IMPACT OF HOSPITAL SOUNDSCAPES ON COGNITIVE PERFORMANCE AND PHYSIOLOGICAL STRESS RESPONSES: A PILOT STUDY

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Abstract

This pilot study aimed to explore the relationship between objective acoustic conditions, perceived soundscape quality, and short-term cognitive and physiological responses in hospital environments. Continuous sound measurements were conducted over seven consecutive days in the emergency department and intensive care unit of Ataşehir Medical Park Hospital using a Type 1 sound level meter (HD2010). Equivalent continuous sound pressure levels (LAeq) and maximum A-weighted levels (LAFmax) were recorded. Audio excerpts were selected using a stratified sampling approach across four daily time periods (morning, afternoon, evening, and night), capturing both typical and peak noise conditions. A total of ten nurses evaluated the selected recordings using perceived affective quality attributes based on ISO 12913, including pleasant, chaotic, eventful, and calm, rated on a Likert scale. To assess short-term cognitive and stress related responses, participants completed a Stroop task before and after exposure to each audio excerpt. In addition, physiological responses were monitored through heart rate measurements to provide an objective indicator of autonomic arousal associated with stress. Preliminary analyses indicated higher LAeq and LAFmax levels in the emergency department compared to the intensive care unit. These elevated sound levels are anticipated to be associated with higher ratings of "eventful" and "chaotic" and lower ratings of "calm" and "pleasant." Exposure to more negatively perceived soundscapes is expected to correspond with elevated heart rate, and reduced cognitive performance, reflected in longer reaction times and decreased accuracy on the Stroop task.

Keywords: *Hospital soundscapes, Emergency department noise Intensive care unit (ICU), Healthcare acoustic environment, Occupational stress in nursing*

1. Introduction

Healthcare facilities deliver essential care and treatment to patients and residents, but they are also dynamic acoustic environments. Sound in these settings typically stems from human interaction—such as conversations between patients and visitors, expressions of distress, and discussions among medical personnel [1]. Additionally, continuous noise is generated by mechanical and medical devices, including ventilators, HVAC systems, equipment, and alarm systems [2]. To manage these soundscapes, the World Health Organization (WHO) established noise level guidelines, advising that noise in inpatient wards remain at or below 30 dB, while levels in operating rooms and intensive care units should be minimized as much as possible [3].

The acoustic environment plays a crucial role in emotional well-being: while comforting sounds foster a sense of security and familiarity, distressing noise often triggers feelings of anxiety and helplessness [2]. Consequently, managing soundscapes in healthcare facilities is essential for safeguarding both the physical comfort and psychological safety of patients, residents, staff, and visitors alike [4]. Over the past few decades, an expanding body of research has highlighted the profound impact of sound environments on healthcare, showing that acoustic conditions directly influence patient recovery outcomes as well as staff morale [5], [6]. Beyond its emotional toll, chronic noise exposure also impairs the functional performance of medical personnel, contributing to reduced concentration, cognitive fatigue, and an increased rate of judgment errors [7].

A review of the previous research indicates associations between architectural elements such as form and material and sound. Spatial design directly impacts ambient noise and privacy. Pod-style NICU layouts significantly reduced sound levels compared to traditional open layouts [8]. Similarly, sound insulation in patient rooms proved effective in walls but was compromised by standard doors with low Sound Transmission Class (STC) ratings, which worsened overall indoor noise [9]. Notably, upgrading room sizes and construction materials in pediatric wards did not automatically translate to lower noise levels [5].

Understanding the complex nature of hospital soundscapes is crucial for healthcare workers, especially nurses in high-acuity units like the Emergency Department (ED) and Intensive Care Unit (ICU). These clinicians face constant auditory overload. Prolonged exposure to noisy environments triggers the body's fight-or-flight response, raising sympathetic nervous system arousal—which shows up physically as an elevated heart rate (HR) and lower heart rate variability (HRV) [10]. At the same time, noisy surroundings drain mental energy. Nurses have to tune out constant background chatter and alarms while carrying out complex, high-stakes tasks. Under cognitive load theory, this continuous effort to filter out noise wears down focus, leading to slower reaction times, poorer working memory, and a higher risk of medical errors [11], [12].

While hospital noise and staff burnout are well-documented, several important gaps remain in the research:

- **Lack of Direct Comparisons in Real Settings:** Few studies directly compare the sound profiles of fast-paced, unpredictable spaces like EDs against highly monitored, steady-state spaces like ICUs using synchronized recordings.
- **Disconnected Methodologies:** Most research looks at noise levels, subjective stress surveys, or physical stress markers separately, rather than combining them into a single, comprehensive test.
- **Unclear Links to Brain Performance:** There is little experimental data directly connecting specific sound qualities (such as "chaotic" versus "calm" under the ISO 12913 standard) to objective tests of mental focus and impulse control, like the Stroop test.

To bridge these gaps, this pilot study examines how objective noise levels LAeq and LAFmax relate to subjective sound ratings, acute physical stress, and cognitive performance among nursing staff at Ataşehir Medical Park Hospital. By playing back real audio recorded over 7-day monitoring periods in the ED and ICU, the study addresses three main questions:

- **RQ1:** How do overall sound levels differ between the ED and ICU throughout the day?
- **RQ2:** How closely do higher sound levels track with negative soundscape ratings (e.g., chaotic vs. pleasant) under the ISO 12913 framework?
- **RQ3:** Does exposure to harsh hospital sounds trigger short-term physical stress (higher heart rate) and measurable drops in mental performance (slower responses or more errors on the Stroop task)?

2. Methodology

The experimental framework employs a multi-modal design combining continuous field acoustic monitoring, audio recordings, subjective soundscape ratings, physiological monitoring, and cognitive performance testing.

Continuous acoustic measurements were conducted over seven consecutive days across two distinct clinical units at Ataşehir Medical Park Hospital: The Emergency Department (ED) and the Intensive Care Unit (ICU). Sound pressure levels were recorded using a calibrated HD2010 Type 1 Sound Level Meter compliant with IEC 61672-1 Class 1 standards. Acoustic field calibration was performed immediately before and after each monitoring session using a Class 1 acoustic calibrator to ensure zero measurement drift. The microphone was mounted on a tripod at a height of 1.5 meters above floor level—representing human ear level in a standing/sitting position—positioned 1.5 meters from primary nursing workstations and clear of immediate acoustic reflecting boundaries (minimum 1.0 meter from surrounding walls). Continuous LAeq and LAFmax values were logged throughout the monitoring period.

Additionally, five-minute binaural audio samples were recorded across three key daily operational periods: morning, afternoon, and night. To eliminate selection bias, representative 1-minute excerpts (one from the ED and one from the ICU) were extracted from these samples using a systematic selection protocol:

- **Peak Impact Excerpts:** Segments containing the maximum LAFmax value to capture acute clinical acoustic events (e.g., equipment alarms, door impacts).
- **Acoustic Diversity:** Segments displaying distinct variance in dominant clinical sound sources (e.g., human speech, medical device telemetry, and mechanical noise).

Playback levels were calibrated using closed-back studio headphones to match the original sound pressure level (SPL) measured in the clinical units. A total of 10 healthcare professionals (nurses and doctors) from Ataşehir Medical Park Hospital were recruited for this pilot study. All participants reported normal hearing and signed informed consent prior to testing. To ensure baseline acoustic consistency, testing sessions were conducted individually in a dedicated, quiet room isolated from clinical disruptions. The experimental protocol evaluated three distinct tiers of human response: subjective perception, cognitive performance, and autonomic physiological arousal.

To evaluate physiological arousal, cognitive performance, and subjective affective perception, participants underwent a multi-modal testing protocol. Autonomic physiological arousal was monitored continuously by logging real-time heart rate (HR) throughout the experimental session. Prior to testing, a two-minute resting baseline HR was recorded in silence, followed by a baseline Stroop task in silence to establish control cognitive and physiological metrics (T_0). Subsequently, participants were exposed to four audio conditions—comprising two emergency department (ED) and two intensive care unit (ICU) hospital soundscapes—presented in a randomized, counterbalanced order to mitigate order and learning effects. During each audio exposure, participants performed a concurrent online Stroop task while HR was continuously recorded to assess sound-induced attentional interference and physiological load. Immediately following each exposure block, participants evaluated the soundscape's perceived affective quality using the ISO 12913-2 circumplex model on 5-point Likert scales across four pairs of bipolar axes representing the circumplex model of soundscape perception (Figure 1) [13]. A 60-second silent washout period was maintained between experimental blocks to allow heart rate metrics to return to baseline prior to the next stimulus.

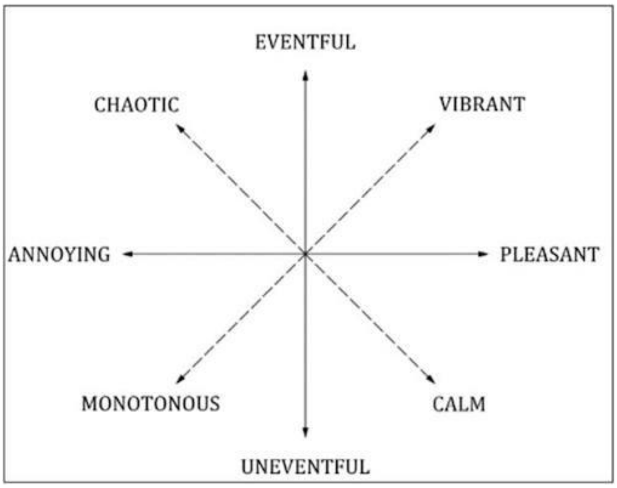

Figure 1. Pleasantness - Eventfulness plot

3. Results and discussion

To establish the baseline acoustic profile of the clinical environments, continuous physical acoustic measurements were recorded across seven consecutive days in both the Emergency Department (ED) and Intensive Care Unit (ICU). To evaluate the acoustic environments and their multi-modal impact on clinical staff, descriptive statistics were first computed for both the physical acoustic properties of the clinical environments and participant response metrics.

Comparative acoustic analyses were conducted between the Emergency Department (ED) and Intensive Care Unit (ICU) environments to quantify differences in baseline equivalent continuous sound pressure levels (L_{Aeq}), peak noise events (L_{AFmax}), and spectral distributions across the two clinical spaces. For participant data, screening for normality (Shapiro-Wilk test) and sphericity (Mauchly's test, with Greenhouse-Geisser corrections applied where appropriate) was performed across baseline (T_0), physiological (mean heart rate in bpm), cognitive (Stroop reaction time and accuracy), and ISO 12913-2 affective attribute metrics across all conditions.

Differences in physical acoustic measurements between the ED and ICU spaces were evaluated using paired-samples t-tests. To determine the downstream effects of acoustic condition and space type on human participants, a series of Repeated Measures Analysis of Variance (RM-ANOVA) tests were conducted with audio condition as the within-subject factor. Post-hoc pairwise comparisons with Bonferroni corrections were applied to identify specific differences between ED and ICU soundscapes as well as against silent baseline controls. Finally, to evaluate how environmental acoustic characteristics directly shape human response, Pearson's r was performed linking objective acoustic metrics (L_{Aeq}) directly to perceived affective attributes, Stroop cognitive interference, and physiological arousal shifts (ΔHR).

Acoustic measurements revealed distinct environmental noise profiles between the Emergency Department (ED) and the Intensive Care Unit (ICU), despite both units exhibiting nearly identical continuous equivalent sound levels (L_{Aeq}). The logarithmic average L_{Aeq} was 58.00 dB(A) in the emergency room and 58.30 dB(A) in the ICU, both substantially exceeding the World Health Organization's recommended hospital baseline limit of 35 dB(A). However, a marked divergence was observed in the maximum fast time-weighted sound levels (L_{AFmax}), with the ER registering an energy-averaged L_{AFmax} of 84.66 dB(A) compared to 65.80 dB(A) in the ICU—a peak sound pressure variance of nearly 20 dB. This structural difference in noise dynamics stems from the operational nature of each clinical unit. The ED's profile reflects a high-transient environment characterized by unpredictable, high-amplitude acoustic events—such as sudden shouting, gurney impacts, rapid door closures, and urgent alarm activations—which generate severe intermittent noise spikes. Conversely, the ICU operates under a steady-state noise profile dominated by continuous, low-frequency sound sources, including mechanical ventilation equipment, infusion pump hums, constant HVAC air turnover, and medical display monitors. Consequently, while total acoustic energy exposure (L_{Aeq}) remains equivalent across both units, the ED presents a heightened risk of acute acoustic startle and physiological stress, whereas the ICU exposes occupants to sustained background noise pollution known to disrupt sleep architecture and patient recovery [14].

These objective acoustic profiles closely align with the perceptual soundscape evaluations captured under the ISO 12913 standardized framework. Driven by the high transient peak levels (L_{AFmax}) and unpredictable noise spikes, the ED soundscape is overwhelmingly displaced into the chaotic quadrant, exhibiting dominant scores in *Eventful* (~3.9), *Chaotic* (~3.6), and *Annoying* (~3.2) that reflect an environment defined by high arousal and volatile acoustic disruption. Conversely, the continuous, steady-state background noise of the ICU shifts its perceptual profile into the monotonous quadrant, characterized by elevated ratings in *Monotonous* (~2.6) and *Uneventful* (~2.3) alongside moderate *Annoyance* (~1.9). Crucially, neither clinical unit projects into positive soundscape dimensions (*Calm*, *Pleasant*, or *Vibrant*, all ≤ 2.0), confirming a baseline absence of restorative acoustic quality across both clinical settings. Ultimately, while physical energy metrics (L_{Aeq}) suggest comparable overall sound exposure, the ISO soundscape analysis uncovers fundamentally distinct psychoacoustic burdens—acute chaotic stress in the ED

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versus chronic, monotonous fatigue in the ICU—underscoring the necessity of targeted environmental design and noise-mitigation strategies tailored to each unit's operational context (Figure 2).

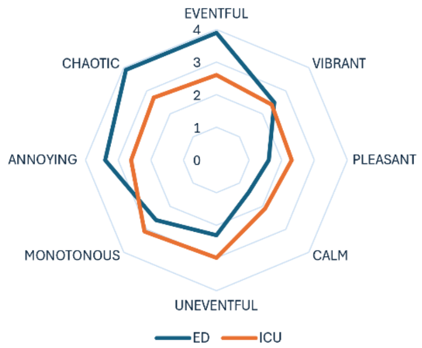

Figure 2. Comparison of soundscape perceptual attributes between the Emergency Department (ED) and Intensive Care Unit (ICU)

A repeated-measures ANOVA was conducted to evaluate the effect of ambient environment conditions during the Stroop task on heart rate across three conditions: resting baseline ($M = 82.50$, $SD = 9.95$), ICU noise ($M = 89.70$, $SD = 12.68$), and ER noise ($M = 91.40$, $SD = 14.63$). Mauchly's test indicated that the assumption of sphericity was met, $\chi^2(2) = 5.39$, $p = .068$. The overall main effect of condition was statistically significant, $F(2,18) = 10.35$, $p = .001$, $\eta_p^2 = .535$, indicating that the environmental conditions had a substantial impact on autonomic arousal.

Post-hoc pairwise comparisons using a Bonferroni adjustment revealed that heart rate was significantly elevated during both the ICU noise condition ($p = .036$) and the ER noise condition ($p = .019$) relative to the resting baseline. However, the difference in heart rate between the ICU noise and ER noise conditions was not statistically significant ($MD = -1.70$, $SE = 1.17$, $p = .535$). Overall, these results demonstrate that engaging in the Stroop task under simulated clinical noise conditions reliably induces physiological stress above resting levels, though the specific high-stress acoustic environment (ICU vs. ER) did not produce a significantly different physiological load (Figure 3).

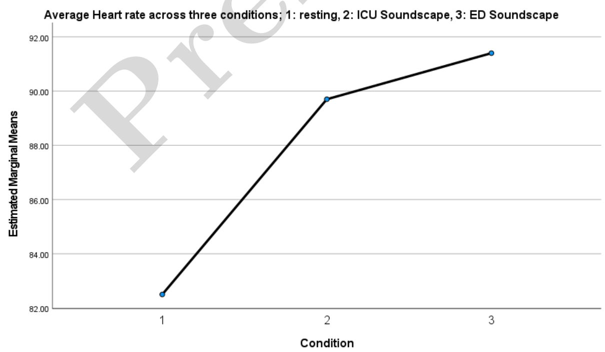

Figure 3. Estimated marginal means of heart rate (BPM) across experimental conditions.

In contrast to autonomic arousal, executive cognitive performance demonstrated marked sensitivity to the specific structural characteristics of the ambient acoustic environment. Evaluation of Stroop reaction time interference ($RT_{incongruent} - RT_{congruent}$) indicated elevated cognitive disruption under noisy conditions relative to quiet baseline controls. Executive function was most severely degraded during exposure to Emergency Department noise, where participants exhibited the greatest latency in suppressing task-irrelevant text information, whereas Intensive Care Unit noise produced a more moderate increase in cognitive interference.

Task accuracy metrics closely mirrored reaction time trends. Error rates peaked under the ER noise condition, driven by a higher frequency of incorrect key presses and delayed responses on conflicting trials. By comparison, accuracy was relatively preserved under ICU noise, though still degraded relative to silent baseline performance. Together, these behavioral metrics demonstrate a clear qualitative gradient of cognitive strain: while both clinical soundscapes impair selective attention relative to quiet baselines, the high-transient, unpredictable acoustic profile of the ER induces noticeably greater executive function disruption and visual-attentional error than the steady-state background hum of the ICU.

Ultimately, these findings highlight the limitations of relying solely on average decibel metrics (L_{Aeq}) when evaluating clinical acoustic design or clinician burnout. While overall sound energy exposure remains comparable across units, acute transient noise in the Emergency Department severely compromises selective attention and task accuracy, whereas steady-state ICU noise fosters chronic mental fatigue.
Standard abbreviations should be used in your bibliography. When the following words appear in the references, please abbreviate them:

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