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Analysing Sound Environment and Architectural Characteristics of Libraries through Indoor Soundscape Framework

Papatya Nur Dokmeci Yorukoglu [1, 2], Jian Kang [1]

[1]*School of Architecture, University of Sheffield, Sheffield, UK*
[2]*Department of Interior Architecture, Cankaya University, Ankara, Turkey*
papatya@cankaya.edu.tr, j.kang@sheffield.edu.tr

Abstract: This study presents the indoor soundscape framework in detail by describing the variables and factors that form an indoor soundscape study. The main objective is to introduce a new indoor soundscaping framework and systematically explain the variables that contribute to the overall evaluation of an indoor soundscape. Hence, the dependencies of physical and psychoacoustical factors of the sound environment and the spatial factors of the built entity are statistically tested. The new indoor soundscaping framework leads to an overarching evaluation perspective of enclosed sound environments, combining objective room acoustics research and noise control engineering with architectural analysis. Therefore, it is hypothesised that case spaces with certain plan organisations, volumetric relations, and spatial referencing lead to differentiated sound pressure level (SPL) and loudness (N) values. SPL and N parametric variances of the sound environments are discussed through the statistical findings with respect to the architectural characteristics of each library case space. The results show that the relation between crowd level variances and sound environment parametric values is statistically significant. It is also found that increasing the atrium height and atrium void volume, the atrium's presence as a common architectural element, and its interpenetrating reference and domain containment results in unwanted variances and acoustic formations, leading to high SPL and N values.

Keywords: soundscape framework; indoor space soundscaping; indoor sound environment; spatial analysis; archi-acoustical characteristics; library; architectural analysis

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1. Introduction

The study of indoor soundscapes has evolved through different approaches, mainly concentrating on the study of acoustic environments, architectural characteristics and human perception. This integrative research field, initially called as 'soundscape', has been studied in the literature since the 1970s, when it was first discussed as part of the World Soundscape Project (1978) and expanded through studies by the pioneers, Schaffer (1994) and Traux (2001). Soundscape studies aim to acknowledge sounds as resources rather than waste and bring a new understanding to the research field of noise control. In soundscape studies, sound sources and overall sonic composition are considered to be important additions to the characteristics of the whole environment. Through that perspective, factors that form the overall sound environment and the subjective reactions given to that experienced sound environment are studied to create pleasant and preferred soundscapes. However, noise control studies that combine noise mapping techniques focus mainly on identifying the acoustic problem using objective parametric measures, most dominantly equivalent sound pressure level in A-weighted decibels (LeqA). However, it is also stated in the literature that A-weighted sound pressure level alone is not sufficient for an overall sound environment analysis or assessment. Therefore, the loudness parameter enters the picture with its orientation and integration of the correctness factors through the human hearing perspective.

Many studies on urban and suburban soundscapes (Liu et al. 2014; Bernet 2013, Traux and Barrett 2011) have concentrated on identifying the acoustical problems from the users' point of view and supporting their subjective findings through objective parametric measurements; however, the indoor soundscape approach has recently emerged in the literature with similar yet enhanced analysis models. The first and most important key factor for indoor soundscaping to be different from urban/open scale soundscaping is the integration of the built entity variable, which specifies the assessment of architectural characteristics. This main difference places 'indoor soundscaping research' between two main acoustic fields: urban soundscape research and architectural/room acoustics research. Therefore, the indoor soundscape methodology acknowledges different approaches because it collates methods and techniques from both research areas to form its own study framework.

In studies that focus on indoor soundscapes, the function and usage of a space and its physical conditions and spatial characteristics are as important as the objective analysis and the subjective evaluation of the sound and overall environment. Spatial characteristics play a particularly key role in the sound and its formation in an enclosure that is closely linked with the building's acoustics and related research fields. Therefore, an analysis of architectural totality and characteristics of an indoor space is crucial for an indoor soundscape study. The built-entity evaluations of the case spaces considered in this study are conducted through certain dissolution and analysis techniques and architectural theories that were previously reviewed and presented (Dokmeci 2014).

Through this perspective, this study first aims to present an indoor soundscape framework that can be applicable to soundscape research conducted in enclosed environments. Therefore, the variables of the indoor soundscape framework and each related factor are explained in detail. Second, it aims to systematically relate the chosen factors of the sound environment with the built entity variables to demonstrate the dependencies and relations between the experimented factors using statistical tests. Sound recordings are used to analyse the parametric values of sound pressure level (SPL) and loudness (N), and architectural analysis techniques and theories are combined for the evaluation of the chosen case library spaces. The objective of this study is to test and understand the dependency tendencies of the sound environment on the built entity and how the objective parametric values show variance according to the changing architectural and spatial characteristics.

2. Indoor Soundscape Framework

The first step in designing the framework of indoor soundscaping research is presented in Figure 1. This framework could potentially be applied to the study of indoor soundscaping in enclosed spaces classified as civil, private, public, or commercial built entities following the standards and measurement procedures that are identified in the building acoustics research field. The main difference between indoor soundscaping and urban/open scale soundscaping lies in the 'architecture' factor; therefore, the framework has a detailed integration of the architectural aspects and building acoustics theories. The term 'indoor' addresses a space as being enclosed by defined walls, floor and ceiling. Spatial characteristics play a particularly significant role for sound and its formation in an enclosure. Whilst architectural/room acoustics research considers theories developed through previous studies, indoor soundscaping builds on these findings to develop a new understanding through the soundscape approach in which space, context and users are as important as the sound itself.

The first variable of this system to be considered is an architectural assessment of the built entity, which comprises function factors (Dovey 1999; Hillier and Hanson 1984; Lawson 2001; Pearson and Richards 1994; Tuan 1977), indoor environmental factors (CEN 2007; ISO 2006), and spatial factors (Arnheim 1977; Ching 1996; Laan 1983; Meiss 1990; Norberg-Schulz 1971; Unwin 2003) that are created through integration of previous research and theories. In studies focusing on enclosures, the architectural assessment of an enclosure directly relates to the acoustic formations, which have a significant effect on the soundscape. Therefore, the architectural assessment of the built entity is an important aspect of indoor soundscape research that should be addressed before drawing any conclusions regarding the acoustic characteristics and the user's perception and experience in the enclosed environment.

Second, indoor soundscape studies should also focus on an objective analysis of the sound environment, which includes physical factors (Barkana and Uzkent 2011; Brown, Kang, and Gjestland 2011), acoustical factors (Botteldooren, De Coensel, and De Muer 2006; Bradley 2011; Thomas, Van Renterghem, and Botteldooren 2011; Yang and Kang 2011) and psychoacoustical factors (Genuit and Fiebig 2006; Rychtáriková and Vermeir 2011; Zwicker 1999) that are identified separately in related studies. The objective analysis of these elements should involve separate assessments using several different parameters to understand sound and how the sound environment can be perceived as a pleasant soundscape.

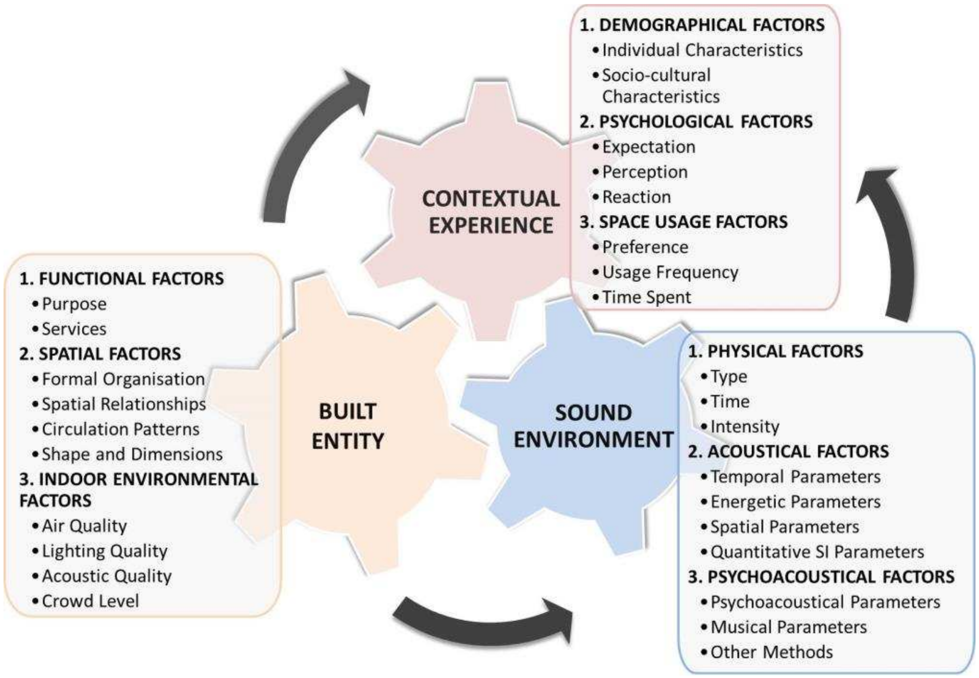


Figure 1. Collaborative system wheel of indoor soundscaping framework with the three main variables and nine related factors.

The third and final variable is the subjective assessment of the users' habitual and functional characteristics within the enclosed environments. This variable includes the contextual experience of the users and includes demographic factors, space usage factors and psychological factors (Bruce, Davies, and Adams 2009; Handel 1989; Moore 1997; Hatfield, van Kamp, and Job 2006). Integrated and sequential study of these three variables with regard to the enclosed soundscape is the key to clearly understand the indoor soundscaping approach (Dökmeci and Kang 2010).

Therefore, the final framework for indoor soundscape research incorporates the three main 'variables'—(1) built entity, (2) sound environment, and (3) contextual experience — and nine associated 'factors' — (1a) function, (1b) indoor environment, (1c) space; (2a) physics, (2b) acoustics, (2c) psychoacoustics; (3a) demographics, (3b) space usage, and (3c) psychology—which are used to explore each variable in developing the indoor soundscaping framework as presented in Figure 1. These factors are derived from the analysis of the 3 main variables and are interdependent. The integration of the three variables of indoor soundscaping is accomplished by reviewing and aggregating the previous research and theories in the literature in combination with the formation of the main collaborative system.

For this study, the two previously introduced variables, (1) built entity and (2) sound environment of the indoor soundscape framework, are identified. As shown in Figure 2 and Figure 3, the highlighted aspects under function, spatial and indoor environmental factors of the built entity variable and the highlighted parameters under the physical and psychoacoustical factors of the sound environment variable are considered for this study. The relationship and correlations among these aspects and parameters under each identified factor between the two variables compose the core of this study.

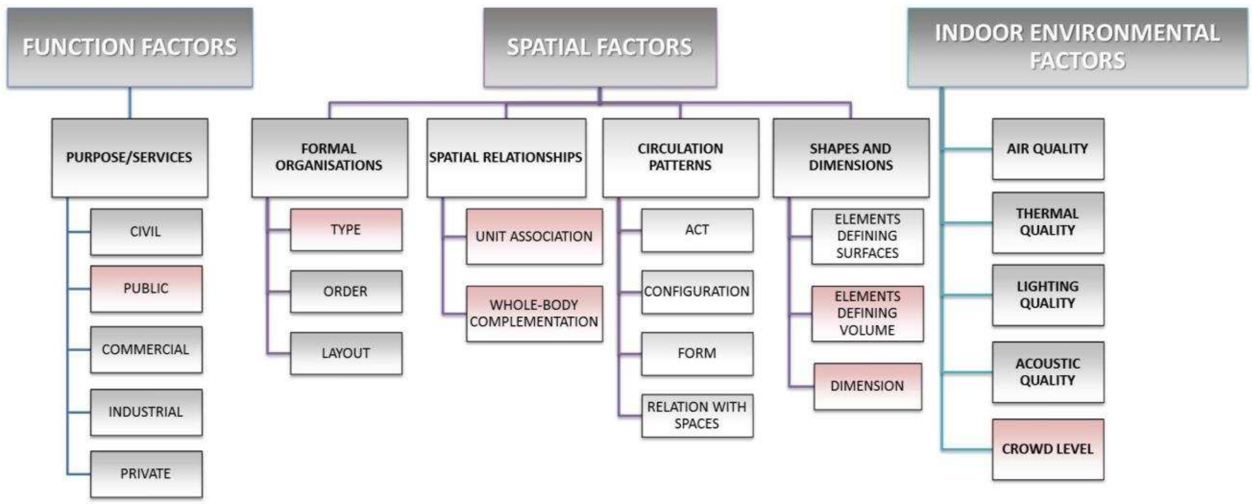


Figure 2. The factors among the built entity variable and the highlighted aspects considered for this study.

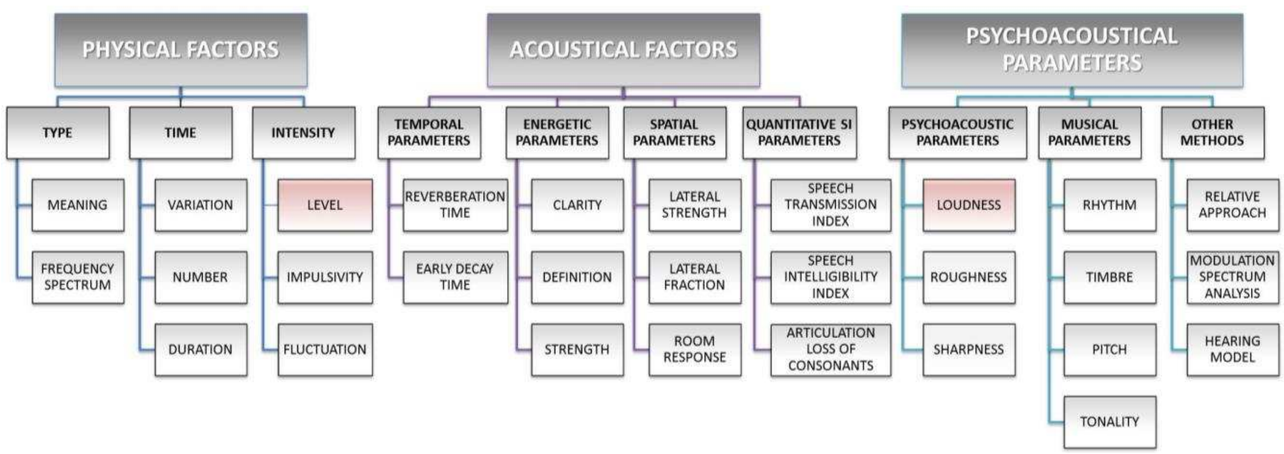


Figure 3. The factors among the sound environment variable and the highlighted parameters considered for this study.

3. Sound Environment and Built Entity Factors of Case Study Sites

Objective analysis of the recorded sound samples and architectural analysis through the combined architectural theories are the two methods used for the evaluation of the chosen case spaces and their sound environment.

3.1. Selection of the Case Study Sites

Public spaces in the built environment that are classified as 'libraries' as their primary function are considered for this study. The review of the architectural characteristics of the three university libraries is based on the previously presented indoor soundscape framework and built entity factors (Dokmeci and Kang 2010). These three different university libraries with comparable architectural characteristics are Western Bank Library (abbreviated as WB), Information Commons Library (abbreviated as IC), and St. George's Library (abbreviated as SG) located in the city of Sheffield, UK. The main user profiles of these libraries do not show great variance. The users are all university students or researchers. The data collection through sound recordings focuses on the similar functional areas in each case library. The main foyer areas in each library were used for the measurements to design a stable discussion point from an architectural perspective.

The classification of the architectural analysis, presented in Figure 2, is considered. The three main aspects—(1) the formal organisation of the layout in a more two-dimensional approach, (2) the spatial relationships among neighbouring voids and solids in three dimensions and (3) the circulation patterns that dominate the usage of spaces within the enclosure—are analysed for each case space. In addition, other related spatial information is included, such as the location of the foyer area, dimensions (area and volume), atrium location, atrium void dimensions, location of the skylight, finishing materials on the surfaces and crowd level in the space during the recordings as shown in Table 1. All of these aspects are integrated into the discussions concentrating on the relation between sound environment and the built entity.

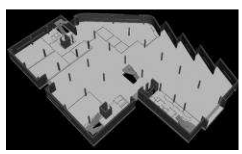
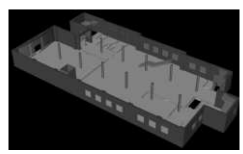
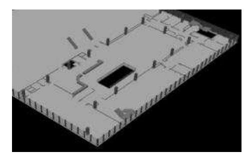
3.2. Characteristics of the Case Study Sites

Information Commons is a relatively new building compared with the other two libraries. The main foyer area is located on the first floor and is larger than the other two library foyers. The circulation elements and atrium void are directly linked with one another and with the main foyer area. In the Western Bank library, the main foyer area is located on the first floor linked with the circulation stairs, above the atrium void. St. George's library is the oldest building (brick facade) among the three. The interior has been refurbished to provide a modern library for students. As in the other two libraries, the reception area is on the side, but the stairs, located in front of the entrance, dominate the space. The ground floor foyer area is located beneath the atrium void.

In terms of the two-dimensional formal organisation, the 'Information Commons' (IC) library has an L-shaped plan, whereas both 'Western Bank' (WB) and 'St. George's' (SG) libraries are rectangular in layout. The dimensions are crucial for the assessment of the spatial characteristics because they are the most effectual properties within an enclosure for determining the sonic environment and the contextual perception. One other important feature is the location of the foyer space. In SG, it is located at the entrance level, which means that people pass through the main foyer to travel between the other spaces in the library. In IC, the foyer is located on the first floor, and in WB, it is located on the second floor.

IC has the largest area and volume, followed by WB and SG as noted in Table 1. Although the areas in square metres do not differ significantly, the volumes vary greatly. The main reasons for this difference are the location and dimensions of the atrium void. IC has the largest atrium void, measuring 1,638 cubic metres, whereas SG's atrium void measures 424 cubic metres and that of WB measures 105.5 cubic metres. The location of the atrium is also important for sound analysis. In WB, which has the smallest atrium void, the atrium is located below the foyer space, with a height of 4 m. In the other two libraries, the atrium is located above the foyer space, with heights of 10.5 m in SG and 14 m in IC.

Table 1. Spatial and architectural analysis of Western Bank library (WB), Information Commons library (IC), and St. George's library (SG).

Factors	**Individual Aspects**	**IC** 	**WB** 	**SG** 
Dimensions	**Area**	*372 m^2*	368 m^2	362 m^2
	Volume	*2,667 m^3*	1,945 m^3	1,548 m^3
Formal Organisation	**Plan type**	*Grid (l-shape)*	Linear (rectangular)	Linear (rectangular)
	Plan order	Common enclosure	Common enclosure	Common enclosure
	Plan layout	Basic	Basic	Basic
Unit Associations	**Relation**	Spaces linked by a common space	*Adjacent*	Spaces linked by a common space
	Reference	Interpenetration	*Juxtaposition*	Interpenetration
	Containment	Domain	*Cells*	Domain
Whole-body Complementation	**System**	Subordinated	*Spaces bordering each other*	Subordinated

Spatial Elements	**Foyer location**	1st floor	2nd floor	*Entrance*
	Atrium location	Above h: 14 m	*Below h: 4 m*	Above h: 10.5 m
	Atrium void	*1,638 m³*	105.5 m³	424 m³
	Glass skylight	Above atrium	Above atrium	Above atrium
Materials	**Wall material**	Plaster & wooden acoustic panels	Wood panels & glass sheets	Painted brick block
	Ceiling material	Acoustic tiles	Hard semi-acrylic	Painted concrete
	Floor material	Carpet	*Vinyl*	Carpet
Usage (mean)	**Crowd level**	*40-Pass, 65-Still*	22-Pass, 14-Still	25-Pass, 10-Still

* Differentiated aspects among the three case sites are emphasised with *italic* characters.

The aspects of each built entity factor that are present in the case study sites are highlighted in Figure 4. The spatial relations in IC and SG are similar compared with WB. IC and SG both have similar 'relation', 'reference', and 'containment' characteristics. Spaces are linked by a common space, which is the 'atrium' that acts as the main circulation artery for IC and SG, whereas in WB, spaces are adjacent to each other. In IC and SG, interpenetration is the spatial 'reference', whereas in WB, it is juxtaposition. Finally, the form of 'containment' in IC and SG is the domain, but for WB, it is the arrangement of different cells within the domain. Additionally, the whole-body complementation analysis of IC and SG shows that the main space subordinates the other spaces with the presence of an interpenetrating foyer area. In contrast, in WB, the spaces border each other, and this system is formed by the separately enclosed adjacent unit spaces. The architectural variances and spatial characteristics in each case space lead to differentiated sound formations and overall indoor environments that are discussed within the scope of this study.

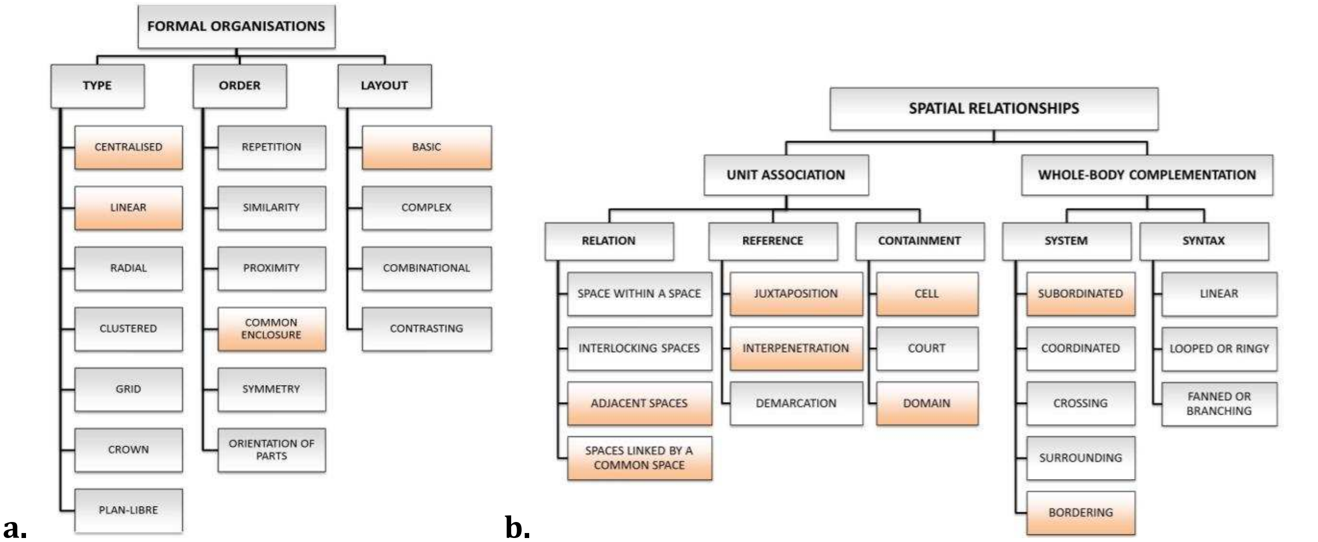


Figure 4. The aspects of built entity factors; (a) formal organisation and (b) spatial relationships, analysed in the case study sites.

In addition to the varying architectural characteristics, materials are crucial for the formation of different sound phenomena that are evaluated in the sound environment analysis. The objective parametric analyses of the indoor acoustic environment for indoor soundscape studies should also consider the material properties such as absorption coefficients similar to the studies in the field of building acoustics. The absorption coefficients of the materials used in all three case spaces are identified in Table 2. The finishing materials in the foyer space in IC are wood cladding on the walls (designed as acoustic panels) and carpet flooring made of materials classified with higher absorption coefficients, especially in the mid- and high-frequency ranges. There is a high skylight ceiling over the atrium void and a suspended ceiling over the lower parts, leading to air absorption. In addition, there are several soft, padded sofas around the main space that contribute to the overall sound absorption in the environment. In the foyer of IC, the absorption quality of the finishing materials, especially on the floor and sofas, is higher than in the other two.

Table 2. Absorption coefficients of the materials used in the case sites.

MATERIALS USED IN CASE SITES	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**
Floor Materials						
Raised computer floor and carpet [2] (IC)	0.27	0.26	0.52	0.43	0.51	0.58
Vinyl tile or linoleum on concrete [2] (WB)	0.02	0.02	0.04	0.05	0.05	0.10
Carpet on concrete [1] (SG)	0.02	0.06	0.14	0.37	0.60	0.65

Ceiling Materials						
Acoustic ceiling tiles [1] (IC)	0.05	0.22	0.52	0.56	0.45	0.32
4 mm glass [2] (WB)	0.30	0.20	0.10	0.07	0.05	0.02
Smooth concrete, painted or glazed [2] (SG)	0.01	0.01	0.01	0.02	0.02	0.02
Wall Materials						
Acoustic timber wall panelling [2] (IC, WB)	0.18	0.34	0.42	0.59	0.83	0.68
Unglazed & painted brick [1] (SG)	0.01	0.01	0.02	0.02	0.02	0.03
Large panes of heavy plate glass [2] (IC)	0.18	0.06	0.04	0.03	0.02	0.02
Ordinary window glass [1] (SG, WB)	0.35	0.25	0.18	0.12	0.07	0.04
Other						
Fully occupied, fabric upholstered [2]	0.60	0.74	0.88	0.96	0.93	0.85
People (adults) [1]	0.25	0.35	0.42	0.46	0.5	0.5

[1] http://www.bembook.ibpsa.us/index.php?title=Absorption_Coefficient

[2] http://www.acoustic.ua/st/web_absorption_data_eng.pdf

The materials used in WB are wooden cladded walls with integrated windows, vinyl flooring, and acrylic panels on the suspended ceiling. There are several leather sofas in the study space. The materials used in the foyer space of WB can be classified as absorbers of the low- to medium-frequency range. Finally, the materials in the foyer of SG are painted brick walls and integrated windows, painted concrete for ceilings and carpet on the floor. Wooden tables and padded chairs are the main furniture items that are present in the main space. In addition, although the highest crowd level is identified in IC, it should be noted that the case spaces are libraries, and in such spaces, human-related sound, such as talking, rarely dominates the overall environment. Therefore, it is expected that people do not act as sound sources but rather as receivers, so an increased number of people hypothetically supports the overall sound absorption qualities of the space.

3.3. Sound Recordings

The sound environments in the three libraries are recorded to analyse the present parametric situation in the identified case locations. The equipment used for the objective assessments is a scientific portable binaural headset-microphone recording system. The recording height is maintained at 165 cm, and the binaural system is placed at least 150 cm away from any reflecting surfaces or boundaries. The audio samples are then analysed by psychoacoustic analysis software.

Table 3. Recording design for case sites based on 3 interchanging sets and 3 time slots.

TIME SLOTS	SET-1	SET-2	SET-3
Morning	WB	SG	IC
Noon	IC	WB	SG
Afternoon	SG	IC	WB

The recordings are captured in the foyer areas of all three libraries to thoroughly discuss the spatial factors considering the specific characteristics of each case. The sound environment of each foyer area is sampled for 15 min on different days in three time slots—morning, noon, and afternoon—as shown in Table 3. A total of nine, 15 min long individual sound samples are post-analysed by special acoustical analysis software, ArtemiS suite. Thus, in each three-case site; 45 min long sound samples that include data from the morning, noon and afternoon have been considered. The sound and visual notes at each measurement point along with the 'usage frequency', 'crowd level' and 'number of people passing through' are noted for further assessment of the sound environment at each location. Physical factors such as the sound event variation, duration, time, intensity, level, fluctuation, spectral distribution, acoustic parameter (sound pressure level-SPL, A-weighted, linear), and psychoacoustic parameter (loudness-N) are considered for this study. The two parameters—sound pressure level and loudness—are commonly used parameters for noise annoyance and soundscape studies to describe the sound environment. However, both lack coherence because they are objective parameters and usually should be supported by the subjective findings through questionnaires or survey analysis. In this study, these two parameters are specifically chosen to be analysed together to understand whether they show a variance and also to observe their differentiation (if there is one) from the 'effect of architectural factors on sound' perspective.

4. Correlation between Sound Environment and Built Entity Factors

4.1. Sound Environment and Crowd Level

First, to examine the relationships between crowd level and sound pressure level (SPL) and between crowd level and loudness (N) in all three libraries, 'Spearman's Rho correlation' is used. This nonparametric statistical test has been chosen to measure the strength of association between the two variables and is calculated by the formula shown in Eq (1). In this test, Spearman's rho (r_s) numerically measures the strength of association between these two variables as 1 (very strong) and 0 (no association). The significance (p) shows the strength of co-occurrence level.

$$1-\left(\frac{6\Sigma d^2}{n(n^2-1)}\right) \quad (1)$$

The statistical analysis shows that there is a significant positive correlation between crowd level and SPL (r_s =.716, p<.001), and N (r_s =.7, p <.001), highlighting the tendency for all considered parameters to increase with an increase in the number of people occupying and using the case study spaces. The relationship was also presented by regression analyses (R^2) as shown in Figure 5.

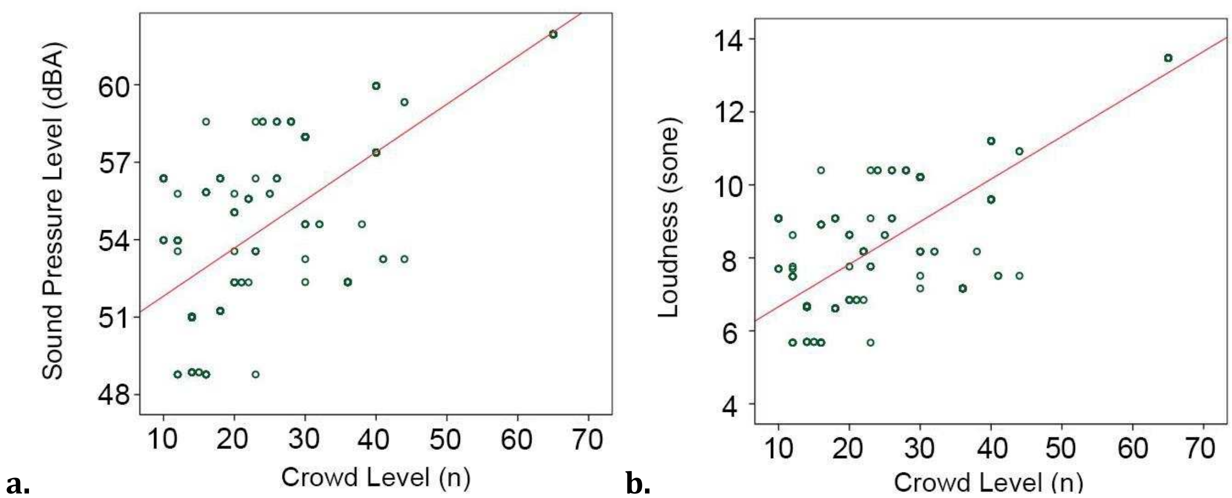


Figure 5. Scatterplot including the regression lines showing the positive correlation between (a) crowd level and sound pressure level-SPL (R^2 = 0. 59), (b) crowd level and loudness-N (R^2 = 0.688).

In addition, one-way analysis of variance (ANOVA) is used to indicate the differences in the means of the test groups. The difference is expressed by the F ratio, which is the ratio of two mean square values of the test groups and is expected to be close to 1. ANOVA alone lacks the ability to distinguish the groups between which the differences are occurring. Therefore, a Bonferroni post hoc test is also used for further analysis to determine the significance levels (p). ANOVA with Bonferroni post hoc results demonstrates the differences among the means of the test groups (sound pressure level-SPL and loudness-N at different crowd levels), and the different means are identified for the three compared crowd level groups (low-high, low-medium, high-medium). The effect of crowd level (here considered as the number of people) on change in sound pressure level is statistically significant ($F(2, 267) = 39.36$, p<.001). When a Bonferroni adjustment was made for the number of comparisons, all three differences were identified as significant. The statistical tests and their results highlight that crowd level as the indoor environmental factor under the built entity variable affects sound pressure level as one of the physical factors, and loudness-N has an effect under the sound environment variable among the psychoacoustic factors. Although humans in library spaces are expected to act as absorbers, human-related activities are found to increase both analysed parameters, SPL and N.

4.2. Effects of Spatial Factors on the Sound Environment

One-way ANOVA and the Bonferroni post hoc test are used to demonstrate the differences among the means of the test groups (sound pressure level-SPL and loudness-N in different libraries), and the differing means are identified for the three compared library groups: Western Bank-Information Commons (WB-IC), Western Bank-St. George's (WB-SG), and Information Commons-St. George's (IC-SG) as shown in Table 4. The effect of the differing architectural characteristics among the case spaces on changing SPL and N are found to be statistically significant. When a Bonferroni adjustment is made for the number of comparisons, all comparisons are identified as significant on two levels. First, significant differences are identified between the mean sound pressure level (SPL) in WB and in IC ($p_{\text{Bonf}} < .001$). The mean SPL value of IC is significantly greater than those of WB and SG. In addition, the effect of differing architectural characteristics and spatial factors on changing loudness is statistically significant for all library comparisons ($p < .001$), with the mean values showing the relation of WB < SG < IC.

Table 4. One-way ANOVA test across the three libraries for varying SPL and N values.

	Libraries			***F***	***p***	Comparisons of Libraries—Bonferroni Adjusted *p*		
	WB	**IC**	**SG**					
	Mean ±SD	**Mean ±SD**	**Mean ±SD**			**WB-IC**	**WB-SG**	**IC-SG**
SPL(dBA)	51.34 ±2.02	57.82 ±3.74	56.48 ±1.94	143.96	0.001	0.001	0.001	0.003
N (sone)	6.80 ±0.93	10.40 ±2.50	9.17 ±1.21	104.5	0.001	0.001	0.001	0.001

With respect to the above findings, architectural and spatial characteristics of the case spaces should be evaluated from the indoor soundscape perspective. It should be highlighted that, through a different soundscape evaluation perspective, architectural characteristics should be included for such sound environment analysis. The spatial relations in IC show significant differences compared with WB yet are in some ways similar to SG. Even with the significant variations regarding volume, dimensions, material usage and absorption efficiency values in both IC and SG, SPL and N values show similar increasing patterns compared with WB. Unit association factor is one of the key architectural characteristics that should be evaluated for indoor sound environment results. In both IC and SG, the overall spaces are linked by a common space, which is the 'atrium', the referencing of overall spaces are interpenetration, and the overall library space contains all other cells within a common domain. These architectural traits lead to a sound environment with comparatively higher SPL and N values because the spatial design itself cannot limit or attenuate sonic formations. In contrast, spaces in WB are adjacent to each other and thus divided or bordered by vertical and horizontal planar elements. Juxtaposition is the spatial 'reference' for the arrangement of different cells within the domain, so the spaces border each other, which helps isolate sound environments in each separate space.

Table 5. Two-way ANOVA test on the interactions of libraries and time slot for varying SPL and N mean values.

	Library Effect		**Time Slot Effect**		**Library*Time Slot Effect**	
	F	***p***	***F***	***p***	***F***	***p***
SPL	582.42	0.001	255.59	0.001	77.01	0.001
Loudness	699.98	0.001	437.71	0.001	163.01	0.001

The second statistical analysis involves two-way ANOVA testing, and the values are shown in Table 5. The results indicate that spatial factors have a significant effect on SPL and N, called the 'library effect', as did the indoor environmental factor crowd level, called the 'time slot effect', in addition to their interactions. Comparative graphs as shown in Figure 6 illustrate the significance of the interactions clearly: the noon time slot, which has the highest crowd level, has significantly greater SPL mean values across all libraries compared with the other two time slots, and the morning time slot, which has the lowest crowd level, has the lowest SPL mean values.

Meanwhile, the largest library space, IC, had higher SPL mean values compared with WB as shown in Figure 6a, where the atrium is located below with a smaller void volume. This is an interesting result when comparing the overall absorption coefficient values. It is identified that even with higher material absorption, varying architectural characteristics may lead to unwanted acoustical formations. When the sound absorption of floor, ceiling and walls are considered, the highest absorption theoretically occurs in IC (especially for floor absorption) and in WB (especially for ceiling absorption) in ranging frequencies. SG has the lowest absorption characteristics; yet when the SPL and N comparative values among libraries are observed, IC—which has the highest void volume, attenuation and absorption characteristics—still has high SPL and N values during different times and crowd levels within a day.

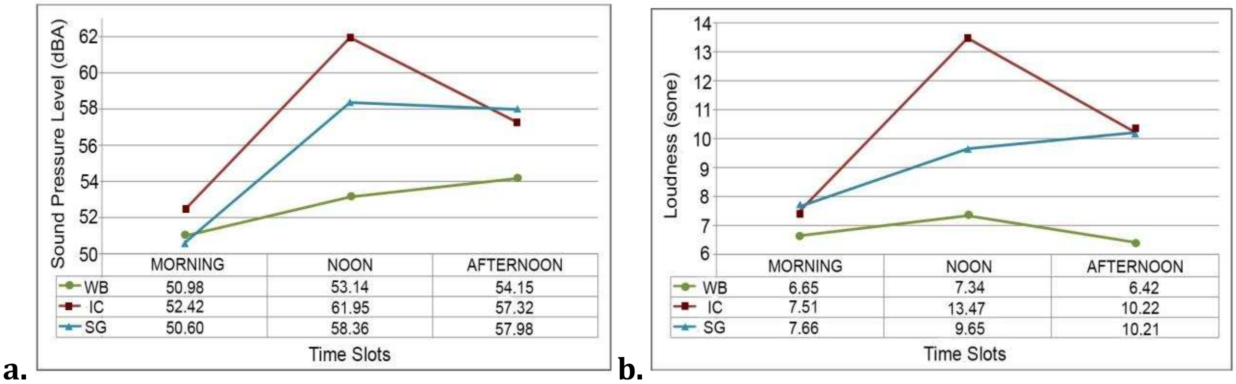


Figure 6. Two-way ANOVA test on the interactions of WB, IC, and SG libraries and morning, noon, and afternoon time slots for varying (a) sound pressure level-SPL, (b) loudness-N.

These findings highlight that the differing architectural characteristics and spatial factors under the built entity variable had a significant effect on the parametric results of the sound environment as analysed with regard to SPL and N, as did the indoor environmental factor of crowd, in addition to their interactions. Moreover, it is found that atrium dimension and void volume, unit relations, reference and whole-body complementation system affect sound pressure level and loudness.

5. Conclusions

This study brings a new perspective for analysing the overall sound environment of enclosed spaces through the architectural and spatial characteristics that are present in a case space. The significance of each indoor soundscaping variable—(1) sound environment, (2) built entity, and (3) contextual experience—and inputs of all individual factors under each variable have been revealed. The relations among the sound environment and built entity variables are proved through statistical correlations of the case study. It was found that crowd level affects the sound pressure level and the loudness values in the foyer areas of the three library case spaces. The most important findings highlight the relations among the spatial factors and the parametric results. Larger overall spatial volume, atrium void and height lead to higher values in SPL and N parameters. Additionally, higher parametric values were recorded in the spaces where there are spaces linked by a common space, separate units referenced by interpenetration, unit containment with 'domain' characteristics, and main space crossing or surrounding other spaces.

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