INFLUENCE OF LATE DIRECTIONAL REVERBERATION ON ENVELOPMENT

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1 INTRODUCTION AND LITERATURE

Room acoustic quality for music performance spaces is supported greatly by *listener envelopment* [1]. Listener envelopment (LEV) refers to a perceptual attribute describing the listeners' feeling of being surrounded by music.
A lack of envelopment can render the concert experience less engaging for the audience. Musicians sometimes use phrases such as "the room can be felt". On the other hand, too much envelopment can disturb or mask the sound source localization on stage. Great concert halls offer a perfect balance.
Directional distribution and strength of reverberation in the room are known as main contributors for perceived envelopment. More precisely, the late energy of the impulse response is responsible [2], subsequently also referred to as "late reverberation" for disambiguation.

With reflections arriving from different directions, the spatial distribution of the late reverberation is important. A number of studies were conducted over the last decades that investigated envelopment and the influence of the energy direction.
Most studies lead to the suggestion that the late lateral energy is decisive [2,3,4,], i. e. late energy from the sides (or in a figure-of-eight oriented to the side). Others argued, that the relationship of frontal and rear late energy is more accurate [5,6].
An influence of late energy from above, i. e. the ceiling, was claimed only by one group of researchers [7]. Thus, the importance of late reverberation from the rear or the ceiling is not clarified.
Nevertheless, the predictor late lateral level $L_{J,}$ is currently accepted and included in the international standard ISO 3382-2 [8].

Further studies found that the time limit introduced to separate early and late sound should be frequency dependent [10]. Two studies pointed towards the notion that IACC, a binaural value that should well predict the amount of envelopment, lacked information about the level or strength of the reverberation [11, 12]. Since IACC is level-insensitive this cannot be predicted properly.

More recently, this author employed the state of the art re-synthesis method SDM, developed at Aalto University[13], to conduct a study about envelopment [14]. With 24 speakers and 3D-sound fields from existing halls it probably offers as close a representation as possible. In the study, it was found that listeners actively increased late energy from the rear and ceiling when asked to set an unknown sound component to their preference, see Figure 1. This increase was larger for a vineyard shaped hall. The perceptual results were not predicted well by late lateral level L_J as the rear and ceiling energy were underestimated.

The research in the following article has also been documented in the PhD thesis of the author[15].

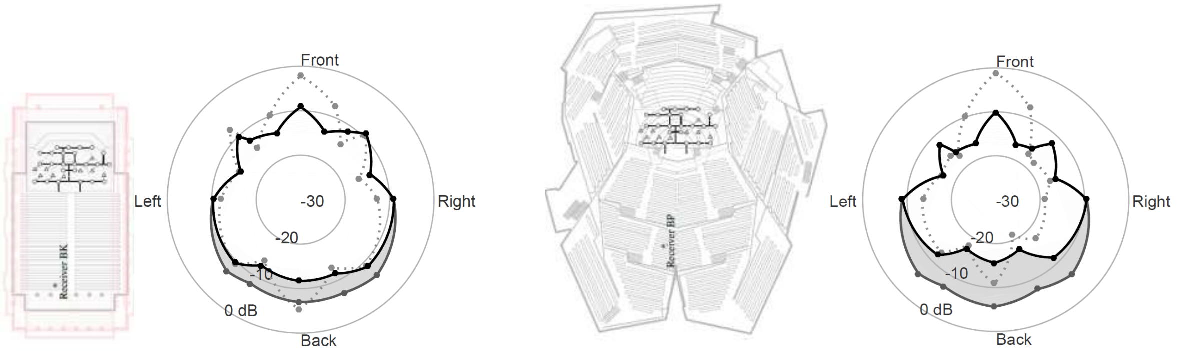
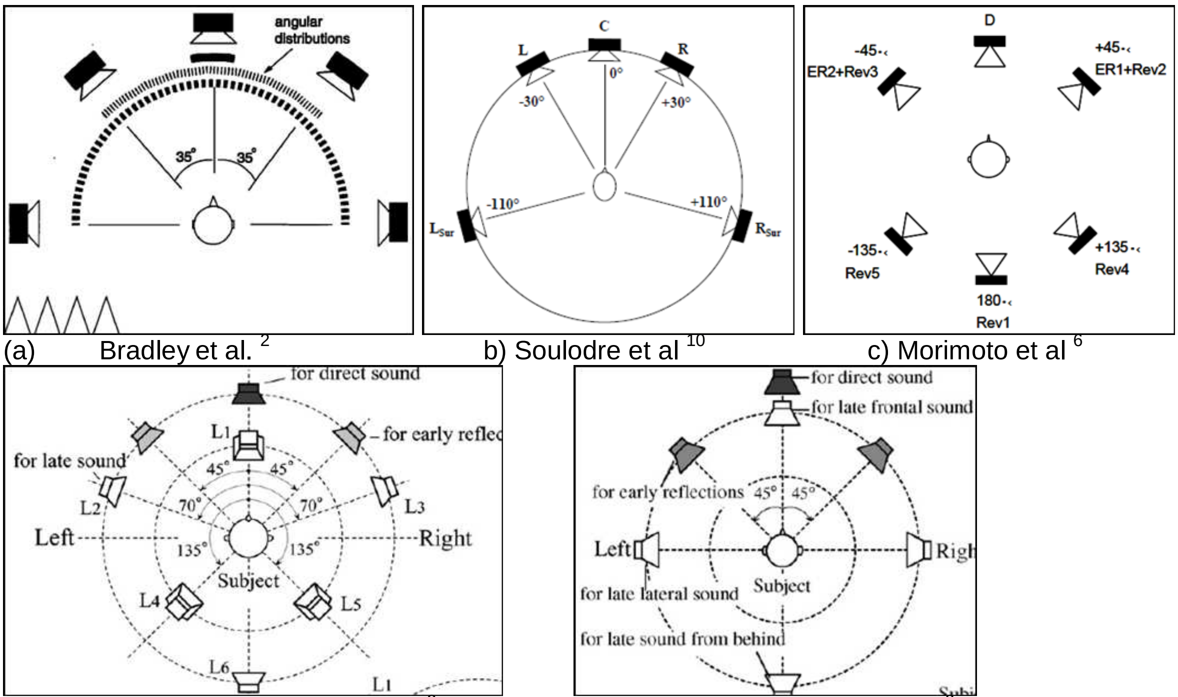


Figure 1, Spatial plot for rectangular Berlin Konzerthaus (left) and vineyard B. Philharmonie (right). Late energy (80 ms – inf) for the original situation in solid black. Participants adjustments in shaded grey (Dotted grey lines show early energy), from [14].

2 SEMI-VIRTUAL TEST ENVIRONMENT

Most of the mentioned studies relied on laboratory testing with setups as shown in Figure 2. Due to the technical limitations of the time, a lot of these setups did not have a spatially equal distribution of loudspeakers all around the listener. These gaps in the sound field can be problematic. Without a speaker, i. e. energy in a certain direction, one cannot judge the influence of reverberation from that direction on envelopment. For instance, the measure L_J was initially derived from experiments without ceiling loudspeakers. It is also not clear if the energy per “spatial angle” was similar enough between directions. E.g. this is surely not the case if reverberation from one frontal speaker is compared to two lateral speakers even if the sound level or energy is matched.



(a) Bradley et al. [2]   b) Soulodre et al [10]   c) Morimoto et al [6]

(d) Furuya et al., Experiment 1 [8]   e) Furuya et al., Experiment 2 [8]

Figure 2, Typical laboratory setups from previous envelopment experiments.

The experiments in this article were conducted in semi-virtual acoustic environments, i.e. the sound field in a real existing room was enhanced by the use of an electronic room acoustic system. Such systems are commercially available and applied for variable acoustics. However, these systems have rarely been used for scientific perceptual studies. Thus, two experiments about envelopment have been conducted with the system VIVACE, developed by Müller-BBM ASO. The convolution based in-line module was used. Multi-channel impulse responses for the convolutions in VIVACE are based on impulse responses measured in real rooms.

Both experiments were designed as paired comparison tests which facilitate the discrimination of differences. The listener had to compare each possible pair of stimuli and pick the more enveloping. A ranking was the established with the most and least enveloping stimuli. Envelopment was defined as the feeling of being surrounded by sound. Strength *G* and late lateral level L_J have been evaluted. Directional impulse response measurements where done with the IRIS system.

3 EXPERIMENT 1: LECTURE HALL

3.1 Setup

In experiment 1, a lecture room with room dimensions of 20.5 x 11.5 x 3.3 m and a room volume of 770 m³ was used. The real reverberation time in the room was 0.7s at mid-frequencies. Lightly upholstered stackable seating present was present. For the experiment, a “direct sound” loud speaker (Genelec 8030A) was placed at a distance of ca. 9.6 m in front of the listener.

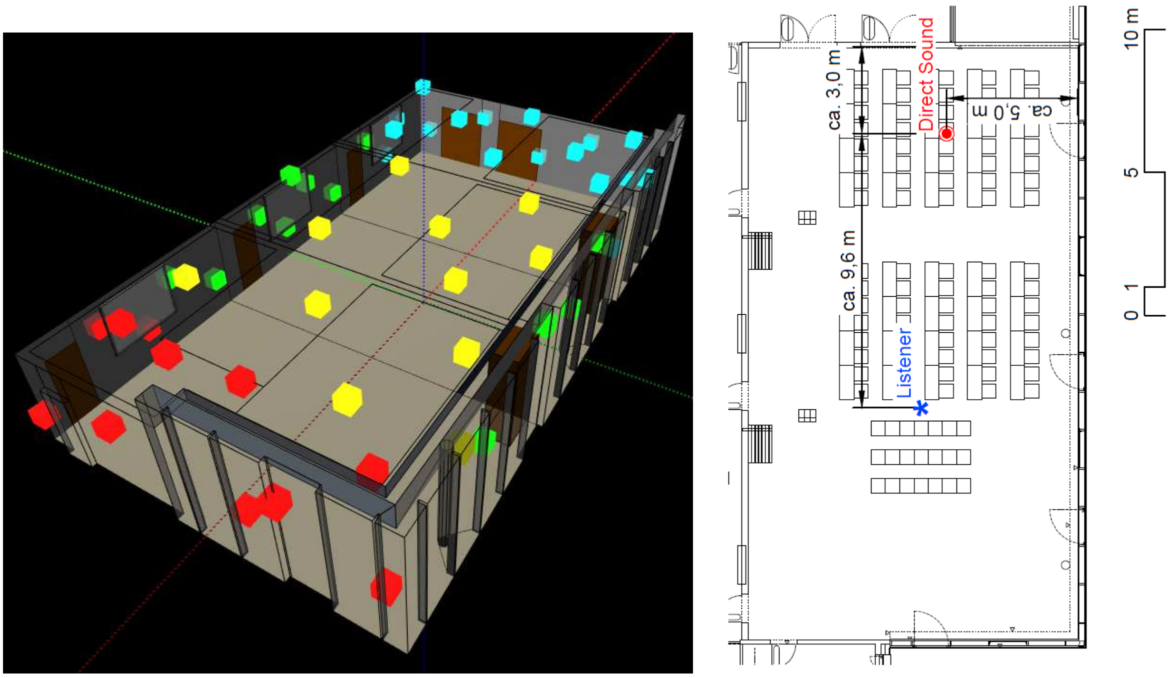


Figure 2, Left: 3D-Model Lecture Hall with loudspeakers and directional late energy groups (colored): “front” speakers (blue), “rear” speakers (red), “side” speakers (green) and “ceiling” speakers (yellow). Right: Ground plan of the lecture hall with the test setup.

A clapping sound was presented as a stimulus because prior testing showed that it provided good cues while still being realistic and relevant to the context. The clapping sequence was an anechoic recording of five similar claps and 4.0 s seconds long, played on continuous loop. A reverberation tail was audible with enhancement on due to a short gap with silence (sequence length 5.5 s before repetition).

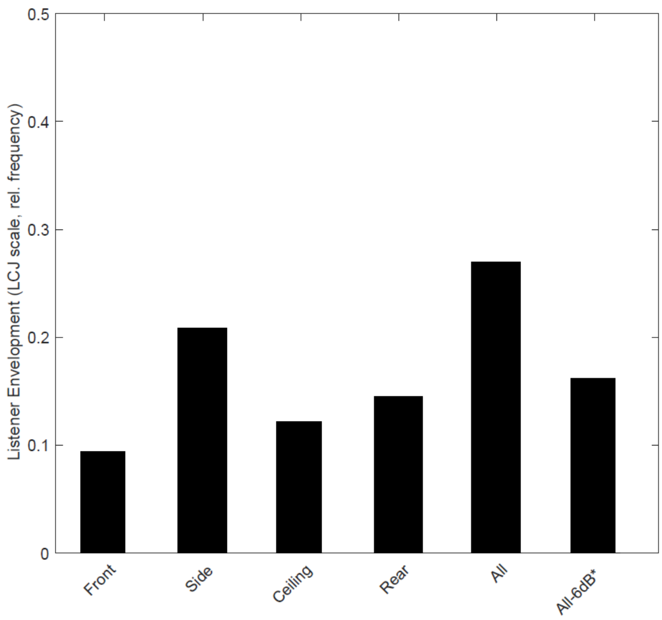
The VIVACE processor was used to create artificial reverberation from the line signal input, only adding reverberation energy to the room after 80 ms.
The 52 loudspeakers in the room were divided in four groups and accessed by four VIVACE engines to corresponding room directions "Front", "Side", "Ceiling", "Rear". The speaker distribution can be seen in Figure 3 on the left. There were an equal number of speakers for each of the four groups, i.e. 13 speakers per direction. Individual speakers were matched regarding level, frequency response and delay. Next, levels between the four directional groups were matched with white noise. The setting was somewhat further refined with the stimulus playing. Clarity C80 was matched as close as possible without altering the stimulus SPL. This was not fully achieved (difference of ca. +-1 dB). Final stimulus levels for the four groups were at L_{Aeq} 60.6 dB +- 0.3 dB. Additionally, there was a setting with all four engines active, i. e. late energy from all directions played simultaneously (L_{Aeq} = 65.6 dB, $L_{AF,max}$ = 72.8 dB) as well as a setting with all directions active but quieter (named "All-6dB"), in order to normalize to the sound strength to the other stimuli.

20 Müller-BBM employees took part in the test (average age 42 years) and completed the task within 11 minutes. Half of the participants could be considered expert listeners due to year-long training in room acoustics and/or listening experience.

3.2 Results

The results from the listening test are shown in Figure 3, left. It can be concluded that the overall reverberation level is dominant for listener envelopment. Late reverberation from the side is rated as second most enveloping, followed by the normalized uniform distribution ("All-6dB") and then rear, ceiling and front reverberation.

Measurement results for late energy, omnidirectional and lateral only, are shown in Figure 4, right. It can be seen that the trend is predicted in accordance with the test results for both parameters.
On closer inspection it can be seen that "side" energy is more accurately rated with late lateral level L_J as expected.



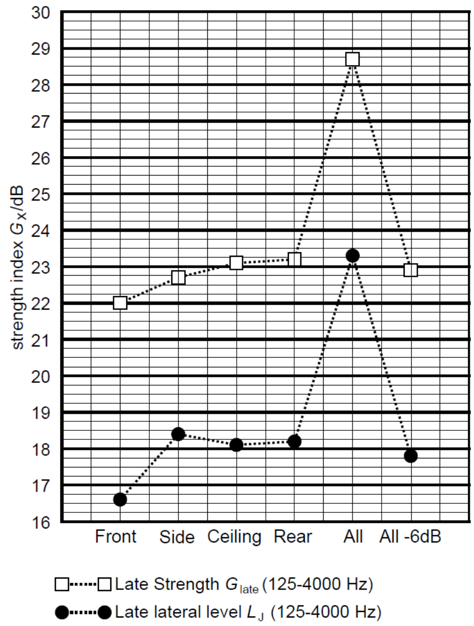


Figure 3, Left: Envelopment (LEV) for different directions of added late energy. Right: Late sound strength and late lateral level for the different late energy directions (power reference estimated).

4 EXPERIMENT 2: CHAMBER MUSIC HALL

4.1 Setup

The second experiment was set in a chamber music hall and thus presents a more practical context. The venue was the concert hall of the Musikhochschule Detmold (music conservatory). With room dimensions of 34 m x 18 m x 6 to 9 m the room volume amounts to ca. 4150 m³ and seats 590 audience members. The reverberation time T_{30} was 1.6 s at mid-frequencies, rising slightly towards low frequencies.

Three loudspeaker types were used: Discrete wall speakers in the rear of the hall, discrete ceiling speakers and Wave-Field-Synthesis (WFS) loudspeakers along the walls. From these loudspeakers, 64 channels of real and virtually created WFS loudspeakers were accessed for the VIVACE enhancement output. The four directional groups of loudspeakers are shown in Figure 4. All speakers were adjusted in level, spectrum and delay.

The levels between loudspeaker groups at the experiment listening position were further adjusted with pink noise. Also, early-to-late energy ratio (clarity C80) was matched as close as possible between the four groups by adjusting the level and spectrum of each reverberation engine. Only late reverberation was added, i. e. energy after 80 ms.

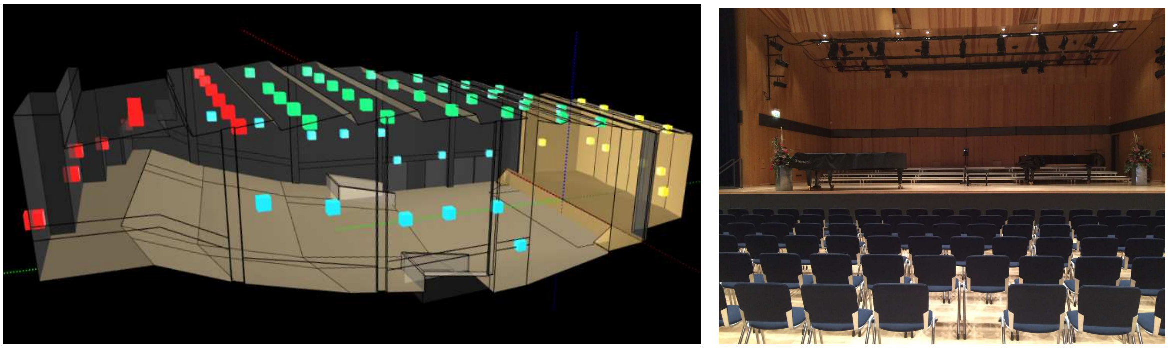


Figure 4, Left: 3D-Model of the Konzerthaus with loudspeakers and directional late reverb groups (colored): “front” speakers (yellow), “rear” speakers (red), “side” speakers (blue) and “ceiling” speakers (green). Right: View towards the stage from the listening position.

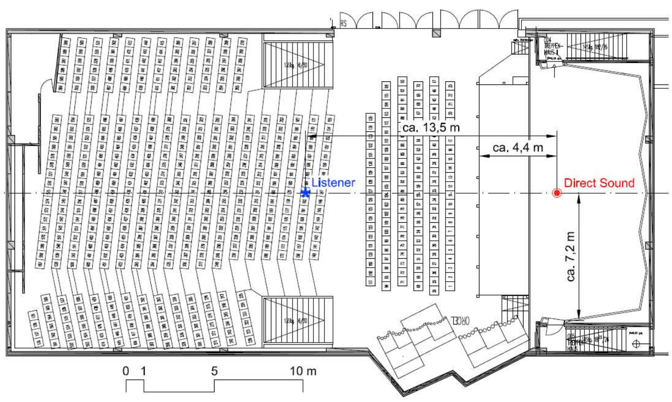


Figure 5, Groundplan of the Konzerthaus with the setup for experiment 2.

The audio stimulus was an anechoic saxophone recording without many dynamic changes. The duration of the audio file was 37 s. The signal was played back on the center of the stage with a directional studio loudspeaker as a direct sound source (Neumann KH120A). The listening position was located ca. 13.5 meters away in the audience area, see Figure 5. The sound pressure level of the direct sound was set to offer a plausible listening impression (L_{Aeq} = 55 dB, $L_{AF,max}$ = 67 dB). None of the participating audio engineers mentioned this as being too loud or quiet.

The audio playback was done with a RME Madiface XT with analog outputs leading to the direct sound speaker and digital MADI output through VIVACE to the reverberation loudspeakers.
After the test design was finalized, the 64 VIVACE output channels were recorded.
digitally for each stimulus as 64 ch - wave files. A MaxMSP patch for paired comparison accommodated the 64 ch-files/outputs and allowed for smooth playback of the stimuli at the push of a button.

The resulting listening levels for the four directional groups ranged from L_{Aeq} 59.4 dB to 60.7 dB, i.e. almost within a just-noticeable-difference. With all reverberation engines active (setting "All") a SPL of 62.3 dB was reached. Background noise level was measured at L_{Aeq} = 20.5 dB.

A paired-comparison design was used - similarly as in the previous experiment. The participant rated each pair of stimuli for more envelopment. The judgment "the same/no difference" could also be given. The audio files were playing on a loop and could be switched seamlessly. The order was randomized for every participant. Each stimulus was rated twice (10 x 2 = total of 20 comparisons).

A short training session of five minutes was completed with every participant to ensure proper understanding. The stimuli from the training also appeared in the test but in a different order. In total, 12 participants took part in the listening test (10 male, 2 female, average age 27 y), eight of which were Tonmeister/ audio engineering students at least 2 years into their studies and thus to be considered expert listeners. The task took an average 11.5 min to complete.

4.2 Results

The results can be seen in Figure 5, left. The probability for a stimulus to provide maximum envelopment is shown. The stimulus "All", with all four directions being played back at the same, time is rated the highest, according to expectation. From the directional groups "side" reverberation is again the most effective, however, not very different from "rear" reverberation. It is followed by "ceiling" and "front" late energy. Comparing the magnitudes, reverberation from behind would be approximately 80% as effective as the "side reverberation" and "ceiling" ca. 35% as effective in terms of LEV.

Directional measurements with a 6-ch-microphone probe and evaluation with the SDM offered a computation of late lateral Level L_J and late strength G_{late} (Figure 5, right). Values of late lateral level L_J are very similar between directions and do not follow the trend of the perceptual data well. The reason for this is not apparent. Late strength G_{late} seems to follow the trend more.

5 DISCUSSION

The perceptual results are mostly conclusive. According to both experiments, the highest envelopment can be achieved when the overall late energy is high. Next, the decreasing importance among the spatial directions is side, rear, ceiling and front, which is according to combined literature findings. That means late energy from other directions than the side can contribute to envelopment.

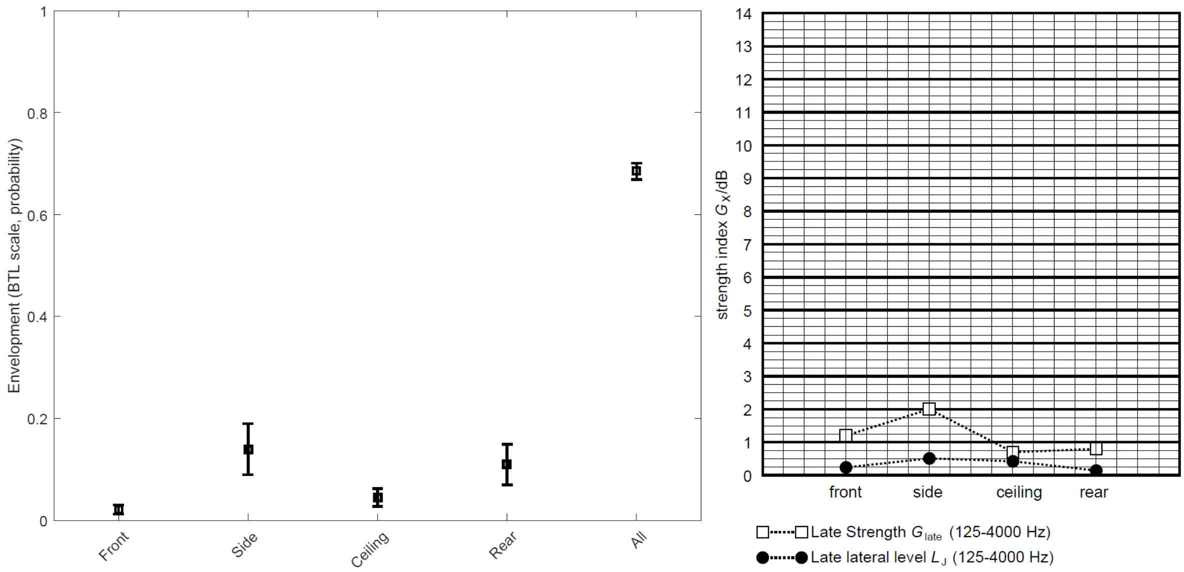


Figure 5, Left: Envelopment for different directions of added artificial late reverberation (n=12 participants, error bars represent +- 1 SE). Right: Late sound strength and late lateral level for the different late energy directions (power reference estimated).

The standardized measure L_J accounts by definition mostly for lateral energy and partly predicts the ranking found in the experiments. In the first experiment in the lecture hall, late lateral level L_J appears to correspond well with the results of the listening test. However, in the second experiment L_J values are almost the same between directions despite perceptual differences between directions. Omnidirectional late strength follows somewhat better. Overall, the measurement results are not fully conclusive and need further evaluation.

For experiment 1, interaural cross-correlation coefficient IACC was calculated from binaural impulse responses that were measured with a dummy-head and then analyzed over time (not shown). Highest IACC values were calculated for late energy from the front, followed by late energy from all directions (“All”) and then side reverberation. However, perceptual results show that the late energy from all directions (“All”) offers most envelopment. Thus, IACC which is insensitive to reverberation level, does not perform well here. Similar observations have been made by other researchers.

Interestingly, the changes in late energy directions are not audible as such - almost no participant noticed what was actually altered. Only some changes in reverberance and spectrum were mentioned, particularly when playing all reverberation engines at the same time. Likewise, the overall late energy level is very important for envelopment.

While the semi-virtual setup provides an interesting and realistic environment for these experiments, it appears challenging to control in terms of sufficient experimental comparability. The overlap of the real and virtual sound fields is somewhat chaotic as for instance secondary “real” reflections can arise from the virtual reflections from the loudspeakers. Creating comparable requires several iterations.

6 CONCLUSION

Envelopment as an important quality factor for room acoustics has been investigated in semi-virtual environments. As expected, late energy from the side is most important in terms of spatial directions. However, late energy from behind and above the listener can also contribute to envelopment. Overall late energy appears dominant in comparison to the effect of the direction.

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7 REFERENCES

1. L. L. Beranek, Concert Halls and Opera Houses: Music, Acoustics and Architecture.New York: Springer, 2004, p. 30
2. J. S. Bradley and G. A. Soulodre, “The influence of late arriving energy on spatial impression,” Journal of the Acoustical Society of America, vol. 97, no. 4, pp. 2264–2271, 1995.
3. J. S. Bradley and G. A. Soulodre, “Objective measures of listener envelopment,” Journal of the Acoustical Society of America, vol. 98, pp. 2590–2597, 1995.
4. P. Evjen, J. S. Bradley, and S. G. Norcross, “The e_ect of late reflections from above and behind on listener envelopment,” Applied Acoustics, vol. 62, pp. 137–153, 2001.
5. M. Morimoto and K. Iida, “A new physical measure for psychological evaluation of a sound field: Front/back energy ratio as a measure of envelopment,” Journal of the Acoustical Society of America, vol. 93, no. 4, p. 2282(A), 1998.
6. M. Morimoto, K. Iida, and K. Sakagami, “The role of reflections from behind the listener in spatial impression,” Applied Acoustics, vol. 62, pp. 109–124, 2001.
7. H. Furuya, K. Fujimoto, and A. Wakuda, “Psychological experiments on listener envelopment when both the early-to-late sound level and directional late energy ratios are varied, and consideration of calculated lev in actual halls,” Applied Acoustics, vol. 69, pp. 1085–1095, 2008.
8. DIN EN ISO 3382-1:2009-10, “Acoustics – Measurement of room acoustic parameters – Part 1: Performance spaces,” October 2009.
9. T. Hanyu and S. Kimura, “A new objective measure for evaluation of listener envelopment focusing on the spatial balance of reflections,” Applied Acoustics, vol. 62, pp. 155–184, 2001.
10. G. A. Soulodre, M. C. Lavoie, and S. G. Norcross, “Objective measures of listener envelopment in multichannel surround systems,” Journal of the Audio Engineering Society, vol. 51, no. 9, pp. 826–840, 2003.
11. G. A. Soulodre, “New objective measures of listener envelopment,” in the 18th International Congress on Acoustics (ICA), pp. 2465–2468, 2004. paper no. Th2.B1.5, Kyoto, Japan, 2004 April 4-9.
12. L. L. Beranek, “Listener envelopment LEV, strength G and reverberation time RT in concert halls,” in the 20th International Congress on Acoustics (ICA), 2010. paper no. 296, Sydney, Australia, 2010 August 23-27.
13. T. Lokki, “Tasting music like wine: Sensory evaluation of concert halls,” Physics Today, vol. 67, no. 1, pp. 27–32, 2014.
14. W. Lachenmayr, A. Haapaniemi, and T. Lokki, “Direction of late reverberation and envelopment in two reproduced Berlin concert halls,” in the 140th Convention of the Audio Engineering Society, 2016. paper no. 9503, Paris, France, 2016 June 4-7.
15. W. Lachenmayr. Perception and Quantification of Reverberation in Concert Venues. PhD thesis, Hochschule für Musik Detmold, Germany, 2017