ACOUSTIC COMFORT IN 'NON-ACOUSTIC' SPACES: A REVIEW OF RECENT WORK IN SHEFFIELD

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1. INTRODUCTION

The acoustics in 'non-acoustic' buildings/spaces is receiving increasing attention. Recently a series of studies has been carried out on this topic at the University of Sheffield School of Architecture, considering various building types/spaces including shopping mall atrium spaces, library reading rooms, football stadia, swimming spaces, churches, dining spaces, as well as urban open public spaces.[1-21] The research work generally includes two aspects, characteristics of the sound fields and perceptions of acoustic comfort, given that with the same acoustic parameters the subjective evaluation may vary significantly. Consequently, some design guidelines and suggestions have been developed. This paper gives a brief overview of the studies.

2. SHOPPING MALL ATRIUM SPACES

A case study was carried out on the acoustic comfort in three atriums in Sheffield's Meadowhall, one of the largest indoor shopping malls in the UK.[1-2] The case study comprises measurements of objective acoustic indices including sound pressure level (SPL) and reverberation time (RT), questionnaires surveying levels of acoustic comfort among customers and staff, and correlations between the two aspects. Three main locations were studied: the Oasis, a multifunctional atrium containing stores, restaurants, cafes, cinemas and a games room; the Lower High Street, a long shopping atrium consisting of stores, booths, resting spaces and plants; and the Upper Central Dome, an open atrium linking the main pedestrian axes.

There are some special features in such spaces in terms of objective acoustic indices. The reverberation is generally long, and the longest RT occurs at middle frequencies. The decay curves are mostly concave, which means the early decay time (EDT) is shorter than RT. Figure 1 shows measured temporal sound fluctuation and typical spectra. The SPL fluctuates considerably at different times of the day and week, and this is related to the number of customers, space features of an atrium, as well as background music. A typical spectrum in such atriums shows a peak at middle frequencies, and a considerable drop at high frequencies. The sound attenuation in the atrium void has also been measured, and it is generally rather significant.

Generally speaking, people are not satisfied with the current acoustic environment in Meadowhall. In terms of demographic factors, no significant correlation was shown between age groups, and between the acoustic condition at interviewees' home and the acoustic evaluation. On the other hand, the results suggest that the acoustic evaluation is affected by the duration of stay and the activities. People feel acoustically uncomfortable just after arriving, but after a short period they may get used to it. After a longer period, they may feel uncomfortable again as they become tired with the continuous high level of noise.

As expected, significant differences have been found between the acoustic sensitivities to different sounds – sounds from fountains are considered the most pleasant and sounds from nearby people are the most annoying.

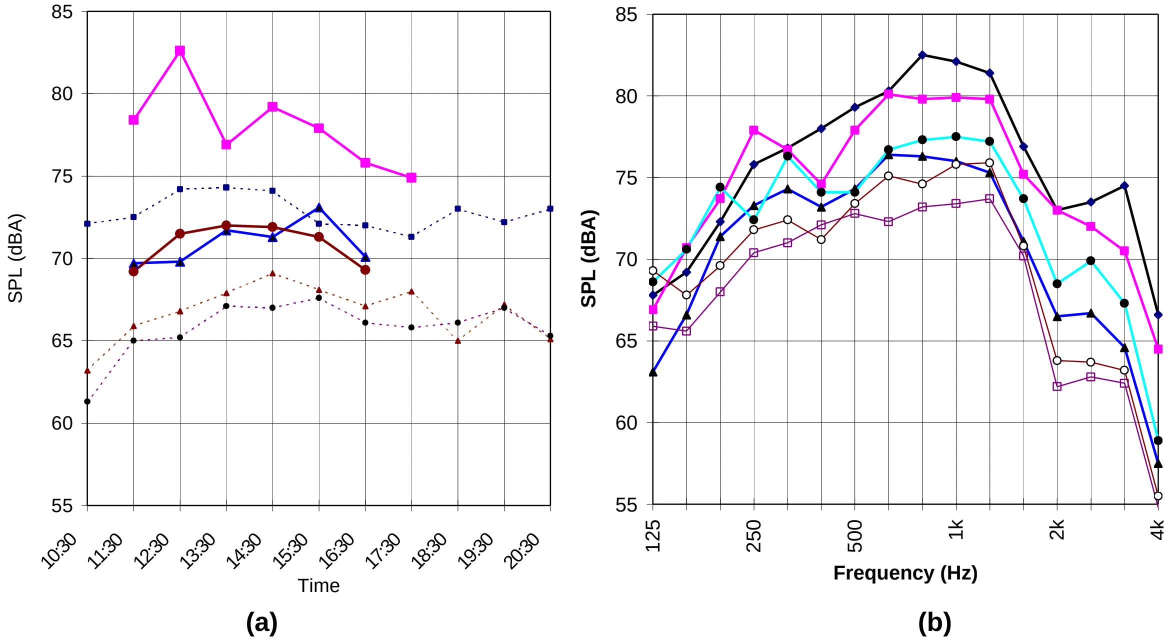


Figure 1. *(a) Temporal sound fluctuations in the three atriums on a Thursday (- - ■ - -, Oasis; - - ▲ - -, Lower High Street; - - ♦ - -, Upper Central Dome) and a Sunday (—■—, Oasis; —▲—, Lower High Street; —♦—, Upper Central Dome). (b) Spectra at four typical locations in the Oasis (—♦—, ground floor; —■—, near the fountain; —▲—, under the porch; —●—, first floor) and two typical situations in the Upper Central Dome (—□—, with background music; —○—, without background music).*

There is a tendency that the overall acoustic comfort evaluation becomes less satisfactory with increasing SPL, but the correlation coefficient is rather low due to the complicated features of the various sound sources. In Figure 2 the correlation between the acoustic comfort rating and the measured SPL is shown. It has also been found that there is generally a good correlation between the sensitivity of loudness and annoyance in such spaces. With a given SPL, the annoyance scores are usually higher than or the same as those for loudness, which shows people's tolerance.

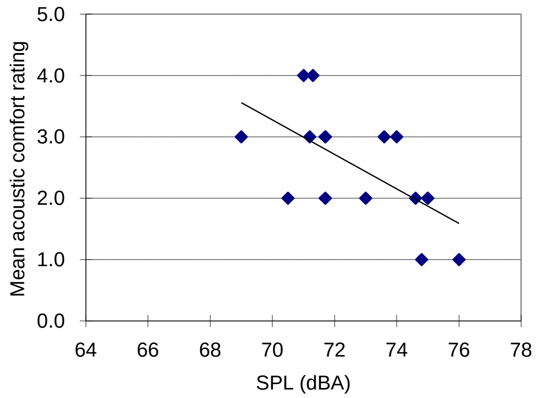


Figure 2. *Correlation between the mean acoustic comfort rating (1, very uncomfortable; 2, a little uncomfortable; 3, neutral; 4, a little comfortable; 5, very comfortable) and the SPL.*

In terms of speech intelligibility, the survey results suggest that there is a good correlation between the communication quality and the EDT. In general, people feel more satisfied with the communication quality than with the overall acoustic comfort. It is interesting to note that the staff group are more tolerant in terms of communication comfort than customers.

3. LIBRARY READING ROOMS

Acoustics in library reading rooms has been investigated through a case study at the Sheffield University Main Library.[3-4] Measurements in the main reading room (MR) and the architectural reading room (AR) show that the SPL attenuation with distance is considerable, the RT is rather short, and the general background noise is not high. However, the acoustic comfort is only at a medium or less satisfactory level, and it seems that there is no correlation between the sound level and acoustic comfort evaluation. This reveals the contradiction in designing the acoustic environment in such spaces - balance between privacy and annoyance.

A main aim of the study was to compare natural and artificial sounds as background in reading rooms. Four sounds were played back in the AR with the same level of 50dBA. The sounds, which were pre-recorded on site, included rain and wind in a small forest, rain hitting the ground, running water in a small stream, and noise from the library ventilation system. The spectra and temporal characteristics of the sounds are shown in Figure 3. In Table 1 the results of four questions in this aspect are shown. It is important to note that the mean evaluation scores for the running water sound are generally higher than those for other sounds. For question B, this score is even higher than that under normal conditions, despite the fact that the sound level with the running water sound is about 5-10dBA higher. A possible reason is that in comparison with other sounds, the running water sound has rather weak low frequency components, as can be seen in Figure 3. Rain/wind and rain sounds, although also from nature, received similar scores to ventilation noise. This is probably due to their notable low frequency components and more importantly, their large dynamic range, as shown in Figure 3.

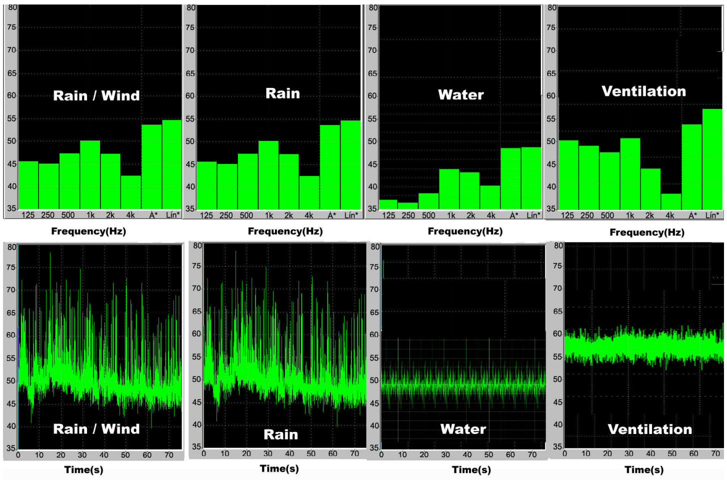


Figure 3. *Spectra and temporal characteristics of the sounds played in the architectural reading room (AR) at the Sheffield University Main Library.*

Table 1. *Acoustic sensation of various background sounds – the numbers are mean evaluation values. Question A – general evaluation of the reading room: 1, strongly dislike; 2, dislike; 3, ambivalent; 4, like; 5, strongly like. Question B – reaction to the acoustic environment: 1, distressed; 2, distracted; 3, ambivalent; 4, calm; 5, appreciative. Question C – description of the acoustic environment: 1, unbearable; 2, disagreeable; 3, reasonable; 4, comfortable; 5, highly conducive to work. Question D – noisiness: 1, very noisy; 2, noisy; 3, medium; 4, quiet; 5, very quiet.*

Question	Normal conditions		With sounds from loudspeakers			
	MR	**AR**	**Rain/wind**	**Rain**	**Water**	**Ventilation**
A	4.0	3.9	3.6	3.7	3.4	3.5
B	2.1	2.6	2.4	2.7	3.3	2.6
C	3.1	2.8	2.5	1.6	2.9	2.3
D			2.4	3	3.2	2.7

4. FOOTBALL STADIA

The atmosphere inside a football stadium is of fundamental importance to the performance of the team, and thus the prosperity of the club. In six typical football grounds around the country, as shown in Figure 4, SPL measurements and subjective surveys were carried out relating to the acoustic atmosphere.[5] Five scales were used. For example, for 'how well can you hear sounds from the pitch', the scales were 1, very well; 2, quite well; 3, ok; 4, not very well; and 5, not at all. 30 fans were interviewed in each stadium. The general aim was to find out what exactly makes a 'good' acoustic atmosphere, and what architectural features of a football stadium combine to this effect.

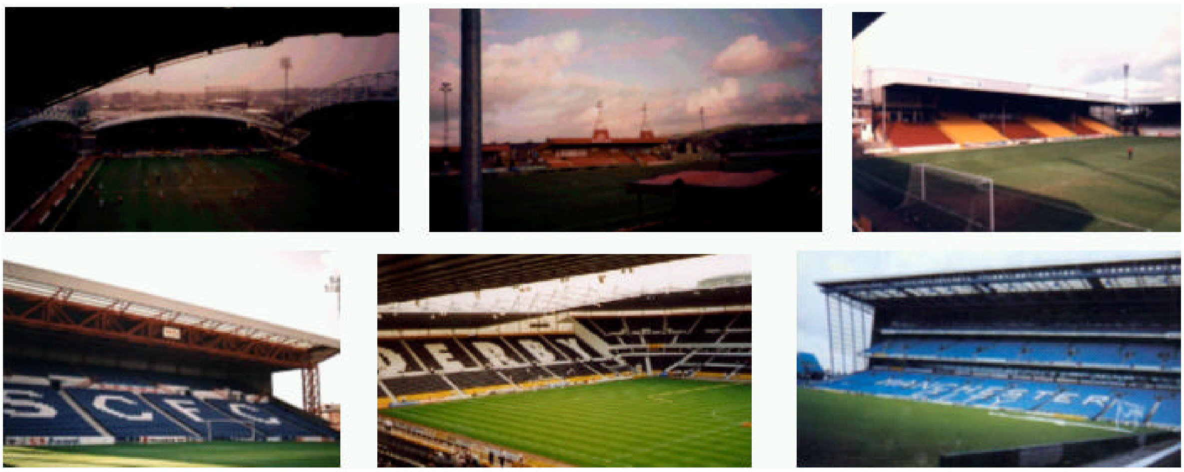


Figure 4. *The McAlpine Stadium, Huddersfield; Ewen Fields, Hyde; Valley Parade, Bradford; Edgeley Park, Stockport; Pride Park, Derby; and Maine Road, Manchester. The measured average SPL was 77-98dBA, and the maximum SPL was 102-120dBA.*

Fans at all stadia except Ewen Fields wanted to hear sounds from the pitch better than they could – mostly by about one point on the scale. The mean answers for all interviewees were 2.99 for how well they could currently hear sounds from the pitch, and 2.14, or 'quite well' for how well they would like to be able to. A mean answer of 2.06 shows the sounds from other parts of the stadia to be very slightly more important to fans than hearing sounds from the pitch.

All the stadia had very audible PA systems. Whilst they are of great importance regarding the safety, these do not seem to contribute to a good atmosphere. Although the mean answers to the question 'how well can you hold a conversation with someone near to you' were invariably either 'very well' or 'quite well', fans often suggested that they would prefer not to be able to communicate with people around them as easily, especially if it was due to a better atmosphere.

At all the grounds, interviewees could hear external noise, such as wind, rain and traffic, better than they would like to. It could be heard best at Ewen Fields, but it was also tolerated most here. Perhaps this is because the fans are used to the noise, or the noise is of a more tolerable variety.

For five of the stadia, the responses to two questions regarding quality of atmosphere and loudness of the stadium were very similar. It seems that most fans do think that the atmosphere is very, if not totally, dependent on sound volume. At Ewen Fields, however, fans rated the stadium considerably better as regards atmosphere than volume. They seemed aware that the ground was not very loud, but believed it had a good atmosphere. For the question of 'how important is the acoustic atmosphere to you', the mean rating for all grounds is 2.21, or 'important'.

The subjective analysis suggests several strategies for a good acoustic atmosphere in a stadium: a large capacity, a high attendance-capacity ratio, huge, multi-tiered stands, standing areas, large proportion of capacity for away fans, and seats close to and all around the pitch.

5. SWIMMING SPACES

Subjective surveys were carried out in three typical swimming spaces in Sheffield, including the Cofield swimming pool at Sheffield University, Ponds Forge sport centre, and Hillsborough leisure centre.[6] The numbers of interviewee were 51, 52 and 90 respectively. The questionnaire included three sections: demographic information of the users and the use of the spaces, general satisfaction of the physical environment and facilities, and the acoustic comfort. The surveys were mainly carried out in swimming and audience areas, but other areas including restaurant areas and changing areas were also considered. The acoustic questions included evaluation of overall acoustic environment as well as of various sound sources. During the survey, the SPL was measured in a number of typical positions. Figure 5 shows the SPL variation with time in the three swimming spaces. It can be seen that the level varies considerably in different pools due to different activities, and the SPL range is about 60-80dBA, which is rather high.

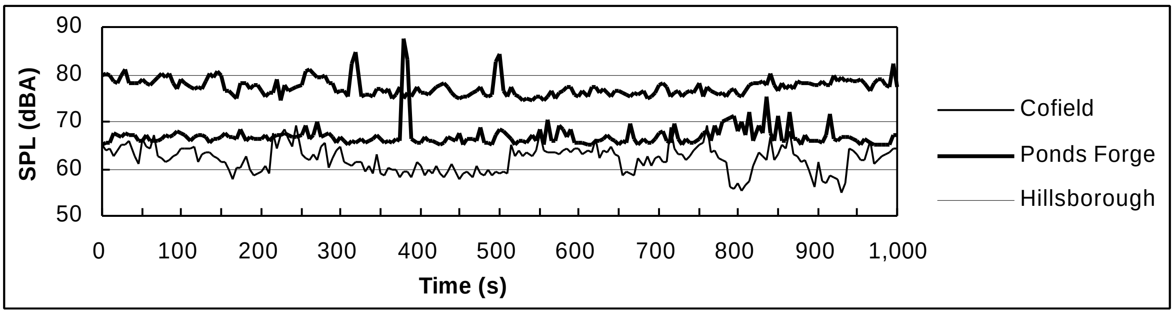


Figure 5. *Typical SPL distribution with time in the main swimming areas in Cofield, Ponds Forge, and Hillsborough.*

The relationships between the overall acoustic comfort of the swimming area and the RT and SPL are shown in Figure 6a and 6b respectively, where the comfort rating is 1, poor; 2, average; 3, good; and 4, excellent. The results suggest that in terms of acoustic comfort, people prefer long reverberation, but not high SPL. Figure 6c shows the correlation between RT and subjective rating of liveliness and reverberation: 1, should be more lively (reverberant); 2, fine; and 3, too lively (reverberant). It seems that people are generally satisfied with the current situation, although the RT varies considerably in the three spaces. The survey results also suggest that in the three spaces studied, there is no strong correlation between RT and subjective evaluation of speech intelligibility, for long and short distance communication as well as for PA system.

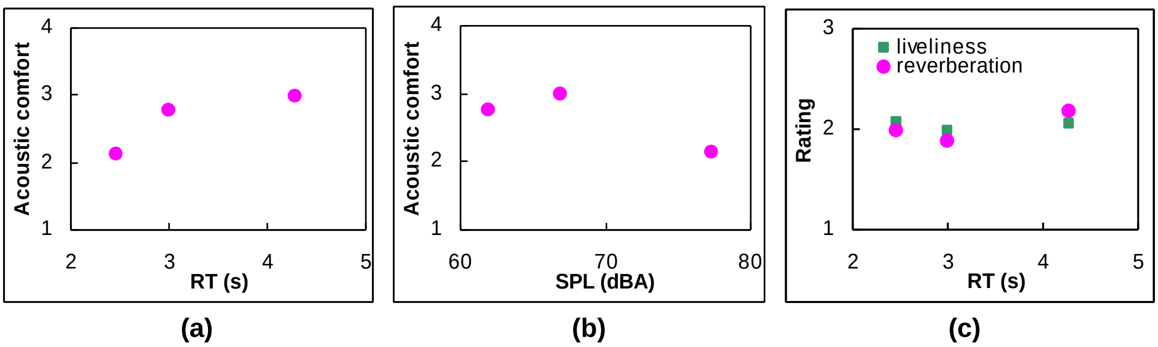


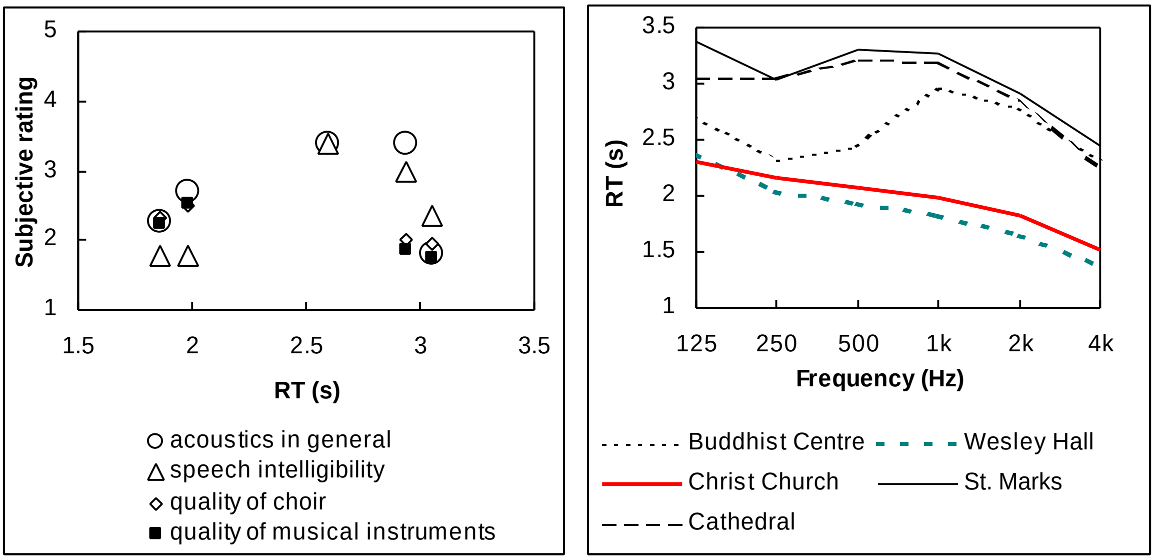
Figure 6. *Correlations between RT (average of 125-4kHz, calculated), SPL and subjective rating of acoustic comfort, liveliness and reverberation.*

On average, in the three swimming spaces 50% of the interviewees believe acoustics is an important or very important issue in swimming spaces; 75% of the interviewees indicate that the major noise source is children's shouting; and 32% of people feel acoustically uncomfortable after swimming, and another 33% sometimes have such feeling.

6. CHURCHES

Objective measurements and questionnaire surveys were carried out in five churches in Sheffield, including the Buddhist Centre (St. Josephs Church), Walkley; St. Marks Church, Broomhill; Wesley Hall, Crookes; Christ Church, Fulwood; and Sheffield Cathedral.[7-9] The measurements included sound pressure level and reverberation, and the questionnaire included people's general feeling about acoustic comfort, and evaluation in various usages. In each church 30-35 interviews were made.

The survey results suggest that within the range of case studies there is no clear correlation between reverberation time of a church and the acoustic comfort, as shown in Figure 7a. The measured RT in the five churches is shown in Figure 7b. For speech intelligibility, from Figure 7a it can be seen that the rating score tends to become less favourable with increasing RT. For the quality of choir and musical instruments, people tend to prefer longer reverberation. Overall, within the studied RT range, no significant correlation has been found between subjective and objective indices; and it seems that a RT value of 1.8-3.3s at middle frequencies corresponds to a 'good' and 'satisfactory' level. Further analysis of the survey results suggests that there are some interactions between acoustic factors and other environmental and architectural factors.[9]



(a) (b)

Figure 7. *(a) Correlations between measured RT (average of 125-4kHz) and subjective ratings, where the scale ranges from 1, excellent, to 5, bad. (b) Measured RT in the five churches.*

For the Buddhist Centre and the St. Marks Church, more detailed measurements including articulation tests were conducted, and more questions regarding speech and music quality were asked. The survey revealed interesting relationships between acoustic comfort and people's evaluation about speech and music quality.[9] The musicians were often more critical of the spaces that they performed in. This reaction could be attributed to a number of factors such as, better trained hearing, a stronger preconception of how the music should sound, and an experience of how the music would sound when preformed in other spaces by the same people.

Acoustic advice was given to the Buddhist Centre, based on the survey results, for a renovation project. Measurements were made before and after the renovation. The tests demonstrated that the suggested treatments were effective. The overall RT was reduced by approximately 1s resulting in a significant increase in speech intelligibility, according to the questionnaire survey as well as the articulation test. Further treatment using banners of certain fabrics and thicknesses to absorb sound at certain specific frequencies are suggested to perfect the acoustics.

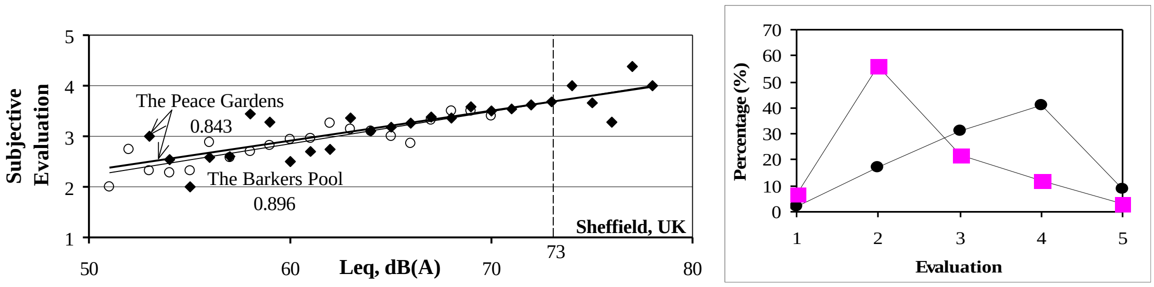
7. URBAN OPEN PUBLIC SPACES

Urban open public space is an important component of a city, and the acoustic environment plays a significant role in the overall comfort. In this study sound propagation and acoustic comfort in urban open public spaces are being systematically studied, including computer simulation, field measurements, questionnaire surveys, semantic differential analysis of the soundscape, and an overall system for soundscape description, evaluation and design.[13-21] The research is part of an overall study on physical comfort of urban open public spaces across Europe.

An intensive questionnaire survey was carried out in four seasons between summer 2001 and spring 2002, in two typical urban squares in Sheffield, the Peace Gardens and the Barkers Pool. The questionnaire includes subjective evaluation of the sound level and acoustic comfort, identification of recognised sounds, classification of sound preference, and indication of wanted and unwanted sounds on the sites. Over 1000 interviewees were made in the two squares. Furthermore, approximately 10,000 interviews were carried out in fourteen urban open public spaces of five European countries, namely Greece, the UK, Italy, Germany and Switzerland. A one-minute Leq (equivalent continuous noise level) was measured for each interview, and the RT measurements were made in selected sites.

The results show that there is generally a good correlation between the sound pressure level and the subjective evaluation of sound level, but the evaluation of acoustic comfort is rather different. An example is shown in Figure 8a and 8b. In addition, it has been demonstrated that in urban open public spaces, the background level, say Leq_{90}, is an essential index. A lower background sound level can make people feel quieter, even when the foreground sounds reach a rather high level.

People's sound preferences are affected considerably by the cultural background, long-term environmental experience, and age, but only slightly by gender. With the increase of age, people are generally more favourable to, or tolerant towards, sounds relating to nature, culture or human activities.



(a) (b)

Figure 8. *(a) Relationship between measured SPL and subjective evaluation of sound level, with correlation coefficient R. Each symbol represents the average of the subjective evaluations at a one-dBA scale. (b) Comparison between the subjective evaluation of sound level (circular symbols) and acoustic comfort (squared symbols) in the Peace Gardens, Sheffield. 1, very quiet (comfortable); 2, quiet (comfortable); 3, neither quiet (comfortable) nor noisy (uncomfortable); 4, noisy (uncomfortable); and 5, very noisy (uncomfortable).*

The semantic differential technique was used to identify the main factors that characterize the soundscape. A soundscape evaluation was carried out with 491 subjects in Sheffield using 18 adjective indices. The results show that the situation in urban open public spaces is complicated, but it is still possible to identify several major factors. Based on the principal component analysis, four factors were determined which covered 53% of the total variance. Factor 1 (26%) is mainly associated with relaxation, including comfort-discomfort, quiet-noisy, pleasant-unpleasant, natural-artificial, like-dislike and gentle-harsh. Factor 2 (12%) is generally associated with communication, including social-unsocial, meaningful-meaningless, calming-agitating and rough-smooth. Factor 3 (8%) is mostly associated with spatiality, including varied-simple, echoed-deadly and far-close. Factor 4 (7%) is principally related to dynamics, including fast-slow and hard-soft.

8. CONCLUSIONS

Both subjective and objective survey results in a number of 'non-acoustic' spaces have been presented and discussed. It has been demonstrated that the acoustic atmosphere is an important consideration in such spaces and the acoustic comfort may vary considerably with the same objective acoustic indices such as sound pressure level and reverberation time. The research reveals that current guidelines and technical regulations are insufficient in terms of acoustic design of these spaces. The relationships based on the surveys between subjective and objective indices would be useful for developing further design guidelines.

ACKNOWLEDGEMENTS

The author is indebted to all the researchers and interviewees involved in the work reviewed in this paper.

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