Megaron, Vol. 19, No. 04, pp. 550–561, December 2024

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2024.69009

Article

Integration of psychoacoustic parameters into acoustic design: The impact of architectural design factors on the indoor soundscape of airport terminal buildings

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ARTICLE INFO

Article history
Received: 15 July 2024
Revised: 03 January 2025
Accepted: 03 January 2025

Key words:
Acoustic comfort; airport terminal buildings; architectural design; indoor soundscape; psychoacoustic parameters.

ABSTRACT

This research examines the complex relationship between architectural design factors and psychoacoustic parameters in airport terminal buildings. Architectural design elements such as surface properties and dimensional aspects, as well as factors such as spatial layouts, were evaluated to investigate how design decisions impact the sound environment and, consequently, passenger comfort. A variety of methods, including on-site measurements, binaural sound recordings, questionnaires, auralizations, and listening tests, were used to analyze and improve the sound environment of airport terminal buildings. Results indicate that differences in loudness values are related to the architectural form, surface properties, and configuration of the circulation paths. Furthermore, it has been revealed that the change in the height of the building affects the sharpness value, and roughness is directly related to the absorbency of surface materials, independent of volume. Essentially, this research underscores the pivotal role of integrating psychoacoustic parameters such as loudness, roughness, and sharpness into the acoustic design framework of airport terminal buildings. Such integration enhances our understanding of the relationship between architectural design and indoor soundscape, as well as informs design decisions aimed at optimizing acoustic comfort in airport facilities.

Cite this article as: Ayık, K. K., İlgürel, M. N. (2024). Integration of psychoacoustic parameters into acoustic design: The impact of architectural design factors on the indoor soundscape of airport terminal buildings. Megaron, 19(4), 550-561.

INTRODUCTION

Modern airports are intricate structures that shape the travel experiences of millions of passengers worldwide. Their effectiveness is determined not only by functionality and aesthetics but also by their acoustic properties, which directly affect user comfort and satisfaction. Airport terminal buildings present several acoustic challenges due to their large spaces, high ceilings, and dense human traffic. Creating an appropriate soundscape in these environments is crucial for enhancing passenger comfort and reducing stress.

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Conventional acoustic design approaches often focus only on physical parameters, while psychoacoustic parameters, which examine the effects of sound on human perception, are mostly overlooked. Room acoustics play a critical role in making design decisions aimed at improving functionality and comfort, and these studies are typically conducted in spaces with homogeneous and specific sound conditions where the primary purpose is acoustics (Barron, 2010; Beranek, 2004; Barron, 2005). However, non-acoustic enclosed public spaces such as shopping malls, stadiums, libraries, open-plan offices, and transport hubs/stations present a special challenge in terms of achieving acoustic comfort (Gül et al., 2021; Wu et al., 2020; Yilmazer and Bora, 2017). Each of these spaces has a unique sound environment, and room acoustic parameters used in conventional treatments alone are insufficient to describe the complex soundscape of such spaces (Kang et al., 2006; Genuit and Fiebig, 2005; Botteldooren et al., 2006). In this context, evaluating and understanding the acoustic comfort of spaces by focusing on the soundscape approach is considered an important step.

Psychoacoustics investigates the mechanisms underlying human perception and interpretation of sound stimuli. It explores the psychological and physiological factors that influence our auditory perception, including how we perceive pitch, loudness, timbre, and spatial location of sounds (Gelfand, 2010). Therefore, psychoacoustics can play an important role in evaluating the acoustic performance of airport terminals. Integration of psychoacoustic parameters can improve not only the physical acoustic performance of the space but also the perceptual and emotional experiences of its occupants.

Research on the acoustic comfort of airport terminal buildings, which is limited, mainly centers on two acoustic parameters: reverberation time and sound pressure level. Haan and Park (2015), Geng et al. (2017), Huang et al. (2019), van Wijngaarden and Atsma (2020), Gül et al. (2021), and Carlucci and Tiano (2021) conducted studies examining the acoustics of terminal buildings through measurements and/or simulations using these parameters. Besides, the soundscape approach, which also considers user perception, has been used in a few studies. Wang et al. (2020) investigated the effects of acoustic sequences on noise acceptance, i.e., sequence sound sessions that occur when users are staying or walking in a transport hub. Sound recordings were captured in 34 transport hubs/stations as part of the research project, including 9 airports, 14 railway stations, 4 bus stations, and 7 subway stations. Listening tests were conducted for the subjective evaluation of the sound recordings. Li and Zhao (2023) conducted questionnaire surveys and sound pressure level measurements to evaluate the sound environment of airport terminal buildings. Similarly, Liu et al. (2023) conducted a comprehensive study investigating passengers' perception of the acoustic environment in an airport terminal. In addition to questionnaire surveys and sound pressure levels, psychoacoustic parameters were also measured.

In this study, an innovative approach is employed to improve the indoor soundscape of airport terminal buildings. The primary aim of the research is to integrate psychoacoustic parameters into the acoustic design process to achieve enhanced acoustic performance. This research seeks to examine how architectural design elements and spatial layouts in airport terminal buildings affect psychoacoustic parameters. Furthermore, it aims to determine the potential effects of these psychoacoustic parameters on user comfort and satisfaction. The findings are intended to contribute to the establishment of specific criteria in the architectural and acoustic design of airport terminal buildings, thereby positively influencing passengers' travel experiences.

MATERIALS AND METHODS

This section provides a detailed overview of the methods used in the research, along with their application processes. Multiple methods were utilized, such as on-site measurements, binaural sound recordings, questionnaires, auralizations, and laboratory listening tests. Listening tests consisted of three main parts: binaural sound recordings captured from on-site measurements, auralizations generated through models calibrated with reverberation time measurements, and auralizations generated using alternative simulation models. This multi-method approach provides a comprehensive analysis of subjective and objective data obtained in both on-site and laboratory settings.

Research Setting

The Izmir Adnan Menderes Airport has been serving as a significant aviation hub in Turkey since 1987. The airport reached its final structure with a series of expansion and improvement works that began with the opening of the international terminal in 2006 and culminated with the addition of the domestic terminal building in 2014 (DHMI, 2024).

The airport facility is designed with a linear concept, distinguishing between the landside and the airside. The international check-in hall (TA) is structured as a standalone unit, while the more recently constructed domestic check-in hall (TB) is linked to the domestic departure lounge (TC) through a common area, an atrium (Fig. 1a). The TA, which has a concave roof system, covers an area of 12,880 m^2 with a volume of 299,000 m^3. The TB features a diagrid vaulted roof system, and the terminal building itself covers an area of 15,360 m^2 with a volume of 241,000 m^3. The TC, connected to the TB via an atrium area with an origami roof system, has an area of 13,500 m^2 and a volume of 161,000 m^3.

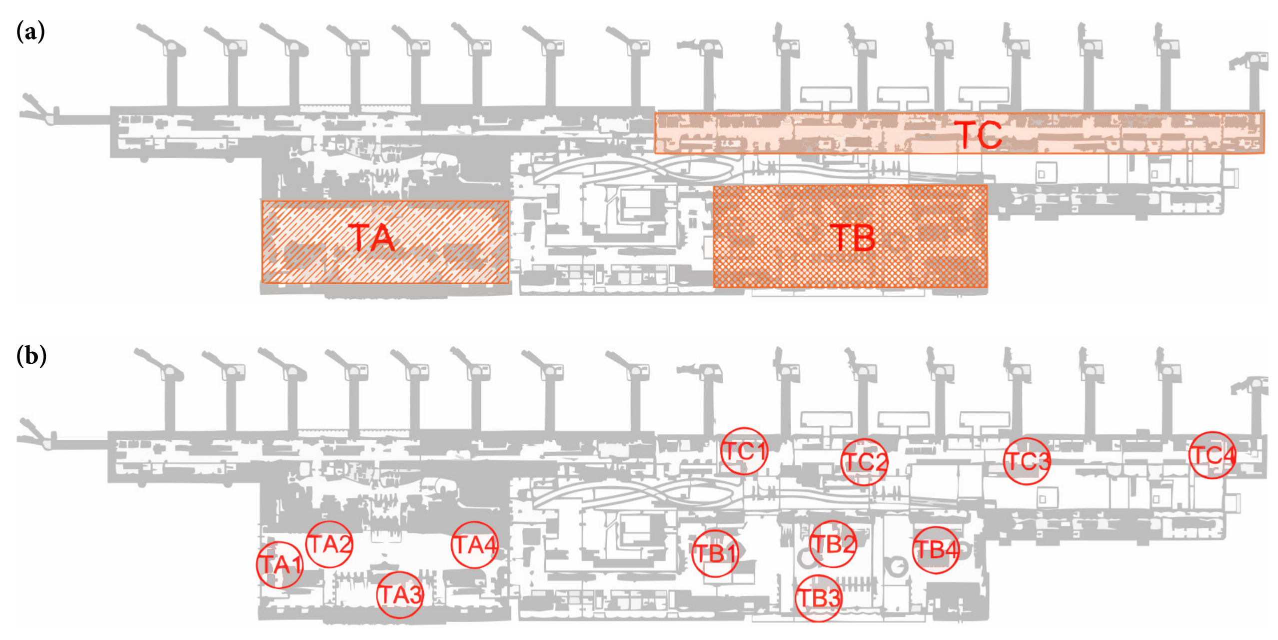


Figure 1. **(a)** Location of terminal buildings, and **(b)** Measurement points.

Equipment and Software

The reverberation time measurements were conducted using a set of equipment that included an omnidirectional source (Brüel & Kjaer–Omni Power 4292-L), a microphone, a power amplifier (Brüel & Kjaer–2734-A), a sound level meter (Brüel & Kjaer–2250), and the M-Track model sound card of M-AUDIO. The microphone was calibrated before the measurements using a calibrator (Brüel & Kjaer–4231). The RT measurements were carried out in terminal buildings without occupants. For binaural sound recordings, a laptop, two G.R.A.S. 40AE 1/2" microphones, two G.R.A.S. 26CA 1/2" preamplifiers, and an 01dB dB4 four-channel sound recorder were used. The acquired data were stored on a portable computer via dBFA recording software and analyzed in detail using the psychoacoustic module of dBSonic v.4.6.4.155 software. Auralizations were generated for listening tests using ODEON software (version 14.05 combined). Sennheiser HD 380 PRO headphones were utilized for the listening tests.

Acoustical Indicators

Reverberation time (RT)

Reverberation is the term used to describe the sound in a room that results from the attenuation of successive reflections after the sound source is switched off. The duration needed for the sound pressure level to decrease by 60 dB is known as the reverberation time (Long, 2014). Reverberation time measurements in terminal buildings were measured using the interrupted method as described by ISO 3382-2. In practice, a decrease of 20 or 30 dB is typically evaluated. In this study, assessments were conducted using RT30 measurements.

The just detectable difference (JND) of RT is accepted in ISO 3382-1 to be 5%, based on work by Seraphim (1958).

Sound pressure level (SPL)

The sound pressure level [dBA] is the most commonly used indicator of acoustic wave strength. It's a way to quantify the intensity of sound waves, representing how loud a sound appears to the human ear (Long, 2014).

The just noticeable difference (JND) for sound pressure level is generally accepted to be about 1 dB, although it varies according to frequency (Long, 2014).

Loudness (N)

Loudness [Sone] is a subjective term describing the magnitude of the perception of a sound by the human ear. It is a psychoacoustic quantity that depends on the sound pressure level, the frequency spectrum, and the temporal behavior of the sound (Fastl and Zwicker, 2007). Loudness corresponds significantly better to the subjective impression of volume compared to the A-weighted level (Bite et al., 2005; Genuit et al., 2010).

W. Rabinowitz estimates the just noticeable difference (JND) level in loudness at 7% (Rabinowitz, 1970).

Sharpness (S)

Sharpness [Acum] is an indicator of the spectral balance between low and high frequencies (Kang, 2007). The computed sharpness values are not significantly affected by the overall level or the detailed spectral structure. The unit of sharpness, 1 Acum, is a narrow-band noise of one critical octave bandwidth at a center frequency of 1 kHz with a level of 60 dB (Fastl and Zwicker, 2007).

The accepted value for the just noticeable difference (JND) of sharpness is taken to be 10%, based on work by Osses et al. (2023).

Roughness (R)

Roughness [Asper] is a subjective measure related to the rapid changes in the loudness of the sound, with maximal roughness often occurring around 70 Hz. This sensation can occur when there are rapid changes in amplitude or frequency in a sound signal, leading to a sensation of roughness (Daniel, 2008). The unit of roughness, 1 asper, is defined as the "roughness" produced by a 1 kHz tone of 60 dB, which is 100% amplitude modulated at 70 Hz (Fastl and Zwicker, 2007).

Research indicates that a relative variation of approximately 17% causes JND in roughness, with the lower limit of roughness perception being 0.07 asper (Daniel and Weber, 1997; Fastl and Zwicker, 2007).

On-site Data Collection

The sound recordings were taken at the measurement points delineated in Figure 1b from October 7th to October 9th, 2023. Recordings were captured twice a day over three days, with each session lasting five minutes at each designated point. The main paths and locations of passengers, as well as the architectural characteristics of the site, were taken into consideration when determining the points where sound recordings were captured. The microphones were placed at a minimum distance of 1 meter from any sound source, with their height adjusted to the user's ear level – set at 1.5 meters above the ground.

The temperature and relative humidity were measured twice a day in each terminal building using the Extech HT30 Instrument. Room temperatures ranged from 23.9°C to 26.1°C, falling within the winter temperature range recommended by CIBSE (2015), considered optimal at 23–26°C. Relative humidity in the terminal buildings was also within acceptable levels (ASHRAE, 2003), ranging from 42.1% to 49.3%.

A questionnaire survey was conducted simultaneously with on-site measurements to understand how the existing soundscape is perceived by users. The necessary ethics committee approval for all studies conducted within the scope of the research was received by the Yıldız Technical University Social Sciences Institute Ethics Committee in September 2023. Interviewees were randomly selected to ensure a representative sample of terminal users, with an equal distribution of male and female participants. The sound environment was assessed using a 5-point scale, with participants being asked to respond to the following questions: "1. Evaluate the acoustic comfort of the terminal building you are currently in.", "2. Evaluate the noise level of the terminal building you are currently in.", "3. Evaluate the reverberation in the space.", "4. Evaluate the overall surrounding sound environment.", "5. How do you think the sound environment affects your experience in the airport terminal building?", "6. Overall, to what extent is the present surrounding sound environment appropriate to the present place?"

Auralizations

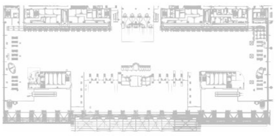
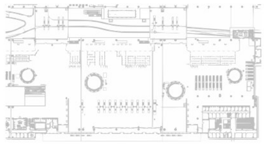
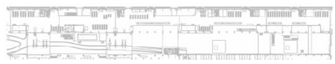
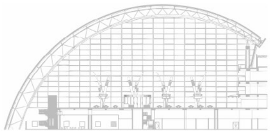
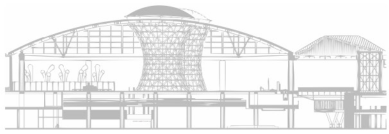
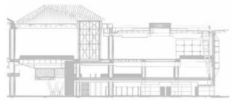
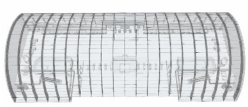
The methodologies for auralization exhibit considerable variation, with procedures tailored to specific applications (Harriet, 2013; Harriet and Murphy, 2015; Chen et al., 2023). In this research, auralization primarily aims to evaluate participants' responses to both the existing sound environment in an airport terminal building and subsequent virtual alterations made to the acoustic design of the terminal building.

Three-dimensional (3D) models representing the terminal buildings were created for auralizations. To be able to conduct an accurate analysis of the existing conditions, these buildings were modeled to precisely replicate the original structures without alterations to their shape, materials, or dimensions (Table 1). Towards this aim, simulation models were calibrated based on measured reverberation time (RT) values to make the sound environment as close as possible to the current situation. The measurement and simulation model reverberation time values for octave band frequencies are shown comparatively in Table 2.

Models were created to represent virtually created variations of the domestic check-in hall (TB): different heights of the enclosure, surface properties, and spatial relationships. Initially, three different room sizes of the terminal building were used. In addition to the existing building, variations of 'lower' and 'higher' were modeled. Alternative models were created by changing only the height of the building while maintaining a similar material layout and characteristics to the existing model. In the second stage, terminal building (TB) models with various surface properties were created for auralizations to investigate the effects of altering the absorption coefficients on the existing sound environment. Finally, models were created for two different cases of spatial relationships: "spaces linked by a common space" – the existing case, and the "standalone unit" – the relationship of the existing terminal building with the atrium is separated by a virtual surface assigned as glass.

In spaces such as airport terminal buildings, passengers typically gather in small groups within designated waiting areas. Auralizations were created in ODEON by assigning both a multi-surface source and point sources to accurately represent these groups. Following Rindel's methodology, the multi-surface source was modeled to cover the area where people were speaking, positioned at a height just above their heads, specifically 0.3 meters (Rindel, 2012). The receivers are the points in a grid covering the same area but

Table 1. Architectural information of terminal buildings

	Int. check-in hall – TA	Domestic check-in hall – TB	Domestic departure lounge – TC
Plan			
Section			
3D Model			
Max. Dimension (l*w*h)	184m*70m *30m	197m*78m *20m	450m*30m *7m
Volume	299,000 m^3	241,000 m^3	161,000 m^3
Room Shape	Rectangular plan, concave ceiling	Rectangular plan, vault ceiling	Rectangular plan
Floor	Granite stone	Granite stone	Granite stone
Wall	Glass	Glass	Glass
Ceiling	Perforated panel, metal cladding	Perforated panel	Perforated panel, gypsum board

TA: International check-in hall; TB: Domestic check-in hall; TC: Domestic departure lounge.

Table 2. RT values of on-site measurements and ODEON simulations

Reverberation Time [s]	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
TA						
Measurements	5.53	5.37	5.60	6.89	5.79	3.34
Simulation	5.50	5.33	5.58	6.88	5.83	3.38
TB						
Measurements	3.00	2.92	2.81	2.97	2.82	2.11
Simulation	3.01	2.92	2.84	2.95	2.84	2.14
TC						
Measurements	3.03	3.68	3.78	4.07	3.84	2.44
Simulation	2.99	3.71	3.90	4.10	3.89	2.39

TA: International check-in hall; TB: Domestic check-in hall; TC: Domestic departure lounge.

at the average ear height. The spectrum and sound power of the source were adjusted to account for the Lombard effect (Rindel et al., 2012). The number of passengers in the terminal building was estimated to be an average of 650 individuals. Surface source calculations were based on a total of 600 individuals, with a group size of 4. Point source assignments were subsequently allocated for the remaining passengers, considering the number of people speaking simultaneously.

Anechoic recordings were used in the convolution process to ensure that room effects originating from the recordings were not included in the auralization (Vigeant et al., 2010).

The “Background Speech” sound file in the ODEON library was used for multi-surface source assignment (ODEON, 2024a). Sound files assigned to point sources were adjusted based on psychoacoustic values, considering on-site measurement data to ensure realistic auralization. The selection of sound files assigned to point sources was drawn from anechoic recordings featured in the Harvard Psychoacoustic Sentences research (ODEON, 2024b). These files were organized based on sharpness values and integrated into the model to meet the requirements for sharp or unsharp sound during auralization calibrations (Çakır, 2019). The measurement and calibrated simulation values of acoustic indicator values are shown in Table 3.

Listening Tests

Listening tests were conducted under laboratory conditions using headphones, with 38 participants comprising 18 females (47.4%) and 20 males (52.6%), all with normal hearing. The average age of the participants was 29 (min. 20; max. 35; SD = 4.19). Their occupations varied and included students, office workers, and freelancers. All participants took part in the experiment voluntarily.

Listening tests consist of five basic parts that involve participants listening to a total of 32 sound files. Pairwise comparison and continuous assessment methods were applied throughout these tests. The pairwise comparison method involves participants evaluating their preferences using a 5-point scale after listening to each sound file (Geissner and Parizet, 2005). The Analytic Hierarchy Process (AHP) method and pairwise comparison matrices were used in calculating acoustic comfort weightings. On the other hand, in the continuous assessment method, participants listen to sounds one by one and evaluate each one separately using a 5-point scale. The acoustic comfort weighting is then determined by averaging all ratings provided. Listening tests took approximately 10 to 15 minutes for each participant.

Table 3. The measurement and calibrated ODEON simulation values of acoustic indicators

	SPL [dBA]	N [Sone]	S [Acum]	R [cAsper]
TA				
Measurements	60.08	13.86	1.07	29.57
Simulation	60.08	13.74	1.07	30.24
TB				
Measurements	58.13	12.37	1.21	27.39
Simulation	58.13	12.35	1.21	25.43
TC				
Measurements	59.06	13.20	1.18	29.19
Simulation	59.06	13.02	1.18	27.91

SPL: Sound pressure level; N: Loudness; S: Sharpness; R: Rougness; TA: International check-in hall; TB: Domestic check-in hall; TC: Domestic departure lounge.

In Part 1, participants listened to sound recordings captured in three different terminal buildings. This part consists of two subsections: in part 1-A, the participants evaluated the sound files of each terminal building separately, and in part 1-B, they compared these sounds in pairs.

In Part 2, participants were presented with sound files featuring identical psychoacoustic attributes created by computer models of the same terminal buildings. This part also consisted of two subsections: participants evaluated the sounds separately in Part 2-A and then made pairwise comparisons in Part 2-B. This approach served to evaluate the accuracy of the models devised for the soundscape evaluations.

In Part 3, which focused on examining varying height values, only the height was changed in the terminal building (TB) simulation model while keeping the sound power of the sound source, surface properties, and the architectural form constant. The pairwise comparison method was used for listening tests in parts 3, 4, and 5.

In Part 4, the total surface absorption in the model was systematically varied while keeping the sound power of the source, architectural dimensions, and architectural form constant.

In Part 5, the impact of the presence or absence of "common space" on soundscape in terms of acoustic comfort was examined. Auralizations created for this purpose were used in listening tests.

RESULTS AND DISCUSSION

On-site Measurements

Five-minute measurements were carried out for three days, twice a day, at each measurement point of the terminal buildings. The level distribution percentages of the measured parameters in the time domain for different terminal buildings are presented in Figure 2.

In the graphs, information such as exceptional events obtained during 5% of the sampling time, average values obtained during 50% of the sampling time, and overall background values dominantly present during 95% of the sampling time are provided.

In terminal buildings, although the mean values are nearly identical, a detailed analysis reveals the potential for discussing both the similarities and differences in the sound environment through an examination of the statistical distribution of the data. The distribution of loudness values obtained from terminal buildings extends from samples where N95 is 6 Sone and N5 is 8 Sone to samples where N95 is 10 Sone and N5 is 31 Sone. N95 values in TB range from

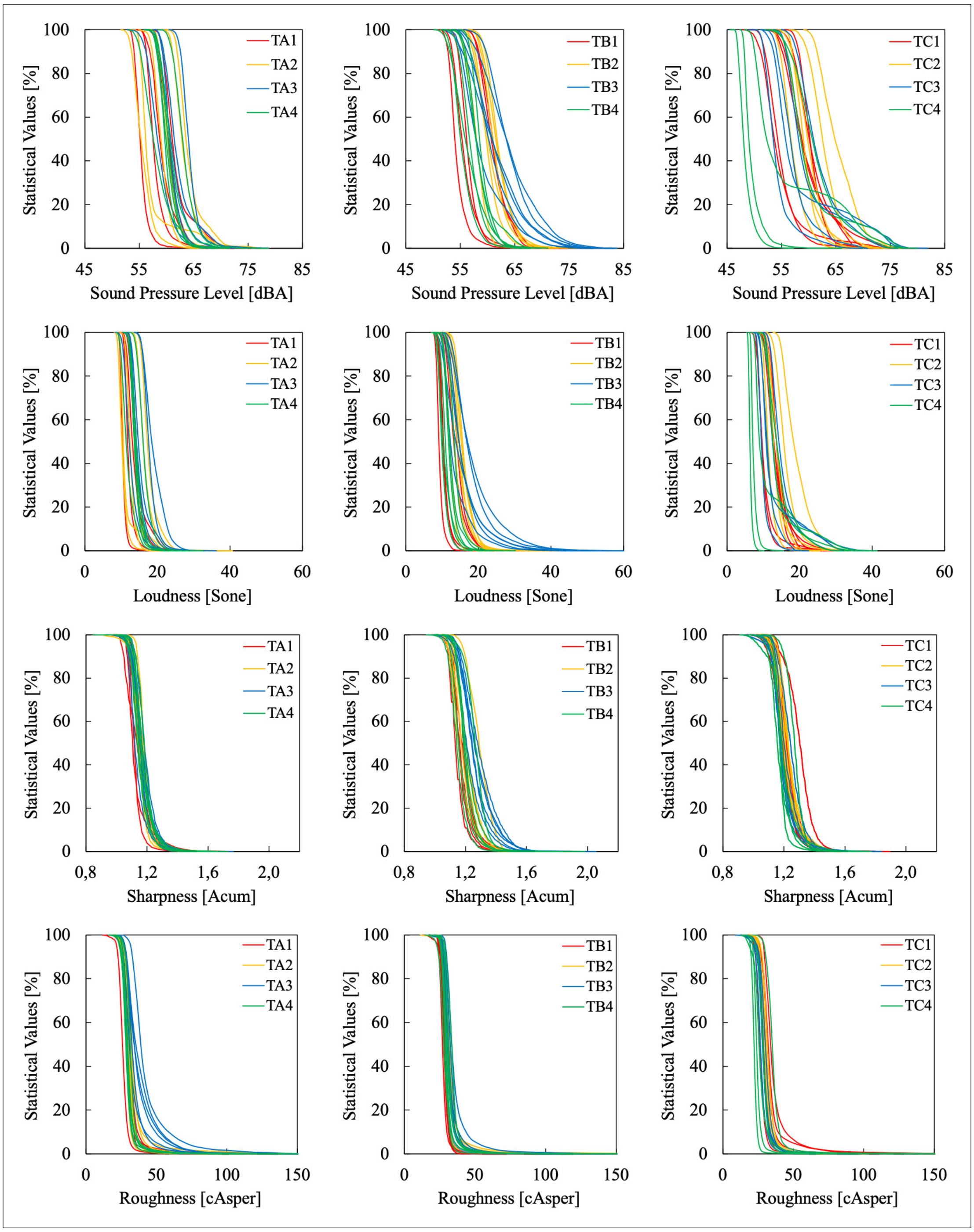


Figure 2. Distribution of the statistical values of on-site measurements

8 to 12 Sone. However, in TA, another landside structure, the distribution shows relatively wider and higher loudness levels, ranging from 9 to 15 Sone. Meanwhile, in TC, this range fluctuates between 6 and 14 Sone. The different slopes of loudness curves in terminal buildings indicate differences in the temporal structure.

The statistical distribution of sound pressure levels exhibits similarities with loudness distributions. Upon examining TC, the values change according to spatial relationships such as the presence of an atrium and circulation paths, as well as functional differences.

The distribution of sharpness values varies between 1.0 and just below 1.30 Acum for the S50: 1.00 – 1.16 Acum in TA, 1.13 – 1.29 Acum in TB, and 1.13 – 1.26 Acum in TC.

The values of roughness data of TB reveal that it has a relatively narrow spread in slopes of the curves and mainly in peak values. However, the R50 values of the three terminal buildings do not differ significantly as much as the level of JND.

On-site Questionnaires

Subjective data were collected using on-site questionnaires. A total of 186 questionnaires were gathered from terminal buildings TA (60), TB (64), and TC (62), respectively. The demographic composition of the respondents consisted of 102 females (54.8%) and 84 males (45.2%). The average age of the participants was 35 years old (min. 18; max. 60; SD=12.51). Detailed responses gathered from each terminal building are presented in Table 4.

The skewness and kurtosis values, along with their respective indices, of the numerical variables were assessed to gauge the normality of the data. As the skewness and kurtosis values of the numerical variables fell within the range of less than ±1, it was assumed that the data exhibited a normal distribution (Tabachnick and Fidell, 2013). A reliability score was computed for all questions included in the survey. Concerning the questions regarding the perception of the sound environment, Cronbach's α coefficient was determined to be 0.783.

According to the subjective survey results, the subjective loudness assessment of all buildings is close to each other and at a medium level (average between 2.25 and 2.33). However, passengers tended to make clearer distinctions between terminal buildings when evaluating acoustic comfort (averaging between 3.10 and 3.57). Participants identified TB as the quietest area, with the lowest level of reverberation and the highest acoustic comfort. Similarly, participants rated TB as having the best sound environment. TA did not receive as positive ratings as other buildings in any question. Additionally, a similar ranking was achieved in terms of the appropriateness of the sound environment. The effect of the sound environment on the experience is marked higher in TC, which is the airside, unlike the other questions.

Analyzing On-site Data: Comparing Objective Metrics with Subjective Evaluations

On-site data collection was conducted to characterize the existing sound environment of terminal buildings for obtaining the most realistic results in auralizations. Overall, TB exhibits lower reverberation time (RT) and loudness (N), and higher sharpness (S) values, according to objective data. Additionally, subjective questionnaire results indicate that the sound environment in TB was more favorably perceived, resulting in a higher acoustic comfort score compared to others. Conversely, the sound environment with psychoacoustic parameters in TA was associated with a lower comfort level by users.

The mean loudness values measured in the terminal buildings are close to each other, with differences within the range of JND. However, acoustic comfort in terminal buildings tends to decrease as loudness increases, as shown in Figure 3. TA has the highest loudness values and the lowest acoustic comfort, whereas TB has the lowest loudness values and the highest acoustic comfort score. Subjective evaluations compared with psychoacoustic parameter values show a direct proportional relationship between sharpness and acoustic comfort, as expected. Çakır and İlal (2021) revealed a strong relationship between sharpness and acoustic comfort in their research. In terminal buildings, it can be stated that as sharpness increases, acoustic comfort also increases, provided it remains within this range. The relationship between mean sharpness values and acoustic comfort is shown in Figure 4.

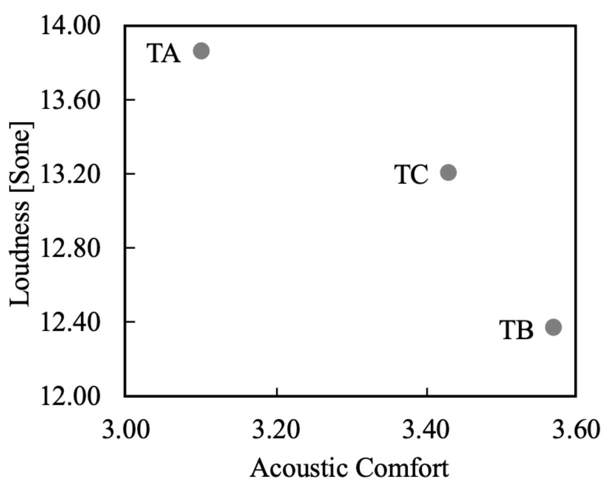


Figure 3. Relationship between mean loudness and acoustic comfort (Pearson's $r = -0.961$; $p = 0.179$).

Table 4. Mean values for subjective evaluations from questionnaires on a scale from 1 (low) to 5 (high)

	Acoustic Comfort		Noisiness		Subjective Reverberation		Sound Environment		The Effect of Sound Environment on Experience		Appropriateness of the Sound Environment	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
TA (60)	3.10	1.06	2.33	0.61	2.30	0.95	3.00	1.08	3.27	1.17	3.50	0.97
TB (64)	3.57	0.98	2.25	0.62	2.09	0.64	3.53	0.98	3.49	1.02	3.81	0.86
TC (62)	3.43	0.82	2.29	0.97	2.26	0.89	3.31	0.91	3.65	0.98	3.77	0.84

SD: Standart deviation; TA: International check-in hall; TB: Domestic check-in hall; TC: Domestic departure lounge.

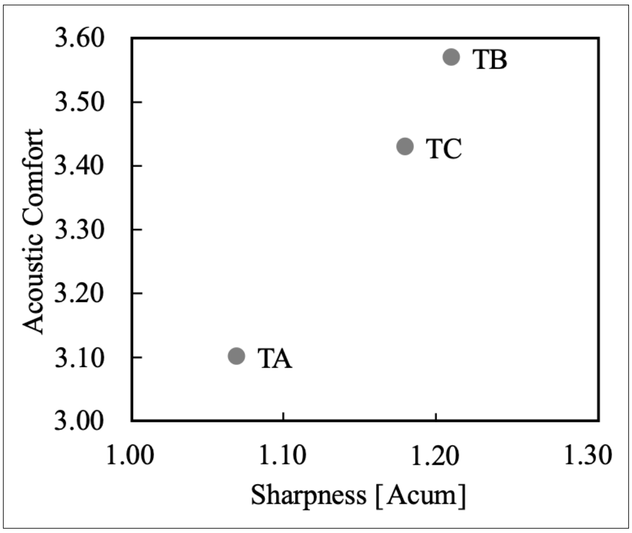


Figure 4. Relationship between acoustic comfort and sharpness (Pearson's r = 0.995; p = 0.066).

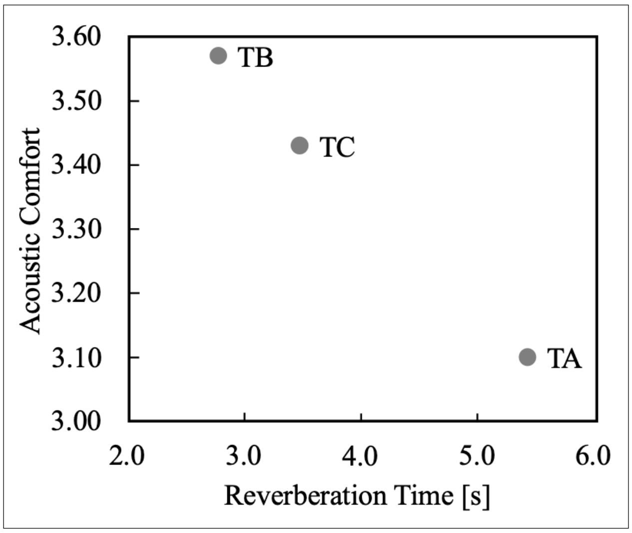


Figure 5. Relationship between acoustic comfort and RT (Pearson's r=-0.999; p=0.023).

The subjective responses to acoustic comfort questions in the questionnaire survey were found to be correlated with reverberation time. As the reverberation time decreases, acoustic comfort increases. The relationship between reverberation time and acoustic comfort in three terminal buildings is shown in Figure 5.

Listening Tests

The consistency ratio (CR) values were calculated in the analytical hierarchy process, where the responses of participants in listening tests were evaluated. The degree of deviation from pure inconsistency is measured by the coefficient of determination (CR) for each matrix size. According to Saaty (1987), this is calculated by dividing a consistency index by the average consistency index obtained from a large set of randomly generated matrices. Four participants' tests were classified as inconsistent due to CR values exceeding 0.2 and were disregarded. The results of the remaining 34 participants were evaluated.

The first two parts of the listening test were carried out to understand how accurately the simulation model reflected the real situation: evaluation of on-site sound recordings and evaluation of sound recordings created with the simulation model.

In Part 1-A, where participants evaluated the on-site sound recordings separately, the average ratings were TB (3.03), TC (2.74), and TA (1.85). In part 1-B, where participants make pairwise comparisons, the average weights of terminal buildings on the matrix were TB (0.49), TC (0.35), and TA (0.16). The highest weight represents the participants' best evaluation. These results indicate that TB has the highest comfort rating, while TA has the lowest comfort rating.

In Part 2-A, where participants evaluated sound recordings separately, created with the simulation model, the average ratings were TB (2.88), TC (2.79), and TA (1.97). In section 2-B, where participants make pairwise comparisons, the average weights of terminal buildings on the matrix were TB (0.44), TC (0.42), and TA (0.14).

A similar ranking was obtained when on-site sound recordings and auralizations were evaluated. Furthermore, these results were supported by findings from on-site questionnaires. Thus, the accuracy of the simulation models created to reflect the real situation and the decisions taken for the auralizations were tested.

In Part 3, models with terminal building heights of 14 m, 20 m, and 26 m were evaluated. The acoustic indicator values of the auralization sound samples for Part 3 are shown in Table 5. The mean acoustic comfort weightings of the sound files on the matrix were 0.40 (h14), 0.31 (h20), and 0.29 (h26) when participants made pairwise comparisons, as shown in Figure 6.

In Part 4, the absorbency of the terminal building's internal surfaces was gradually changed: α20, α50, and α80. The acoustic indicator values of the auralization sound samples for Part 4 are shown in Table 6. The mean acoustic comfort weightings of the sound files on the matrix were 0.58 (α80), 0.28 (α50), and 0.14 (α20) when participants made pairwise comparisons, as shown in Figure 7.

Table 5. Three auralizations for Part 3 with the values of acoustic indicators obtained by changing the enclosure's height

	h [m]	RT [s]	SPL [dBA]	N [Sone]	S [Acum]	R [cAsper]
Sound 1	14	1.97	58.66	12.58	1.28	24.95
Sound 2	20	2.78	58.13	12.35	1.21	25.43
Sound 3	26	3.49	57.89	12.04	1.17	25.19

SPL: Sound pressure level; N: Loudness; S: Sharpness; R: Rougness.

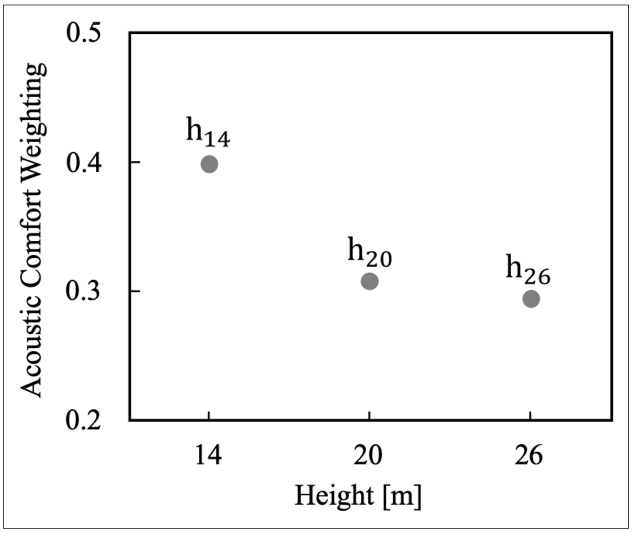


Figure 6. The tendency of participants to rate low room height values better in terms of acoustic comfort (Pearson's =-0.938; p=0.224).

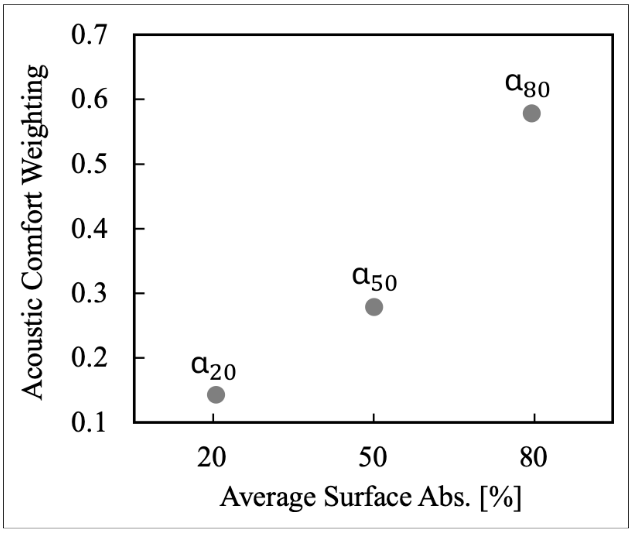


Figure 7. The tendency of participants to rate higher surface absorption values better in terms of acoustic comfort (Pearson's r=0.978; p=0.132).

In Part 5, the scenario of whether there were spaces linked by a common space was evaluated in terms of acoustic comfort. The acoustic indicator values of the auralization sound samples for Part 5 are shown in Table 7. There was no significant difference in the averages of the acoustic comfort weightings of the sound files in the pairwise comparison matrix: 0.51 (yes) and 0.49 (no).

CONCLUSION

The indoor soundscape approach should be considered in the design process of non-acoustic spaces in addition to conventional methods in acoustic design. Integrating psychoacoustic parameters into the process provides a more comprehensive and descriptive perspective for enhancing acoustic performance in such spaces.

In this research, the impact of architectural design factors on the sound environment in the acoustic design of airport terminal buildings was examined in terms of subjective and objective data. The research demonstrates that architectural design elements such as surface properties, spatial layouts, and building dimensions significantly affect the indoor sound environment, shaping both objective acoustic indicators and subjective user perceptions.

The results indicate that the landside terminal buildings, TA and TB, exhibit similar sound environment characteristics. However, when airside and landside terminal buildings are compared, different sound environment characteristics are displayed due to the variation in volume, dimensions, and surface properties. These results are consistent with the research conducted by Dökmeci and Kang (2011), which demonstrates that spaces with particular functions exhibit different soundscape characteristics. Additionally, it has been observed that architectural features such as circulation layouts and atriums contribute to the diversity of the sound environment. The architectural design of the structures and the configuration of the circulation paths have an impact on the variations in loudness values.

A summary of the research findings and design implications for the investigated acoustic indicators and their relationships with subjective evaluations obtained from questionnaires and listening tests are as follows:

Table 6. Three auralizations for Part 4 with the values of acoustic indicators obtained by changing the total absorbance

	α [%]	RT [s]	SPL [dBA]	N [Sone]	S [Acum]	R [cAsper]
Sound 1	20	3.21	55.79	11.67	1.21	23.13
Sound 2	50	1.45	49.25	8.31	1.25	19.03
Sound 3	80	0.99	44.01	6.33	1.30	15.63

SPL: Sound pressure level; N: Loudness; S: Sharpness; R: Rougness.

Table 7. Two auralizations for Part 5 with the values of acoustic indicators obtained by the scenarios of whether there were spaces linked by a common space

	Linked Space? [-]	RT [s]	SPL [dBA]	N [Sone]	S [Acum]	R [cAsper]
Sound 1	No	2.73	58.83	12.97	1.23	26.30
Sound 2	Yes	2.78	58.13	12.35	1.21	25.43

SPL: Sound pressure level; N: Loudness; S: Sharpness; R: Rougness.

- Acoustic comfort increases as the reverberation time (RT) decreases (valid for the examined range: 1.0–3.5 s).
- Loudness is in close relation with reverberant sounds affected by the surface absorption and air volume inside the space, hence, as loudness increases, acoustic comfort tends to decrease.
- Higher sharpness values are correlated with better acoustic comfort (valid for the examined range: 1.17–1.30 Acum).
- The increase in acoustic comfort is correlated with low roughness values (valid for the examined range: 15.63–23.13 cAsper).
- Changing the height of the building affects the sharpness value, especially due to changing volume and air absorption at high frequencies, but does not change the roughness value. On the loudness parameter, a height difference of 12 m has an effect as much as JND (valid for the examined range: 14–26 m).
- Changing the total surface absorption significantly impacts all psychoacoustic parameters: as surface absorption increases, both loudness and roughness decrease, while sharpness increases.
- Roughness is independent of volume and can be controlled by changing the absorption of surface materials.
- The presence of a common space affects the loudness value by as much as JND. However, it does not have a significant effect on sharpness and roughness values.
- Reduction in height substantially enhances the acoustic comfort when the enclosure height is below 20 m. Conversely, the influence of height on acoustic comfort becomes less significant when the enclosure height exceeds 20 m (valid for the examined range: 14–26 m).

In characterizing the sound environment through measurement in structures with large-scale spaces, such as terminal buildings, evaluating it with the statistical values of measurement points' results instead of overall mean values provides detailed information and enables a more specific analysis. It is considered that further research is needed in terms of properties of architectural spaces such as shape, surface, dimensions, configuration, and openings, and spatial relationships (space within a space, interlocking spaces, adjacent spaces, and spaces linked by a common space) to better understand the relationship between architectural design factors and the indoor soundscape.

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The authors declared that this study has received no financial support.

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