SUBJECTIVE STUDY ON LISTENER ENVELOPMENT USING HYBRID ROOM ACOUSTICS SIMULATION AND HIGHER ORDER AMBISONICS REPRODUCTION

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1 INTRODUCTION

In concert hall acoustics, the spatial character of a sound field has been understood as important for quite some time. Reichardt and Schmidt performed initial studies on the perception of directional reflections and reverberation[1]. Identifying lateral reflections as important, Reichardt and Lehmann proposed a metric, Room Impression Index (R), to predict subjective room impression, mainly in terms of spaciousness and liveliness[2]. Around the time of Reichardt's first work, Marshall also introduced the concept of spatial responsiveness, and he concluded that a narrower hall cross-section created a higher sense of spatial and overall acoustic impression[3].

The next appearance of the connection between spaciousness and overall impression came from Barron's study of British concert halls[4]. While listening to live performance in 11 halls, Barron had listeners rate a variety of subjective attributes, including intimacy, clarity, reverberance, envelopment, and overall acoustic impression. Using a correlation analysis to identify which attributes were highly correlated to overall impression, two main groups of subjects emerged: those that associated reverberance versus those that associated intimacy the most with overall impression. Despite the differences between the two groups, both groups showed that the second highest attribute to correlate with overall impression was envelopment. Even with a connection between envelopment and overall room impression, still questions remain as to what creates a sense of envelopment. Despite research efforts, results are still unclear and even contradictory at times.

2 PREVIOUS FACTORS CONTRIBUTING TO ENVELOPMENT

The first researchers to pioneer the idea of spaciousness into a generally accepted metric were Barron and Marshall[5]. The sense of spatial impression was connected to the early lateral reflections in the impulse response (IR), and the metric lateral energy fraction (J_{LF}) was developed to predict the subjective effects of lateral reflections. J_{LF} was the primary metric used to predict a sense of spatial impression until Bradley and Soulodre explored another aspect of spatial impression. Bradley and Soulodre hypothesized and confirmed that the idea of spaciousness could be divided into two separate perceptions: apparent source width (ASW) and listener envelopment (LEV)[6]. ASW was found to correlate with early lateral reflections, as predicted by J_{LF}. Bradley and Soulodre proposed a new metric to predict LEV: the late lateral energy level (L_J)[7]. L_J is the lateral energy of the IR occurring 80 ms after the direct sound, measured with a figure-of-eight microphone, normalized to the level of the sound source measured at a distance of 10 meters in a free field.

Since Bradley and Soulodre's work, other researchers have confirmed the importance of lateral reflections contributing to a sense of LEV[8-11]. The suitability of the L_J metric has been questioned because it excludes reflections from above and behind a listener, which have been found to impact LEV[8,10,12]. However, others have found that energy above and behind a listener does not affect LEV[13].

Another key finding from Bradley and Soulodre's work was that a strong, linear relationship between overall A-weighted sound pressure level and LEV exists, which L_J takes into account. This finding was echoed by Barron[14] and Soulodre[11] in follow-up studies. The final factor that has been researched is the interaction between reverberance, predicted by reverberation time (RT), and LEV. Morimoto found that there is a clear, direct relationship between RT and LEV[15]. On the other hand, Bradley and Soulodre found very little change in LEV ratings when varying RT, contradictory to Morimoto's work[7]. More work is need to clarity the connection between LEV and RT.

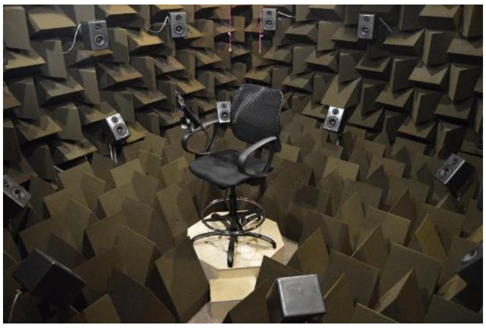
Overall, it is clear that future work is needed to untangle the idea of envelopment in concert hall acoustics. Research has been conducted on this topic, yet conflicting and unclear results still exist. Along with these inconsistencies, most of the previous work on LEV employed perceptually-motivated sound-field simulations, without a physical basis. In other words, sound fields were created by playing reflections and reverberation out of a small group of loudspeakers, instead of attempting to physically reconstruct a sound field. To create a sound field, direct sound was played through a front loudspeaker and the early reflections from all or a subset of the loudspeakers in the array, with a time delay and attenuation applied. Finally, spatially distributed reverberant energy was played through all or a subset of the loudspeakers by applying artificial reverberation of the anechoic signal.

3 AURALIZATION AND SIMULATION METHODS

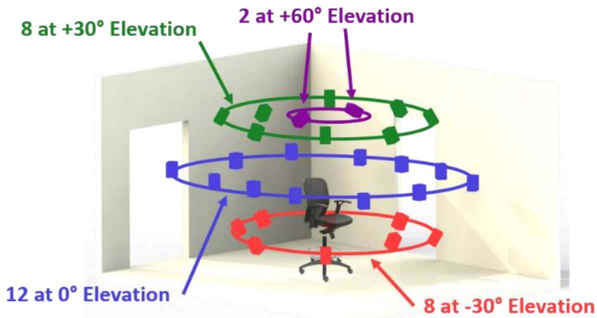
When researching LEV, it is important to ensure that a spatially accurate auralization is presented to the study participants. In most previous LEV research, no physical basis for the auralizations has been provided. Although researchers may be able to create different perceptions of envelopment with such loudspeaker setups, it is unknown if these sound fields could actually exist in a real room. This study aims to conduct LEV research using a physically based simulation technique and spatially accurate sound field reproductions using Higher Order Ambisonics (HOA).

3.1 Auralization and Reproduction of Acoustic Sound Fields Facility

To reproduce simulated sound fields for listeners, the AUralization and Reproduction of Acoustic Sound fields (AURAS) facility was used (Fig. 1a)[16]. This facility consists of 30 two-way loudspeakers placed within an anechoic chamber, distributed in a roughly even spacing around the listener location, which is at the center of the chamber. As seen in Fig. 1b, 8 loudspeakers are placed at -30°elevation (measured from the horizontal plane), 12 at 0° elevation, 8 at +30° elevation, and 2 loudspeakers at +60° elevation to the left and right of the listener.



(a)



(b)

Figure 1: (a) AUralization and Reproduction of Acoustic Sound fields (AURAS) facility at Penn State University. (b) The 30 loudspeakers were installed at four different elevations as labeled.

The room measures 11' wide (3.4 m) by 14' deep (4.3 m) by 8.5' tall (2.6 m) and the foam wedges are 18" deep (0.46 m). The room was measured to exhibit free-field behavior down to the 200 Hz third-octave band. Required level adjustments and time delays are applied to compensate for non-spherical loudspeaker locations. An IR measurement of each loudspeaker was performed in a larger anechoic chamber, which has a lower free-field cut-off frequency of approximately 100 Hz. These measurements were used to develop a FIR equalization filter for each loudspeaker by inverting the IR with a low-frequency inversion cutoff at 60 Hz. A height adjustable chair is used to accurately position each subject during testing, and a webcam is used to monitor the subject's head position.

3.2 Hybrid Simulation Technique

For this study, the stimuli were generated using simulations rather than measurements to allow for a high degree of control over the auralizations. Although some commercially available room acoustic simulation programs provide second-order Ambisonic outputs, this auralization facility is capable of achieving third-order Ambisonic reproduction. To achieve this higher order, a custom hybrid simulation program was developed, using the image source method and a statistical reverberation method. This program is based in MATLAB and it produces third-order Ambisonic signals for a simple rectangular room. Inputs to the simulation program include room dimensions, source location, receiver location, wall absorption coefficients, wall scattering coefficients, and a transition time.

For efficient room simulation, the early and late parts of the IR were created separately, using a hybrid simulation method. The early reflections in the IR were simulated using the image source method[17]. Image source locations up to the third-order were calculated for a rectangular room, and directions were calculated for each image source, relative to the receiver location facing the source. Finally, the level of each reflection was calculated, accounting for spherical spreading, air absorption, wall absorption, and wall scattering. For the reverberant energy, a Poisson noise process was used for the simulation[18-19]. This process generates a random series of reflections in the reverberant tail of the IR, with the spacing in time between reflections controlled by the reflection density calculated for the given room. After the reflections were distributed in time, each reflection was attenuated for spherical spreading, air absorption, and wall absorption. A transition time was specified for switching from the early to the late IR simulation methods. This transition time must be adapted by the user so that enough early reflections are simulated before diffuse reverberant energy dominates the IR. Much more details of the simulation, including the Poisson process calculation, can be found in Ref. 16].

3.3 Higher Order Ambisonics (HOA)

For the reproduction of the simulated sound fields, near-field compensated HOA was used[20]. Assuming plane wave type behavior of room reflections at a listener's location, the simulated IR was encoded into third-order spherical harmonic components, and then convolved with orchestral anechoic music from the Denon recordings[21]. To encode the IR into spherical harmonic compoenents, the following definition of real-valued spherical harmonics was used, up to the third order ($l = 3$)[22]:

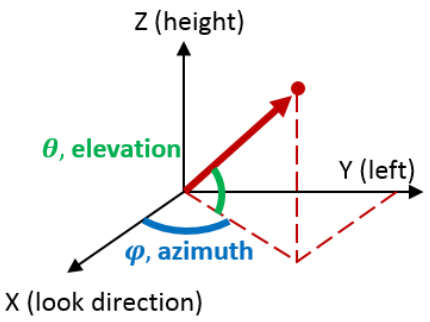
$$Y_l^m(\varphi,\theta) = \sqrt{\frac{2-\delta_m}{4\pi}\frac{(l-|m|)!}{(l+|m|)!}}\, P_l^{|m|}(\sin\theta)\begin{cases}\sin(|m|\varphi) & \text{for} \quad m<0 \\ \cos(|m|\varphi) & \text{for} \quad m\geq 0\end{cases}, \qquad 3\text{-}1$$

where,

$$\delta_m = \begin{cases}1 & for \quad m=0 \\ 0 & for \quad m\neq 0\end{cases}. \qquad 3\text{-}2$$

This definition uses the SN3D normalization scheme, with l as the order of the spherical harmonics, and m as the degree of the associated Legendre polynomials, defined as an integer where, $-l \leq m \leq +l$. The angles, θ and φ, indicate the direction of arrival of each reflection and are defined in Fig. 2a. Each of the early and reverberant reflections are encoded into Ambisonic IRs by multiplying their attenuated amplitude by $Y_l^m(\varphi,\theta)$, and populating each reflection into the 16 third-order Ambisonic IRs. Fig. 2b shows the 16 real-value spherical harmonics plotted using Eqns. 3-1 and 3-2. Each Ambisonic IR is convolved with anechoic music to create the final Ambisonic signals.

For the final reproduction of the sound field, the Ambisonic signals were decoded into loudspeaker signals. The decoder for the 30-channel loudspeaker array was a dual-band decoder designed using the Ambisonic Decoder Toolbox based in MATLAB[23]. The decoding, along with the loudspeaker equalization, was performed using VST plug-ins developed by Kronlachner[24] within the digital audio workstation REAPER. More information on the decoder can be found in Ref. [16].



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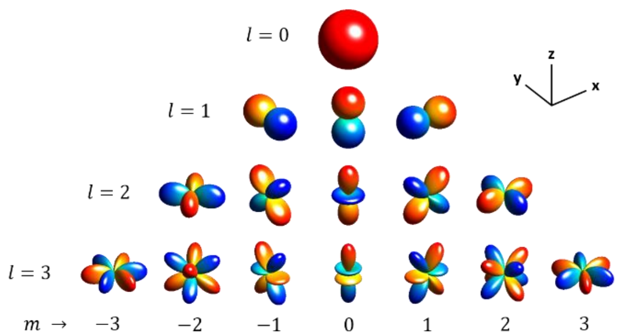


(b)

Figure 2: (a) The coordinate axes used in this study and (b) real third-order spherical harmonics, where red and blue represent a positive and negative value, respectively.

4 SUBJECTIVE STUDY ON LISTENER ENVELOPEMENT

The goal of this study was to observe how the perception of LEV changed as room simulation parameters, described in section 3.2, were adjusted. The overall parameters of interest were room size, RT, receiver location, early-to-late energy scaling, and A-weighted level. These parameters were selected based upon previous LEV research described above. The experimental design of this test consisted of four sets of eight stimuli, all created by adjusting a group of the simulation parameters. All simulated room sizes were scaled sizes of Boston Symphony Hall (BSH), assuming a simple rectangular geometry (48.8 m x 22.9 m x 18.6 m)[25] as shown in Fig. 3a. The anechoic motif, which was convolved with the IRs, was a 60 second excerpt from the overture of *Ruslan y Lyudmila*[21].

4.1 Stimuli Sets and Generation

In the first stimuli set, Set 1, the two independent variables that were varied were RT and room size. The stimuli incorporated four different RTs, varying from approximately 1.0 s to 2.9 s, and the 80% and 120% BSH room sizes (see Table 1). The source-receiver distance was constant for both room sizes, shown in Fig. 3a. The stimuli in Set 1 were also level equalized, so that all were presented at the same overall A-weighted level.

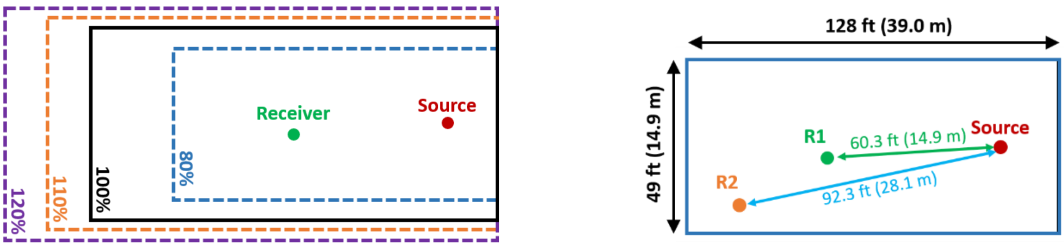
Stimuli Set 2 adjusted the early-to-late energy scaling of the stimuli at two different receiver locations (R1 and R2). For this set, the receivers were placed in the 80% BSH room, at the locations shown in Fig. 3b. The image source part of all simulations remained the same, but for the reverberant simulation, the IR was scaled by a factor of 0.5, 0.7, 1.0 and 1.5. For the purposes of plotting the results in the next section, the clarity index (C80) was used, since it is the ratio of early–to-late energy on a dB scale. A higher early-to-late scaling will cause a drop in C80, since the variables are inversely proportional. This produced two sets of four stimuli with the same early reflections, and varying amounts of late energy. Again, this set of stimuli was also level equalized.

Stimuli Set 3 was very similar to Set A, but instead, the primary variable being adjusted was hall size with four different cases (80, 100, 110, and 120% BSH), and two T30s in each room (1.4 and 2.1 s) as a secondary variable. The same source-receiver location from Set 1 (see Fig. 3a) was used in Set 3. Stimuli Set 3 was also level equalized, as was done in Sets 1 and 2. The final stimuli set, Set 4, was identical to Set 3, but no level equalization was performed. Since the source-receiver distance was constant in Set 4, the direct sound was the same amplitude, but the differences in the reverberant energy caused changes in level between auralizations. Table 1 gives a summary of all four sets.

Table 1: Summary of four stimuli sets used in the LEV study.

Stimuli Set	Primary Variable		Secondary Variable	
	Variable	Cases	Variable	Cases
1	T30	1.0, 1.4, 1.9, 2.4, and 2.9 s	Room Size	80% & 120%
2	Early-to-Late Scaling	0.5, 0.7, 1.0, and 1.5	Receiver	R1 & R2
3	Room Size	80, 100, 110, and 120%	T30	1.4 s & 2.1 s
4*	Room Size	80, 100, 110, and 120%	T30	1.4 s & 2.1 s

*Indicates stimuli set was not level equalized



(a) (b)

Figure 3: The hall size(s) and receiver location (a) for Sets A, C, and D, and (b) for Set B.

4.2 Subjective Testing Setup

For the testing, subjects were recruited from Penn State's School of Music and various performing ensembles on campus. To participate, musicians were required to have at least five years of formal musical training, be currently involved in private study or a musical ensemble, and have a minimum hearing threshold of 15 dB HL in the 250 – 8000 Hz octave bands, measured at the time of the test. Subjects first received a training tutorial, which defined the sense of LEV and familiarized them with the testing interface. Subjects then rated a practice set of four stimuli and a hidden practice set of eight stimuli, which subjects believed was not a practice set. After that, a five minute break was taken, and subjects were presented with two of the four sets. After another break, they rated the remaining two sets. The order of the sets and the stimuli within the sets were randomized across all participants.

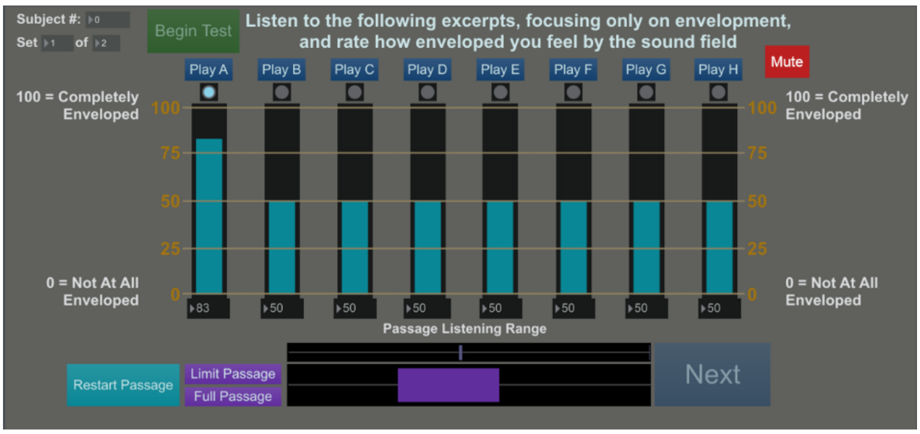


Figure 4: The testing interface, which provided comparison of eight stimuli simultaneously.

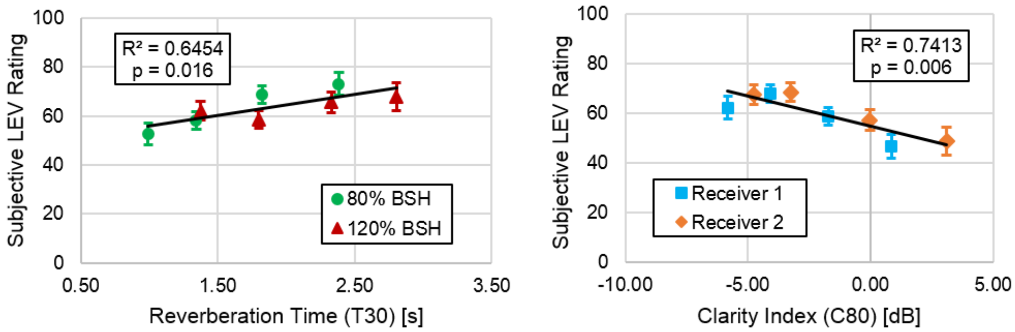
To allow for direct comparison between all stimuli in a set, a testing interface was developed in MAX 7, a program that allows for real-time audio processing, shown in Fig. 4. With this interface, subjects could switch in real-time between all eight stimuli and rate all stimuli within a given set. The musical passage was continuous, and subjects rated all stimuli using the slider bars. Additionally, subjects could limit the listening range of the passage with a horizontal slider at the bottom of the screen.

5 RESULTS AND DISCUSSION

Initially, a one-way repeated measures analysis of variance (ANOVA) was run for each of the four stimuli sets to determine if there were any significant differences in the ratings of the eight stimuli within a set. The analysis showed that all sets contained significant differences between stimuli, with $p = 0.007$ (Set 1), $p < 0.001$ (Set 2), $p = 0.028$ (Set 3), and $p < 0.001$ (Set 4). A two-way repeated measures ANOVA was then run for all sets, using the two independent variables for each set as listed in Table 1. For all ANOVAs, Mauchley's test of sphericity was checked to determine if the variances of the differences between all possible pairs were equal. If violated, the degrees of freedom were corrected using the Greenhouse-Geisser estimates.

The independent variables for the two-way ANOVA for Set 1 were RT (two levels) and room size (four levels). The effect of RT was significant ($p = 0.013$), as shown in Fig. 5a, but the effect of room size ($p = 0.783$) and the interaction effect between RT and room size ($p = 0.086$) were not found to be significant. Visually, an increase in RT caused an increases sense of envelopment, but this is more apparent in the smaller hall. An interaction between RT and room size might be present, so the borderline significance of the interaction effect ($p = 0.086$) may turn out to impact the sense of envelopment if more subjects had been tested. A regression analysis was run on all eight stimuli in Set 1, between LEV rating and T30. The regression was significant with an $R^2 = 0.645$ ($p = 0.016$).

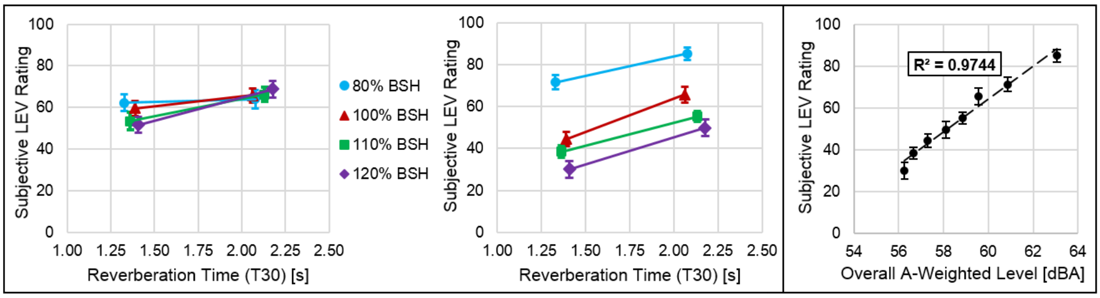
For Set 2, the two-way ANOVA was run using early-to-late scaling and receiver as the independent variables, including a term to account for a possible interaction between the two variables. Early-to-late scaling caused a significant difference in mean LEV ratings ($p < 0.001$), but both receiver ($p = 0.341$) and the interaction effect ($p = 0.559$) were not significant. This result is shown in Fig. 5b, where for both receivers, an increase in LEV is seen with increasing late energy. To represent the change in the early-to-late energy scaling, the ratings are plotted against C80 for reasons described above in section 4.1. Also, it appears that as the early-to-late scaling was increased from 100% to 150%, less of an increase, or even a decrease, in mean LEV was observed. This might point to a non-linear relationship between late energy and LEV. A linear regression between C80 and LEV rating for all eight stimuli in Set 2 was significant ($p = 0.006$), with an $R^2 = 0.741$. The early/late energy balance clearly relates to LEV.



(a) (b)

Figure 5: Plots of mean subjective LEV ratings and standard error bars versus (a) changes in RT for Set 1 and (b) changes in early-to-late scaling factor, represented by C80, for Set 2. LEV rating increases with RT, and when C80 is lower (more late energy), LEV rating also increases.

For Sets 3 and 4, the same two-way ANOVA was run with independent variables of RT (two levels) and room size (four levels) and an interaction term. The stimuli in Sets 3 and 4 were identical, except that the Set 4 stimuli were not level equalized. For Set 3, RT was found to cause significant differences ($p = 0.017$), and both room size ($p = 0.676$) and the interaction effect ($p = 0.068$) did not cause significant differences. A positive trend with RT, similar to Set 1, is also found in this set (see Fig. 6a). Again, the interaction effect of room size is bordering on significance, so no clear conclusion can be drawn. Looking at Set 4, shown in Fig. 6b, very clear subjective differences, larger than any other sets, are found. For this set, the two-way ANOVA showed that both RT ($p < 0.001$) and room size ($p < 0.001$) created significant differences in mean LEV rating with an insignificant interaction ($p = 0.475$).



(a) (b) (c)

Figure 6: Plots of mean subjective LEV ratings and standard error bars for (a) Set 3 and (b) Set 4 versus RT, and for (c) Set 4 versus overall A-weighted level. In both sets, a positive relationship between RT and LEV rating is found, but the impact of RT is noticeably more subtle than level.

It is clear that the mean ratings from Set 4 have much larger differences than those from Set 3. Since the only difference between Sets 3 and 4 was level equalization, level had a significant impact upon perceived LEV ratings. To test this, a stepwise multiple linear regression between overall A-weighted level, T30, and room size versus LEV rating was performed on Set 4, with an entry criterion of $p < 0.05$. From this analysis, level was included in the model ($p < 0.001$), while volume ($p = 0.530$) and RT ($p = 0.681$) were excluded from the model. Figure 6c shows the linear regression between level and mean LEV rating. This linear regression model was found to explain 97.4% of the variance in the data ($R^2 = 0.974$). Although both RT and room size were significant, it appears that level alone is a better predictor for explaining the change in LEV ratings than either room size, RT, or a combination of the two. When level was not a factor, as was the case in Sets 1, 2, and 3, the effect of RT was significant. The effect of RT appears to be more subtle than the dominant perception of level.

6 CONCLUSIONS

Despite the known correlation between LEV perception and overall hall impression, still more understanding is needed to quantify our understanding of LEV. From the present study, the impact of overall level on LEV rating is clear, shown from a strong linear relationship in Set 4. The level differences were significant, spanning a range of 7 dBA, caused by changes in simulated room volume and materials. With the levels of the stimuli equalized in Set 3, room size did not significantly impact LEV, but a significant effect due to RT did appear. The positive linear relationship between LEV and RT was clear in both Set 3 and in Set 1. Although clear, RT appears to create a much more subtle change in LEV perception compared to level. The masking of the RTs effect by level could explain why contradictions exist in literature when relating RT to LEV[7,15].

Along with level, the early-to-late energy balance had a clear relationship with LEV. From Set 2, as late energy increased (or as C80 decreased), LEV rating increased as well. For the largest late energy scaling, the LEV rating increases were not found, potentially indicating a non-linear relationship. While late energy increases LEV perception, after a certain amount of late energy, additional energy may no longer increase LEV, and potentially decrease LEV. The range of late energy scaling in this study was limited, so a larger scaling range should be used in further investigations. Additionally, the factors from this study should be connected to directional aspects of the sound field, including potentially non-uniform reverberant energy, using spatially accurate room measurements. Our understanding of LEV is growing, but more work is need to better quantify its perception.

7 ACKNOWLEDGEMENTS

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