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SPEECH INTELLIGIBILITY IN THEATRES

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INTRODUCTION

Speech intelligibility, expressed in terms of Percentage Syllable Articulation (PSA) has been the accepted criterion for the evaluation of the acoustical quality of theatres. The determination of PSA through subjective evaluation test is, however, time consuming and several objective measures, some of which have been shown to be highly correlated with PSA, have been, therefore, proposed as effective predictors of speech intelligibility.

To obtain information on these objective measures and to gain a better understanding of the effects of design on speech intelligibility, extensive objective measurements have been carried out in twelve British theatres.

THEATRES SURVEYED

In the study, four types of theatre form were used with the proscenium-type theatres being the main theatre form investigated. The selection is generally to include both small and large theatres, modern and old and theatres with special design feature. The twelve theatres are as classified below:-

A) Proscenium-type theatres

1) Arts Theatre, Cambridge - small, 2 tiered and of simple design
2) Towngate Theatre, Poole - single-tiered, small with shaped ceiling & walls
3) Wyndham's Theatre - medium, three-tiered, Victorian
4) Theatre Royal, Bristol - small, three-tiered, old, restored
5) Royal Shakespeare Theatre - large, three-tiered with overhead reflector
6) Lyttleton Theatre - medium, two-tiered, modern.

B) Open-Stage Theatres

7) Shakespeare Theatre, Barbican - large, four-tiered
8) Olivier Theatre, London - large, 2-tiered.

C) Thrust stage Theatres

9) Festival Theatre, Chichester - open roof truss
10) Crucible, Sheffield - directive ceiling panel on underside of walkway.

D) Theatre-in-the-round

11) Royal Exchange Theatre, Manchester - small, compact in 3 tiers
12) Roundhouse, London - 2 tiered, converted to theatre with large absorbent curtains around perimeter.

MEASUREMENT TECHNIQUE AND PROCEDURES

Measurements were made in unoccupied auditoria and two types of measurements were undertaken; impulse measurements and steady state measurements.

A directional loudspeaker with directionality characteristics similar to the human speaker was used for the measurements. An omni-directional loudspeaker

was used for Reverberation Time (RT) and Early Decay Time (EDT) measurements. For impulse measurements, impulses of 1 kHz and 4 kHz were emitted in order to cover the four octave frequency bands of 500 Hz to 4 kHz. For steady-state measurements, filtered octave band pink noise was fed to the directional loudspeaker. Two source positions were used; a central position facing into the auditorium and a lateral position facing across the stage away from the recording positions which are all in one half of the auditorium. The impulse responses were recorded on tape using omni-directional microphone. The steady-state sound level distribution was recorded manually using a B & K sound level meter. Ten to thirteen measuring positions were used.

From the impulse responses, the following objective measures have been derived; RT, EDT, 50 ms energy fraction (EF_{50}), centre time (CT), Lochner and Burger's Signal to Noise Ratio (S/N) and the Modulation Transfer Function (MTF). The first three objective measures were derived at the Cambridge Laboratory with the rest of the objective measures being derived using the computer facility at the Data Analysis Centre at the University of Southampton. With the exception of RT and EDT, the mean value over the four octave bands was used in the analysis of results.

Direct comparison between theatres for loudness level and distribution has also been made from the steady state measurements whereby the sound source was calibrated to a standard level for each set of measurement.

RESULTS AND DISCUSSION

RT and EDT

Although RT is no longer the only important criterion, nevertheless it is considered important that auditorium for speech should have an optimum value (1s is the generally accepted value). The results show that this optimum value is generally achieved with a small standard deviation of $\pm$ 0.1s. (RT has been shown to be location independent) Except for Crucible Theatre and the Roundhouse, the variation in RT with frequency is also small ($\pm$ 0.1s).

EDT has somewhat been accepted as subjectively more important than RT[1]. A comparison between EDT and RT values shows very small difference (less than - 0.15s) with only four theatres having a mean deviation of between - 0.15s to - 0.2s. The subjective significance of this deviation of - 0.15s to - 0.2s is not established. The standard deviation of EDT (over 10 to 13 measuring points) is generally within $\pm$ 0.1s with the Royal Shakespeare Theatre, Towngate Theatre and the Roundhouse having a higher standard deviation of $\pm$ 0.2s.

Other Objective Measures of Speech Intelligibility

Several criteria have been proposed for speech intelligibility and in this investigation, the three criteria calculated are:-

1) 50 ms energy fraction[2] $EF_{50} = \dfrac{\int_0^{50} p^2_{(t)}\ dt}{\int_0^{\infty} p^2_{(t)}\ dt}$

2) Lochner and Burger's signal to Noise Ratio, [3]

$$S/N = 10 \log \frac{\int_0^{95} p^2_{(t)} a_{(t)}\ dt}{\int_{95}^{\infty} p^2_{(t)}\ dt} \quad dB$$

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3) Centre-Time CT [4]= $\dfrac{\int_0^\infty t p^2_{(t)}\, dt}{\int_0^\infty p^2_{(t)}\, dt}$ ms

The results are given as the mean over the four octave frequency bands. Figure 1 shows the range of values within each theatre and the overall mean for each of the two source positions. Not surprisingly, speech intelligibility, as given by these criteria, worsens when the source is in the lateral position, facing across the stage.

It is expected that effects of design are likely to affect all these objective measures and as a first step is the analysis, the relationship of these objective measures to one another was investigated using bivariate correlation analysis. The 50 ms energy fraction (EF_{50}) is found to be highly correlated to both CT and S/N. In the first case, the correlation coefficient ranges from - 0.91 to - 0.99 for the twelve theatres studied. In the latter analysis, the correlation coefficient ranges from 0.85 to 0.98. An EF_{50} value of 0.5 (that is, early energy equals late energy) corresponds to a mean CT of 68 ms ($\pm$ 4.5 ms) and a mean S/N of 3.3 dB ($\pm$ 0.5 dB). The results therefore suggest that it is acceptable to use EF_{50} as the objective measure of speech intelligibility for a detailed study of the effects of room design. The 50 ms energy fraction has the advantage of being easily derived from the impulse response recordings. Based on the findings of Kurer [5] and from the above bivariate correlation analysis, it follows that the optimum value of EF_{50} is 0.5.

Energy Levels on a Function of Source-Received Distance

Total Sound Level as a function of distance is a common method of analysis for sound behaviour in factories and in concert halls, the total reflected energy is found to be, in most cases, to decrease with increasing distance. In this study, regression analysis has been applied using total energy (dB re direct sound at 10 m), total reflected energy (total energy minus theoretical direct energy), measured early energy (calculated from early energy fraction and total energy), measured early reflected energy (early energy minus theoretical direct sound) and measured late energy, in turn with source-receiver distance. The following observations are made for central source position. (Measured late energy will be discussed separately).

A) Proscenium type theatres (to include the Shakespeare Theatre)

Only in the Arts Theatre is there a high correlation between the various energy levels and distance (r is 0.94 to 0.95). Although there is a significant correlation between total sound and distance in Wyndham's Theatre (r = 0.92), significant correlation is only found for the other energy levels when the regression analysis is applied to the Stall seatings. Poor correlation between each of the energy levels and distance is found in all the other theatres and correlation becomes significant only if the regression analysis excludes seating areas receiving directed reflections (such as the rear part of Towngate Theatre) and, in most cases, when the regression analysis is applied to the Stalls seating. The outstanding exception is that of Theatre Royal, Bristol, where there is only a small stalls seating area, box-like circle seating, divided seating areas (resulting in "wedge walls") and concave rear walls and in this theatre, no correlation was found

between any of the energy levels and distance.

B) Thrust Stage-type Theatres (including Olivier Theatre)

In this type of theatre, it is not expected that total energy be well correlated with distance because of the directionality of the source. It is, however, interesting to note that in spite of the directionality of the source, a much higher correlation was found in thrust stage theatres than in the proscenium-type theatres previously discussed (r = 0.74, 0.85 and 0.83). The correlation was found to be significant (r = 0.92, 0.99 and 0.98) when only seats within 30° of the central axis with respect to the source were used in the regression. This is also observed for the other energy levels.

C) Theatres-in-the-round

This method of analysis produces results of limited use as the source-receiver distance is relatively small and the effects of directionality of the source are significant.

Early Energy Fraction and Early Reflected Energy

A higher early energy fraction means a higher level of clarity and in theatres, early reflections, particularly ceiling reflections, are often provided to the rear part of the theatres. Closer examination of the results for proscenium theatres with poor correlation of energy levels with distance, reveals important overhead reflections resulting in higher EF_{50} values, higher early reflected energy levels (E - D) compared to seats with similar source-receiver distance but without such reflections. This is found in the second half of the Towngate Theatre, upper seating levels of the Royal Shakespeare Theatre, rear balcony seats of Lyttleton and balcony seating of the Shakespeare Theatre.

The large, wide, Olivier Theatre with non-directive ceiling has high EF_{50} values (mean 0.75 $\pm$ 0.06) but are mainly due to the domination of the direct sound in the absence of any important early reflected energy (mean value of - 3.4 dB compared to + 2.5 dB of Crucible Theatre and - 1.4 dB of the Shakespeare Theatre which has similar seating capacity but is more compact). Of the thrust-stage type theatres, the bigger Festival Theatre with open roof truss (diffusing) has a lower mean EF_{50} value (0.67) and a lower E - D value (- 0.03 dB) compared to the Crucible Theatre (EF_{50} = 0.76) which has directive ceiling panels. The Royal Exchange Theatre with 686 seats has a higher EF_{50} value and E - D values (0.72 $\pm$ 0.11 and 4.5 dB respectively) than the 543 seats Roundhouse (EF_{50} = 0.62 $\pm$ 0.12 and mean E - D value = - 1.2 dB).

CONCLUSIONS

The selection of the 50 ms energy fraction as the objective measure of speech intelligibility in this study has been justified on the grounds of its high correlation with the other proposed objective measures. The sound behaviour of theatres has been studied in terms of energy levels as a function of distance and generally found to have a linear relationship provided there has been no attempt in the design to direct sound energy. Some design elements which increase the early reflected energy and 50 ms energy fraction have been identified.

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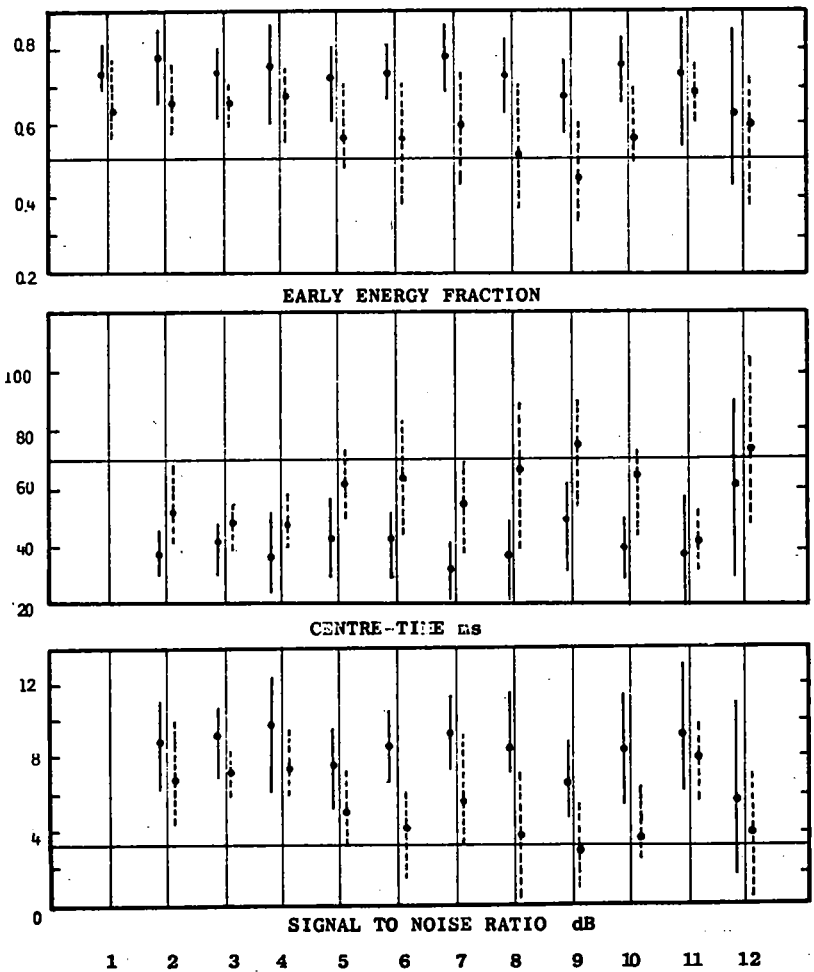

Figure 1 Measured values of EF_{50}, CT and S/N (—•— Central source, --•-- lateral)