Proceedings of the International Symposium on Room Acoustics, ISRA 2010

29-31 August 2010, Melbourne, Australia

Investigation of the Correlation between Late Lateral Sound Level and Total Acoustic Absorption, and an Overview of a Related Subjective Study

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PACS: 43.55.Hy, 43.55.Mc, 43.55.Ka

ABSTRACT

Listener envelopment (LEV), the sense of being immersed in a sound field, can be quantified in terms of Bradley and Soulodre's parameter called late lateral sound level (GLL) (1995). Room acoustics parameters, including GLL, were measured in a 900-seat theatre with variable acoustics in five receiver locations in three hall settings, with the mid-frequency reverberation time ranging between 1.35 to 1.59 s. The overall range of measured GLL values, across all receivers and configurations, was between 16.1 to 20.4 dB. Binaural recordings were also obtained for most receiver and hall setting combinations. A detailed model of the space was created in ODEON v9.20 and validated using the measured reverberation time, early decay time, and clarity index values within less than 2 just-noticeable-differences. Barron's theory, that GLL is related to total acoustic absorption in a hall (2001) was tested using the measured GLL values and the estimated total acoustic absorption values from the validated model. A significant correlation was found for the upper octave bands only. A listening test was also conducted using the binaural recordings to determine the correlation of the subjective LEV ratings of these recordings with the measured GLL values. The subjects rated LEV on a scale from 1 to 5, and a significant linear correlation was found between the LEV ratings and the measured GLL values.

INTRODUCTION

Spatial impression is an important component of the listening experience in a concert hall. One of the earliest introductions of the concept was by Reichardt and Schmidt [1, 2] in the late 1960's, who explored spatial impression (SI) by examining the importance of reflections from well-defined directions between the direct and reverberant sound fields. Barron investigated the effects of both the timing and arrival direction of early reflections on SI and proposed that the degree of SI could be quantified in terms of the ratio of the early lateral energy to the non-lateral late energy [3]. Subjective studies were conducted by Morimoto and Maekawa [4], and Morimoto and Iida [5], to further investigate the subjective impression of SI through listening tests. From these studies, they proposed that SI could be separated into two distinct components and that each component is a function of the early or late lateral energy, respectively.

The separation of SI into two components as proposed by Morimoto *et al* was investigated in great detail by Bradley and Soulodre [6] who formally named the two components: apparent source width (ASW), which correlates to the early lateral reflections, and listener envelopment (LEV), which correlates to the late lateral reflections. Extensive listening tests were conducted to isolate the differences between ASW and LEV, and also to gain a better understanding of LEV, as the research in SI had primarily focused on the early lateral energy and what they had termed ASW. Bradley and Soulodre found that ASW correlated to the existing parameters of lateral energy fraction (LF) and the interaural cross correlation (IACC) for the early sound field, however they did not find a good correlation of the late sound field of the existing parameters with LEV. A new parameter was proposed, the late lateral sound level, GLL (or LG_{80}^{∞}), which is the ratio of the late lateral energy, p_F, after 80 ms to the energy of the measurement source at 10 m away in a free field, p_A:

$$GLL = 10log\left[\frac{\int_{80\,ms}^{\infty} p_F^2(t)dt}{\int_0^{\infty} p_A^2(t)dt}\right] \qquad (1)$$

Bradley and Soulodre further examined the subjective impression of LEV as a function of reverberation time, clarity index, overall level, and angular distribution of the late energy [7]. The simulations were presented from five loudspeakers in an anechoic chamber and were generated using programmable digital equalizers and reverberators. The results of their studies indicated a high correlation between LEV and GLL.

Once SI had been formally divided into two components, the research focus shifted to investigating the importance of the timing and arrival direction of the late reflections on LEV [8-11]. Soulodre *et al* have investigated how the correlation of the subjective impressions of LEV with GLL might be improved by using different integration times for the lower time limit in the numerator of Equation 1 [12].

Barron took room acoustic measurements in 17 unoccupied British halls and used these data to investigate GLL [13]. GLL was not measured directly, but was calculated from a proposed formula containing the total relative sound level (G), the clarity index (C80) and the late lateral energy fraction (LLF). Barron proposed that GLL is a function of the late level (G_L), which he computed using G and C80, and LLF. He determined the relative contribution of these two parameters to GLL. Through an analysis of computed GLL values from his measured data in the halls, Barron found that G_L actually accounts for 83% of GLL, while LLF accounts for the remaining 17%. Since he concluded that GLL is primarily a function of G_L, and Barron's revised theory of the late sound level being a function of the reverberation time (T30), auditorium volume (V) and source-receiver distance (r) (Equation 2), he proposed that GLL should primarily be a function of the ratio of the first two parameters, or the total acoustic absorption.

$$G_{L_{Th}} = 10log\left(\frac{31200T_{30}}{V}\right) - \frac{4.82}{T_{30}} - \frac{0.174r}{T_{30}} \qquad (2)$$

The primary purpose of this study is to test Barron's theory that GLL is primarily a function of the total acoustic absorption in a hall, ABS_{Total}, which was carried out by taking GLL measurements in a hall with variable absorption. The ABS_{Total} was obtained from a validated computer model. In addition, a subjective study was conducted to examine the relationship between GLL and LEV through the use of actual binaural recordings made in the same hall.

HALL MEASUREMENTS AND RECORDINGS

Hall settings and receiver locations

The measurements were taken in the Maxwell M. & Ruth R. Belding Theatre (Figure 1), which is part of The Bushnell Performing Arts Center in Hartford, CT. The hall, which seats 908, is a multi-purpose venue that is used for symphonic and chamber music, small touring Broadway shows, dance, and theatre. The total volume of the hall is approximately 16,500 m^3 (580,000 ft^3) including the stage house and four small coupled volumes totalling approximately 310 m^3 (11,000 ft^3). The chambers can be essentially closed off from the hall by extending heavy velour curtains in front of the openings. In addition to the variable acoustics provided by the coupled volumes, banners that cover the side walls can be deployed and heavy velour curtains can be extended across the lower back wall and in the catwalks.

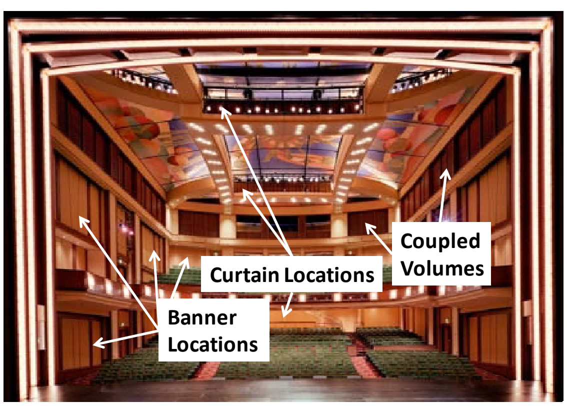

Figure 1. View of the Belding Theatre located in Hartford, CT, USA, from the stage. The variable acoustics in the hall include banners, velour curtains, and small coupled volumes.

Measurements were made at five receiver locations, three on the lower orchestra level and two on the upper mezzanine level, with the source position on the stage, as shown in Figure 2. The measurements were made with WinMLS 2004 software using the sine sweep method. The sound source was an omni-directional loudspeaker, a Brüel & Kjær (B&K) OmniPower Sound Source Type 4292. The receiver locations were measured with two microphones simultaneously in order to measure the late lateral sound level, as shown in Figure 3. The omni-directional microphone was a B&K Type 4190 and the figure-of-eight directivity microphone was a Neumann Type KM120 pressure gradient microphone with a single diaphragm. The microphones were spaced 64 mm (2.5") apart using a custom stand adapter.

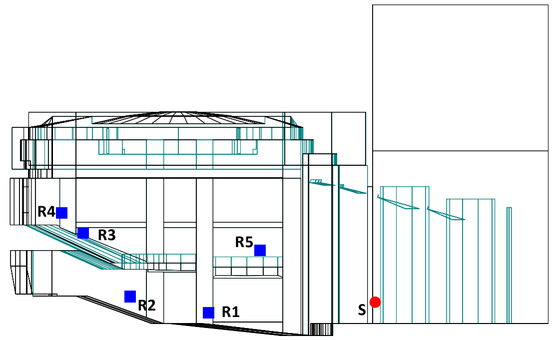

Figure 2. Measurement locations in Belding Theatre. The source was centred on the stage. R1 and R3 are towards the centre of the seating area, while the other three receivers are close to the side wall.

Figure 3. Microphones in custom mic-stand used for the impulse response measurements.

The hall was measured in three settings: Setting 1 had none of the variable absorption deployed, Setting 2 had all of the variable absorption deployed, and Setting 3 employed the front side orchestra level banners only. The average measured mid-frequency reverberation time (T30), early decay time (EDT), and clarity index (C80) for each setting are summarized in Table 1.

Table 1. Measured room acoustic parameters in Belding Theatre for the three hall settings, averaged over the five receivers. Values shown are averaged over the 500–2,000 Hz octave bands.

	T30 (s)	EDT (s)	C80 (dB)
Setting 1	1.59	1.52	1.2
Setting 2	1.35	1.45	1.9
Setting 3	1.59	1.42	1.7

In order to calculate GLL from the hall measurements, the measurement chain must be calibrated and the sound pressure level of the sound source at 10 m away in a free field must be measured for the denominator in Equation 1. The input from the omni-directional microphone was calibrated using a B&K Calibrator Type 4231. For the figure-of-eight microphone calibration, the sensitivity for each side of the microphone's diaphragm was measured in an anechoic chamber by playing a 1 kHz tone through the omni-directional loudspeaker approximately 3 m away from the microphone and measuring the sound pressure level using a B&K Sound Level Analyzer Type 2250. The two sensitivity values were then averaged. The overall sound pressure level of the measurement setup 10 m away in a free field was calculated from a total of 29 measurements of the omni-directional loudspeaker, rotating the loudspeaker 12.5° for each measurement, according to ISO 3382-1:2009 in an anechoic chamber 3 m away. [14].

Binaural recordings

Binaural recordings were made in nearly all hall setting and receiver location combinations. The equipment used to make the recordings was a B&K Type 4100D Sound Quality Head and Torso Simulator, to capture the recordings with an average head-related-transfer-function, connected to a Marantz Digital Portable Recorder Model PMD670.

Three anechoic motifs were played through the omni-directional loudspeaker and then captured by the B&K binaural head: Motif 1 – "L'Arlésienne Suite No. 2" Menuet by Bizet (20 s), Motif 2 – "Le Nozze di Figaro" Overture by Mozart (16 s), and Motif 3 – "Theme" by Weber for solo cello (18 s). The orchestral pieces were obtained from the DENON *Anechoic Orchestral Music Recordings* CD [15], and the solo cello recording was taken from the Bang & Olufsen *Music for Archimedes* CD [16].

ROOM ACOUSTICS COMPUTER MODEL

Model details

The model of Belding Theatre was constructed using ODEON v9.20 (Figure 4). ODEON uses a combination of techniques to model both the early and late parts of the impulse response. The model contains 963 surfaces, but the smallest surfaces modelled were on the order of 152 mm (6"). Part of the reason that the model contains so many surfaces is the complex ceiling design (a dome shape integrated with catwalks). In addition, each reflector above the stage has eight surfaces. A total of 25,000 rays were used in the simulation and the sound power level of the sound source was set to the values obtained from the free field measurement of the measurement-system setup in order to model the same conditions that were used in the actual measurements.

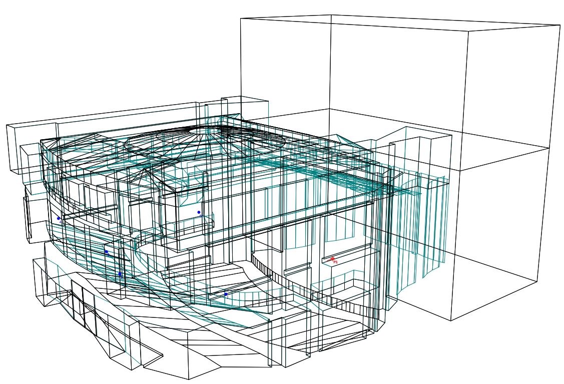

Figure 4. ODEON v9.20 model of Belding Theatre.

Model validation

The model was initially validated for Setting 1, which had none of the variable absorption deployed. The absorption and scattering coefficients were adjusted until the measured and predicted values of T30, EDT, and C80 were within 2 just-noticeable-differences (JNDs), where the JNDs were set to the values listed in ISO3382 of 5% for T30 and EDT, and 1 dB for C80. Once the model was validated for Setting 1, the variable absorption in the form of banners and velour curtains was added to model Setting 2. Finally, with the absorption coefficients obtained from the Setting 2 model, Setting 3 with two side banners on the orchestra level was modelled. The overall average difference between the measured and simulated parameters, across the three hall settings, is 1.3 JNDs for T30, 2.0 JNDs for EDT, and 1.3 JNDs for C80. These average differences include the data from R2-R5, as it was difficult to validate R1, since this position was so close to the sound source.

ANALYSIS OF GLL RELATIONSHIPS

Comparison of measured and modelled results

The measured late lateral sound levels (GLL) were plotted versus the predicted GLL values as shown in Figure 5. The data were fitted to a linear regression trendline and the correlation coefficient for this regression is $R^2 = 0.632$ $p < 0.001$. The general trend between the two data sets is a positive slope, which shows that the model is, in general, accurately predicted the relative change in GLL between each setting and receiver combination. However, the model under predicts the value of GLL on average by 4.3 dB.

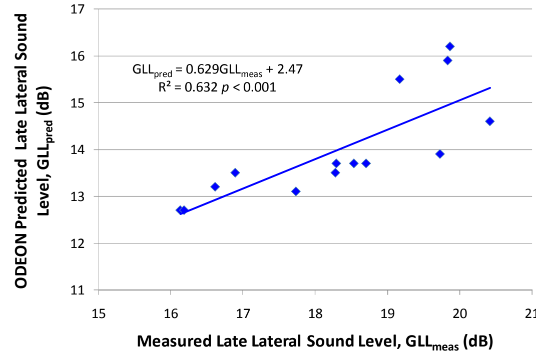

Figure 5. Measured versus predicted late lateral sound level, GLL, for the Belding Theatre.

Testing Barron's theory

The theoretical late level, G_L, was calculated for each receiver, each hall setting, and for the octave bands centred at 125-8000 Hz. G_L is a function of the reverberation time (T30), source-receiver distance (r) and hall volume (Equation 2 [13]). The first two parameters were obtained from the measurements, while an estimate of the total hall volume was taken from the computer model. A regression analysis with the calculated G_L and the total acoustic absorption, ABS_{Total}, as estimated by the model, for each setting and octave band, was conducted. A strong linear correlation was found between these two variables between 250-8000 Hz, where $R^2 = 0.978$ and $p < 0.0001$, as expected.

A second regression analysis was then carried out to test Barron's theory that since GLL is primarily a function of G_L, and since G_L is correlated with ABS_{Total}, that GLL should also have a linear correlation with ABS_{Total}. When the data from all seven octave bands were plotted the relationship between these two variables was initially unclear, but a linear relationship emerged when only the data from 2000-4000 Hz were plotted, as shown in Figure 6. The regression analysis revealed $R^2 = 0.992$ and $p < 0.0001$. Thus, based on a combination of measured data and predicted data from a validated room acoustics model, the theory holds true for the high frequencies. However, LEV is thought to correlate to GLL summed between 125 – 1000 Hz [7]. More detailed plots and further data analysis of these two regressions will be presented in a future publication.

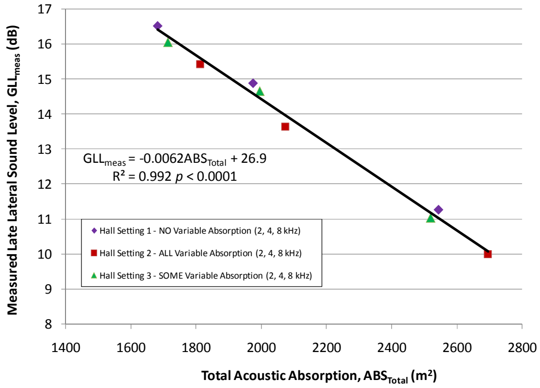

Figure 6. Measured late lateral sound level, GLL, versus total acoustic absorption, ABS_{Total}, for the Belding Theatre.

LEV LISTENING TEST

A listening test was carried out to evaluate the relationship between subjective LEV ratings of the binaural recordings with the measured GLL values, as most of the work to date in this area has used simulated sound fields.

Binaural recordings

The binaural recordings were edited to shorten the motifs to approximately 10 s to make them more uniform in length and more suitable for the subjective test. All recordings were initially evaluated by the researchers to estimate which recordings would provide the largest range of LEV, in order to decrease the difficulty of the test and also to shorten the overall testing time. Out of the 39 total recordings, 18 were used in the study. Three were used for a formal training section, another three were used for additional practice trials, and the remaining 12 recordings were used in the actual test, which are shown in Table 2.

Table 2. Hall setting, receiver, and motif combinations for the 12 binaural recordings used in the listening test.

Motif	Hall Setting	Receiver
Bizet, orchestral	1	R2
	1	R4
	2	R4
Mozart, orchestral	1	R3
	1	R5
	2	R2
	3	R3
	3	R4
Weber, solo cello	1	R5
	3	R2
	3	R3
	3	R4

Test subjects

A total of 35 test subjects participated in this study, with a nearly equal ratio of males (18) to females (17). A hearing threshold of 15 dB HL or lower between 250 – 8,000 Hz was a requirement for all test subjects. In addition, all subjects needed to have a minimum of five years of musical training. The subjects reported having an average of 9.7 years of formal training and attending 2 to 3 classical concerts per month on average.

Testing procedure

The subjects were initially given a tutorial that defined listener envelopment as the *sense of feeling surrounded by the sound or immersed in the sound* and also included examples of sound recordings. The amount of LEV for each recording was not specifically mentioned, but rather that the sample recordings provided a general range of LEV. The tutorial also had specific instructions about how to use the testing program.

The sound pressure levels of all of the test signals were normalized to avoid an interaction effect with loudness. The recordings were presented to each subject at an average level of 64 dBA (re: 20 μPa) one at a time over a pair of STAX SR-404 signature headphones, powered by a SRM-727II solid state driver unit. The task for each subject was to rate each recording on a nine-point scale of LEV from 1 to 5 with 0.5 steps, where *1 means NOT IMMERSED in the sound* and *5 means FULLY IMMERSED in the sound*. The presentation order was randomized for all 35 subjects.

Listening test results and discussion

The LEV ratings of the 12 binaural recordings from the actual test portion of the experiment were averaged across all subjects and plotted versus the measured GLL values, as shown in Figure 7. A regression analysis revealed a significant linear relationship, where $R^2 = 0.424$ and $p < 0.02$. These findings support results from previous work by Bradley and Soulodre [7] that LEV and GLL are correlated, but the experimental method differs. These results were obtained using actual binaural recordings, as opposed to simulated sound fields from digital signal processing equipment. Further research will be conducted to investigate the relationship between subjective LEV ratings of auralizations versus the measured and predicted GLL values.

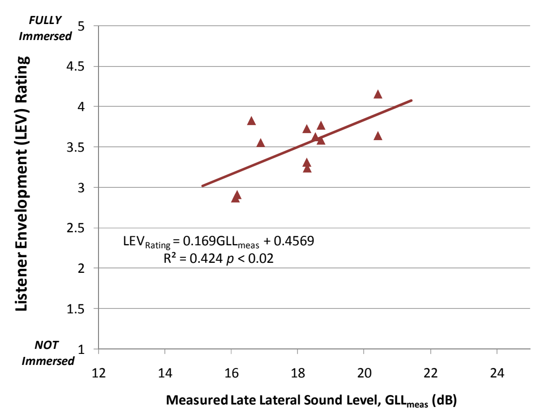

Figure 7. Results of listening test: subjective listener envelopment ratings of the set of binaural recordings plotted versus the measured late lateral sound level, GLL.

SUMMARY

An investigation was carried out to test Barron's theory that the late lateral sound level (GLL) is linearly related to the total acoustic absorption in a hall (ABS_{Total}). GLL was measured in a moderate-sized theatre in five receiver locations in three hall settings, where Setting 1 had no variable absorption exposed, Setting 2 had all of the variable absorption deployed, and Setting 3 had a small amount of the variable absorption extended. A room acoustics computer model of the hall was created in ODEON v9.20 and validated using the measured quantities of reverberation time (T30), early decay time (EDT) and clarity index (C80). The validated model was used to obtain the volume and ABS_{Total} estimates required for the data analysis. GLL was found to be linearly correlated with ABS_{Total}, but only for the high frequency octave bands of 2, 4 and 8 kHz, and not for the low frequencies, which have been shown to be the primary contributors to the subjective impression of listener envelopment (LEV). Further work is needed to develop a better understanding of how a hall's properties contribute to GLL.

In addition to this investigation, a listening test was conducted to examine the relationship between subjective LEV ratings of binaural recordings, made in the same hall, and the measured GLL values. A linear correlation was found between these two quantities, which provide further evidence of this relationship between the subjective parameter of LEV and the objective parameter of GLL.

ACKNOWLEDGMENTS

This work was supported in part by a University of Hartford Greenberg Junior Faculty Grant. (This support does not necessarily imply endorsement by the University of Hartford of project conclusions.) The authors wish to thank Madison Ford and Carl Vogel who carried out the listening test for their senior project. In addition, the authors acknowledge the following students who assisted with the measurements taken in the Belding Theatre: Michael Dick, Clothilde Giacomoni and Amy Scherma. The authors also wish to thank Russell Cooper and Michael Cain of Jaffe Holden Acoustics, Inc. for supplying drawings of the theatre, and Michael Sivo, Operations Manager at the Belding Theatre, for his assistance with coordinating the measurements. The subjective testing software used in this work was developed at the University of Nebraska-Lincoln by Dr. Lily Wang.

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