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A comparative case study of indoor soundscape approach on objective analyses and subjective evaluations of libraries

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Indoor soundscaping approaches were used to evaluate 3 different libraries in Sheffield, United Kingdom. Noise measurement and recordings as well as socio-acoustic questionnaire on indoor soundscapes of public spaces were carried out in different functional areas of each library. Usage, time spent, evaluation of physical conditions, demographics, sound perception, noise annoyance, and sound preferences were included within the questionnaire. In addition, relevant techniques and frameworks were used for reviewing the architectural characteristics. Post-signal analyses of the recorded data to examine the parameters like sound pressure level, frequency spectrum, loudness, roughness, and sharpness were carried out using ArtemiS psychoacoustic analysis software. The survey data was evaluated through SPSS statistical analysis software to assess the correlations between objective parametric results and subjective ratings. Findings indicate that the architectural and functional differences have an effect on the variances of subjective evaluation within the indoor sound environment. The survey results imply significant differences with regards to; gender, academic level, and usage in the evaluation of factors and annoyance from sound sources. Furthermore, the objective parametric results show correlations with related subjective evaluation ratings; especially, sound pressure level (SPL) and loudness (N) were found to be significantly related with subjective evaluation.

1 Introduction

The study of indoor soundscapes has been evolved through different approaches since 1970s when it was first being studied as an accepted field [1]. From then on, human perception of the sonic environments has been an important topic for many architectural acoustics and soundscape studies. Different measurement and recording techniques have been used in the literature and they are still evolving with the integration of new equipment and software designs [2, 3, 4, 5]. In addition, the investigations on the questionnaire/survey designs [6, 7], tools and application techniques [4, 8, 9], which can be used for the soundscape research, and ways to standardize this new research field [10, 11] are still being evolved. While there has not been a widely accepted standard on survey design, which would be applicable to related soundscape studies, 'ISO/TS 15666:2003(E)' document that entitles, 'assessment of noise annoyance by means of social and socio-acoustic surveys' is one of the most widely used technical specification for subjective acoustic evaluation [12]. This ISO standard, can be seen as the starting point for standardization of related, subjective evaluation criteria, although this standard and the rating scales are produced for noise annoyance 'at home', a similar method and rating scale was used in the questionnaires of this study to gather information on the noise annoyance in public spaces.

Relevant soundscape studies concentrate mainly on, the urban/open soundscapes, and city scales. The indoor soundscape approach on the other hand has emerged into the literature lately; and concentrates on the enclosed sound environment, with a distinct focus on the architectural and functional characteristics of the space, the perceived subjective evaluation, and the physical, acoustic and psychoacoustic characteristics of the sound environment. Analysis of architectural totality and characteristics of an indoor space is crucial for an indoor soundscape study. This built-entity assessment of the case spaces can be studied through certain dissolution, analysis techniques, and architectural theories, which were previously reviewed and presented [13]. Function and usage of a space, its physical conditions and spatial characteristics are as important as the objective analysis, the subjective evaluation of the sound, and the overall environment. Spatial characteristics in particular play a key role for the sound and its formation in an enclosure. Architectural/room acoustics research consider the theories that have been stated through previous studies, yet indoor soundscaping combines these previous findings and reveals a new understanding through the soundscape approach, in which space, context and users can be considered as important as the sound itself. The classification of enclosed built entities [13] and the methodological aspects to study indoor soundscapes [14], as well as the acoustic and psychoacoustic parameters that should be used to gather detailed information were presented. In addition, for the pilot study of this paper, the architectural dissolution and sound environment of two different enclosed public spaces (enclosed recreational garden and student union building) have been characterised through architectural analysis techniques and space usage [15]. The sound environments in the different functional areas were also evaluated by different parameters

(e.g. sound pressure level, loudness, roughness and sharpness) and presented as the initial phase of this study. In this paper, the research was advanced with the use of questionnaire evaluations, statistical tests and post-signal sound analysis.

The main purpose of this study is to understand the recorded objective sound environment through the acoustic and psychoacoustic parameters and correlate the objective measures with the perceived evaluation. In addition, correlations regarding the subjective evaluation of the soundscapes and the overall environment, usage and demographics were considered to understand the users' mind-set and how the different factors would be affecting their soundscape perception. Architectural analysis and usage were also addressed as the most distinctive concepts for indoor soundscaping.

2 Methods for Indoor Soundscaping in Library Spaces

In order to carry out a comparable study, two different methods were used in the research; objective measurements, and subjective evaluation. The sound measurements and questionnaires were performed simultaneously in order to achieve reliable comparisons and correlations with the two different types and sets of data. In addition, other factors including physical comfort requirements, architectural characteristics and usage were linked with the objective and subjective evaluation of the study.

2.1 Site Selection and Architectural Characteristics

Three different libraries; Western Bank library (abbreviated as WB), Information Commons library (abbreviated as IC), and St. George's library (abbreviated as SG) were chosen for this study. Each library is used mainly by university students in the city of Sheffield, UK. The main foyer areas in each library were used for the measurements and synchronized questionnaires.

In Western Bank library, the main foyer area is located on the first floor and is an open plan rectangular space directly related with the circulation stairs from the lower ground by a 2-level atrium and situated on the second level of the atrium void. The walls are covered by book and CD shelves and the space contains the reception area, photocopy and print station, 2 catalogue search computers, 2 book return/barrow machines and one elevator. The architecture section and silent study room are also through the main foyer space. The materials are; wooden/glass walls, vinyl flooring, and hard plastic suspended ceiling, leather sofas. The materials present in the space can be classified as low/medium absorbers for the frequency range within the space.

Information Commons is a relatively new building in comparison to the other two libraries. The main foyer area is located on the first floor and is larger than the two library foyers with an L-shaped floor plan that is directly linked by the circulation stairs and a 4-level atrium and situated on the first level of the atrium. The space contains, the reception area, book shelves, 45 computer stations, photocopy and print station, catalogue search computers, 2 book return/barrow machines and 2 elevators. The finishing materials in the space are plaster/wooden walls (designed as acoustic panels), carpet flooring, very high ceiling on the atrium void and suspended ceiling on the lower parts, in addition with soft padded sofas. In this space the absorption qualities of the finishing materials especially on floors and sofas are noted to be higher.

St. George's library is the oldest building (brick facade) compared with the other two. The interior has been refurbished to be a modern library for students. Similar to other two libraries, the reception area welcomes on the side, yet the stairs located in front of the entrance dominate the space. The ground floor foyer area is located beneath the 2-level atrium. The space contains the reception area, book shelves, group work desks, 5 computers, photocopy and print station, catalogue search computers, 2 book return/barrow machines and 1 elevator. The materials in the space are plastered/glass walls, suspended plaster ceilings and carpeted floor. The wooden tables and padded chairs are the dominating furniture.

2.2 Questionnaires

The socio-acoustic questionnaire was designed for the research especially concentrating on the libraries. The questionnaires were applied to participants of the 3 different libraries simultaneously with the sound measurements only in the foyer areas. A total of 90 participants were considered for the study. They were divided into three groups being n=30 for each different library foyer area. The data collection procedure was the non-experimental sample survey sampling [16]. The survey sampling was accomplished by simple random sampling

technique, which was classified as a probability sampling method.

The questionnaire is designed with 4 different parts; (1) open-ended questions on usage of the space, (2) time spent, like/dislike, basic demographics, (3) 5-point rating scale for the evaluation of different factors in the space, (4) 5-point rating scale for the subjective evaluation of sound sources.

2.3 Measurements

Objective measurements were carried out by binaural recording system. The equipment used for the objective part was Neumann KU100 Dummy head and Edirol R-44 portable recorder. The sound environment was recorded binaurally by the dummy head. The dummy head was situated on a tripod approximately 165cm high and at least 150cm away from any reflecting surfaces or boundaries.

The total measurements of the 3 foyer points, each sample 15 minutes long, in the 3 different libraries were carried out in one day. The sound and visual notes at each measurement point as well as the usage and the number of people passing through the space were noted for further assessment of the sound environment at each location. The audio samples were then analysed by ArtemiS psychoacoustic analysis software. Physical factors (sound event variation, duration, time, intensity level, fluctuation, spectral distribution), acoustic parameters sound pressure level (a-weighted, un-weighted), and psychoacoustic acoustic parameters (loudness, roughness, sharpness) were considered for this study and their relation with subjective evaluation of the sound environment was assessed.

3 Results of the Questionnaires

The results show that, 93.3% of the questionnaire participants have used that particular library before. In addition, 82.2% of the participants noted that they liked spending time in the library, where they had taken the questionnaire. Lastly, 71.1% of them noted that they prefer the library space that they were in to other similar library or spaces. These results showed that there were no highly or negatively biased participants regarding presence, usage and like/dislike of the library space.

In addition, 14 different factors related with, indoor physical comfort (acoustics, air quality, humidity, temperature, light); acoustics (sound level, sound types, sound intelligibility, reverberation level, noise from other spaces, locating by sound); and architecture (way finding, spaciousness, level of crowd) were asked regarding their importance and quality for the case spaces. The ratings for the quality of the factors for all three libraries have been presented. Way finding, thermal comfort and air quality were rated to have higher qualities than other factors. The least qualities were noted for the factors; spaciousness and crowd.

The 19 different sound sources were identified by initial pilot studies and were included in the questionnaire for evaluation. The most and least annoying sound sources were identified for further investigation. Mobile phones, personal music players, and construction noise were rated highest for annoyance. On the other hand, walking/footsteps and page turning were rated as least annoying and even for some participants preferable in a library environment.

3.1 Comparison of the Libraries

The three different libraries were compared with each other to find statistically significant differences, regarding the factors and sound sources in the environment. The participants from St. George's (SG) library found the importance of 'acoustic comfort level' ($p=0.078$) and 'diversity of different sounds' ($p<0.05$) being more important than the participants from the other two libraries. The annoyance ratings were highest from the sound sources of 'printers/copiers' ($p<0.05$), 'book trolleys' ($p<0.05$), 'mobile phones' ($p<0.05$), 'elevators' ($p<0.05$), and 'personal music players' ($p<0.05$) in the Western Bank (WB) library. On the other hand, annoyance rate from 'printers/copiers' ($p<0.05$) in the Information Commons (IC) was rated lowest. When the quality of factors were considered, 'level of sound' ($p<0.05$), 'level of acoustic comfort' ($p<0.05$), 'level of crowd' ($p<0.05$), and 'level of noise from neighbouring spaces' ($p<0.05$) were all rated to have the highest quality in the WB. The 'way-finding factor' ($p<0.05$) was rated to be the easiest in the IC, and the 'level of brightness' ($p<0.05$) to be the brightest in the SG library when compared to the other two libraries. These results show the significant differences between 3 libraries regarding the subjective evaluation of different factors. The reasons for these variances are presented in detail later.

3.2 Correlations among Different Factors

Spearman's Rho non-parametric test was used to examine correlations between two

ordinal variables. Correlations between two different questions on the overall noise; 'how disturbing or preferable is the overall noise?' and 'how much does overall noise annoy you?' were investigated. Five factors; 'level of sounds' ($p<0.05$), 'level of acoustic comfort' ($p<0.01$), 'intelligibility of sounds' ($p<0.01$), 'ability to locate via sounds' ($p<0.01$), and 'way-finding' ($p<0.05$) were found to be significantly correlated with the answers given to these two questions. It can be concluded that these five factors were found to highly effect the auditory perception of overall noise within a library soundscape.

In addition, the 14 different factors on, indoor physical comfort, acoustics, and architecture and their relation with each other are also analysed. The results show that quality assessments of the factors were indeed significantly related with each other. That means the quality of one physical and/or architectural factor was always or somehow related with some other factor for the users in the given case space. The factor indicated as 'level of acoustic comfort' and its correlation with the factors; 'level of indoor air quality' ($p<0.05$), 'level of thermal comfort' ($p<0.01$), 'level of sounds' ($p<0.01$), 'intelligibility of sounds' ($p<0.01$), 'level of reverberation' ($p<0.01$), 'ability to locate via sounds' ($p<0.05$), 'level of crowd' ($p<0.01$), and 'noise from neighbouring spaces' ($p<0.01$) were archived by statistical analysis.

3.3 Correlations among Gender, Academic Level, and Usage

Non-parametric Mann-Whitney U test was used to understand the statistical significance between a nominal variable with only 2-categories (ex. gender, yes/no) and an ordinal variable. Another non-parametric test, Kruskall-Wallis was used to understand the statistical significance between a nominal variable with more categories (i.e. time spent, usage) and an ordinal variable. The two different tests were used to analyse the correlations of gender, academic level and usage with the 14 different factors (related to indoor physical comfort, acoustics, and architecture) and the annoyance from the sound sources that were present in each case space.

Gender differences were analysed in relation to the different factors and the annoyance from different sound sources. All three library foyer spaces were evaluated together for these analyses. The female participants found the quality for the 'level of reverberation' to be more echoey than that of male participants ($p<0.05$). They also found the importance of the 'level of thermal comfort' ($p<0.05$) to be more important than that of male participants. The male participants on the other hand, found the importance of the 'ability to locate via sounds' ($p<0.05$); and the importance of the 'noise from neighbouring spaces' ($p<0.05$) to be more important than that of female participants. Furthermore, the male participants found the sound source 'laughter' to be more preferable/less disturbing when compared to the answers of female participants ($p<0.05$). For the evaluation of different sound sources, the female participants found the sound from 'mobile phones' ($p=0.078$) and 'personal music players' ($p=0.075$) to be more annoying than the male participants.

Secondly, academic level was considered for the analyses. The undergraduate participants in all 3 foyer areas found the quality for the 'level of acoustic comfort' to be more comfortable than the graduate/post-doc/staff participants ($p<0.05$). Similarly, the undergraduate participants perceived the 'quality for the level of crowd' (user density) space to be less crowded when compared to other participants ($p<0.05$). When the importance of factors are analysed, 'level of indoor humidity' ($p=0.058$), 'level of acoustic comfort' ($p=0.078$), and 'different types of sounds' ($p=0.051$) were all rated as more important by the graduate/post-doc/staff participants. Only the importance of 'noise from the neighbouring spaces' ($p<0.05$) was rated more important by the undergraduate participants. In addition, the undergraduate participants perceived the sound from 'printers/copiers' to be more preferable ($p<0.05$) than the graduate/post-doc/staff participants. Conversily, they found the same sound source to be more annoying ($p=0.086$).

When the usage frequency was analysed, participants who use the library space 2-3 times per week perceived the sound of 'book trolleys' ($p<0.05$) more annoying when compared to rare users (1-2 times/month) and very frequent users (4-5 times/week). This might be explained by the adaptation of ear or by the expectation of frequent user to change to sub-consciously lower the annoyance level.

Finally, the number of people passing through during the evaluation of the sound environment was also considered. The most crowded library was the IC, followed by SG and lastly, WB. Annoyance from specific sounds such as 'book trolleys' ($p<0.05$), 'mobile phones' ($p<0.05$), 'elevator' ($p<0.05$), and 'personal music players' ($p<0.05$) were rated more annoying in the WB with the lowest number of people who were passing

through. Possible reasons for this may be due to the visual distraction (people passing through) and the masking effect of combined footsteps to be low, so that participants were highly aware of the sound sources identified above. In terms of the quality of factors and how their evaluation was affected by the numbers of people; in WB, 'level of sounds' ($p<0.05$) was rated very quiet, 'level of acoustic comfort' ($p<0.05$) was rated very comfortable, 'level of crowd' ($p<0.05$) was rated very empty, and 'level of noise from neighbouring spaces' ($p<0.05$) was rated very inaudible. These four acoustic factors were rated most positively in WB, where least number of people passed through during the evaluation. One other significant finding is that, the IC with the highest number of people passing through, it was found to be statistically significant regarding the 'way-finding' ($p<0.05$) factor. This is possibly because the dynamic space gives clues on the circulation of the interior space while it is used by several people.

4 Results of the Measurements and Post-Analysis

The acoustic parameter; sound pressure level (SPL-dBA), and the psychoaouctic parameters; loudness (N-soneGF), roughness (R-asper), sharpness (S-acum), fluctuation strength (FS-vacil), tonality (Ton.-tu) values were analysed. The highest values for all parameters occur in the foyer of the IC. SG have the second highest values and WB the the lowest values, however, SPL and N show noticeable variances, and R and S should be analysed in more detail.

Furthermore, the fluctuation strength shows noticeable differences for each library. There are many variances on the signal plots that highlight the different sound events. It can be noted that the highest vacil values for fluctuation strength was noted in the IC library where, more sound events and number of people passing through were present. The second highest vacil values were found in WB and the lowest in SG. Regarding tonality, considerable differences are also shown in among the three spaces. In depth analysis is necessary to further investigate the fluctuation strength and tonality characteristics of the indoor soundscapes.

4.1 Correlations on Objective Measures

Two objective measures, sound pressure level (dBA) and loudness (soneGF) were considered for the correlation analysis with quality evaluation of the factors and subjective evaluation of annoyance from the different sound sources. There are statistically significant differences between three libraries. For example, in WB the library with the lowest SPL and N values, annoyance from 'printer-copiers', 'book trolleys', 'personal music players' and 'elevator' was rated the highest. These findings indicate the fact that, these four sound sources were perceived dominantly in the space and may not be masked by other sound sources. Five factors including 'level of sounds', 'level of acoustic comfort', 'way-finding', 'level of crowd', and 'noise from neighbouring spaces' were rated highest in WB, also with a statistically significant correlation between SPL and the rating of these 5 factors. Similar to the relation between number of pass by people (crowd) and the quality of way finding, IC was found to be significantly different from the other two libraries, as the quality of way finding was rated highest.

More detailed analysis on objective measures and their relationships with perceived indoor soundscape will be discussed in further paper due to the space limit of this paper.

5 Conclusions

The concepts that have been pointed out previously for indoor soundscape studies were researched in this study. Firstly, the architectural analysis on the formal organisation of the plans and the materials in the case spaces are discussed. Secondly, the specially designed indoor soundscaping questionnaire that concentrates on the subjective evaluation of the sound environment, the perceived factors, and sound sources were described and the results were presented. The synchronised measurements and post-signal analyses were considered to understand the quantitative attributes of the sound environment.

The results reveal the importance of considering variances on the methodology and analysis of the soundscape, regarding the context, function, architecture, and subjective/objective evaluations. It has been shown that (1) architectural factors play an important role in soundscape evaluation; (2) In all three libraries, the factors; 'way-finding', 'thermal comfort', and 'air quality' were found to have the highest qualities, and the least quality was rated for 'spaciousness' and 'crowd', (3) In all three libraries, sound sources including 'mobile phones', 'personal music players', and 'construction noise' were found to be the most annoying, and the least

annoying sound sources were noted as 'walking/footsteps' and 'page turning', (4) Acoustic comfort factor and its correlation with other factors have been analysed to understand cross-effects of different factors; (5) Significant effects have been detected from gender, academic level and usage variances regarding factor ratings and annoyance from sound sources; (6) There are considerable difference in objective parameters among the survey sites; (7) Significant differences between libraries regarding SPL and N values were noted considering quality ratings of factors and annoyance from sound sources.

Further assessment should be carried out by detailed architectural and objective post-signal analysis. Architecture and function related correlations could be achieved by larger sample sizes. In addition, evaluations should involve questionnaires that are designed for specific purposes in identified case sites; yet, the scaling and question structures should be analysed in detail considering different extents of biases. One possible way would be to consider psychometric theory, which is helpful to accomplish the aims of introducing more competent, yet comprehensive subjective evaluation material, that would include questions on overall sensual attributes as well as spatial presence within an enclosure. A multi-dimensional and holistic approach should be carried out for the design of indoor soundscape studies that could include different field and methodologies that was explained by this study.

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