Acoustic quality in non-acoustic public buildings

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Abstract: This paper analyses the case study results in eight types of public buildings, including railway stations, shopping malls, libraries, open plan offices, football stadia, swimming spaces, dining spaces, and churches, aiming at examining relationships between subjective and objective indices, as well as principles and framework for creating comfortable acoustic environments in such 'non-acoustic' buildings. It is revealed that acoustic quality is an important consideration in these buildings, and it may vary considerably with the same objective acoustic indices such as sound pressure level and reverberation time. Key factors to be considered include social demographic background, psychological adaptation, sound preference, preference of acoustic treatments, interactions between acoustic and other environmental factors, and possible health effects of unsatisfactory acoustic quality.

Key words: acoustic quality; acoustic comfort; public building

非声学公共建筑中的声品质

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摘要: 本文分析了在八种公共建筑类型中的声学专题研究结果, 包括火车站、商城、图书馆、开敞式办公室、足球场、游泳空间、用餐空间、及教堂, 旨在考查主观评价和客观指标之间的关系, 并且探索在非声学建筑中创造舒适的声环境的原则和框架。分析表明了声品质在这类非声学建筑中的重要性, 另外, 即使客观指标例如声压级和混响时间相同, 声舒适度亦可能完全不同。其它关键因素包括社会背景、心理调节、声音喜好、声学处理的接受程度, 声学与其他环境因素的相互作用、以及不满意的声品质可能造成的健康影响。

关键词: 声品质; 声舒适; 公共建筑
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1 INTRODUCTION

Whilst the acoustics in 'acoustic buildings' such as concert halls has been intensively investigated, the acoustic quality in 'non-acoustic' buildings is receiving increasing attention[1-2]. Previous works on this topic have mostly concentrated on certain basic technical indices, with little attention to the acoustic quality, comfort and atmosphere. Note as the term product sound quality often refers to a single sound source, in buildings the term acoustic quality and or acoustic comfort would be more appropriate. Recently a series of case studies have been carried out in various types of public buildings[2-20], considering characteristics of sound fields as well as perceptions of acoustic quality and comfort. This paper analyses

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2 RAILWAY STATIONS

Objective measurements and subjective surveys were carried out in two typical medium-sized UK railway stations, Sheffield and Derby[3-4]. The temporal sound pressure level (SPL) distribution is shown in Fig.1, based on L_{Aeq} of 15s with an interval of 3 minutes. It can be seen that the SPL fluctuated significantly, mainly due to trains and PA announcements, by about 20dBA, and the fluctuations usually happened in a very short period. The measured reverberation times (RT) ranged from about 0.3 to 0.8s on the platforms and in the lounges.

In the two stations 179 questionnaires were handed out to travellers and 28 to the station staff members. The relationship between the acoustic comfort evaluation and the measured SPL was rather strong, with R^2=0.82, indicating that the acoustic comfort level became lower as SPL increased, where for the acoustic comfort evaluation five scales were used: 1, very uncomfortable; 2, a little uncomfortable; 3, average; 4, comfortable; 5, very comfortable.

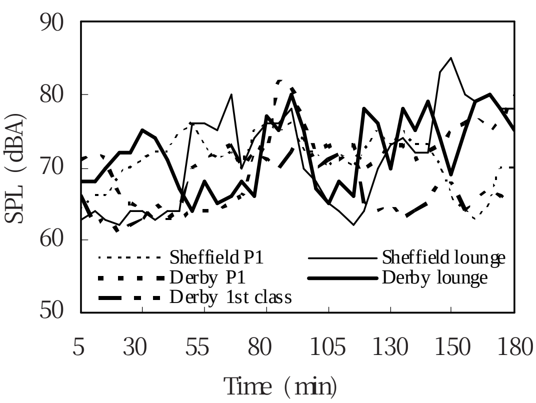

Fig.1 Measured temporal SPL distribution in stations.

The mean acoustic comfort score of the staff members was 3.46, significantly ($p<0.01$) higher than that of travellers, 3.07. Moreover, 50% of the staff regarded the acoustic environment as comfortable or very comfortable, whereas this figure was only 26% with travellers. Conversely, 54% of the staff members found the station noise contributed to their stress level comparing to the level of 40% for travellers.

In average female travellers were slightly more satisfied about the acoustic comfort than males, with a difference of 0.16 in the evaluation score, although the difference was not statistically significant due to the fact that females tended to choose extreme scales. With the increase of age, there was a slight increase in evaluation score, namely 2.95 for <20 group, 3.10 for 20-40 group, and 3.30 for >40 group, but this increase was again not statistically significant.

There was a significant correlation, with R^2=0.82, between acoustic comfort scores and the duration of stay, from less than 5 minutes to over 30 minutes, suggesting that people felt acoustically uncomfortable as they stayed longer in the stations. There was also a significant correlation, with R^2=0.67, between acoustic comfort and the frequency of travel, ranging from everyday to less than 5 times a year, suggesting that people who travelled less frequently tended to feel acoustically more uncomfortable.

It is noted that despite the high background noise, the clarity of announcement was generally acceptable, with a mean score of 3.49 on the platforms and 3.88 in the lounges, where the scales were 1, cannot hear; 2, not clear; 3, average; 4, clear; 5, very clear.

Although the reverberation time was not long, the level of echoes seemed to be serious, as almost 80% of interviewees heard 'some' or 'a lot of' echoes. Although echoes might not have a serious impact on the subjective evaluation of announcement clarity in this case, it would probably contribute to acoustic discomfort, particularly for conversation.

The disturbance of five typical sounds was evaluated by travellers, with four scales: 1, very disturbing; 2, disturbing; 3, a little disturbing; 4, not disturbing. The SPL of those sounds ranged from 65 to 85dBA. The mean scores were: train, 2.55; announcement, 2.87; baby screaming, 3.02; mobile ringing, 3.18; people chatting, 3.54. It is noted that although train was on the top of the list, only 46% of the travellers found it disturbing or very disturbing. This could be explained by their high level of expectation for train noise, reflected in the detailed comments.

The disturbance level for various activities was evaluated, with three scales: 1, very disturbing; 2, disturbing; 3, not disturbing. The mean scores were: talking on mobile phone, 1.80; reading business documents, 2.22; listening to music, 2.30; reading magazine, 2.40. It should be indicated that whilst 48% of the travellers found listening music was not disturbed, their comments actually suggested that they did not attempt to listen to music as the station was too noisy.

The importance of various environmental factors was compared and acoustic quality was regarded as an important factor by travellers as well as by staff members. The correlation between the evaluation of acoustic comfort and general comfort in the stations was rather strong, with R^2=0.87.

3 SHOPPING MALLS

Sheffield's Meadowhall, one of the largest indoor shopping malls in the UK, was studied. Three main spaces were considered: the Oasis, a multi-functional 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[5-6].

The reverberation was generally long, around 2-3s, and the longest RT occurred at middle frequencies. Fig.2 shows measured temporal SPL distribution and typical spectra. The SPL fluctuated considerably at different times of a day and different days of a week, relating to the number of customers, space features of an atrium, as well as background music. The spectra showed a peak at middle frequencies, and a considerable drop at high frequencies. The sound attenuation in the atrium void was also measured, which was generally rather significant.

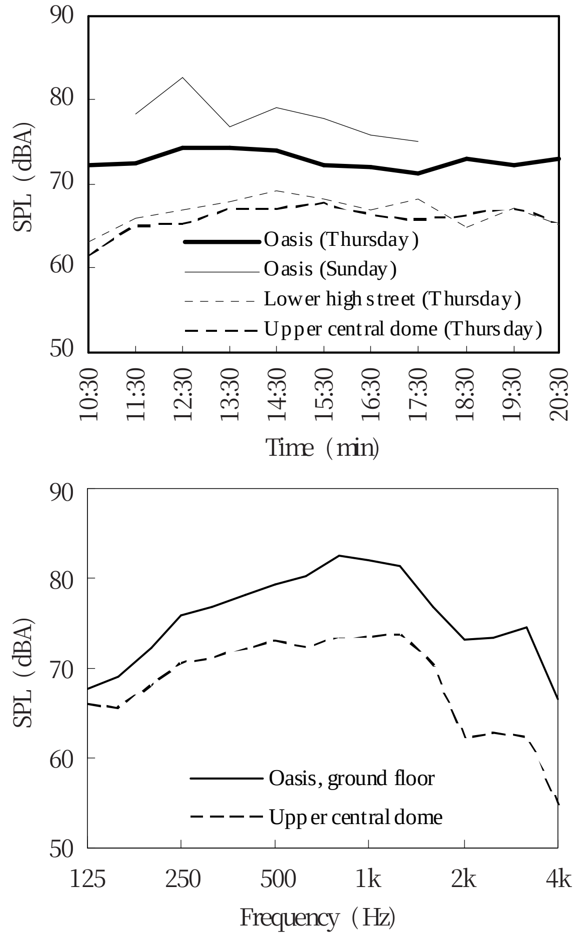

Fig.2 SPL and spectra in shopping mall Meadowhall.

There was a tendency that the overall acoustic comfort evaluation became less satisfactory with increasing SPL, as shown in Fig.3, where the scale was 1, very uncomfortable; 2, a little uncomfortable; 3, neutral; 4, a little comfortable; 5, very comfortable, but the correlation coefficient is rather low, with R^2=0.40 ($p<0.01$), due to the complicated features of the sound sources. With a given SPL, the annoyance scores were usually higher than or the same as those for loudness, showing people's tolerance. Generally speaking, people were not satisfied with the current acoustic quality.

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 acoustic evaluation was affected by the duration of stay and the activities. People felt acoustically uncomfortable just after arriving, but after a short period they might get used to it. After a longer period, they felt uncomfortable again as they became tired with the continuous high level of noise.

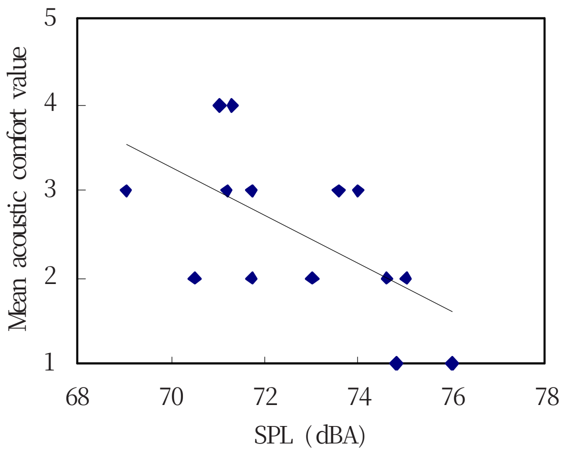

Fig.3 Correlation between acoustic comfort and SPL.

In terms of speech intelligibility, there was a good correlation between the communication quality and the early decay time (EDT). In general, people felt more satisfied with the communication quality than with the overall acoustic comfort. It is interesting to note that the staff group were more tolerant in terms of communication comfort than customers.

As expected, significant differences were found between the acoustic sensitivities to different sounds. Sounds from fountains were considered the most pleasant and sounds from nearby people were the most annoying.

4 LIBRARIES

The main reading room (MR) and the architectural reading room (AR) at the Sheffield University Main Library were investigated[7-8]. Measurements showed that the SPL attenuation with distance was considerable (15-25dB), the RT was rather short (0.3-0.5s), and the general background noise was not high (37-45dBA). However, the acoustic comfort was only at a medium or less satisfactory level, and it seemed that there was no correlation between the sound level and acoustic comfort evaluation. This revealed the contradiction in designing the acoustic environment in such spaces, namely balance between privacy and annoyance.

A main aim of the study was to compare natural and artificial sounds as background/masking sounds in reading rooms. Four sounds were played back in the AR with the same level of 50dBA, including 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 Fig. 4. In Table 1 the results of four questions in this aspect are shown, where 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; and question D-noisiness: 1, very noisy; 2, noisy; 3, medium; 4, quiet; 5, very quiet. It is important to note that the mean evaluation scores for the running water sound were generally higher than those for other sounds. For question B, this score was even higher than that under normal conditions, namely without masking sound, despite the fact that the sound level with the running water sound was about 5-10dBA higher. A possible reason is that in comparison with other sounds, the running water sound had rather weak low frequency components, as can be seen in Fig. 4. Rain/wind and rain sounds, although also from nature, received similar scores to ventilation noise.

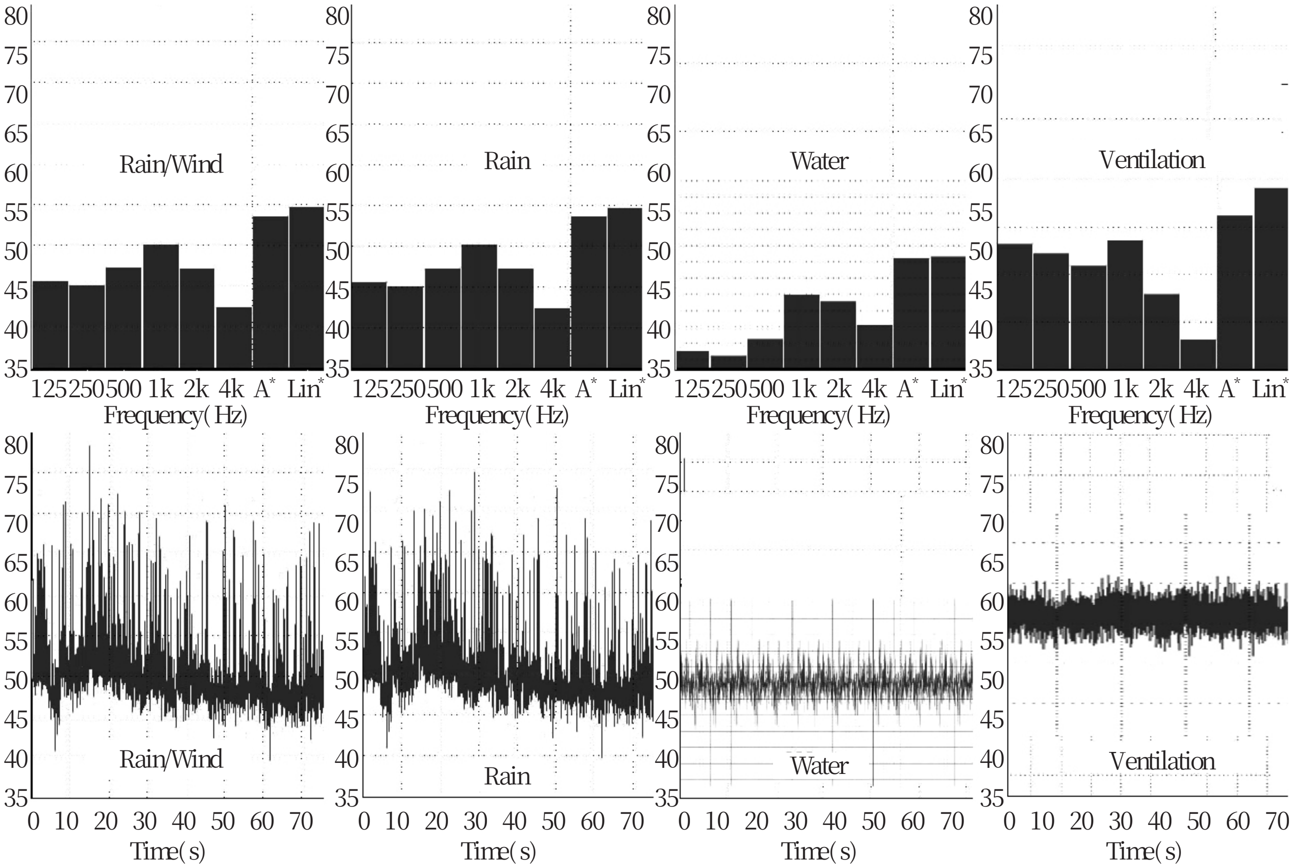

Fig.4 Spectra and time variation of the masking sounds.

Table 1 Acoustic sensation with the masking sounds.

Question	No masking sound		With masking sounds			
	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

This is probably due to their notable low frequency components and more importantly, their large dynamic range, as also illustrated in Fig.4.

5 OPEN PLAN OFFICES

Three open plan offices were studied, including the Mercury Taxi call centre in Sheffield, with 50 telephone operators; the NHS Primary Care Trust in Rotherham, mainly the financial and IT departments; and the architectural practice AEDAS in Manchester, with about 60-70 staff members[4,9].

In Fig.5 the temporal SPL distribution is shown, where the dots indicate peaks from raised voice, printers and door slamming. Although the average SPL in the three offices differed, the ranges of variation were similar, with L90, L50 and L10 of 55.1, 61.5, 67.2dBA in Mercury, 47.3, 50.8, 56.7dBA in NHS, and 46.6, 50.5, 58.2dBA in AEDAS. In the three offices the external noise level was all rather low.

A questionnaire survey was conducted with 105 people participated, 30 in Mercury, 38 in NHS, and 37 in AEDAS. In terms of the subjective evaluation of sound level, the percentages of choosing various categories were: 1-very quiet, 1%; 2-quiet, 13.3%; 3-acceptable, 56.2%; 4-noisy, 25.7%; 5-very noisy, 3.8%. The mean score was 3.47 in Mercury, 3.18 in NHS, and 2.95 in AEDAS, generally corresponding to the average SPL in the three offices: 60.9, 51.7, and 51.2dBA, respectively. This suggested that a noise level of around 51dBA might be generally at an 'acceptable' level for open plan offices. It is noted, however, that the standard deviation in the evaluation scores was 0.51 in

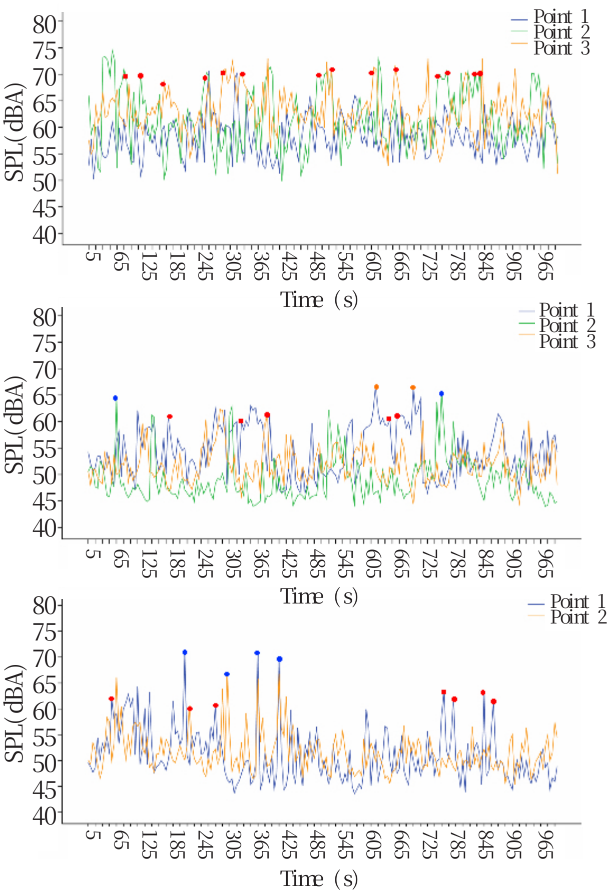

Fig.5 Measured temporal SPL distribution in offices.

Mercury, 0.83 in NHS and 0.74 in AEDAS, indicating that there was a considerable variation of people's opinion. A question was asked about preferred sound level at work. The percentages of choosing various scales were: deadly, 0%; quiet, 25%; acceptable, 70%; loud, 5%; very loud, 0%-it is very interesting to note that the percentage of people of preferring just 'acceptable' noise level, rather than 'quiet', was actually very high in such a working environment.

The annoyance level of typical sounds in open plan offices was evaluated using five scales: 1, very disturbing; 2, disturbing; 3, acceptable; 4, noticeable; 5, hardly noticeable. The mean scores were: telephones ringing, 2.52; colleagues chatting, 2.80; office equipment, 3.89; keyboard typing, 4.08; external noise, 4.16; and ventilation, 4.21. It is noted that telephones ringing and colleagues chatting were the most annoying sounds, significantly different from the other sounds ($p<0.001$). It was also indicated by many interviewees that door slamming was a major noise source.

A number of possible treatments were evaluated in terms of their usefulness and preference in reducing background noise in the offices, where five scales were used, with 1 being not useful and 5 very useful. The mean scores were: installing higher panels to separate work space, 1.99; work in a close cell workstation, 1.45; fitting in some natural features (e.g. fish tanks), 2.09; introducing natural background sounds (e.g. birds singing), 0.89; and better headsets (Mercury only), 2.76. It can be seen that these conventional treatments were generally not preferred by the users.

An evaluation of various environmental factors was made, including temperature, lighting, humidity, comfort of own work space, degree of privacy, and overall working environment, where five scales were used: 1, unacceptable; 2, poor; 3, satisfactory; 4, good; 5, very good. The mean evaluation score was mainly around 3, namely at a satisfactory level, for various factors as well as for the overall environment, except for privacy, which had a mean score of 2.58, significantly ($p<0.001$) lower than that for other factors.

The percentage of people who experienced work-related symptoms was surveyed, including tinnitus (Mercury only), hypersensitivity to loud sounds, easily getting tired, and depression. A high percentage people, around 20-30%, had various symptoms. The percentage of tiredness was particularly high, with 67% people choosing sometimes, often, and frequently. Acoustic environment might be a contributing factor on this, although further research is needed.

6 FOOT BALL STADIA

SPL measurements in six typical football grounds around the UK, including the McAlpine Stadium, Huddersfield; Ewen Fields, Hyde; Valley Parade, Bradford; Edgeley Park, Stockport; Pride Park, Derby; and Maine Road, Manchester, showed that the average SPL was 77-98dBA, and the maximum SPL was 102-120dBA[10]. In the subjective surveys relating to the acoustic atmosphere, 30 fans were interviewed in each stadium, and 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. 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.

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. For the question of 'how important is the acoustic atmosphere to you', the mean rating for all grounds was 2.21, or 'important'.

All the stadia had very audible PA systems. Whilst they are of great importance regarding the safety, these did 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.

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 showed the sounds from other parts of the stadia to be very slightly more important to fans than hearing sounds from the pitch. On the other hand, at all the grounds, interviewees could hear external noise, such as wind, rain and traffic, better than they would like to.

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.

7 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[11]. The numbers of interviewee were 51, 52 and 90 respectively. Fig.5 shows the measured temporal SPL distribution in the three swimming spaces. The level varied considerably in different pools due to different activities, and the SPL was generally rather high.

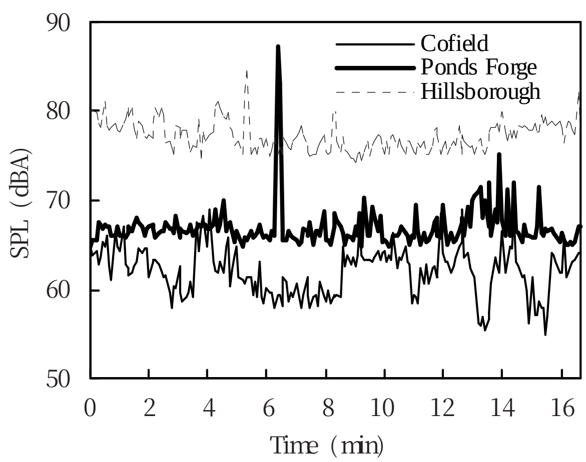

Fig.6 Measured SPL variation in the swimming areas.

On average, in the three swimming spaces 50% of the interviewees believed acoustics was an important or very important issue in swimming spaces. The relationships between the overall acoustic comfort of the swimming area and the RT and SPL suggest that in terms of acoustic comfort, people preferred long reverberation, but not high SPL. The current acoustic quality was generally satisfactory, although the RT varied considerably in the three spaces, from 2.4 to 4.2s at middle frequencies.

The survey results also suggested that in the three spaces studied, there was no strong correlation between RT and subjective evaluation of speech intelligibility, for long and short distance communication as well as for PA systems.

In terms of sound preference, 75% of the interviewees rated children's shouting as the major noise source. It is interesting to note that 32% of people felt acoustically uncomfortable after swimming, and another 33% sometimes had such feeling.

8 DINING SPACES

Measurements in a medium-sized Italian restaurant called BB's on Division Street in Sheffield under unoccupied condition showed that the average SPL throughout the restaurant without music was 61dBA. With music the average SPL increased to 80dBA. Other main noise sources included the fridge (63-68dBA), cutlery (68-75dBA), talking from counter (63-75dBA), arranging chairs (75-82dBA), and talking and walking of the staff members (70-88dBA). The SPL under occupied condition is shown in Fig.6. The levels were rather high, mostly at 80-90dBA. The RT in this restaurant was rather low, at around 0.4s at 250-8kHz.

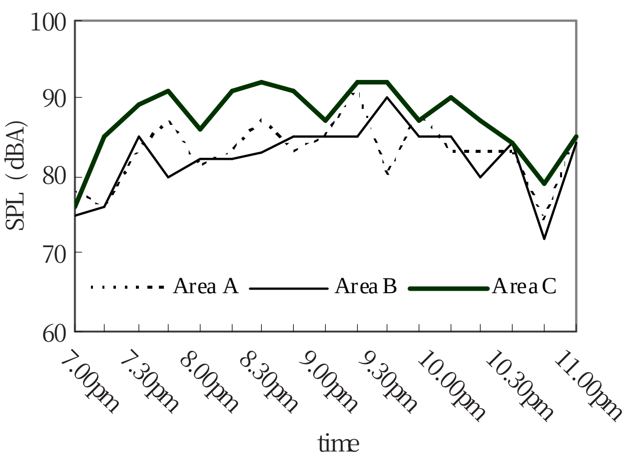

Fig.7 Measured SPL variation in BB's restaurant.

Questionnaire surveys were conducted in a number of dining spaces in Sheffield, and in total 141 valid questionnaires were collected, 29 from BB's restaurant. The questionnaire was designed to explore effects of acoustics and music on the dining experience[14-15].

A question was asked about whether conversations could be held without having to raise voices. In BB's restaurant 86% of the interviewees answered yes and 14% answered no. It is interesting to note that even when the background noise was 80-90dBA, the majority of people could still hold conversation. A following question was then asked about whether noise/music/sound level in the restaurant affected their experience of enjoying meal, and 48% of the interviewees answered yes and 52% answered no. This clearly demonstrates the importance of acoustic environment in restaurants.

To examine the relationships between the above two aspects, namely speech intelligibility and dining enjoyment, t-tests were made based on the data of the 141 interviewees. Between people who gave different answers in terms of conversation quality (yes, 1; no, 2), there was a significant difference ($p<0.001$) in their answer on the effect of acoustics on dining experience (yes, 1; no, 2), with a mean value of 1.54 and 1.00, respectively. In other words, people who experienced conversation difficulties all indicated the importance of acoustics for dining enjoyment.

A related question was also asked: if a restaurant's acoustic quality, i.e music, noise level etc is not to your taste, but the food is great, would it deter you from returning to the restaurant in the future? The percentage of answering yes was 33% when all the 141 samples were taken into account. This further demonstrates the importance of considering acoustics in dining spaces.

Previous studies have shown that the speed at which people eat their food is affected by music[21]. In this study, this was further examined by asking: what do you think of the idea that noise/music/sound level actually influences the speed at which people eat their food, i.e. loud music and noise makes one tense, and therefore eat faster? A 10-point scale was used, ranging from 1, strongly agree, to 10, strongly disagree. Whilst the result of all the interviewees shows approximately a normal distribution, with an average evaluation score of 4.63, namely, slightly towards 'agree', there are significant differences between people with different music backgrounds. People who play an instrument or sing had an average evaluation score of 3.10, significantly higher than that of people who only enjoy music occasionally, 4.94 ($p<0.05$); and people who listen to music all the time, 4.75 ($p<0.01$).

Interviewees were asked to select the types of music they would prefer being heard in a restaurant, including no music, soft music, loud music, popular music, instrumental music, vocal music, oldies, music related to food origin, and other types of music, where multiple choices were allowed. The results of 141 interviewees show that there was a high preference for soft music, followed by instrumental music. The most unpopular type of music was loud music, which was not selected by any interviewee. This suggests that people generally prefer music which serves as a background rather than a foreground element. It is interesting to note that 8.4% of the votes went to 'no music', and 'music related to food origin' only took 9.3% of the vote.

9 CHURCHES

Five churches in Sheffield were studied, including the Buddhist Centre (St. Josephs Church), Walkley; St. Marks Church, Broomhill; Wesley Hall, Crookes; Christ Church, Fulwood; and Sheffield Cathedral[16-18]. In each church 30-35 interviews were made.

Fig.8 shows the relationships between measured RT (average of 125-4kHz) and subjective ratings, where the scale ranges from 1, excellent, to 5, bad. The results suggest that within the range of case studies there was no clear correlation between RT and the acoustic comfort. For speech intelligibility, the rating score tended to become less favourable with increasing RT. For the quality of choir and musical instruments, people tended to prefer longer reverberation. Overall, within the studied RT range, no significant correlation was found between subjective and objective indices; and it seems that a RT value of 1.8-3.3s at middle frequencies corresponded to a 'good' and 'satisfactory' level.

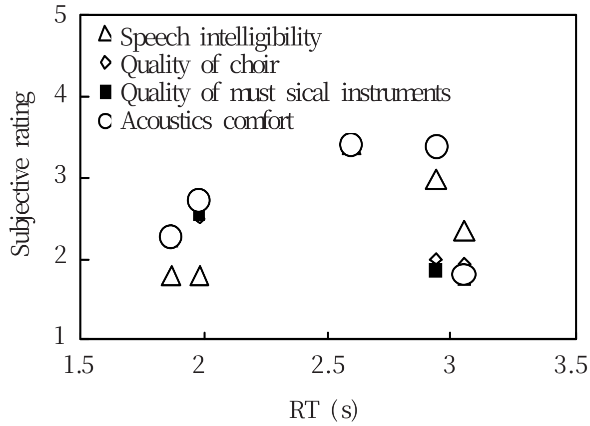

Fig.8 Correlations between RT and subjective rating.

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. The musicians were often more critical of the spaces that they performed in.

Further analysis of the results suggests the importance for designers to consider whether people are coming to a church for the sole purpose of hearing the priest's sermon and then praying or they are also coming to share in a collective atmospheric experience. Perhaps going to church is all about community and spirituality and if the acoustics serve only to facilitate the basic functions but dampen the communal atmosphere then the building is failing in its deeper purpose. It seems clear that there is an important differentiation to be made between how well a church is performing its acoustic functions and its level of acoustic comfort. Acoustic comfort is less easily definable than function; it requires the designer to think of space as an acoustic environment rather than a facilitator of events. It is to do with creating a feeling rather than fulfilling a function.

10 CONCLUSIONS

Both subjective and objective survey results in a number of ‘non-acoustic’ building types have been presented and discussed. The research reveals that acoustic quality is an important consideration in these buildings, and it may vary considerably with the same objective acoustic indices such as SPL and RT. Current guidelines and technical regulations are thus insufficient in terms of acoustic design of these spaces. Whilst the relationships based on the surveys between subjective and objective indices would be useful for developing further design guidelines, a number of key factors to be considered in a design framework have been identified, including social/demographic factors such as age, gender and acoustic condition at home; psychological adaptation such as difference between customers and staff members and between frequent and occasional users; preferences of various sound; subjective evaluation and preference of certain acoustic treatments; interactions between acoustic and other environmental factors; and possible health effects of unsatisfactory acoustic quality.

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