SPEECH INTELLIGIBILITY
PREDICTIONS AND MEASUREMENTS
– MAKING THE ENDS MEET

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1 INTRODUCTION

As consultants, it is our responsibility to deliver sound-systems designs whose performances meet clients' requirements or relevant standards. Our work in the context of highly demanding architecture, with the strong challenges of acoustic environment and physical integration that such spaces are well known for, increases the need to " get it right".

It is a rare client who would provide the means for us to compare in detail how well the performance of the installed system agrees with our design predictions. Regrettably, we do not have as many opportunities as we would hope for to make the ends of the design loop meet. However, closing the design loop is a valuable way to calibrate and refine design skills and to validate the assumptions and accuracy of our predictions.

This paper describes the process and results of comparing predictions and measurements of speech intelligibility for three simple systems, using both software that predicts impulse responses and simple equations employing statistical reverberation. While we do not present any new techniques, some interesting observations and correlations have resulted.

2 AIMS

When using computer modelling to design loudspeaker systems, the designer sometimes must trust that the software developer has correctly implemented the accepted algorithms or chosen the most suitable algorithms. While predicting intelligibility from the computed impulse response should yield the most accurate results, there are some advantages that "hand" calculations using simple spreadsheets have over impulse-response methods. Hand calculations may be better suited to the early stages of design when various configurations are explored, as they allow rapid changes to loudspeaker parameters such as directivity and configurations (eg distributed or cluster). Potentially non-trivial time required to manufacture the computer model for physically complex spaces may also be avoided. Hand calculations also give the designer freedom to use specific algorithms.

The aims of this project were:

i) To compare "hand" and computer predictions of speech intelligibility STI with the measured STI for three types of loudspeaker systems within a single church environment. The systems were:

    - omni directional source
    - low directionality source simulating a human voice
    - the church sound system comprising of four moderately directional loudspeakers

ii) To compare measured differences in the performances of an omni-directional source, a source with low directionality, and a moderately directional loudspeaker system with respect to STI, and C_{50}.

iii) To compare “hand” and computer predictions of the STI and the octave band Modulation Transfer Indices (MTI) (which comprise the STI) and clarity ratios C_{50} with those measured for each system.

iv) To explore the validity of assumptions and relationships made in the prediction process. eg a) should the EDT be used rather than the RT_{60} b) does EDT correlate with the measured reduction in modulation at a given modulation frequency.

v) To investigate the relationship between C50 and STI as described by Bradley [1], as this relationship could be a useful tool for our kit bag.

3 METHODOLOGY

Christ Church Winchester in the UK was chosen for our study as agreement has been reached that will allow an ongoing series of experiments within this largely constant acoustic environment. It is shown in Figure 1.

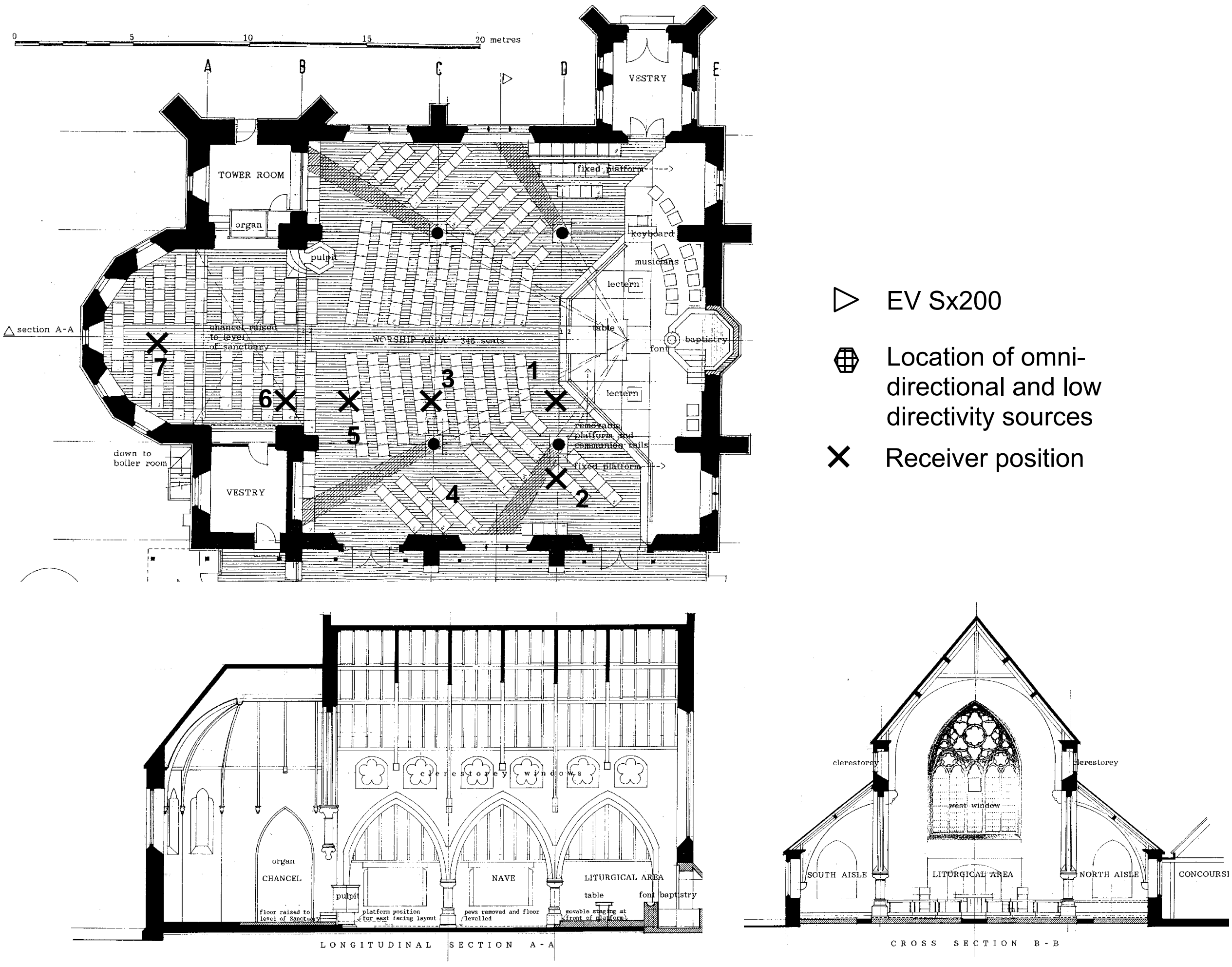

Fig 1. Plan, elevation and sectional view of Christ Church Winchester

The ambient noise level inside the church was 20 dBA. The reverberation times RT_{60} were measured with the MLSSA ver 10W analyser and the omni-directional source. Table 1 gives the reverberation times secs, measured using the omni-directional source. In each octave, the EDT and the RT60 based on decay between –10 dB and –25 dB were within 0.1 secs.

Frequency Hz	125	250	500	1000	2000	4000	8000
Measured RT60 secs	2.2	2.5	2.5	2.1	1.7	1.3	0.9

Table 1

As the ambient noise level was sufficiently low, the damaging role that background noise plays in determining speech intelligibility could be ignored, thus simplifying our exploration in this paper to temporal issues only. As the STI parameter does not include the effect of a non-flat frequency response (in a low noise environment) in its assessment of intelligibility, we were able to ignore the frequency responses of the systems. We note however that subjective intelligibility appears to be dependent on frequency response from our own observations and those of Mapp [2].

For each speaker system, MLSSA was used to measure the STI and octave band MTI (Modulation Transfer Index) and the broadband and octave band clarity ratios C_{50}.

3.1 Loudspeaker Types

- The omni-directional speaker was a Bruel and Kjaer 4296 dodecahedral type.
- The low directionality source was a Fostex 6301B Powered Monitor, with a 100 mm driver mounted in a small baffle.
- The church loudspeaker system comprises of four Electro-Voice Sx200 devices, located on the front columns as shown on the plan. Each Sx200 has a 300 mm woofer and a 65*65 degree high frequency horn.

Figure 1 shows the location of the speakers.

3.2 Hand Equations

The following equations were used in our prediction of STI, and octave band values of MTI and C_{50}:

1) The Peutz long form equation

$$\%AL_{cons} = 100\left[10^{-2[(A+BC)-ABC]} + 0.015\right] \qquad (1)$$

$$A = -0.32\log\left[(L_R + L_N)/(10L_D + L_R + L_N)\right]$$

$$B = -0.32\log\left[L_N/(10L_R + L_N)\right]$$

$$C = -0.5\log\left[RT_{60}/12\right]$$

$$L_D = 10^{l_D/10} \qquad L_D = 10^{l_R/10} \qquad L_N = 10^{l_N/10}$$

where l_D is the direct field level

l_R is the direct field level

l_N is the noise level

2) Ahnert gives a relationship for the C50 in terms of the distances and RT :[3]

$$C_{50} = 10\log\left[\frac{\left(\frac{D_C}{D_L}\right)^2 + 1 - e^{\left(\frac{-0.69}{RT_{60}}\right)}}{e^{\left(\frac{-0.69}{RT_{60}}\right)}}\right] \qquad (2)$$

3) The Peutz short-form equation $\%AL_{cons} \frac{= 200D_L{}^2RT^2N}{VQM}$ (3)

In the equations 1, 2 and 3, D_C is the critical distance, D_L is the distance to the listener, V is volume of the room, Q is the Q of the loudspeaker, N is the number of sources, RT is the reverberation time, N is the ratio of the equivalent number of sources contributing direct-field pressure to total the number of sources contributing reverberant pressure.

4) $STI = 0.9482 - 0.1845L_N\left(\%AL_{cons}\right)$ (4)

This is sometimes known as the Farrel-Becker equation

5) $STI = 0.033C_{50} - .000311C_{50}^2 - .0000101C_{50}^3 + 0.544$ (5)

This relationship is from Bradley and is empirically derived. We have also tested the validity of a modified version in Eqn 6

$$MTI_j = 0.033C_{50_j} - .000311C_{50_j}^2 - .0000101C_{50_j}^3 + 0.544 \qquad (6)$$

where MTI_j and C_{50_j} is the MTI and C_{50} in the *j*th octave band respectively

3.3 Difficulties with these equations

Among the difficulties that are encountered with rapid “hand” calculations are:

1) Whenever late-arriving energy is degrading speech intelligibility, the primary task of a sound system is to decrease the EDT. According to [3] (p254 and Appendix X), Eqn 1 relates to measured data and uses measurements of the EDT and direct and reverberant levels. But as it is not possible with “hand” calculations to determine the EDT with a system, it cannot be reliably used for predicting intelligibility. With Eqn 1, experience shows that continually increasing the directivity of the loudspeakers but with a constant RT_{60} fails to improve the intelligibility beyond a certain (relatively low) level.

2) As Eqns 1 and 3 only relate to the 2 kHz octave band and therefore ignore the contribution of other octave bands to intelligibility, their use is apparently limited. They also ignore the degradation from upward masking that can occur when a lower frequency band with an excess of late-arriving energy effectively amplifies and therefore exacerbates the differences in the spectral balance of speech between low and high frequencies. It is therefore important to find a way to predict the equivalent “%Alcons” in other octave bands.

3) Eqn 2 is based on a receiver being located on axis of a single source, and therefore does not readily accommodate multiple loudspeakers and different directional losses to a

receiver. To account for the total direct and reverberant levels when more than one speaker is used, modifications must be made to D_L and D_c.

4) Difficulties arise with hand calculations in determining the true total direct level at a receiver. Issues such as loudspeaker coverage patterns, power, or complex summations of pressure from each source and the differential arrival times of the sources must be included. These issues may be readily accounted for with computer modelling. Our spreadsheet methods used only power summation but included estimates of the directional losses of each speaker. As the arrival time of each source was within 35 ms at any receiver, they each contributed direct field.

5) We are unsure if Eqn 4 is meant to convert a 2 kHz predicted result into a full STI (or at least a RASTI) result, or whether it relates to a measured $\%Al_{cons}$ word score. Use for octave band calculations may not be intended.

6) Equation 5 is meant to convert a linear or A weighted result into a STI result. Bradley [1] does not discuss its validity for octave bands.

3.4 Procedure

In spite of the above difficulties and "illegitimacies", we used the following procedures to calculate the MTI in each octave band between 125 Hz and 8 kHz. The MTIs were then weighted according to the factors used by the MLSSA analyser and averaged to obtain a STI value.

Method 1

Eqn 1 was used to produce a $\%AL_{cons}$ in each octave band, which was then converted to octave-band MTI using Eqn 4.

Method 2

Equation 2 was used to predict the C50 in each octave band, which was then converted to the MTI using Eqn 6. To account for the difference between the total direct field with multiple sources having directional losses, the listener distance term in Eqn 2 was modified according to Eqn 7.

$$D_{L_{equiv}} = D_{L_{simple}} * 10^{-(L_{D_{tot}} - L_{D_{simple}})/10} \qquad (7)$$

where $D_{L_{equiv}}$ is the apparent distance of the receiver from the source, $D_{L_{simple}}$ is the direct level at the receiver using a single omni-directional source located at the closest loudspeaker, $L_{D_{tot}}$ is the total direct field with all sources, and $L_{D_{simple}}$ is the direct field with omni source.

To account for the total reverberant field, the critical distance term in Eqn 3 was modified according to Equation 8.

$$D_{C_{equiv}} = D_{C_{simple}} * 10^{-(L_{D_{tot}} - L_{D_{simple}})/10} \qquad (8)$$

where $D_{C_{equiv}}$ is the equivalent critical distance of system, the level $D_{C_{simple}}$ is the critical distance for a single source with the directivity of the loudspeaker that is closest to the listener.

Method 3.

Eqn 3 was used to produce a $\%AL_{cons}$ in each octave band, which was then converted to the octave-band MTI using Eqn 4. To account for the difference between the total direct field with multiple sources having directional losses, the N term in Eqn 3 was modified according to Eqn 9. The terms in Eqn 9 are as defined above.

$$N_{equiv}=N_{simple}*10^{(L_{R_{total}}-L_{R_{simple}})/10}*10^{-(L_{D_{total}}-L_{D_{simple}})/10} \tag{9}$$

3.5 Computer Modelling

EASE 3.0 only uses statistical analysis techniques and calculates its STI from direct and reverberant levels. It is therefore appropriate to calculate the reverberation time by whatever means are available (eg spreadsheet tools, professional experience) and to enter these directly (along with the room volume) into EASE. This simplifies the level of detail required in the model, reducing it to sources and audience planes.

A computer model of the church was constructed in EASE v3 and its Sabine reverberation times fixed to those of Table 1. EASE's prediction of the STI is really an MTI for which the user can select 500 Hz, 1 kHz and 2 kHz bands. EASE was set to use both the Peutz long form (Eqn 1) and TEF equations, from which the MTIs were found using Eqn 4. it should be noted that EASE uses the "omni-directional source" RT_{60} data for these equations. Difficulties noted in Section 3.3 also apply here.

In contrast, CATT calculates the impulse response of the sound at a receiver, and from this calculates the modulation transfer function, the MTI values, and the associated STI value. The weightings (proposed by Houtgast and Steeneken in 1985) used by MLSSA are also used by CATT. A detailed model of the church was constructed and the absorption co-efficients of surfaces and seats entered. The absorption co-efficients of the seats were then adjusted so that the Sabine reverberation time predicted by CATT was within 8% of the measured value.

3.6 C_{50} and STI

In [1], Bradley presents equation 3 for the relationship between STI and C_{50}. Although this relationship is intended to relate either a broadband or A weighted C50 ratio with STI, we have tested to see if this relationship holds between the measured C50 data and the MTI in octave bands. As the MLSSA analyser is only able to implement bandpass filtering of its time-domain data, a pseudo "speech band" filter was constructed between 375 Hz and 6 kHz (four octaves wide) to assess the effect of the A weighting.

4 MEASURED AND PREDICTED INTELLIGIBILITY - RESULTS AND DISCUSSION

4.1 Measured Differences between Systems

4.1.1 Differences in STI with system type

Figure 2 shows STI values for each source type and receiver position. While the trends of increasing STI with increasing directivity and decreasing distance make sense, there are some differences that are unexpected. For example, with R4 and R7, the low Q source performs worse than the omni source, but this behaviour is not reflected in the clarity ratios. Comparison of the octave band MTI results for these positions and sources shows that the higher STIs of the omni source are due to its higher MTIs in the 125 Hz and 250 Hz bands.[1]

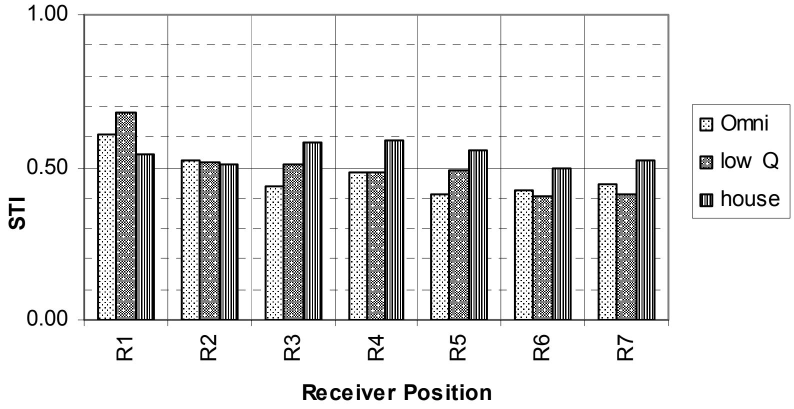

Fig. 2 Measured STI for the three loudspeaker types

4.1.2 Differences in measured Clarity Ratios C_{50}

Although there are exceptions, the general trend of results follows expectations; viz increasing directionality produces an increase of clarity ratio C_{50}. Figure 3 shows two examples. Note that 125 Hz has been omitted, as there is evidence of background noise corrupting the temporal response of this octave band.

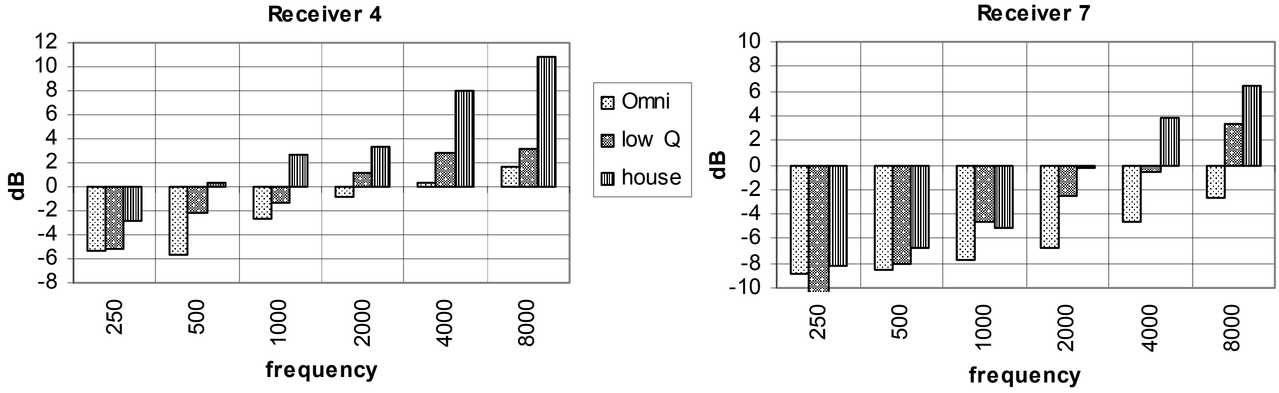

Fig. 3 Examples at two locations of measured Clarity Ratio C_{50} for the three loudspeaker types

4.1.3 Relationship between measured C_{50} and MTI results

For the three source types and seven receiver positions, the octave band MTI values were calculated from the measured C_{50} data using Eqn 5 ie ($MTI = 0.033C_{50} - .000311C_{50}^{2} - .0000101C_{50}^{3} + 0.544$).

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[1] While not discussed in this paper, the STIs were also measured using the STI-PA meter and the TEF analyser. At these locations, different readings were obtained between the STI-PA meter and MLSSA and TEF analysers.

Table 2 gives parameters of the differences between the measured and calculated octave band MTI results.

Frequency Hz	125	250	500	1000	2000	4000	8000
average difference	0.05	0.07	0.04	0.03	0.03	0.03	0.03
standard deviation of difference	0.08	0.05	0.03	0.02	0.03	0.04	0.03

Table 2

Bradley's relationship appears to hold very well for predicted and calculated MTI results in octave bands.

In contrast, Eqn 5 failed to reliably describe the relationship between STI and broadband C_{50} ratios with broadband or speech-band filtering of the impulse response. In those instances that did not meet the relationship, the C_{50} data showed strong dependence on the upper frequency limit of the filtering bandwidth. In turn, this was due to the higher spectral density of the impulse response at frequencies near the filter cut-off frequency. To illustrate the mechanism, Table 3 gives the C_{50} data for the low Q source at receiver 4. The higher C_{50} ratios at and above 2 kHz have increased the overall C_{50} ratio. In contrast, the relationship of Eqn 6 between the octave band C_{50} and the measured MTI data was very good for this situation.

broadband C50	speech band C50	measured STI	C50 required for meas. STI	C50s in Octave Bands						
				125	250	500	1000	2000	4000	8000
-0.8	0.8	0.483	-2.0	-5.2	-5.2	-2.1	-1.4	1.1	2.8	3.1

Table 3

There were instances in which agreements between predicted and measured STIs were close, and inspection of the octave-band clarity ratios showed that they substantially more constant over the frequency range than those in Table 3.

4.2 Differences Between Measured and Spreadsheet-Predicted STI values

Fig .4 shows the measured STIs and those predicted with Methods 1 and 2 for each system and receiver. As the predictions with the Method 3 (Peutz short form Eqn 3) often gave STIs greater than 1 or less than 0.3, they were deemed unreliable, and were not pursued in this analysis.

Table 4 gives the statistics for the absolute value of the differences between the measured and predicted STIs over all seven positions. Taken as a whole, the low mean and standard deviation levels indicate good agreement between measured and both hand calculated values.

	Differences between measured and calculated with Method 1	Differences between measured and calculated with Method 2
Maximum	.091	.071
Mean difference	.022	.019
Standard Deviation	.025	.022

Table 4 Statistics of the absolute value of the differences between measured and predicted STIs

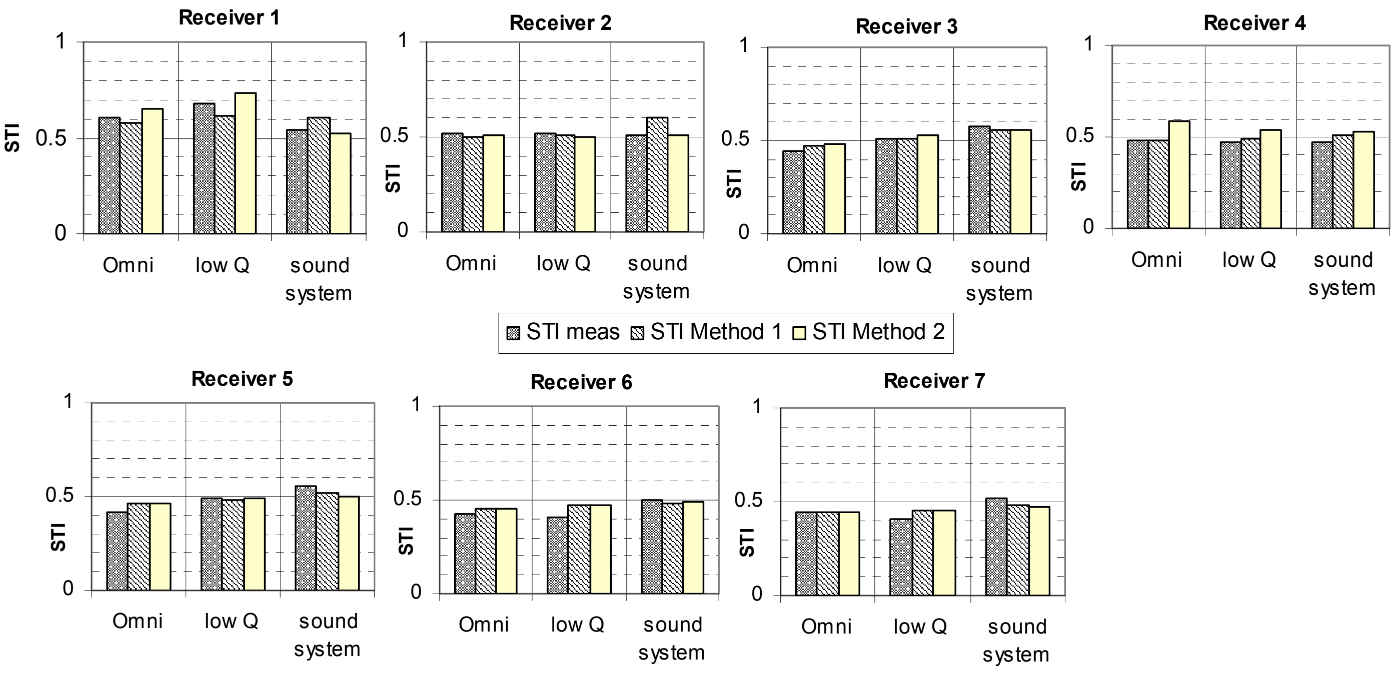

Fig. 4 Measured and predicted STIs at each receiver

4.3 Differences Between Measured and Spreadsheet-Predicted MTI values

4.3.1 Differences between Methods 1 and 2

To determine the most accurate prediction method, the relationships between the measured MTIs and those calculated by Methods 1 and 2 were first investigated. Initially, for each octave band, receiver, and system type, the absolute value of the difference in the MTIs between the measured value and those predicted by Method 1 and 2 were found. Then for a given system type and octave band, the maximum, standard deviations and means were determined for the MTIs over the seven receivers for both Methods 1 and 2. Table 5 gives the results.

		Meas. – Predict.	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**% won by M2**
Omni	**Max Diff**	Method 1	0.13	0.05	0.08	0.05	0.08	0.08	0.09	71%
		Method 2	0.19	0.04	0.08	0.06	0.05	0.07	0.05	
	Std Dev	Method 1	0.07	0.03	0.05	0.03	0.05	0.05	0.04	57%
		Method 2	0.09	0.02	0.05	0.03	0.04	0.04	0.02	
	Mean	Method 1	0.05	0.02	0.05	0.03	0.05	0.04	0.03	57%
		Method 2	0.06	0.02	0.05	0.03	0.04	0.04	0.02	
Low Q	**Max Diff**	Method 1	0.34	0.15	0.10	0.08	0.14	0.15	0.15	100%
		Method 2	0.34	0.15	0.09	0.07	0.06	0.07	0.15	
	Std Dev	Method 1	0.15	0.08	0.07	0.05	0.05	0.06	0.05	71%
		Method 2	0.15	0.07	0.05	0.04	0.02	0.03	0.08	
	Mean	Method 1	0.19	0.08	0.06	0.04	0.05	0.06	0.07	86%
		Method 2	0.20	0.07	0.04	0.03	0.03	0.03	0.07	
Sound System	**Max Diff**	Method 1	0.09	0.06	0.12	0.09	0.16	0.14	0.16	57%
		Method 2	0.07	0.08	0.11	0.13	0.06	0.15	0.14	
	Std Dev	Method 1	0.05	0.04	0.07	0.06	0.07	0.10	0.10	86%
		Method 2	0.04	0.05	0.06	0.04	0.03	0.05	0.06	
	Mean	Method 1	0.04	0.03	0.05	0.05	0.04	0.09	0.11	86%
		Method 2	0.03	0.03	0.05	0.04	0.03	0.07	0.09	

Table 5. Statistics of differences between Methods 1 and 2 over the seven positions

In the light of their vastly different derivations, Methods 1 and 2 show reasonable agreement. In our situation Method 2 gives better agreement with the measured MTIs. As the average deviations of the differences are relatively low, both methods appear to be useful.

It is interesting that Method 1 gave slightly better agreement with the measured STIs (as discussed in Section 4.2). This is due to the weighting and summation process used to form the STIs from the MTIs. Two explanations are possible:

i) For each location, there is a better balance of positive and negative differences between Method 1's calculated MTIs and those measured over the octave bands than those of Method 2, which were biased more in one direction.

ii) The accuracy of Method 1 is higher in the MTI bands that have greater weighting.

Mathematical investigations showed that the MTIs predicted by Methods 1 and 2 have very similar sensitivities to reverberation time, while those of Method 1 are more sensitive to changes in direct field level. However, both Methods show much greater sensitivity to reverberation time than direct field level.

4.3.2 Positional Differences between Measured and Calculated with Method 2

As Method 2 had slightly more agreement than Method 1, the errors in the MTIs were explored for each receiver. Fig. 5 shows the data.

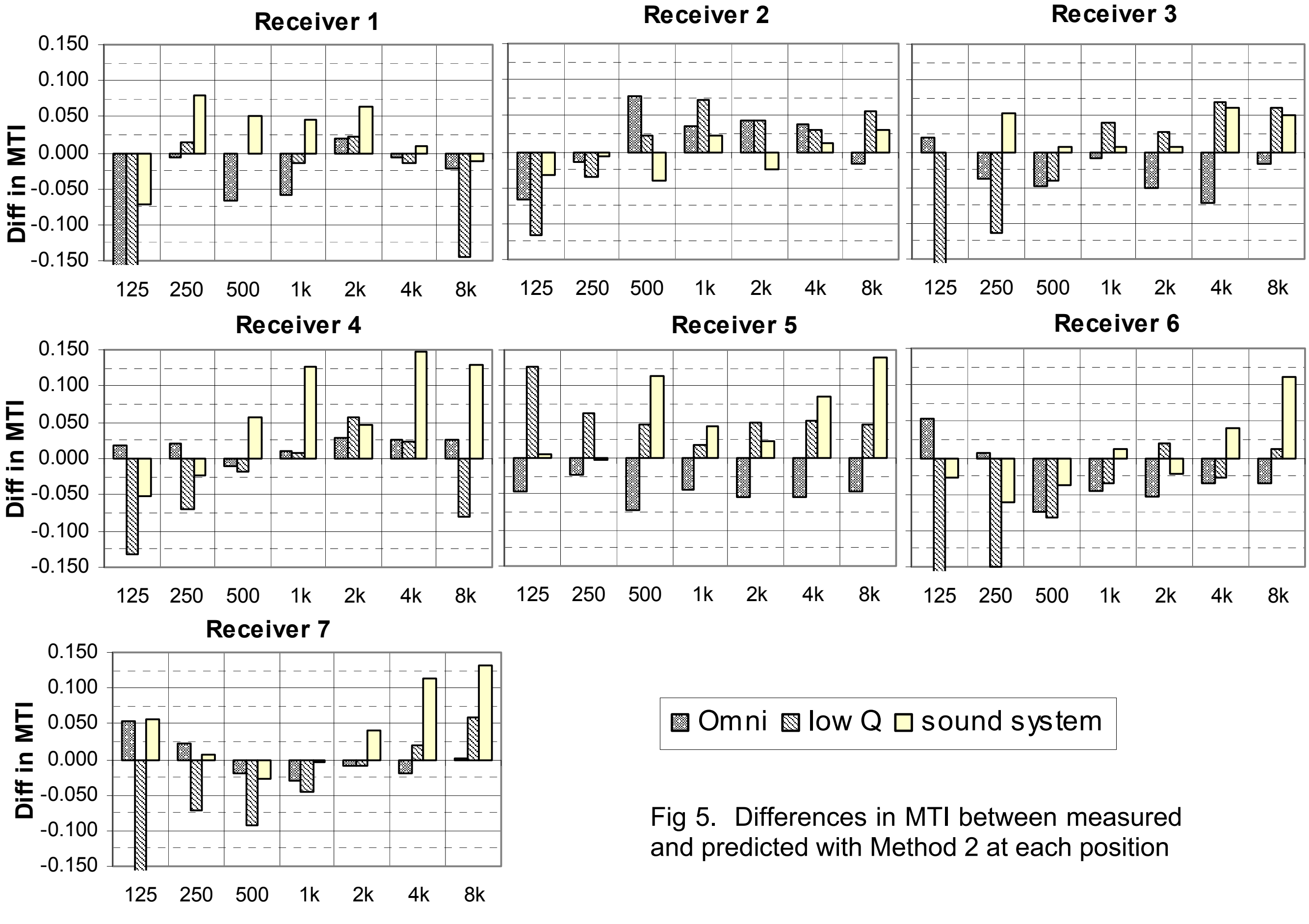

Fig 5. Differences in MTI between measured and predicted with Method 2 at each position

Note that in Fig. 5, a positive number indicates that the measured MTI is larger than the calculated MTIs. A negative number means that the measured MTI is lower than calculated, which may indicate corruption by noise. Some discussion points emerge:

- The large error at 125 Hz with the low Q speaker appears to be due to noise.
- The large "error" at Receiver 5 at 500 Hz with the sound system is unexplained. As the difference in MTI between Method 1 and 2 was 0.01, the measured MTI may have been unusually high and was investigated theoretically.
  Eqn 10 from Steeneken [4] gives the modulation reduction factor at a particular 1/3 octave modulation frequency due to reverberation.

  $$m(F) = 1/\sqrt{1+\left(2\pi FT/13.8\right)^2} \tag{10}$$

  where F is the modulation frequency and T is the reverberation time in the octave band

  This equation is valid for exponential decay only and the EDT must be used for the T term, rather than the RT_{60}. Schroeder [5] noted that the duration of the first 6 dB of decay effectively sets the reverberation time in terms of its effect on modulation reduction, as –6 dB point is an approximate centre of gravity of the reverberant decay. (This is analogous to the use of EDT in the Peutz long form equation as discussed in Section 3.3.) From the Schroeder integration plot of the impulse response, the equivalent RT over the first –6 dB for Receiver 5 at 500 Hz was found to be 2.27 secs. Using this RT value and the modulation frequency range 0.63 Hz to 12.5 Hz, an MTI of 0.39 was predicted. This compares favourably with the value of 0.42 predicted by Methods 1 and 2. In contrast, the measured MTI was 0.53, which corresponds almost identically to the measured C_{50} of 0 dB. We have no explanation for this unusually high C_{50}/MTI result. Spot checks showed that other measured MTI values are higher than their predicted counter parts based on the measured RT based on the decay to –6 dB.
- With the sound system and the higher frequencies (4 kHz and 8 kHz), the predicted MTIs are lower than measured. While the data of Fig 5 is for Method 2, Method 1's results are similar. As the sound system speakers are most directional in these octave bands, it seems that both these methods are beginning to break down with higher directivities, as we noted in Section 3.3. Equation 10 was again used to check the nature of the MTI at Receiver 4 in the 1 and 4 kHz octave band and at Receiver 7 in the 4 kHz band. Table 6 gives the results.

Receiver and oct. band	RT type	Measured RT secs	Predicted MTI from Eqn 10	Predicted MTI with Methods 1 & 2	Measured MTI
R4 1 kHz	RT60 omni	2.1	0.405		
	EDT with sound system	1.7	0.458		
	RT60 re –6dB for s/system	1.25	0.538		
				0.46 & 0.50	0.59
R4 4 kHz	RT60 omni	1.3	0.527		
	EDT with sound system	0.52	0.751		
	RT60 re –6dB for s/system	0.51	0.755		
				0.63 & 0.62	0.765
R7 4 kHz	RT60 omni	1.3	0.527		
	EDT with sound system	0.93	0.614		
	RT60 re –6dB for s/system	0.66	0.696	0.55 & 0.55	
					0.664

Table 6 Comparison of Predicted and Measured MTIs with sound system

While Eqn 10 appears to give a better match with measured at the higher frequencies, the predictions are low compared to measured and the most suitable RT type to use in Eqn 10 is unclear.

4.4 Differences Between Measured and Computer-Predicted STI values

Fig. 10 shows for each position, the STIs predicted by CATT for each system against those measured. As EASE outputs MTI data, its results are discussed in Section 5.5.

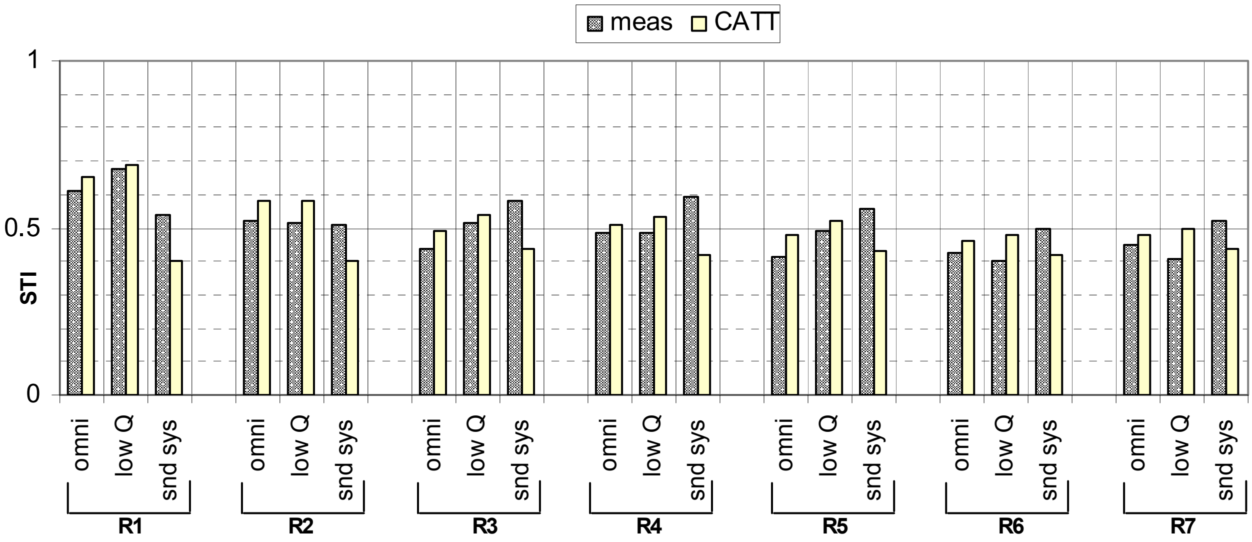

Fig. 10 Comparison of measured and CATT-predicted STIs at each Receiver

Table 7 gives the statistics for the absolute value of the differences between the measured and CATT-predicted STIs over all seven positions. Overall, there is moderate agreement between measured and predicted values for the omni-directional and low Q sources, and poor agreement with the sound system.

CATT v8		**Differences between measured and calculated STI**
Omni	**Max Diff**	0.066
	Std Dev	0.015
	Mean	0.044
Low Q	**Max Diff**	0.091
	Std Dev	0.029
	Mean	0.050
Sound System	**Max Diff**	0.170
	Std Dev	0.033
	Mean	0.121

Table 7 Statistics of the absolute value of the differences between measured and CATT-predicted STIs

4.5 Differences Between Measured and Computer-Predicted MTI values

Initially, for each octave band, receiver and system type, the absolute value of the difference in the MTIs between the measured value and those predicted by CATT and EASE were found for various systems. Then for a given system type and octave band, the maximum, standard deviations, and means were determined for the MTIs over the seven receivers for both methods. Table 8 gives the results. The predicted MTIs for the sound-system are missing, as CATT does not output MTI values when more than one source is used. The MTIs were not predicted with EASE for the omni and low Q systems.

		Meas. – Predict.	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Omni	**Max Diff**	CATT	0.16	0.07	0.08	0.07	0.07	0.09	0.15
	Std Dev		0.05	0.02	0.02	0.02	0.02	0.03	0.03
	Mean		0.06	0.03	0.05	0.05	0.04	0.05	0.09
Low Q	**Max Diff**	CATT	0.33	0.14	0.13	0.09	0.05	0.07	0.10
	Std Dev		0.08	0.04	0.04	0.03	0.02	0.02	0.03
	Mean		0.19	0.08	0.06	0.03	0.03	0.05	0.06
Sound System	**Max Diff**	EASE Peutz long form			0.11	0.10	0.08		
	Std Dev				0.04	0.03	0.03		
	Mean				0.06	0.06	0.04		
	Max Diff	EASE TEF equation			0.14	0.14	0.12		
	Std Dev				0.05	0.04	0.04		
	Mean				0.07	0.08	0.07		

Table 8. Maximum, standard deviation and mean of differences (absolute value) between measured and predicted MTIs using CATT and EASE over the seven positions

It can be seen that the MTIs predicted by EASE using the Peutz long form method are closer to the measured values. The predictions with the TEF equation were consistently 0.03 to 0.04 above those of the Peutz long form method.

4.6 Differences Between Measured and Computer-Predicted C_{50} values

As the STI at position 5 with the sound system showed the poorest agreement between that predicted by CATT and measured, the CATT C_{50} results were inspected and found to range between 6 and 15 dB below the measured C_{50} data.

The C50 data predicted by EASE were significantly closer to the measured values. Fig. 11 shows the difference between the measured C_{50} data and that predicted by EASE.

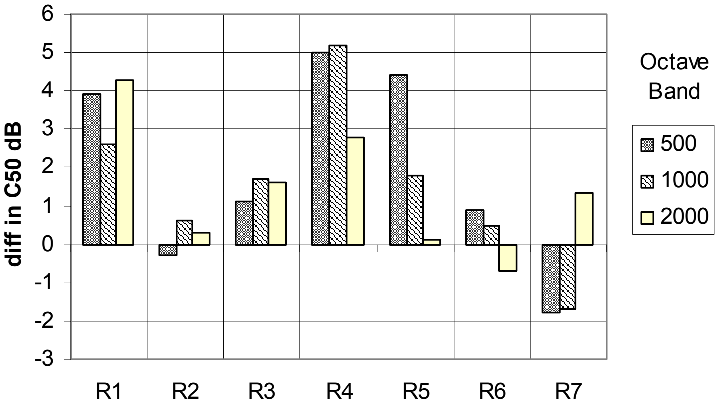

Fig. 11 Difference between measured and EASE-predicted C_{50}

5 CONCLUSIONS

- Although there are exceptions, there is a general trend indicating that increasing source directionality produces an increase in clarity ratio C_{50}.
- Bradley's equation can be used to relate measured C50 to measured MTI in octave bands.
- With broad or speech-band impulse response data, Bradley's equation shows high sensitivity to the upper bandwidth limit of the signal for which the C_{50} is determined.
- The original Peutz short-form equation is unsuitable for use in octave bands.
- There is reasonable agreement between the STI values predicted by spreadsheet Methods 1 and 2 and the measured STI. Method 2 seems to have slightly more agreement.
- While in some situations, Methods 1 and 2 show differences of up to 0.1 in the octave band MTIs, they are mostly very close.
- With regard to the octave band MTIs predicted by spreadsheet Method 2, the mean, standard deviation and maximum of the difference between the measured and calculated values are typically 0.05, 0.05 and 0.15 respectively.
- The differences between measured and spreadsheet-calculated MTIs appear to become less important when the STIs are formed from those MTIs.
- In spite of the "illegitimacies" discussed in Section 3, the spreadsheet methods seem to offer benefits, but seem yield conservative results with higher loudspeaker directivities.
- We could not observe a strong correlation between the measured EDTs based on decay to –10 dB or –6 dB and the measured MTI as expected from the theory of modulation reduction (Eqn 10). In all cases, the MTI was higher than expected from the EDT.
- The differences between the measured MTI data and that predicted by CATT and the spreadsheet calculations for the omni-directional and low-Q sources are similar.
- The differences between the measured MTI data and those predicted by EASE and the spreadsheet calculations for the sound system sources are similar.
- CATT predictions of STI values for the sound system were significantly poorer than measured.
- The TEF equation in EASE produced slightly larger differences between the measured and predicted MTIs than the Peutz long form equation gave.
- In spite of all this work, differences of at least 0.1 STI between measured and predicted exist, and in the context of meeting a given standard, this difference is problematic.

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