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NOTE ON THE APPLICATIONS OF A SIMPLE ACOUSTIC IMMERSION INDEX

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The applicability of a simple acoustic immersion index for halls is investigated by calculating the values of the index for many well-documented halls and theatres. Correlations between the immersion index S_1 and other auditorium acoustic parameters are investigated, as well as the effectiveness of the index in describing subjective evaluations of halls. The index S_1 appears to broadly correspond to subjective ratings of halls, both from published data and from experiences in Australian halls, but is only weakly correlated with technical parameters describing the immersion of the sound field. However, the index appears to be reasonably correlated with Binaural Quality Index (BQI), and therefore may be useful as a "spaciousness index" as a means of estimating BQI during the early design of a hall.

INTRODUCTION

The immersion index S_1 has been proposed as a simple parameter able to describe the degree of immersion in the sound field experienced by a listener [1]. S_1 is able to be calculated using basic hall dimensions, hall volume, and reverberation time, and therefore can be obtained very early in the design process for a new hall, without requiring the detailed acoustic modelling necessary to calculate other more detailed acoustic parameters. S_1 therefore offers potential benefits in being an early design tool for hall designers, being able to be used with RT and details of the room geometry (e.g. volume per seat) as a "high level" estimate of the room acoustic properties.

S_1 was calculated for five well-known concert halls in [1], with the values of S_1 obtained corresponding with the subjective characteristics of the halls – e.g. Royal Festival Hall, with a low value of S_1, is subjectively dry and less enveloping, while Concertgebouw, with a higher value of S_1, is more reverberant.

The purpose of this study is to calculate the value of the immersion index S_1 for several halls where acoustic data is available, particularly from reference texts such as [2] and [3], and to investigate correlations between S_1 and more complicated room acoustic parameters, and between S_1 and subjective rankings of halls.

IMMERSION INDEX, S_1

S_1 in its original form was derived for rectangular hall geometries. In this study, S_1 will be calculated for actual concert halls, which generally are not purely rectangular in plan. Therefore, the modified form of S_1, (denoted S_{1A} in this paper; Equation (5) in [1]), which is applicable for any shape, will be used:

$$S_{1A} = 10 \log_{10} (25T_{60}/L) \quad \text{dB} \tag{1}$$

where T_{60} is the reverberation time of the hall and L is the average length of the hall.

Although S_1 was developed for evaluating the immersion of organ music, in principle it may be used for the evaluation of halls for other types of music provided that the assumptions used to derive the index are met. The main assumption used to derive the first-order index S_1 is that the entire acoustic power of the source is spread uniformly across the entire cross-section of the hall as it propagates (assuming that losses from surfaces near the source are negligible).

For solo organ music with an organ at one end of a hall, or for unaccompanied choir music, in both cases with no orchestra on the platform, the assumption that reflection losses close to the source are negligible seems reasonable as a first estimate for high-frequency sound, considering that typical hall materials are highly-reflective at mid to high frequencies. This assumption may also be useful for small chamber groups where the source size is small relative to the platform area and therefore the area surrounding the source is largely acoustically-reflective. However, for orchestral music, or for halls with audience seating surrounding the stage, the presence of the orchestra or audience would mean there would be significant high-frequency absorption close to the source, and this assumption would be less valid. Therefore, S_1 is expected to be more applicable for organ music, small ensembles and unaccompanied choir music than for orchestral music.

ACOUSTIC PARAMETERS CONSIDERED

Being an "immersion index", S_1 would be expected to provide some description of how uniform is the sound field in a hall. Where a diffuse reverberant field is dominant, a mostly-uniform sound field would be expected, resulting in a high degree of subjective "immersion" in the sound field, as well as a high value of S_1.

S_1 would be expected to relate to other acoustic parameters which describe the spatial quality of the sound field (Inter-aural cross-correlation coefficient IACC and lateral energy fraction, LF_{80}) or which describe the balance between early and reverberant sound (clarity, C_{80}). IACC in particular has become increasingly used to describe the degree to which the sound field in a hall is uniform. Two main time periods are used for IACC: $IACC_E$, which is based on energy up to 80 ms after the direct sound, and $IACC_L$, which is based on the energy received between 80 and 1000 ms after the direct sound. Higher values of IACC indicate that the sound field experienced by the two ears is more uniform. $IACC_L$ theoretically may be used as an index for the envelopment/"immersion" experienced by listeners, but it has been found to not vary significantly from hall to hall and is therefore not considered a useful index. $IACC_E$, usually expressed as the Binaural Quality Index (BQI; 1-$IACC_E$), can be used to represent the spaciousness of a hall. Lateral energy fraction, LF_{80}, is a measure of the proportion of energy arriving at a receiver from the sides (lateral directions) within the first 80 ms after the direct sound. Musical clarity, C_{80}, is the ratio (expressed in decibels) of the acoustic energy arriving within the first 80 ms after the direct sound to the acoustic energy arriving after 80 ms.

CALCULATION OF INDEX

S_1 has been calculated for 94 concert halls, recital halls and opera houses, using published room data from reference books ([2], [3]), or from Arup measurements from completed projects. The hall volume, reverberation time (occupied) averaged over 500 Hz and 1 kHz and the hall length have been used to calculate S_1 using the modified form of the index given in Equation (1). The data used to calculate S_1 and the calculated value of S_1 using Equation (1) for each hall is listed in Table 1, with values of other acoustic parameters of interest (BQI, $IACC_L$, LF_{80} and C_{80}) for each hall, where available. Due to the different sources of the hall data, not all parameters are available for every hall. A three letter code is assigned to each hall to assist in labelling data points on graphs.

The calculated values of S_1 for the halls have been compared to other acoustic parameters and to subjective rankings for the halls, sourced from the conductor surveys presented in Beranek [2].

Table 1: Data used to calculate immersion index S_1, and other room acoustic parameters of interest for each hall.

City	Hall	Type	Code	V (m^3)	L (m)	T_{60} (s)	S_{1A} (dB)	BQI	1-$IACC_L$	LF_{80}	C_{80}
Aldeburgh	Snape Maltings	Recital Hall	ASM	7,590	41	1.80	0.4			0.24	
Amsterdam	Concertgebouw	Concert Hall	CBW	18,780	43	2.00	0.7	0.56	0.88	0.18	-3.6
Baltimore	Meyerhoff Hall	Concert Hall	BMH	21,524	49	2.00	0.1	0.52	0.86	0.17	-2.0
Basel	Stadt-Casino	Concert Hall	BSC	10,471	33	1.75	1.2	0.60	0.87		-2.6
Bayreuth	Festspielhaus	Opera Theatre	FES	10,308	32	1.55	0.8				
Belfast	Waterfront Hall	Concert Hall	BEL	30,800	51	1.88	-0.4			0.195	0.0
Berlin	Deutsches Oper	Opera Theatre	BDO	10,800	33	1.35	0.1				
Berlin	Kammermusiksaal	Recital Hall	KAM	12,500	45	1.70	-0.2				-1.8
Berlin	Konzerthaus	Concert Hall	KHS	15,500	49	2.05	0.2	0.67	0.85		-3.1
Berlin	Philharmonie	Concert Hall	BPH	21,000	66	1.90	-1.4	0.45	0.86		-0.6
Bonn	Beethovenhalle	Concert Hall	BBH	15,716	35	1.70	0.9				
Boston	Symphony Hall	Concert Hall	BSH	18,750	49	1.80	-0.4	0.60	0.82	0.235	-2.6
Bristol	Colston Hall	Concert Hall	BCH	13,450	48	1.70	-0.5			0.185	0.2
Buenos Aires	Teatro Colon	Opera Theatre	BTC	20,570	34	1.63	0.7	0.62	0.80		0.8
Buffalo	Kleinhans Music Hall	Concert Hall	KMH	18,240	52	1.35	-1.9	0.30	0.65	0.1	2.8
Buxton	Buxton Opera House	Opera Theatre	BOH	3,100	18	0.90	1.0			0.23	
Cambridge	Faculty of Music	Recital Hall	CFM	4,100	29	1.50	1.1			0.25	
Canberra	Llewellyn Hall	Concert Hall	LLH	10,500	43	2.00	0.7			0.25	-0.6
Cardiff	St Davids Hall	Concert Hall	STD	22,000	48	1.90	0.0			0.17	-0.7
Cardiff	Wales Millennium Centre	Opera Theatre	WMC	11,500	34	1.30	-0.1				
Chicago	Orchestra Hall	Concert Hall	COH	17,410	40	1.60	0.0				
Christchurch	Christchurch Town Hall	Concert Hall	CTH	20,500	43	1.80	0.2			0.14	1.6
Cleveland	Severance Hall	Concert Hall	SEV	15,690	33	1.48	0.5	0.54	0.79	0.14	0.0
Copenhagen	Opera House	Opera Theatre	COP	10,700	30	1.40	0.7				2.1
Costa Mesa	Segerstrom Hall	Opera Theatre	SEG	27,800	49	2.20	0.5	0.58	0.86	0.225	-0.7
Croydon	Fairfield Hall	Concert Hall	CFH	15,400	48	1.70	-0.5			0.15	
Derby	Assembly Rooms	Concert Hall	DAR	15,401	43	1.10	-1.9			0.2	
Denver	Boettcher Hall	Concert Hall	DBH	37,444	46	2.40	1.2	0.25		0.11	0.6
Dresden	Semperoper	Opera Theatre	DSO	12,500	26	1.68	2.1	0.71			
Edinburgh	Usher Hall	Concert Hall	USH	16,000	45	1.70	-0.2			0.3	-1.3
Edmonton/Calgary	Alberta Jubilee Auditoria (before renovations)	Opera Theatre	EJA	21,492	58	1.40	-2.2			0.135	3.7
Fort Worth	Bass Performance Hall	Opera Theatre	BFW	27,300	48	1.95	0.1	0.46	0.71		-2.0
Glasgow	Royal Concert Hall	Concert Hall	GCH	22,700	43	1.75	0.1			0.215	0.9

Glyndebourne	Festival Opera	Opera Theatre	GFO	8,287	29	1.25	0.4			0.155	4.5
Jerusalem	Congress Hall	Concert Hall	JCH	24,700	60	1.75	-1.4	0.53	0.84		-0.4
Leipzig	Altes Gewandhaus (1781)	Recital Hall	LAG	2,130	23	1.30	1.5				
Leipzig	Gewandhaus (1981)	Concert Hall	LGH	21,560	54	2.00	-0.3				
Leipzig	Neus Gewandhaus (1884)	Concert Hall	LNG	10,620	39	1.60	0.1				
Lenox	Koussetitzkty Music Shed	Concert Hall	KMS	42,480	76	1.89	-2.1	0.32	0.76	0.11	-3.8
Liverpool	Philharmonic Hall	Concert Hall	LPH	13,560	50	1.50	-1.2			0.17	1.0
London	Barbican Hall (Before 2001)	Concert Hall	BAR	17,750	44	1.65	-0.3			0.12	-1.2
London	Barbican Hall (Renovated 2001)	Concert Hall	BHR	17,000	44	1.40	-1.0				0.3
London	Coliseum	Opera Theatre	COL	13,600	33	1.40	0.3			0.18	
London	Kings Place	Recital Hall	LKP	3,540	25	1.70	2.3				
London	Queen Elizabeth Hall	Recital Hall	QEH	9,600	44	2.05	0.7			0.18	
London	Royal Albert Hall	Concert Hall	RAH	86,650	67	2.50	-0.3			0.14	0.5
London	Royal Festival Hall	Concert Hall	RFH	21,950	51	1.45	-1.5				1.0
London	Royal Festival Hall (assisted resonance)	Concert Hall	RFH_R	21,950	51	1.80	-0.5			0.195	0.8
London	Royal Opera House	Opera Theatre	ROH	12,250	28	1.10	0.0			0.19	4.8
London	Wigmore Hall	Recital Hall	WIG	2,900	24	1.50	1.9			0.25	
Madrid	Auditorio Nacional de Música	Concert Hall	ANM	20,000	54	1.74	-1.0			0.31	-0.6
Manchester	Free Trade Hall	Concert Hall	FTH	15,430	48	1.50	-1.0			0.24	1.1
Manchester	Bridgewater Hall	Concert Hall	BWH	25,000	49	2.00	0.1			0.25	-1.5
Melbourne	Hamer Hall	Concert Hall	HAM	26,900	53	2.20	0.2				
Melbourne	Melbourne Recital Centre	Recital Hall	MRC	9,000	37	1.90	1.1				-2.5
Minneapolis	Minnesota Orchestra Hall	Concert Hall	MOH	18,975	49	1.85	-0.2				
Milan	La Scala	Opera Theatre	LSC	11,252	30	1.25	0.1	0.49	0.74		2.9
Munich	Gasteig Philharmonie	Concert Hall	GAS	29,737	48	2.10	0.4			0.11	-0.4
Munich	Herkulessaal	Concert Hall	HKS	13,592	42	2.00	0.8				
New York	Avery Fisher Hall	Concert Hall	AVF	18,691	52	1.80	-0.6			0.12	-2.2
New York	Carnegie Hall	Concert Hall	CAR	24,270	52	1.70	-0.9				
New York	Metropolitan Opera House	Opera Theatre	MET	24,724	40	1.55	-0.1	0.60	0.83		1.5
Northampton	Derngate	Concert Hall	DER	13,500	45	1.80	0.0			0.17	
Nottingham	Royal Concert Hall	Concert Hall	RCN	17,510	50	1.90	-0.2			0.21	
Oslo	Opera House	Opera Theatre	OOH	11,789	31	1.70	1.4				
Paris	Opera Garnier	Opera Theatre	PAR	10,000	28	1.10	0.0	0.47	0.79		4.4
Poole	Wessex Hall	Concert Hall	PWH	12,430	41	1.70	0.1			0.2	
San Francisco	Davies Hall	Concert Hall	SFD	24,070	54	1.85	-0.7	0.41	0.84		-1.5
San Francisco	War Memorial Opera	Opera Theatre	WMO	20,900	37	1.50	0.1				
Salt Lake City	Abranavel Hall	Concert Hall	SLC	19,500	38	1.75	0.6	0.56	0.84		-2.0
Salzburg	Festspielhaus	Opera Theatre	SFH	15,500	30	1.50	1.0			0.14	-0.7
Sapporo	Kitaka Concert Hall	Concert Hall	SKH	28,800	50	1.80	-0.5	0.44	0.83	0.12	0.7
Stuttgart	Liederhalle	Recital Hall	SLH	16,000	42	1.65	-0.1			0.13	2.0
Sydney	City Recital Hall	Recital Hall	APL	10,850	35	1.75	1.0				-1.0
Sydney	SOH Concert Hall	Concert Hall	SOH	24,600	67	2.20	-0.8				
Sydney	SOH Opera Theatre	Opera Theatre	SOP	8,200	33	1.10	-0.8				
Taipei	Taipei Cultural Centre Concert Hall	Concert Hall	TCC	16,700	45	2.00	0.4	0.83		0.245	-4.0
Tel Aviv	Mann Auditorium	Concert Hall	MNN	21,238	47	1.50	-0.9	0.37	0.82		-0.9
Tokyo	Asahi Hall	Recital Hall	AHT	5,800	31	1.73	1.4	0.66	0.85		-0.6
Tokyo	Bunka Kaikan	Concert Hall	TBK	17,300	47	1.50	-1.0	0.56	0.85	0.19	-0.7
Tokyo	Dai-Ichi Seimei Hall	Recital Hall	DAS	6,800	31	1.56	0.9	0.86			-0.5
Tokyo	Metropolitan Art Space	Concert Hall	MAS	25,000	48	2.15	0.5	0.58	0.86		-1.2
Tokyo	New National Theatre	Opera Theatre	NNT	14,500	31	1.50	0.8	0.64	0.84		1.7

Tokyo	Opera City Concert Hall	Concert Hall	TOC	15,300	47	1.96	0.2	0.70	0.88		-2.8
Tokyo	Suntory Hall	Concert Hall	TSH	21,000	55	2.00	-0.4	0.51	0.84	0.165	-0.9
Valencia	Palau de la Música	Concert Hall	PMV	15,400	40	2.05	1.0			0.35	-4.0
Vienna	Grosser Musikveriensaal	Concert Hall	MKV	15,000	53	2.00	-0.3	0.63	0.86	0.18	-4.3
Vienna	Konzerthaus	Concert Hall	VKH	16,600	37	1.88	1.0	0.66			-1.2
Vienna	Staatsoper	Opera Theatre	VSO	10,665	27	1.30	0.9	0.61	0.80		-0.7
Washington	Kennedy Center Concert Hall (pre-renovation)	Concert Hall	KCW	22,300	37	1.85	1.0	0.59	0.86	0.22	-0.4
Washington	Kennedy Center Opera House	Opera Theatre	KCO	13,027	32	1.50	0.7				
Watford	Watford Town Hall	Concert Hall	WTH	11,600	50	1.45	-1.4			0.15	
Wellington	Michael Fowler Centre	Concert Hall	MFC	22,700	48	2.00	0.2				
Worcester	Mechanics Hall	Concert Hall	WMH	10,760	41	1.55	-0.2	0.54	0.78	0.2	-1.5
Zurich	Grosser Tonhalle	Concert Hall	ZGT	11,398	38	2.05	1.3	0.63	0.88		-4.0

SUBJECTIVE RANKINGS

Beranek [2] presents two subjective rankings of halls, one for concert halls and one for opera theatres, based on interviews and questionnaires of conductors and music critics. These subjective rankings have been used to examine the calculated S_1 values for these halls to investigate whether there is a relationship between S_1 and the acoustic quality of a hall.

Subjective Rankings – Concert Halls

For concert halls, Beranek ranks 58 concert halls in order of perceived quality. Acoustic data was available for 36 of these halls, and S_1 has been calculated for these halls. The subjective rankings divide the halls into three groups:

- 20 "upper group" halls (here denoted Group A), which are considered to be of highest quality
- 19 "middle group" halls (here denoted Group B), which are judged to lie below the Group A hall in quality. Note that no ranking order was given for the Group B halls as they were not considered to be clearly separated in acoustic quality; the ranking numbers used in this paper were based on the alphabetical listing of the halls;
- 19 "lower group" halls (here denoted Group C), which were ranked as being below both Group A and Group B in quality.

A summary of the 36 halls included in Beranek's ranking, including calculated S1 values is provided in Table 2.

Figure 1 presents an overview of the relationship between the S_1 index for each hall and the subjective hall ranking from Beranek. It can be seen from Figure 1 that generally speaking, the higher ranked halls have higher calculated values of S_1. However, there is considerable spread in the dataset, as can be seen when a linear regression curve is applied to the data, as shown in Figure 2. The correlation between S_1 and subjective ranking is relatively weak, with a coefficient of determination (R^2 value) for a linear regression of 0.25, and a standard deviation of 0.7 dB.

Table 2: Subjective Concert Hall Rankings (from Beranek [2])

City	Hall	Code	Subjective Ranking	S_{1A} (dB)
Vienna	Grosser Musikveriensaal	MKV	1	-0.3
Boston	Symphony Hall	BSH	2	-0.4
Berlin	Konzerthaus	KHS	4	0.2
Amsterdam	Concertgebouw	CBW	5	0.7
Tokyo	Opera City Concert Hall	TOC	6	0.2
Zurich	Grosser Tonhalle	ZGT	7	1.3
New York	Carnegie Hall	CAR	8	-0.9
Basel	Stadt-Casino	BSC	9	1.2
Cardiff	St Davids Hall	STD	10	0.0
Bristol	Colston Hall	BCH	12	-0.5
Costa Mesa	Segerstrom Hall	SEG	14	0.5
Salt Lake City	Abranavel Hall	SLC	15	0.6
Berlin	Philharmonie	BPH	16	-1.4
Tokyo	Suntory Hall	TSH	17	-0.4
Tokyo	Bunka Kaikan	TBK	18	-1.0
Baltimore	Meyerhoff Hall	BMH	20	0.1
Christchurch	Christchurch Town Hall	CTH	24	0.2
Cleveland	Severance Hall	SEV	25	0.5
Jerusalem	Congress Hall	JCH	27	-1.4
Leipzig	Gewandhaus	LGH	29	-0.3
Munich	Gasteig Philharmonie	GAS	31	0.4
Tokyo	Metropolitan Art Space	MAS	34	0.5
Stuttgart	Liederhalle	SLH	41	-0.1
New York	Avery Fisher Hall	AVF	42	-0.6
Edinburgh	Usher Hall	USH	44	-0.2
Glasgow	Royal Concert Hall	GCH	45	0.1
London	Royal Festival Hall	RFH	46	-1.5
Liverpool	Philharmonic Hall	LPH	47	-1.2
Manchester	Free Trade Hall	FTH	48	-1.0
Edmonton/Calgary	Alberta Jubilee Auditoria (before renovations)	EJA	50	-2.2
Sydney	SOH Concert Hall	SOH	53	-0.8
San Francisco	Davies Hall	SFD	54	-0.7
Tel Aviv	Mann Auditorium	MNN	55	-0.9
London	Barbican Hall	BAR	56	-0.3
Buffalo	Kleinhans Music Hall	KMH	57	-1.9
London	Royal Albert Hall	RAH	58	-0.3

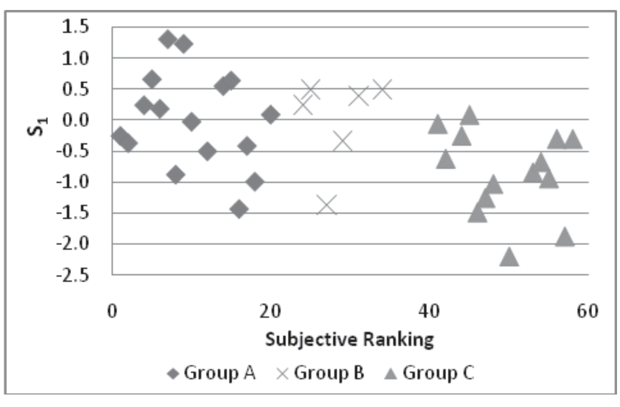

Figure 1: Comparison of calculated S_1 values against subjective concert hall ranking.

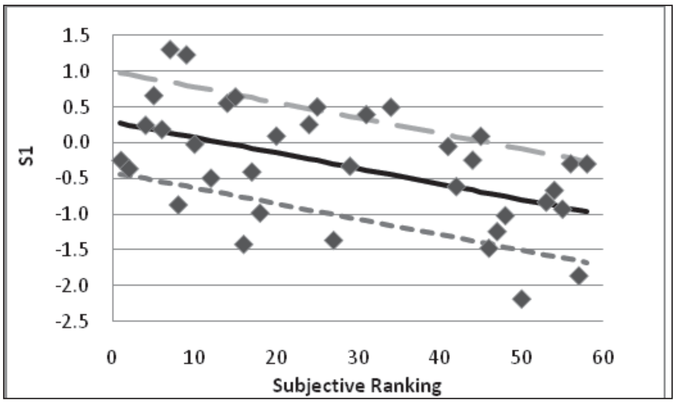

Figure 2: Relationship between S_1 index and subjective hall ranking, showing linear regression relationship (solid black line) and standard deviation of the dataset (dashed grey lines).

The average value of S_1 for each of the three groups has been calculated:

- Group A: 0.1 dB (standard deviation 0.8 dB)
- Group B: 0.0 dB (standard deviation 0.7 dB)
- Group C: -0.8 dB (standard deviation 0.7 dB)

The average values of S_1 for each group match the subjective rankings for these halls, however there is considerable overlap between the three groups. Therefore, S_1 does not appear to distinctly separate concert halls in the different subjective groups, although the overall trend is for higher S_1 for higher-rated halls.

Subjective Rankings – Opera Theatres

Beranek also presents a subjective ranking of 21 opera theatres, based on surveys of conductors. Acoustic data for 11 theatres was available, and was used to calculate S_1. A summary of the rankings and calculated S_1 values for the 11 opera theatres is provided in Table 3.

Table 3: Subjective Opera House Rankings (from Beranek [2])

City	Opera House	Code	Subjective Ranking	S_{1A} (dB)
Buenos Aires	Teatro Colón	BTC	1	0.7
Dresden	Semperoper	DSO	2	2.1
Milan	La Scala	LSC	3	0.1
Tokyo	New National Theatre	NNT	4	0.8
Paris	Opéra Garnier	PAR	7	0.0
Vienna	Staatsoper	VSO	9	0.9
New York	Metropolitan Opera House	MET	10	-0.1
Salzburg	Festspielhaus	SFH	11	1.0
San Francisco	War Memorial Opera House	WMO	13	0.1
London	Royal Opera House	ROH	14	0.0
Berlin	Deutsches Opera	BDO	17	0.1

A comparison of the predicted S_1 values and the subjective ranking for the 11 opera theatres is presented in Figure 3. As for concert halls, generally speaking the higher-ranked opera theatres have higher values of S_1. However, there again is considerable spread in the data, with a R^2 value for a linear regression of 0.26, and a standard deviation of 0.6 dB.

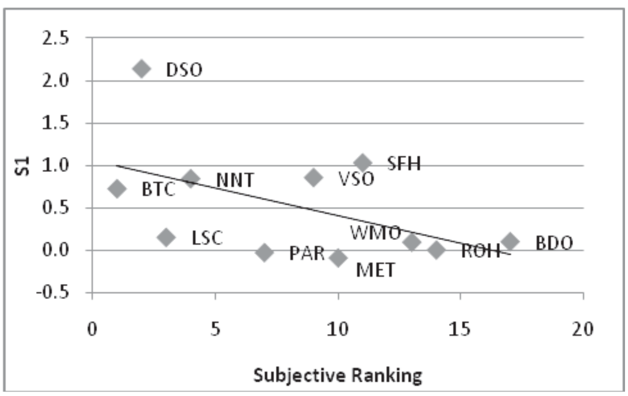

Figure 3: Comparison of S_1 index and subjective ranking for opera theatres, showing linear regression relationship (black line)

AUSTRALIAN HALLS

It is considered informative to focus on Australian halls, which may be more familiar, in order to investigate the subjective aspects of the S_1 index. The predicted values for the six Australian halls included in this study range between -0.8 dB (Sydney Opera House Concert Hall and Opera Theatre), to 1.1 dB (Melbourne Recital Centre). Subjectively, the high values of ~1 dB for the Sydney City Recital Hall and Melbourne Recital Centre corresponds to the spacious and enveloping sound in these halls, which is perhaps assisted by these halls being essentially "shoebox" shape.

For the almost fan-shaped geometry of Llewellyn Hall, and the Sydney Opera House Opera Theatre, the complicated surround shape of the Sydney Opera House Concert Hall, and the wide outer walls and high ceiling of Melbourne Hamer Hall, the resultant sound field is less enveloping and spacious, corresponding to the lower values of S_1 for these spaces. The calculated values of S_1 for Australian halls appear to match the subjective experiences of the sound field in these halls.

BINAURAL QUALITY INDEX, BQI (1-IACC$_E$)

Although S_1 is intended as an index for describing the listener envelopment due to the late reverberant sound, it is informative to consider its usefulness in describing the spaciousness of the early sound field. Accordingly, the calculated S_1 values for 36 halls has been compared to the BQI values for halls (where available), calculated using the unoccupied $IACC_E$ data, as shown in Figure 4. Interestingly, BQI and S_1 appear to be reasonably well correlated (R^2 0.61), with increased S_1 generally corresponding to an increased value of BQI. The standard deviation in the dataset is 0.09 BQI. The correlation is stronger than seen between S_1 and the subjective ranking of the hall. Three halls were excluded from the dataset used to generate the regression relationship: Tokyo Dai-Ichi Seimei Hall (DAS) and Taipei Cultural Centre (TCC), which both have significantly higher values of BQI than other halls, and Denver Boettcher Hall (DBH), which has a significantly lower value for BQI (perhaps due to its “surround” plan form). Beranek notes that BQI greater than 0.5 is associated with satisfactory halls, with the highest rated halls having BQI over 0.6. This roughly corresponds to S_1 values greater than ~0 dB.

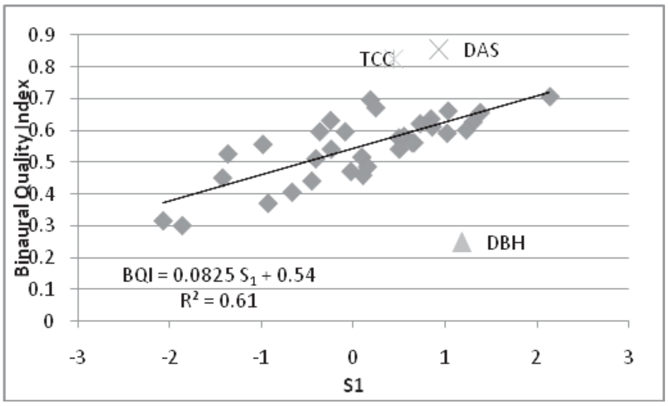

Figure 4: Comparison of S_1 index and Binaural Quality Index, showing linear regression relationship (solid black line). Data points not included in the regression are shown separately and labelled with hall code.

LATERAL ENERGY FRACTION

Although lateral energy fraction (LF_{80}) was found by Beranek to be less useful in accounting for the subjective ranking of halls, given the correlation seen between S_1 and BQI, it is of interest to see whether there is a similar relationship with LF_{80}.

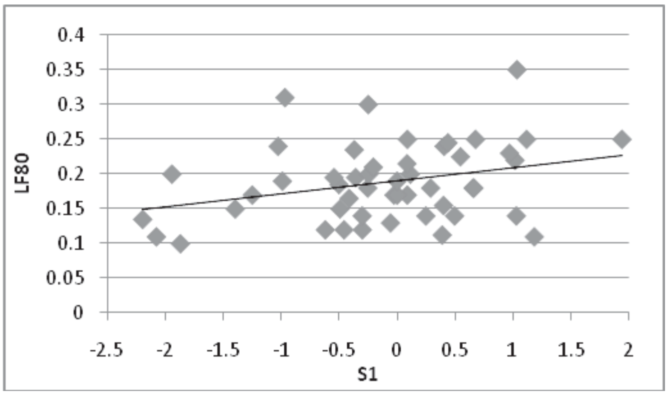

Figure 5: Comparison of S_1 index and Lateral Energy Fraction LF_{80}, showing linear regression relationship

There is only a very weak correlation (R^2 0.09) between S_1 and LF_{80}, with significant spread in the dataset (standard deviation of 0.05 LF_{80}). Other than a very broad trend for increasing LF_{80} with increasing S_1, there seems to be no real relationship between the parameters. This is perhaps not surprising, since LF_{80} is not a particularly useful parameter for resolving differences between halls [2], and since S_1 is only calculated with the hall RT and length and therefore does not consider the more detailed room shape, which may have a significant effect on LF_{80}.

IMMERSION, 1-$IACC_L$

One of the only numerical parameters suggested to describe the degree of listener envelopment or immersion in the sound field is the IACC (late, from 80 ms to 1000 ms), $IACC_L$, (usually expressed as the parameter 1-$IACC_L$), although this was found to be approximately constant for most halls and was therefore not considered to be a particularly useful parameter. However, in the absence of other technical parameters to describe immersion, the S_1 and 1-$IACC_L$ values for 31 halls where $IACC_L$ data was available have been compared.

As seen in Figure 6, the 1-$IACC_L$ values for most halls lie within the range 0.8-0.9, independent of the change in S_1. This is not surprising, since Beranek also found that $IACC_L$ does not vary significantly between highly-rated halls and lower-rated halls. The lowest values of (1-$IACC_L$) occur for Kleinhans Music Hall, Buffalo (KMH), Koussetitzky Music Shed, Lenox (KMS), which are both large fan-shaped halls, and for Bass Performance Hall, Fort Worth (BFW) and La Scala, Milan (LSC), which are both horseshoe-shaped opera theatres.

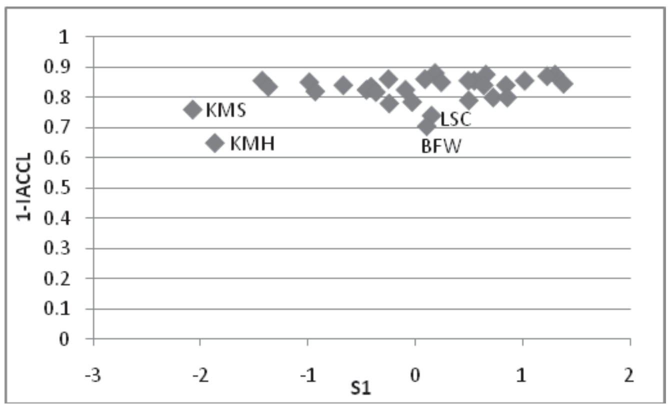

Figure 6: Comparison of S_1 and (1-$IACC_L$). Halls discussed in the text are labelled with identification codes on the graph.

Both Kleinhans Hall and Koussetitzky Music Shed have significant areas of smooth boundary surfaces, which may contribute to the reverberant field being less diffuse in these halls, and hence the lower $IACC_L$ values. However, the surface properties of the room are not taken into account (directly) in calculating S_1, and therefore it would not be expected to account for the reduced (1-$IACC_L$) values for these halls.

A less-diffuse reverberant field is a characteristic of traditional horseshoe-form opera houses, since balcony overhangs and the flytower opening limit the angles from which the reverberant field may be “seen” by seats. This likely explains why the (1-$IACC_L$) values for traditional opera theatres are lower (e.g. La Scala and Bass Hall; Paris Opera Garnier and Teatro Colon, Buenos Aires also have 1-$IACC_L$ values of 0.80 or lower). Again, the factors contributing to the lower "immersion" in traditional opera theatres are more complicated than the assumptions used to derive S_1, and therefore it would not be expected to account for these effects.

It is clear that for most halls, (1-$IACC_L$) is not a particularly useful descriptor of the degree of listener envelopment. Therefore, comparison with (1-$IACC_L$) may not provide a meaningful evaluation of the effectiveness of S_1 as a descriptor for listener envelopment/"immersion".

MUSICAL CLARITY, C_{80}

In the derivation of S_1, it was described as the "inverse of various types of 'clarity index'" [1], and theoretically S_1 indeed is calculated from the ratio of reverberant to "prompt" sound (not necessarily sound arriving within 80 ms as in the clarity index C_{80}). S_1 would therefore be expected to be inversely related to C_{80}, since S_1 is the ratio of reverberant sound to "prompt" sound, whereas C_{80} is the ratio of early sound to late sound.

Figure 7 presents an overview of the relationship between the predicted S_1 values and the measured C_{80} values for the 63 halls where C_{80} data was available. There is significant variation in the data for C_{80}, with only a very slight inverse relationship between S_1 and C_{80} visible, and several outlying data points. The correlation between C_{80} and S_1 is very weak (R^2 0.04), with a standard deviation of 2 dB. This indicates that S_1 and C_{80} appear to be essentially independent. A reason for S_1 and C_{80} not being more closely correlated (as expected) may be that the "early" sound has different definitions in the two parameters. S_1 includes only first-order reflections in its definition of "prompt" sound, while C_{80} includes all energy received up to 80 ms, regardless of the order of reflection. Additionally, the variation may be accounted for by the influence of the room shaping on C_{80} – the dimensions and orientation of the room boundaries can have a significant impact on how much energy is received within 80 ms, whereas in S_1 essentially only reflections from the stage zone are included in the "prompt" sound.

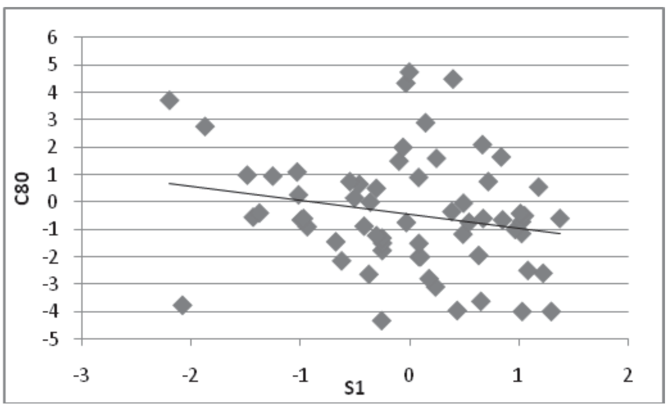

Figure 7: Comparison of S_1 and C_{80}, showing linear regression relationship.

DISCUSSION

Because only subjective evaluations are available for evaluating S_1, and because the subjective evaluations did not specifically focus on the degree of listener envelopment, but on overall hall quality, it is difficult to comment on its effectiveness as an "immersion" index.

From the subjective evaluations, S_1 values in the range ~0 1 dB appear to be associated with the highest rated halls. These are generally halls where the reverberant field is perceived as being rich and enveloping (e.g. Musikverein), although other aspects of the room acoustic may also contribute to the high subjective ratings of these halls.

Although the (1-$IACC_L$) data is not particularly useful, for the few halls where (1-$IACC_L$) is lower, S_1 does not reflect this change (e.g. traditional opera theatres such as La Scala where S_1~0 dB have similar values of (1-$IACC_L$) to Koussetitzky Music Shed with S_1 ~ -2 dB). This suggests that S_1 may not be very effective at capturing the degree to which the reverberant field is diffusive and "immersive". Additional subjective evaluations focussing on listener envelopment or comparison with another parameter that better reflects the listener envelopment than (1-$IACC_L$) would assist in gaining more understanding into the applicability of S_1.

The assumptions inherent in calculating S_1 have the consequence that S_1 is expected to be less effective for "surround"-type halls, or halls with unusual geometry or material finishes than for traditional halls, particularly "shoebox"-type halls or other rectangular-plan halls. Due to these simplifying assumptions, which do not take into account more detailed aspects of the room shape, surface finishes etc that are considered in other, more detailed parameters, there is no strong correlation between S_1 and more detailed acoustic parameters, even C_{80}, which theoretically is close to being the "inverse" parameter of S_1.

The strongest correlation between S_1 and other parameters is between S_1 and Binaural Quality Index (BQI). This suggests that S_1 may be useful as a "spaciousness" index during early design, and as a means of gaining a first estimation of the Binaural Quality Index for a hall before undertaking detailed acoustic modelling. This suggests that S_1 may be able to be used with reverberation time (RT), and room geometry ratios (such as volume per seat, V/N) as an initial design parameter for use in evaluating concepts for a hall design, and is an unexpected result in that S_1 is not intended as a "spaciousness" index!

S_1 can provide a useful supplement to existing design tools in that it would allow the spaciousness of the hall (as expressed as Binaural Quality Index) to be estimated via a simple calculation, before detailed acoustic modelling is conducted. Comparison with highly-rated halls suggests that a S_1 value of ~0-1 dB would be desirable. Further subjective studies of listener envelopment would allow the usefulness of S_1 as a parameter describing "immersion" in the reverberant field to be determined further. Initial findings by comparing with the (admittedly less useful) parameter (1-IACCL) suggests that S_1 may not be particularly useful in instances where the listener envelopment is low.

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