analysis was performed on the results of each frequency band of T30 and noisiness to determine their correlation [30]. The results are shown in Table 4.

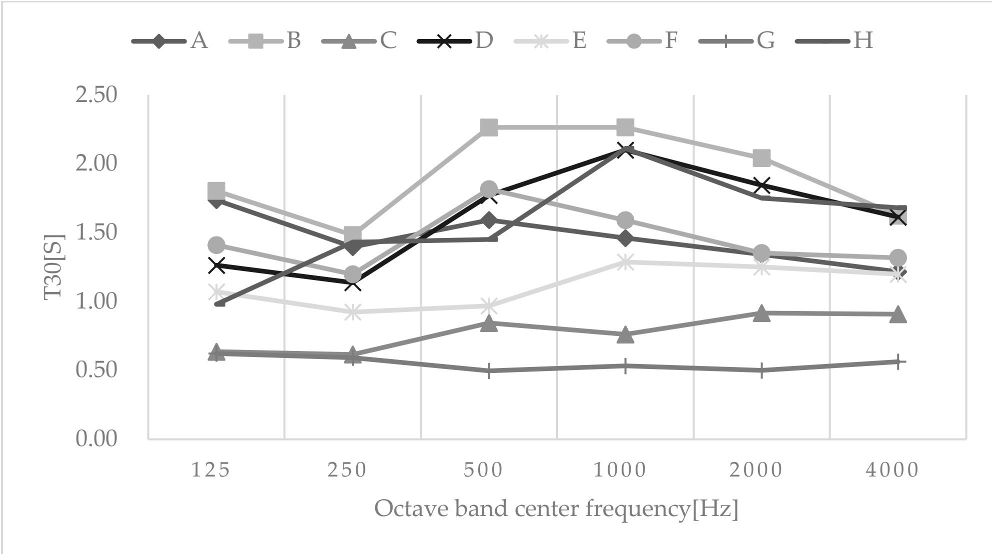


Figure 4. Reverberation time (T30) of the 8 hospital lobbies.

Table 4. T30 frequency band (125 Hz–4 kHz) correlation analysis.

Frequency Band (Hz)	Correlation
125	−0.21
250	−0.32
500	−0.52
1000	−0.72
2000	−0.74
4000	−0.71

Notes: In this study, Microsoft 365 Excel 2209 software was used for analysis.

According to the results, it is evident that there is no correlation between T30 and noisiness. Therefore, the results of T30 are not included in the reference range in this study.

3.6. Noise Criterion, dB (C) and dB (A)

In this study, the noise criterion (NC), dB (C), and dB (A) data of the eight hospitals were obtained by calculating the audio data (according to ANSI/ASA S12.2-2019). The results are shown in Table 5. The obtained data related to noisiness were subsequently analyzed to determine their correlation.

Table 5. NC (noise criterion), dB (C), and dB (A) correlation analysis.

Name	NC	Correlation	dB (C)	Correlation	dB (A)	Correlation
Hospital A	56	0.298	63.8	0.270	61.4	0.368
Hospital B	51		61		55.6	
Hospital C	54		65.1		57.3	
Hospital D	55		64.2		59.3	
Hospital E	59		69.2		62	
Hospital F	64		69.6		66.9	
Hospital G	59		67.6		63.5	
Hospital H	60		67.4		63.3	

Notes: In this study, Microsoft 365 Excel 2209 spreadsheet software was used for analysis.

According to the analysis results, it is evident that there is no correlation between NC, dB (C), dB (A), and noise.

This study referred to ISO 15666 [35] and decided to use decibels dB as the parameter basis for subsequent analysis.

3.7. Loudness Review

In addition to the functional partition attributes of the lobby of each hospital, the recorded audio files were also analyzed to review the grouping problem from the perspective of acoustic data. Therefore, the loudness of each hospital hall was analyzed, as shown in Figure 5. The location of the measuring point is shown in Figure 1.

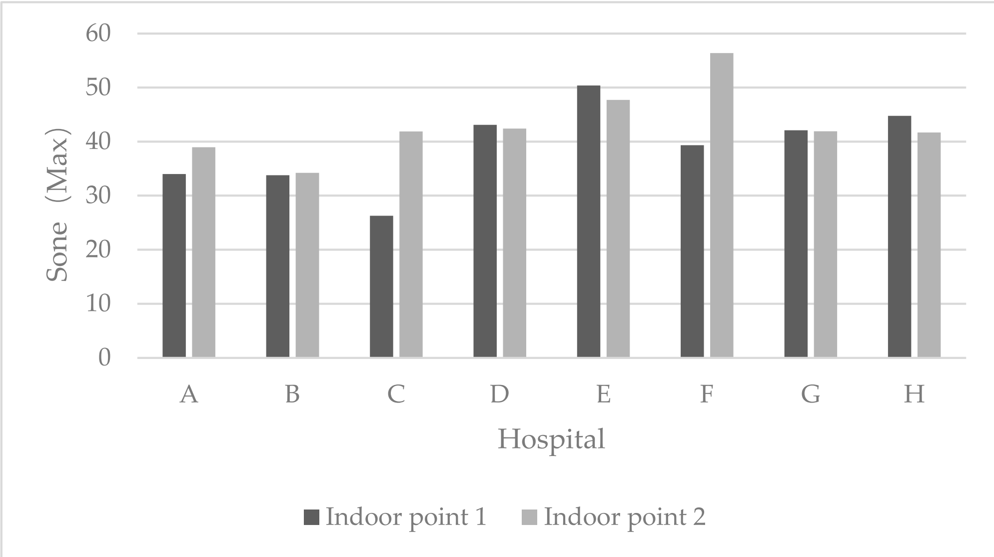


Figure 5. Loudness analysis from the hospitals with two tested points.

It is evident that the maximum loudness values of the three hospitals in the α group previously divided into the α group through the hall functional attributes were all below 40 Sones, while the maximum loudness values of the β group all exceeded 40 Sones. Hence, through the acoustic data, the samples in group A and the samples in group B could finally be clarified after a further group review (team composition shown in Table 3).

3.8. Spectrum Acquisition

Recording equipment was utilized in this study for field measurements in a sample hospital on weekdays, Monday through Friday, to avoid the unique noise associated with the hospital's morning activities, such as the opening of iron doors, air conditioning operations, and the trial operation of mechanical equipment.

The measurement point selection was arranged in full according to the plane icon points provided above. For any sudden noise (except for noise from outside the hospital such as ambulance sirens), the measurement was terminated. The measurement duration lasted 3 min, and the measurement was repeated twice. Lastly, the two-spectrum values were averaged to ensure accuracy. The measurement results are shown in Figure 6.

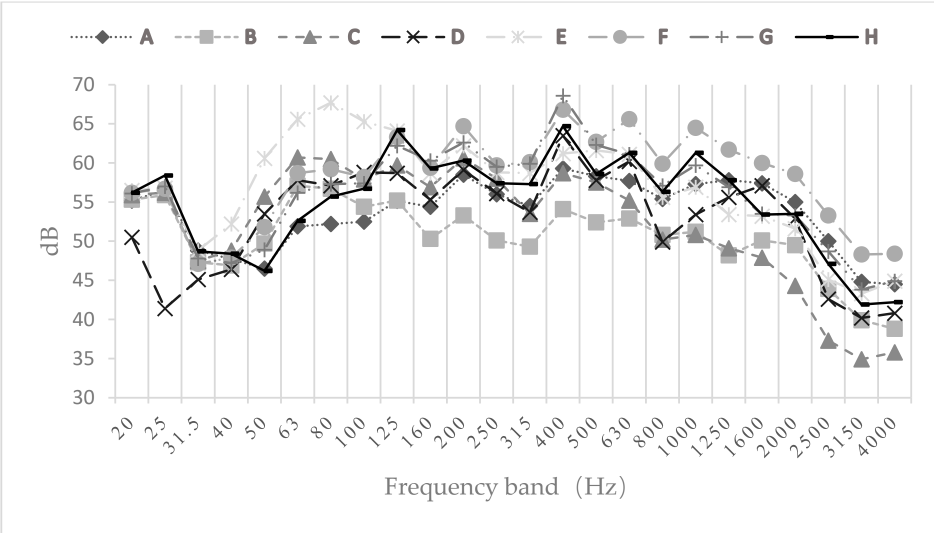


Figure 6. Frequency band (20 Hz–4 kHz) of the 8 hospitals.

4. Discussion

4.1. Factor Analysis

The compiled questionnaire data were subjected to factor analysis to ascertain the main components of the noise sources in the hospital lobby. The contents of the questionnaire were grouped, with the noise situation in the hospital lobby as one group and that in the medical functional area as the other group. The noise situation was divided into two aspects according to the results, with one aspect being the incidental noise timing and the other being the primary noise events for analysis. Events with relatively low correlation were removed during analysis. The experimental results are shown in Table 6.

Table 6. Analysis of major noise event factors.

Team Lobby	Factor Loading	Eigenvalue	Percent of Total Variance Explained
***Factor 1*: *Lobby primary noise* (*N* = 3) (*Kaiser–Meyer–Olkin (KMO) = 0.607*)**			
Sound of footsteps and carts	0.968	2.461	41.016%
Door opening and closing sound	0.847		
Ambulance siren sound	0.808		
***Factor 2*: *Lobby accidental noise* (*N* = 3) (*Kaiser–Meyer–Olkin (KMO) = 0.607*)**			
External car sounds	0.916	2.213	36.889%
Talking	0.882		
Broadcast	0.628		
Team Ribbon	**Factorloading**	**Eigenvalue**	**Percentof total variance explained**
***Factor 1*: *Ribbon primary noise* (*N* = 3) (*Kaiser–Meyer–Olkin (KMO) = 0.630*)**			
Medical machinery sounds	0.973	3.012	50.196%
Sound of footsteps and carts	0.890		
Elevator	0.846		
***Factor 2*: *Ribbon accidental noise* (*N* = 3) (*Kaiser–Meyer–Olkin (KMO) = 0.630*)**			
Traffic	0.815	1.784	29.741%
Talking	0.708		
Emergency room	0.626		

Notes: In this study, IBM SPSS Statistics 22 statistical analysis software was used for analysis.

Noise events with low correlation in the lobby group, such as noise from children playing and noise produced by the operation of mechanical equipment, were excluded from the analysis. The results showed that the main noise events common to both sets of data are footsteps, and the noise caused by the sound of medical carts showed the greatest correlation. In occasional noise events, traffic noise is more prominent, followed by noise caused by conversations, and lastly, noise events caused by ambulances and emergency rooms. The difference lies in the fact that the main noise events in the lobby group are also related to the noise caused by opening and closing doors in addition to the noise from ambulances; in comparison, the medical functional area group's highest correlation is with the noise generated by the operation of medical equipment, which is attributed to the concentration of medical equipment in the functional areas.

4.2. Correlation

The eight hospitals were hereby grouped according to the functional attributes of the lobby, involving α group hospitals (A, B, and C) and β group hospitals (D, E, F, G, and H). The correlation analysis was conducted between the psychological noisiness of the two groups of hospitals (refer to Figure 2) as well as the spectrum (20 Hz–4 kHz) compiled from field measurements (refer to Figure 6). The results are shown in Table 7. (* Data for ≥ 0.7).

Table 7. Team α (hospitals A, B, and C) and Team β (hospitals D, E, F, G, and H).

Team α/Hz	Correlation	Team β/Hz	Correlation
20	−0.37	20	0.77 *
25	0.96 *	25	0.78 *
31.5	0.98 *	31.5	0.45
40	0.17	40	−0.03
50	−0.57	50	−0.44
63	−0.77	63	−0.25
80	−0.73	80	−0.15
100	−0.57	100	−0.37
125	−0.26	125	0.63
160	0.39	160	0.86 *
200	0.48	200	0.82 *
250	0.51	250	0.81 *
315	0.82 *	315	0.87 *
400	0.78 *	400	0.70 *
500	0.79 *	500	0.72 *
630	0.97 *	630	0.76 *
800	0.93 *	800	0.96 *
1000	0.94 *	1000	0.96 *
1250	0.98 *	1250	0.76 *
1600	0.88 *	1600	0.20
2000	0.71 *	2000	0.70 *
2500	0.68	2500	0.96 *
3150	0.69	3150	0.84 *
4000	0.81 *	4000	0.80 *

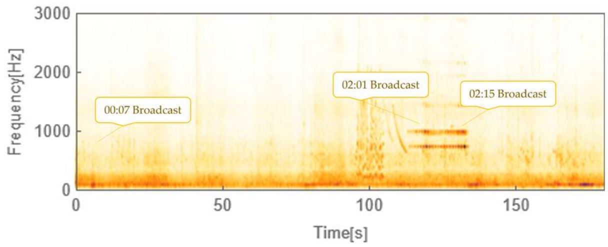
Notes: In this study, Microsoft 365 Excel 2209 spreadsheet software was used for analysis.

The commonality between the two data sets is that the subjects' perception of psychological noise is predominantly within the frequency range of 160–1250 Hz because the analysis results are all greater than or equal to 0.7 [30]. Specifically, following analysis, it is clear that the frequency bands experienced by users in the hospital lobby are mainly concentrated in the medium frequency (MF) and high frequency (HF). This finding is also roughly the same as our previous factor analysis results. The results of this analysis will also be used for subsequent studies to compare specific noise events to verify their authenticity.

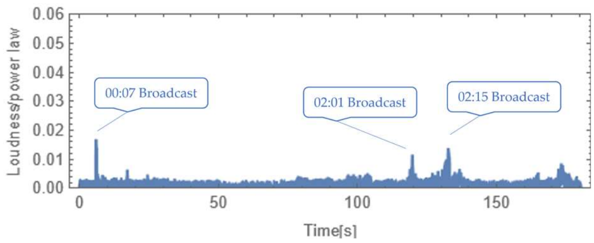
4.3. Time-Varying Analysis

Through the factor analysis questionnaire results, we determined several major noise events that affect hospital lobbies, and through correlation analysis, we determined the main frequency bands that affect hospital lobbies.

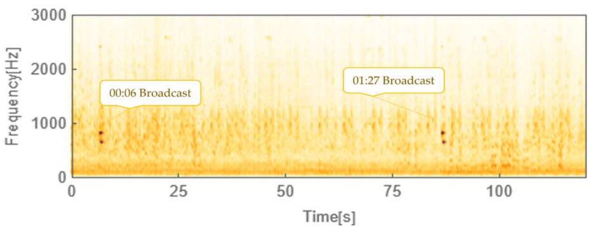
Lastly, we needed to ascertain the specific noise events in the mid- and high-frequency bands that affect the hall. We therefore conducted time-varying loudness power law and frequency analysis on the audio samples from Hospital C in team α and Hospital F in team β and then manually listened to the audio samples to determine the specific noise events. The results are shown in Figure 7.



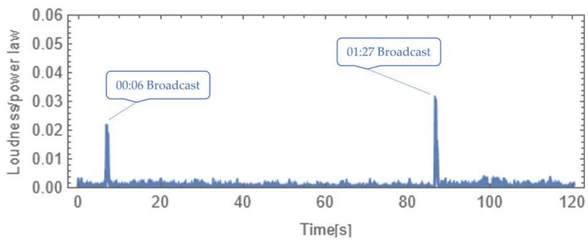
(**a**) Hospital C time-varying frequency analysis



(**b**) Hospital C time-varying loudness power law analysis



(**c**) Hospital F time-varying frequency analysis



(**d**) Hospital F time-varying loudness power law analysis

Figure 7. Hospitals C and F time-varying loudness power law analysis [36] and frequency analysis (conversations and footsteps principally cover the entire audio; thus, they are not marked specifically).

We can clearly see that the frequency of noise events is mainly concentrated in the 630–1600 Hz range. Combined with the manual listening and reading of audio files, we determined that the noise event that occurs most frequently in the hall and has the greatest impact on the human auditory system is footsteps and conversation sound (MF) and radio broadcast sound (HF). Combining our judgment results with picture analysis, there are several obvious waveform fluctuations in the loudness analysis, and the corresponding black mark points (noise events) in the spectrum analysis diagram are consistent. This noise represents the sound of the radio announcement.

Combining the above results, we can draw the following two conclusions:

1. To verify the findings of Antonio J. Torija et al. [7] we uncovered through the above research that the main psychological feeling frequency band of the subjects indoors is concentrated in the MF band in field measurements, followed by the LF band. This result deviates from the results presented by Antonio J. Torija et al.; however, this finding also corroborates the proposed initial assertion that field measurements are likely to yield more accurate experimental results than those simulated in a laboratory setting.
2. Compared with previous studies by Sandrock et al. and ABo-Oudais and ABuO-dais [9], field measurements, questionnaire surveys, correlation analysis, and factor analysis were used in this study in complex hospital halls. Using these research methods, several main noise sources and main frequency bands (mid-frequency) affecting the hospitals' halls were determined. Moreover, data obtained by analyzing multiple hospitals are more reliable than studying the data of a single hospital.

5. Conclusions

In this study, the acoustic environment conditions of eight hospital lobbies in central and northern Taiwan were investigated. By analyzing the functional attributes of the halls of these eight hospitals, the loudness of the acoustic environment, and the location attributes, the eight samples were divided into two groups. Simultaneously, while using recording equipment to conduct on-site measurements at two measurement points in each hospital lobby, questionnaires were distributed to users in the lobby for noise data collection.

First, we discovered several major noise events in the hospital lobby through factor analysis of subjects' noise perception. Subsequently, a correlation analysis was conducted between the noise data and the spectrum data (20 Hz–4 kHz) of the eight hospitals, and it was determined that the frequency bands that affect noise in the hospital lobby are mainly concentrated in the mid- and high-frequency bands. Lastly, the samples from the tested hospitals were randomly sampled (one from the α group and one from the β group), and the loudness power law and frequency in the audio data were analyzed over time. After confirmation that the analysis results were consistent with our experimental results, the sampled audio files were manually listened to and analyzed to determine that the main noise events that affect the subjects' noise perception in the hospital lobby are footsteps and conversations (MF) and radio sounds (HF).

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due privacy.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Questionnaire content and questionnaire results.

No.	Questionnaire	A	B	C	D	E	F	G	H
1	Is indoor noise a serious problem in hospitals?	3.16	2.85	3.01	2.85	2.62	3.03	3.38	2.97
2	Are conversations inside the hospital disruptive?	3.06	2.95	3.16	2.97	2.79	3.20	3.06	3.12
3	Will the sound of children playing in the hospital cause disturbance?	3.52	3.31	2.23	3.17	2.84	3.32	3.14	3.23
4	Will hospital ambulance sirens cause disruption?	3.15	2.85	2.70	2.70	2.63	3.52	2.68	2.93
5	Does the sound of operating machinery and equipment in the hospital cause disturbance?	2.47	2.4	2.36	2.13	2.30	2.41	2.21	2.53
6	Will the radio sound in the hospital cause disturbance?	2.81	2.88	2.65	2.36	2.58	2.80	3.22	2.98
7	Will footsteps in the hospital cause disturbance?	2.93	2.70	2.53	2.33	2.69	2.98	2.58	2.67
8	Will the sound of opening and closing doors in the hospital cause disturbance?	2.56	2.63	2.51	2.22	2.66	2.90	2.64	2.59
9	Will the sound of cars outside the hospital cause disturbance?	2.70	2.85	2.98	2.5	2.52	3.03	2.81	3.10
10	Will the registration area and medicine collection area be disturbed by outdoor traffic noise?	2.44	2.60	2.96	2.16	2.95	2.65	2.60	2.59
11	Will the registration area and medicine collection area be disturbed by the sound of elevators/escalators?	2.61	2.25	2.36	1.89	2.13	2.49	2.21	2.51
12	Will the registration area and medicine collection area be disturbed by the voice at the counter?	2.64	2.33	2.68	2.14	2.38	2.74	2.50	2.59
13	Will the registration area and medicine collection area be disturbed by the sound of walking footsteps?	2.89	2.51	2.33	2.19	2.72	2.70	2.41	2.54
14	Are the registration areas and medication collection areas affected by the sound of medical machinery?	2.78	2.38	2.33	2.13	2.46	2.61	2.45	2.56
15	Will the registration area and medication collection area be disturbed by the sound from the emergency room?	2.43	2.55	2.46	2.17	2.20	2.63	2.53	2.44

Appendix B

Table A2. SONY PCM-A10 main functions.

Name	Features	
SONY PCM-A10	Built-in memory	16 GB
	Playback format	MP3/AAC/WMA/WAV/FLAC

Table A3. B&K Nor 140 main functions.

Name		Features
Nor140 Sound analyzer	System	Base 10 system (IEC 61260) and ANSI S1.11-2004 Class

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