SOUNDSCAPE QUALITY ACROSS HOSPITAL DEPARTMENTS: PSYCHOACOUSTICS AND ISO 12913 ASSESSMENT

Pasupathan Chithra Barani[1], Ajayshankar Jagadeesh[1], Ela Fasllija[2,3], Natalie van der Wal[4], Hester Thoen[5]

[1] *Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands*
[2] *Faculty of Industrial Design Engineering, Delft University of Technology, The Netherlands*
[3] *Department of Intensive Care Adults, Erasmus Medical Center, Rotterdam, The Netherlands*
[4] *Faculty of Technology, Policy and Management, Delft University of Technology, The Netherlands*
[5] *Haskoning Nederland B.V., Mijnbouwstraat 120, 2628 RX Delft, The Netherlands*

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

Abstract

Hospital noise is a clinical concern, but average A-weighted sound pressure levels (LA_{eq}) do not explain how people experience sound in different departments. This study examined whether department type drives hospital soundscape quality by combining psychoacoustic measures with soundscape questionnaires based on ISO 12913. We collected 124 acoustic measurements and 86 questionnaire responses across four departments: Emergency, Intensive Care Unit (ICU), Oncology, and Hematology, in four Dutch tertiary hospitals. Psychoacoustic annoyance (PA) was computed using the Zwicker–Fastl model alongside Loudness (N5), sharpness, roughness, and fluctuation strength. Results showed clear department-specific profiles. ICU and Oncology had nearly identical LA_{eq} values (54.15 vs. 54.17 dB(A)) but differed substantially in psychoacoustic profile and perceived sound quality, showing that equal dB levels can mask meaningful experiential differences. Emergency had the highest annoyance (PA = 15.80) and lowest perceived sound quality, while Hematology had the lowest annoyance (PA = 9.13) and highest appropriateness. PA correlated positively with ISO Eventfulness ($\rho = 0.41$) and negatively with ISO Pleasantness ($\rho = -0.22$). Roughness and Loudness (N5) showed the strongest negative associations with perceived pleasantness. Staff and ICU patients rated the same environment markedly differently, highlighting the role of listener context. These findings support department-specific interventions and show the value of integrating psychoacoustics with ISO 12913 soundscape assessment.

Corresponding author: *chachintendulkar@gmail.com.*

Keywords: *hospital soundscape, psychoacoustics, perception, environmental quality, well-being*

1. Introduction

Hospitals are acoustically demanding environments. Clinical alarms, staff communication, medical equipment, and building services combine to produce sound levels that consistently exceed recovery-oriented guidelines in virtually every study that has measured them [1], [2]. The consequence is not merely discomfort. For patients, excessive or poorly structured noise disrupts sleep, prolongs physiological stress responses, and delays recovery [3]. For staff, dense and conflicting acoustic signals contribute to alarm fatigue, degraded communication, and cognitive overload [4], [5]. These are well-established findings.

What is less established is how acoustic conditions differ systematically across the different types of departments within a hospital, and what drives those differences. Hospital noise research has tended to focus on individual units, particularly ICUs, rather than comparing departments with genuinely distinct operational profiles [6], [7]. This matters because an intervention that is appropriate in a general ward may be irrelevant or even counterproductive in an emergency department.

The standard measurement metric, A-weighted equivalent continuous sound pressure level (LA_{eq}), does not help here. It represents average acoustic energy over time and is insensitive to the perceptually relevant features of sound that differ most across departments: the sharpness of alarm tones, the roughness of overlapping voices, and the contrast between quiet periods and loud events [8], [9]. Two departments can share the same LA_{eq} while their occupants experience them completely differently.

Psychoacoustic metrics address this gap. Loudness (sone), sharpness (acum), roughness (asper), and fluctuation strength (vacil) encode perceptually salient features of sound that intensity measures miss [10]. Combined with the ISO 12913-1 soundscape framework [11], which treats acoustic environments as contextual human experiences rather than physical noise problems, they allow a richer characterisation of what people actually hear in each department, and why it affects them the way it does.

The aim of this study is to determine whether clinical department type is the primary driver of hospital soundscape quality when psychoacoustic measurements are combined with ISO 12913 soundscape assessment. To address this aim, we compare four departments, Emergency, ICU, Oncology, and Hematology, representing a deliberate gradient of clinical intensity and operational character. Two specific contributions follow. First, we show that psychoacoustic indicators reveal between-department differences that identical LA_{eq} values conceal. Second, we show that these objective differences align with how occupants rate the soundscape, except where listener context, such as clinical role, changes that relationship.

2. Methods

2.1. Study Design And Sites

Data were collected across four hospital departments in four Dutch tertiary hospitals (names withheld for anonymity). Departments were selected to span a gradient of clinical function: Emergency operates under continuous high-urgency and unpredictable patient flow, the ICU provides 24-hour critical care in a heavily instrumented environment, Oncology supports structured long-stay treatment with infusion systems and specialised ventilation, and Hematology provides a more controlled, rest-oriented setting with smaller care teams. ICU data were collected across three hospital sites to capture within-type variability; these sites differ in spatial layout and building services, which introduces site effects into pooled ICU distributions that should be interpreted accordingly. Objective measurements and soundscape assessments were conducted simultaneously in the same department and time window, enabling the direct pairing of objective and subjective data required for the analysis procedures of ISO/TS 12913-3 [12].

2.2. Acoustic Measurements And Psychoacoustic Analysis

Measurements were made using a Bruel and Kjaer 2250 sound level meter, calibrated before each session, tripod-mounted at 1.2–1.5 m height with a windshield (Figure 1). Within each department, 20–30 locations were selected near patient beds, treatment chairs, and central nursing zones, the areas most directly relevant to patient and staff exposure. Each measurement lasted 3–15 minutes during daytime hours on weekdays, yielding 124 measurements in total (Emergency: $n = 19$; ICU: $n = 62$; Oncology: $n = 29$; Hematology: $n = 14$). During each recording, the researcher documented dominant sound sources at the measurement location. These notes were then used in post-processing to exclude segments containing atypical, non-representative events.

The audio recordings captured by the sound level meter were analysed in ArtemiS SUITE 17.1 to extract LA_{eq} (dB(A), integrated over the full 3–15 min duration of each measurement), Loudness (N5) and N95 loudness percentiles (sone), sharpness S (acum), roughness R (asper), and fluctuation strength F (vacil) [10]. Sharpness quantifies the high-frequency spectral content of a sound (acum), roughness encodes rapid amplitude modulations perceived as harshness (asper), and fluctuation strength captures slow modulations associated with a wavering quality (vacil). These metrics collectively characterise the spectral and temporal texture of the sound environment beyond what level alone conveys. Loudness (N5) captures the loudness exceeded 5% of the time and reflects acute peak events, N95 captures background loudness. Psychoacoustic annoyance (PA) was computed for each measurement following Zwicker and Fastl [10], [13]:

$$\mathrm{PA} = N_5 \cdot \left(1 + \sqrt{w_{\mathrm{S}}^2 + w_{\mathrm{FR}}^2}\right) \tag{1}$$

where w_{S} encodes the contribution of sharpness relative to 1.75 acum, and w_{FR} combines roughness and fluctuation strength. PA integrates the perceptual dimensions that individual metrics capture separately into a single scalar that reflects composite acoustic discomfort, making it suitable as the primary cross-department comparator [12].

2.3. Soundscape Assessment

Subjective data were collected using a structured questionnaire based on ISO/TS 12913-2 Method A [14], administered on-site in the same department and time window as the acoustic measurements. The questionnaire included eight Perceptual Affective Quality (PAQ) attributes rated on five-point ordinal scales (pleasant–annoying, eventful–uneventful, calm–chaotic, vibrant–monotonous), overall soundscape quality and appropriateness items (both 1–5 Likert), and a source-specific annoyance scale covering nine sound categories. Both paper and digital (Qualtrics, via QR code) formats were used to accommodate clinical constraints.

ISO circumplex coordinates (ISOPleasant, ISOEventful) were derived from PAQ responses via the Axelsson principal components transformation [15] and processed using the Soundscapy library [16]. The cleaned dataset comprised 86 responses: Emergency $n = 13$ (staff only, as patient participation was not possible in this setting); ICU $n = 39$ (30 staff, 9 patients - a methodologically notable subgroup given the rarity of direct ICU patient responses in published studies [3]); Oncology $n = 21$ (11 staff, 10 patients); Hematology $n = 13$ (8 staff, 5 patients). Non-parametric statistics (Kruskal–Wallis with Dunn pairwise contrasts, Spearman correlations) were used throughout given the ordinal nature of questionnaire data and

Figure 1: Typical in-situ measurement setup (Bruel and Kjaer 2250, tripod-mounted, windshield fitted). Measurements were conducted during daytime hours on weekdays across 20–30 locations per department.

non-normal distributions.

3. Results

3.1. Acoustic And Psychoacoustic Profiles By Department

Figure 2 summarises the psychoacoustic gradient across departments and provides an overview of the contrasts discussed in this section. All four departments exceeded the WHO recovery guideline of $LA_{eq} \leq 35$ dB(A) [3], Emergency by 23.7 dB(A) and Hematology, the quietest, by 13.1 dB(A). But the more important finding is the dissociation between LA_{eq} and the psychoacoustic profile. ICU and Oncology recorded essentially identical mean LA_{eq} values (54.15 vs. 54.17 dB(A)), yet their psychoacoustic profiles diverge in diagnostically important ways. ICU and Oncology showed comparable mean sharpness (both 2.14 acum), but ICU's high-frequency character was sustained by continuous monitoring equipment and frequent alarm tones rather than intermittent sources. ICU also showed higher roughness (0.109 vs. 0.095 asper). This is not a small distinction: it points to the ICU's alarm-dense environment producing a harsher psychoacoustic burden than the numerically equivalent Oncology level would suggest.

Emergency occupied a different register altogether. Its mean LA_{eq} (58.65 dB(A)) was nearly 5 dB(A) above ICU and Oncology, but the PA value (15.80) was 73% higher than Hematology's (9.13), a gap much larger than the dB(A) difference alone would predict. Emergency also showed the highest roughness in the dataset (0.134 asper), consistent with frequent overlapping communication and alarm-related events observed during measurements. High roughness is perceptually associated with harshness and cognitive intrusion [10], and together with elevated PA it indicates that Emergency is demanding not only because it is loud, but because of the harsh temporal texture of its sound.

Hematology presented the most acoustically distinct profile. Its high Loudness (N5)/N95 ratio of 2.78 (compared to Emergency's 2.20) reflects a genuinely quiet baseline (N95 = 2.86 sone) against which discrete events stand out sharply, whereas Emergency's lower ratio indicates a chronically elevated baseline with suppressed relative contrast between peaks and background. Observational notes suggested a larger contribution from building-service noise and fewer alarm-related events in Hematology, which is consistent with its low roughness and tight intra-department variability (coefficient of variation = 0.27, lowest of all departments).

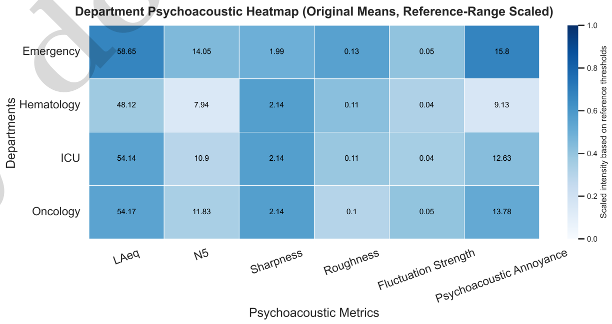

Figure 2: Psychoacoustic metric heatmap across four departments. Emergency ranks highest across most metrics, while Hematology is lowest.

3.2. Soundscape Patterns

Figure 3 shows the ISO 12913 circumplex density distributions for each department, separated by listener role. Considering the overall pattern across both staff and patient distributions, the department-level positions are consistent with the psychoacoustic profiles: Emergency clusters in the high-eventfulness, low-pleasantness quadrant; Hematology sits in the calm region; Oncology shows a broader distribution that extends toward the pleasant side with moderate eventfulness rather than a tight pleasant cluster; ICU sits near-neutral.

The staff-patient divergence in the ICU is particularly important. Staff distributions cluster toward the vibrant quadrant, while ICU patients are distributed more broadly, extending into the less pleasant regions of the circumplex. This divergence is expected within the ISO soundscape framework, which defines soundscape as the acoustic environment as perceived in context [11]. Building on the Methods section, Q5 is the source-specific annoyance item in the ISO-based questionnaire, where respondents rated annoyance for nine sound-source categories. This item complements the circumplex view by indicating which concrete sources drive annoyance in each department.

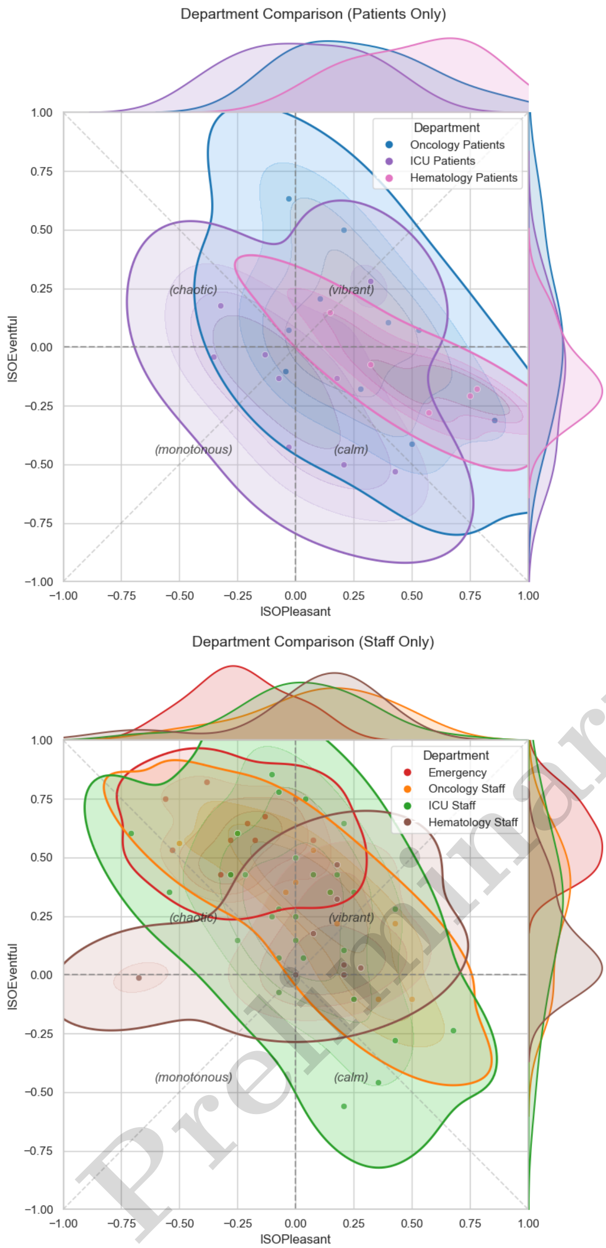

Figure 3: Role-separated ISO 12913 circumplex density distributions: patients (top) and staff (bottom). Contours show kernel density estimates; points show individual responses. ICU staff (bottom) cluster toward the vibrant quadrant, whereas ICU patients (top) are more broadly distributed, extending into less pleasant regions, reflecting the contextual nature of soundscape perception.

To further interpret these perceptual differences, Figure 4 shows Q5 source-specific annoyance by department.

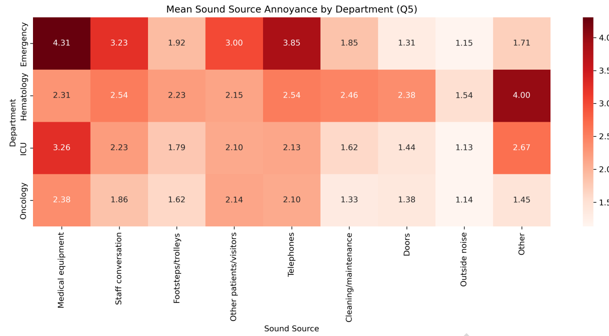

Figure 4: Q5 heatmap of mean source-specific annoyance by department (medical equipment, staff conversation, footsteps/trolleys, other patients/visitors, telephones, cleaning/maintenance, doors, outside noise, and other).

3.3. Objective-Subjective Relationships

PA correlated positively with ISO Eventfulness (Spearman $\rho = 0.41$, $p = 9.8 \times 10^{-5}$, significant at $p < 0.001$) and negatively with ISO Pleasantness (Spearman $\rho = -0.22$, $p = 0.039$, significant at $p < 0.05$). Spearman correlation was selected throughout given the ordinal nature of perception data and non-normal distributions. Loudness (N5) showed similar directions. When aggregated to site means (Emergency, three ICU sites, Oncology, Hematology; $n = 6$ site points), the PA-Eventfulness association strengthened to $\rho \approx 0.77$ and the PA-Pleasantness association to $\rho \approx -0.49$.

These site-mean correlations should be interpreted as exploratory summary patterns rather than inferential tests, because they are based on only six site points. Across these site-mean values, both Roughness and Loudness (N5) correlated with ISO Pleasantness at $\rho \approx -0.66$, more strongly than PA ($\rho \approx -0.49$). This suggests that reducing roughness may improve perceived sound quality in addition to reducing overall level.

Figures 5 and 6 show the response-level relationships of PA with ISO Eventfulness and ISO Pleasantness, respectively. The PA-Pleasantness pattern is visibly weaker than the PA-Eventfulness pattern, consistent with the correlation coefficients reported above.

Table 1 presents the combined acoustic and perceptual summary for each department.

Table 1: Department acoustic-perceptual profile summary (PA = psychoacoustic annoyance; Approp. = perceived appropriateness, 1–5).

Dept.	LA_{eq} (dB(A))	PA	Approp.	ISOPl.	ISOEv.
Emergency	58.65	15.80	2.23	−0.24	0.58
ICU	54.15	12.63	3.08	0.03	0.15
Oncology	54.17	13.78	3.48	0.19	0.17
Hematology	48.12	9.13	3.92	0.23	0.03

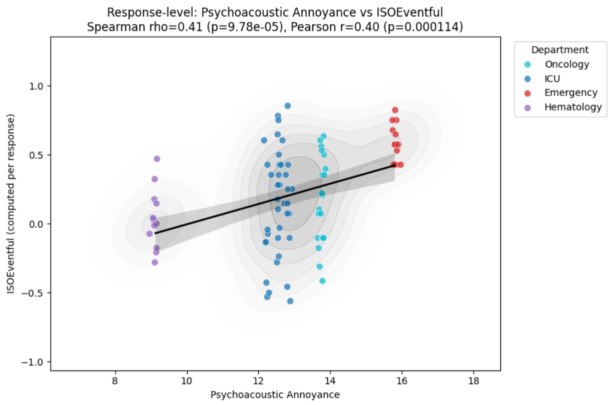

Figure 5: Response-level relationship between psychoacoustic annoyance (PA) and ISO Eventfulness across responses.

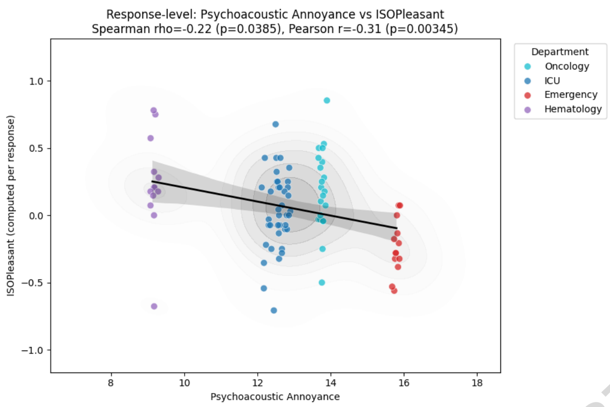

Figure 6: Response-level relationship between psychoacoustic annoyance (PA) and ISO Pleasantness across responses.

4. Discussion

4.1. Department Type As The Primary Explanatory Factor

The central finding of this study is that departments sharing similar mean sound levels can produce substantially different soundscape experiences, and that the reason lies in their source composition, the mix of alarms, speech, equipment, and building services that reflects each department's clinical function. ICU and Oncology demonstrate this most clearly: essentially identical LA_{eq}, but ICU has a harsher alarm-weighted character, higher roughness, and lower perceived appropriateness.

This matters for hospital acoustic management. A generic dB reduction target applied uniformly across a hospital will not address ICU problems, because the core issue is not only overall level but alarm density, spectral composition, and contextual interpretability. Emergency similarly needs communication spillover control and alarm governance rather than only blanket level reduction. This matters for recovery: a pattern of intermittent disruption against quiet allows physiological recovery between events, whereas a uniformly elevated baseline, as in Emergency, sustains activation continuously [17].

4.2. Psychoacoustics–Soundscape Assessment Link

The stronger association of PA with Eventfulness than with Pleasantness is theoretically coherent. Eventfulness is driven primarily by intensity and variability, which PA encodes well. Pleasantness also depends on contextual interpretation, whether sound is necessary, controllable, and meaningful [11], [18]. This contextual mediation explains why PA predicts Eventfulness more strongly than Pleasantness.

Roughness deserves specific design attention alongside loudness. Reducing roughness requires alarm tone redesign, communication zoning, equipment placement improvements, and mitigation of abrupt transients, intervention levers that are not directly targeted by level-based specifications [19].

4.3. Staff-Patient Divergence And Implications

The ICU staff-patient divergence is clinically significant and methodologically important, because it surfaces the tension between two occupant groups with different needs in the same space. Staff perceptions under-report burden relative to patient perceptions, because staff interpret alarms as task-relevant while patients may experience the same sounds as externally imposed and intrusive [3], [18]. This interpretation should be treated with caution, however, because respondents were not given a standardised listening task when completing the questionnaire, so role-related differences in how the questions were approached cannot be ruled out. Collecting direct patient responses in ICU should therefore be treated as a methodological priority.

4.4. Strengths and Limitations

A key strength of this study is the simultaneous, paired collection of psychoacoustic measurements and ISO 12913 questionnaires across four contrasting departments, including rare direct ICU patient responses. Limitations remain. Measurements covered daytime weekdays only. Departments other than ICU were measured at a single site, so between-department differences may include site effects, while the three ICU sites introduce within-ICU heterogeneity. The dataset was unbalanced across departments, measurement locations, and respondent groups: ICU accounted for 62 of 124 acoustic measurements, Hematology for only 14, and the perception dataset was staff-heavy, with no patient responses in Emergency. Reported relationships are correlational and do not establish causal response functions.

5. Conclusions

This research tested the claim that clinical department type is the primary driver of hospital soundscape quality, and that this is only visible when psychoacoustic measurement and ISO 12913 soundscape assessment are used together. The evidence supports that claim. The ICU-Oncology comparison shows most clearly that similar LA_{eq} values can conceal meaningfully different soundscapes. Source composition determines psychoacoustic profile, and psychoacoustic profile shapes perceived quality. The practical implication is clear: hospital acoustic management should be department-specific rather than uniformly level-driven.

Psychoacoustic annoyance and ISO 12913 soundscape assessments together provide a diagnostic framework to identify and prioritize interventions where they will have the strongest effect. The goal is acoustic appropriateness: the right sounds, at the right level, in the right place, for the people who depend on them.

6. Acknowledgments

This work was carried out as part of the first author's MSc thesis at Delft University of Technology, with Haskoning as industry partner. The authors are grateful to all staff and patients at the participating hospitals who gave their time and perspectives; hospital names are withheld to protect institutional anonymity. Thanks also to the HEAD Acoustics team for providing the ArtemiS SUITE license.

References

[1] I. J. Busch-Vishniac, J. E. West, C. Barnhill, T. Hunter, D. Orellana, and R. Chivukula, "Noise levels in Johns Hopkins Hospital," *The Journal of the Acoustical Society of America*, vol. 118, no. 6, pp. 3629–3645, 2005. DOI: 10.1121/1.2118327

[2] Z. Deng, H. Xie, and J. Kang, "The effectiveness of acoustic treatments in general hospital wards in China," *Building and Environment*, vol. 244, p. 110 728, 2023. DOI: 10.1016/j.buildenv.2023.110728

[3] H. Xie, J. Kang, and G. H. Mills, "Clinical review: The impact of noise on patients' sleep and the effectiveness of noise reduction strategies in intensive care units," *Critical Care*, vol. 13, no. 2, p. 208, 2009. DOI: 10.1186/cc7154

[4] M. Cvach, "Monitor alarm fatigue: An integrative review," *Biomedical Instrumentation and Technology*, vol. 46, no. 4, pp. 268–277, 2012. DOI: 10.2345/0899-8205-46.4.268

[5] S. Sendelbach and M. Funk, "Alarm fatigue: A patient safety concern," *AACN Advanced Critical Care*, vol. 24, no. 4, pp. 378–386, 2013. DOI: 10.1097/NCI.0b013e3182a903f9

[6] W. Filus, A. B. Moreira de Lacerda, and E. Albizu, "Ambient noise in emergency rooms and its health hazards," *International Archives of Otorhinolaryngology*, vol. 19, no. 3, pp. 205–209, 2015. DOI: 10.1055/s-0034-1387165

[7] J. L. Darbyshire and D. J. Young, "An investigation of sound levels on intensive care units with reference to the WHO guidelines," *Critical Care*, vol. 17, R187, 2013. DOI: 10.1186/cc12870

[8] A. Fiebig, "Psychoacoustic evaluation of soundscapes by means of repeated measurements," *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, vol. 263, no. 1, pp. 5485–5490, 2021. DOI: 10.3397/IN-2021-3118

[9] T. Y. Hsu, E. E. Ryherd, J. Ackerman, and K. P. Waye, "Psychoacoustic measures and their relationship to patient physiology in an intensive care unit," *The Journal of the Acoustical Society of America*, vol. 129, no. 4, p. 2635, 2011. DOI: 10.1121/1.3588772

[10] E. Zwicker and H. Fastl, *Psychoacoustics: Facts and Models*. Berlin, Germany: Springer, 1999.

[11] International Organization for Standardization, *Acoustics – soundscape – Part 1: Definition and Conceptual Framework (ISO 12913-1:2014)*, Geneva, Switzerland, 2014.

[12] International Organization for Standardization, *Acoustics – soundscape – Part 3: Data Analysis (ISO/TS 12913-3:2025)*, Geneva, Switzerland, 2025.

[13] E. Zwicker, "Psychoacoustics and annoyance: Effects of noise and vibration on well-being," *The Journal of the Acoustical Society of America*, vol. 105, no. 3, p. 1697, 1999.

[14] International Organization for Standardization, *Acoustics – soundscape – Part 2: Data Collection and Reporting Requirements (ISO/TS 12913-2:2018)*, Geneva, Switzerland, 2018.

[15] O. Axelsson, M. E. Nilsson, and B. Berglund, "A principal components model of soundscape perception," *The Journal of the Acoustical Society of America*, vol. 128, no. 5, pp. 2836–2846, 2010. DOI: 10.1121/1.3493436

[16] A. Mitchell, F. Aletta, and J. Kang, *Soundscapy: A Python library for soundscape analysis [computer software]*, 2022. [Online]. Available: https://soundscapy.readthedocs.io/

[17] D. C. Glass and J. L. Singer, *Urban Stress: Experiments on Noise and Social Stressors*. New York, NY: Academic Press, 1972.

[18] J. Mackrill, R. Cain, and P. Jennings, "Experiencing the hospital ward soundscape: Towards a model," *Journal of Environmental Psychology*, vol. 36, pp. 1–8, 2013. DOI: 10.1016/j.jenvp.2013.06.004

[19] M. S. Engel, A. Fiebig, C. Pfaffenbach, et al., "A review of the use of psychoacoustic indicators on soundscape studies," *Current Pollution Reports*, vol. 7, pp. 359–378, 2021. DOI: 10.1007/s40726-021-00197-1