TOWARDS AN IN-SITU PERCEPTUAL EXPERIMENT IN EARLY REFLECTION LEVELS IN A CONCERT HALL

Otavio Colella Gomes[1], Jithin Thilakan[2], Malte Kob[1]

[1] *Erich Thienhaus Institut, Hochschule für Musik Detmold*
[2] *Institute for Hearing Technology and Acoustics, RWTH Aachen*

Abstract

The perceptual characteristics of early reflections in concert halls have been extensively studied using controlled experiments based on measured or simulated spatial room impulse responses (SRIRs). In contrast, the present study adopts an in-situ approach, in which participants were invited to the Detmold Concert Hall to evaluate perceptual changes induced by controlled modifications of the sound field. The hall's wave field synthesis (WFS) system, consisting of 300 flat-panel loudspeakers, was used to introduce first-order early reflections. It was hypothesized that artificially increasing early reflection levels would lead to measurable enhancements in perceptual attributes. Contrary to expectation, clarity decreased with increasing reflection level, indicating that both early and late reflections were affected by the modifications. Analysis of the SRIRs using the Spatial Decomposition Method (SDM) revealed an increase in late reflection energy, possibly related to loudspeaker directivity. The WFS system is primarily designed for artificial reverberation (i.e., diffuse late reflections), and the results highlight its sensitivity when used to modify early reflections in reflective environments. Despite these deviations, psychometric analysis revealed distinct discrimination thresholds in the *Discrimination* task that increased across reflection configurations, whereas judgments of perceptual attributes (*Clarity*, *Width*, *Envelopment*, and *Loudness*) exhibited weaker trends.

Keywords: *early reflections, perceptual evaluation, listening test*

1. Introduction

Early reflections play an important role in the perception of concert hall acoustics. Their physical characteristics, such as level, delay, direction and frequency response influence several perceptual attributes, including perceived Loudness, Clarity, spectral characteristics and spatial impression.

Spatial Impression is commonly described in terms of Apparent Source Width (ASW) and Listener Envelopment (LEV). Early lateral reflections are particularly associated with ASW [1], [2], whereas LEV is more strongly related to late lateral energy [3]. Early and late reflections are perceptually interdependent. Increased early energy can mask later reflections, reducing the perception of reverberation (running reverberation) and LEV, whereas sufficiently strong late lateral energy can reduce sensitivity to early lateral reflections and consequently reduce perceived ASW. There is evidence that early reflections are generally a stronger masker than the late ones [3], [4], [5]. The perceptual consequences of a single reflection depend strongly on its delay, level, incidence direction, stimuli, listening level, and interaction with the surrounding sound field [5], [6], [7], [8].

Different experimental designs have found varied thresholds for the perception of early reflections. When experiments are conducted under simplified conditions, the perceptual threshold of a single early reflection is between approximately −10 and −25 dB relative to the direct sound, depending on signal, delay, and direction [1], [7], [9], [10]. When reflections are embedded in a complex or reverberant sound field, the found thresholds are closer to the direct sound level [11], [12]. In a recent study, a single lateral reflection arriving approximately 20 ms after the direct sound was evaluated using measured SRIRs from a chamber music hall. The threshold in this more realistic sound field was approximately −2.11 dB relative to the direct sound [13].

Most perceptual studies on early reflection perception have been conducted under controlled conditions. Early studies were performed under simplified conditions with loudspeakers in an anechoic space to synthesize the direct sound and discrete reflections

Corresponding author: *otavio.colella@gmail.com.*

[1], [6]. Later studies increased the complexity of the experiments using complete simulated room responses, multichannel loudspeaker reproduction, and binaural virtual acoustic environments [3], [7], [11], [12]. These approaches provide a high degree of experimental control, but the evaluated sound field remains either synthetically reproduced or simulated rather than a physical modification to the sound field of an existing concert hall.

In-situ perceptual research using active acoustics has more commonly addressed changes to reverberation and the late sound field, while active acoustics experiments specifically addressing early reflections have generally been conducted in anechoic environments, controlled listening rooms, or comparatively low reverberation spaces [14], [15]. Enhancing early reflections with an active acoustic system in a concert hall, however, presents an additional challenge: the loudspeakers reproducing the reflections also act as additional acoustic sources, and their radiation pattern can excite the hall beyond the intended single reflection depending on their directivity, position, and distance from the listening area. One approach that could avoid such complications is the use of open or acoustically transparent headphones, which allow listeners to remain in the physical room while controlled virtual acoustic conditions are reproduced binaurally [16], [17]. To the authors' knowledge, however, no previous perceptual experiment has systematically varied the level of controlled early reflections physically introduced into the sound field of an existing concert hall.

To assess the perceptual consequences of the reflection manipulations, listeners evaluated *Clarity*, *Width*, *Envelopment*, and *Loudness*, four principal perceptual dimensions of concert hall acoustics [18]. *Reverberance* was not included because the experiment was designed to manipulate early reflections rather than the late reverberant field.

Here, individual early reflection level was manipulated directly using the Wave Field Synthesis (WFS) system installed in the concert hall. Selected reflections were reproduced at progressively increasing levels, either individually or simultaneously, while listeners compared the modified and unmodified hall responses in terms of *Discrimination* and the four perceptual attributes introduced above. Room acoustic measurements of the different acoustic conditions were used to verify the direction and arrival time of the added reflections and to determine whether the modification remained confined to the intended early reflection window. The experiment is intended as a first step towards an in-situ methodology for investigating early reflection perception under the acoustic conditions of a real concert hall.

2. Methodology

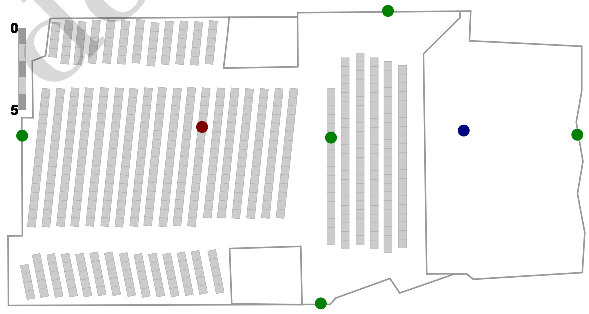
2.1. Venue and Reproduction System

The experiment was conducted at the Konzerthaus Detmold (KHD), a 4150 m^3, 600 seat concert hall with a 1.1 m high stage and an average EDT of 1.3 s across the 500 and 1000 Hz octave bands. The hall is equipped with an IOSONO WFS system with over 300 loudspeakers, including Multi Actuator Panels (MAPs) integrated into the walls surrounding the stage and audience area and discrete ceiling loudspeakers. The system was primarily designed for active acoustic enhancement, including the extension of the reverberant response of the hall.

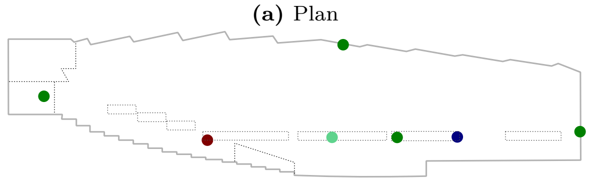
The system supports object-based reproduction using plane-wave synthesis or point-source rendering. Preliminary tests showed that plane-wave reproduction, which activates a large portion of the array, substantially altered the hall's reverberant response. Point-source rendering was therefore used, with only the loudspeakers closest to the desired reflection position activated.

2.2. Acoustic Configurations

A Neumann KH120 studio monitor was positioned on stage at a height of 1.5 m, 1 m from the hall centre axis and 2 m from the stage edge. The listening position was located 15 m from the source. An anechoic trumpet recording was used as the stimulus [19]. The studio monitor was selected instead of an omnidirectional dodecahedron to better approximate the directivity characteristics of the trumpet [20]. System latency was measured and compensated.



(a) Plan



(b) Long Section

Figure 1: KHD: main source (blue), approximate added reflection positions (green), and listening position (red).

Five audio-object positions approximately corresponding to selected first order reflections were created using point-source rendering: *Ceiling* (15 ms), *Left* (20 ms), *Right* (30 ms), *Back Stage* (46 ms), and *Rear* (67 ms), with delays given relative to the direct sound. Their approximate positions are shown in Figure 1.

Three configurations were evaluated: a single *Left* reflection, a single *Ceiling* reflection, and all five reflections simultaneously (*All Five*). Eight reproduction gain settings were tested per configuration: -18 to -4 dB in 2 dB steps for *Left*; -16 to -2 dB in 2 dB steps for *Ceiling*; and -20 to -16 dB in 1 dB steps followed by -14, -12, and -10 dB for *All Five*. The ranges were selected during a pilot test to cover conditions from perceptually negligible to clearly audible modifications.

2.3. Listening Experiment

Ten students from the Tonmeister program at HfM Detmold participated in the test. All participants were trained in musical and technical hearing, with previous formal listening test experience. The experiment was completed with all participants simultaneously in the hall. They occupied two rows of five adjacent seats within an approximately 2 m $\times$ 1.5 m region centered on the nominal listening position.

A pair of audio samples was presented to the participants, which consisted of a reference and a probe. The reference contained only the main source without added reflections, whereas the probe varied according to reflection configuration and level. The experiment consisted of A/B comparisons in which participants first judged whether the samples were the same or different (*Discrimination*) and then indicated which of the two presented samples had greater Clarity, Width, Envelopment, and Loudness. The *Discrimination* response was mandatory, whereas the attribute responses could be left blank when no reliable difference was perceived. There were 24 A/B pairs, each presented three times, resulting in 72 presentations evaluated simultaneously by the group of listeners. Participants could request an extra replay of the current pair before responding.

Configuration order was fixed as *Left*, *Ceiling*, and *All Five*; reflection levels and A/B assignment were randomized within each configuration. The reference level at the listening position was $L_{\text{Aeq}} = 72.6$ dBA. The playback level (L_{Aeq}) of every trial was also registered and a ΔL_{Aeq} was computed as the difference in level of the probe and reference.

2.4. Room Acoustic Measurements

Spatial room impulse responses (SRIRs) were measured in the unoccupied hall for the unmodified reference condition and for each experimental configuration (including different levels). SRIRs of each of the five individual reflections were also measured. A G.R.A.S. 50VI-1 vector intensity probe with a 25 mm spacer was positioned at the nominal listening position, and a four second exponential sine sweep was used as the excitation signal.

Conventional room acoustic parameters were calculated according to ISO 3382-1 where applicable [21], together with spatial descriptors derived from the SRIRs. Because no free-field calibration measurement was available, Strength was evaluated relatively using the direct sound energy within the first 5 ms of the reference response, geometrically corrected to a distance of 10 m. The resulting values are therefore interpreted as relative rather than absolute ISO 3382-1 compliant Strength values. The analysed parameters were G_{rel}, $G_{\text{early,rel}}$, $G_{\text{late,rel}}$, C_{80}, EDT, J_{LF}, L_J, and $IACC_{\text{early}}$. Changes in early and late energy were quantified using $G_{\text{early,rel}}$ and $G_{\text{late,rel}}$, with the response divided at 80 ms after the direct sound arrival.

The measured SRIRs were additionally analysed using the Spatial Decomposition Method (SDM) [22]. SDM was used to verify the approximate direction and arrival time of each reproduced reflection and to inspect whether the artificially added early reflections also introduced energy beyond the intended early arrivals. The SDM estimates were additionally summarized into azimuthal sectors using the spatial energy analysis (simplified SDM) described in [23].

Finally, the 3D radiation characteristics of a representative MAP transducer were also independently measured in an anechoic chamber to evaluate the directional behaviour of the reproduction system.

2.5. Statistical Analysis

Perceptual responses were analysed using generalized linear mixed-effects models (GLMMs) with a binomial distribution and logit link. The measured level increase ΔL_{Aeq} and reflection configuration were included as fixed effects, with participant as a random intercept. Discrimination responses were coded as 0 for *same* and 1 for *different*. Attribute responses were coded as 1 when the added reflection condition was judged higher in the evaluated attribute and 0 when the reference was judged higher. Unanswered attribute responses were excluded from the models and additionally analysed as a binary measure of perceptual uncertainty.

For the *Discrimination* task, psychometric functions were fitted separately for each reflection configuration and used to estimate the ΔL_{Aeq} corresponding to a 50% probability of a *different* response. An exploratory PCA was performed on the standardized objective acoustic parameters, with mean perceptual responses for each reflection configuration and level projected as supplementary variables.

Clarity judgments were then compared with changes in C_{80} expressed in units of the adopted 1 dB JND. Binomial GLMMs were used to evaluate whether the magnitude of the C_{80} change affected the probability of unanswered responses and whether the signed C_{80} change predicted the probability of judging the modified condition as clearer.

3. Results

3.1. Objective Effects of Added Reflections

Figure 2 shows systematic changes in the measured parameters with increasing modified reflection levels, described here by the ΔL_{Aeq}. Most parameters increased with reflection level, while C_{80} decreased and $IACC_{\text{early}}$ depended more strongly on the configuration. The smallest changes were generally found for *Ceiling*. The largest changes in C_{80}, EDT, and J_{LF} occurred for *Left*, while *All Five* produced the largest changes in L_J and $IACC_{\text{early}}$.

The SDM results confirmed that the expected arrival times and directions of the targeted reflections were correctly reproduced. However, the overall acoustical change was not limited to early energy. $G_{\text{late,rel}}$

increased in all three configurations and showed a steeper relative increase than $G_{\mathrm{early,rel}}$. The simplified SDM analysis of the late energy (Figure 3) confirmed the increase in energy after 80 ms and showed that

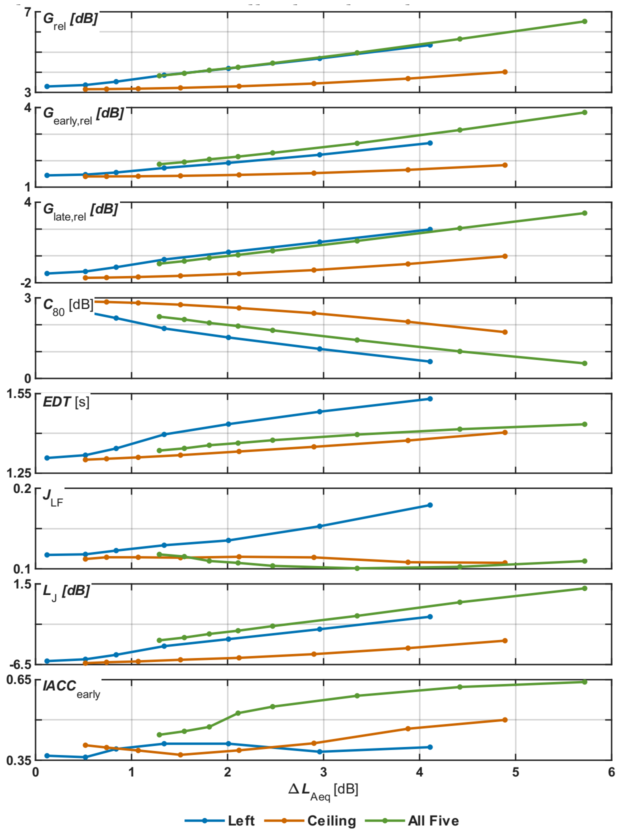


Figure 2: Selected acoustic parameters versus measured level increase ΔL_{Aeq} for the three reflection configurations.

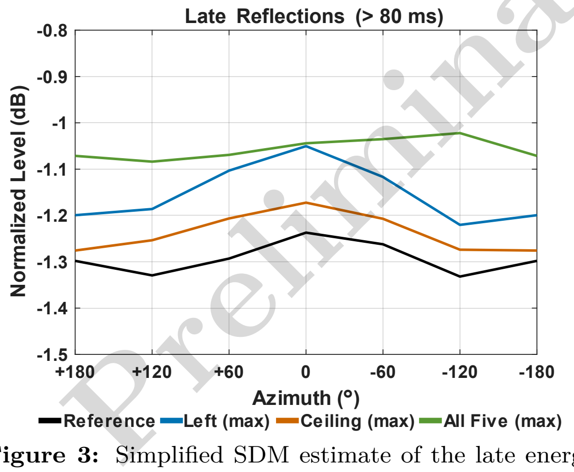


Figure 3: Simplified SDM estimate of the late energy (> 80 ms) for the reference and the maximum modification level of each reflection configuration.

Figure 4 shows the horizontal directivity (around the transducer at a fixed height) relative to the forward direction of the representative MAP transducer. The radiation pattern becomes increasingly complex above approximately 500 to 1000 Hz, with multiple pronounced off-axis lobes indicating substantial radiation outside the forward direction. This complex multi-directional radiation can excite the room beyond the desired individual reflection path.

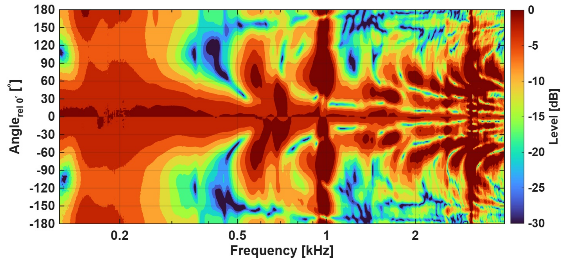


Figure 4: Horizontal directivity of the representative MAP transducer, normalized to the on-axis response.

3.2. Perceptual Effects

The clearest level dependent perceptual effect was observed for *Discrimination*. When responses from all three reflection configurations were analysed together, the probability of a *different* response increased significantly with reflection level ($\beta = 1.66$, $p < 0.001$). Configuration specific psychometric functions yielded 50% *Discrimination* thresholds at $\Delta L_{\mathrm{Aeq}} = 0.36$, 0.73, and 1.29 dB for *Left*, *Ceiling*, and *All Five*, respectively. For the two single-reflection configurations, these corresponded to reflection levels of approximately -6.01 and -3.83 dB relative to the direct sound. An equivalent reflection-to-direct-sound ratio was not defined for *All Five*. These thresholds represent the level increases at which the modified condition was judged as *different* from the reference in 50% of the comparisons. Among the specific attributes, only *Clarity* changed significantly ($\beta \approx -0.65$, $p = 0.003$), with the added reflection condition increasingly judged as less clear. No significant overall trends were found for *Width*, *Envelopment*, or *Loudness*.

The proportion of unanswered attribute responses decreased with reflection level, consistent with increasing confidence in assigning the perceived differences to specific attributes.

Figure 5 shows the exploratory PCA, in which the first two components accounted for 97.9% of the variance in the objective parameters. The main energetic and reverberant changes were represented by PC1: G_{rel}, L_J, and EDT pointed in one direction, with C_{80} in the opposite direction. J_{LF} was primarily represented by PC2, while $IACC_{\mathrm{early}}$ contributed to both components. The projected *Discrimination* responses followed the dominant dimension of acoustic change, while *Clarity* was more closely aligned with C_{80}. The remaining perceptual attributes showed weaker associations in the combined projection.

Because *Clarity* was the only attribute with a significant overall level effect and was most closely related to its expected objective descriptor, the judgments were compared with differences in C_{80} expressed in JND normalized units. Two aspects of the responses were examined separately. First, increasing the magnitude of the objective difference, $|\Delta C_{80}|$, significantly reduced the probability of an unanswered *Clarity* response ($\beta = -3.02$, $p < 0.001$). Second, among the answered comparisons, signed ΔC_{80} significantly pre-

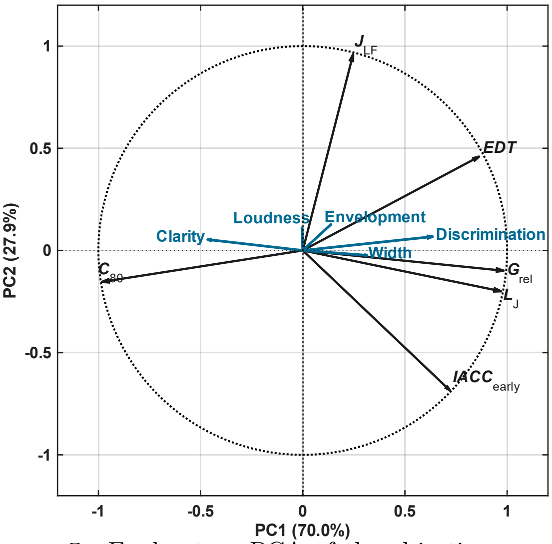


Figure 5: Exploratory PCA of the objective acoustic parameters with mean perceptual responses projected as supplementary variables.

dicted which condition was judged clearer ($\beta = 1.69$, $p = 0.002$), with listeners generally selecting the condition with the higher C_{80}. For the *Left* configuration, the condition with the higher C_{80} was selected as clearer in 75% of answered comparisons when the objective difference reached approximately 0.88 JND.

4. Discussion

The change in level of the added reflections produced a clear effect in perceptual *Discrimination*, while the effects on the other perceptual attributes were less uniform. *Clarity* was the only attribute that changed significantly with reflection level, decreasing as the added reflection became stronger. *Width*, *Envelopment* and *Loudness* showed no significant overall trends, although the decreasing proportion of unanswered responses indicated greater confidence at higher reflection levels. For the *Left* configuration, when the difference in C_{80} approached one JND, people rated the higher C_{80} condition as clearer in approximately 75% of the answered comparisons. Both *Discrimination* and *Clarity* were associated with the dominant PCA dimension, but in opposite directions.

The 50% *Discrimination* threshold differed across configurations. The *Left* and *Ceiling* reflections reached this point at approximately -6.0 and -3.8 dB relative to the direct sound, respectively, whereas *All Five* required an overall increase of $\Delta L_{\mathrm{Aeq}} = 1.29$ dB. These thresholds are closer to the direct sound than those commonly reported for isolated reflections, but are consistent with studies using complete reverberant sound fields. Their differences indicate that early reflection thresholds must be interpreted in relation to direction, delay, reproduction method, and the surrounding sound field. The *Left* threshold also occurred at a lower reflection level than the -2.11 dB previously obtained for a lateral reflection of similar delay using processed SRIRs [13]. In that experiment, the reflection level modification was isolated from the rest of the response, whereas here, it affected the broader room response, which may have contributed to the lower threshold.

The acoustic effects of the manipulation were not restricted to the intended early reflection window. Although $G_{\mathrm{early,rel}}$ increased as expected, $G_{\mathrm{late,rel}}$ increased more strongly in all three configurations. Consequently, C_{80} decreased and EDT increased despite the added early energy. The SDM analysis supported this interpretation by showing additional energy after 80 ms and across directions beyond those of the intended reflections.

The measured MAP directivity provides a plausible, although not exclusive, explanation for the increase in late energy. Its frequency dependent off-axis lobes could excite other propagation paths, causing energy to return later to the listening area. However, even an ideal loudspeaker with smooth hemispherical radiation would only approximate a wall reflection: a wall redirects the incident wave along a geometric reflection path, whereas a loudspeaker radiates a new wave into the room. The observed MAP radiation likely increased this difference further. Such multidirectional radiation is appropriate for reverberation enhancement, but complicates the reproduction of isolated early reflections. The perceptual results must therefore be interpreted as the combined effects of the intended reflections and their interaction with the existing hall response.

5. Conclusion

This study demonstrated that controlled in-situ manipulation of early reflection levels in a concert hall is feasible and can produce measurable perceptual effects, although the added reflections also interacted with the existing hall response. Increasing reflection level produced clear, configuration dependent discrimination thresholds. Perceived *Clarity* also changed systematically, but in the opposite direction to that hypothesised: rather than improving with increasing early reflection level, it decreased. This indicated that the reproduced modifications were not fully confined to the intended early reflections but also affected the broader sound field. *Width*, *Envelopment*, and *Loudness* showed weaker overall trends. *Discrimination* was associated with the multivariate changes in the sound field, whereas *Clarity* showed the clearest relationship with its expected objective descriptor, C_{80}.

The room acoustic measurements confirmed that the modifications affected both early and late energy, with a larger relative increase in $G_{\mathrm{late,rel}}$, accompanied by increasing EDT and decreasing C_{80}. The measured MAP directivity provides a plausible explanation for this behaviour, since off-axis radiation can excite other propagation paths in the reverberant hall. More generally, reproducing a wall reflection from a loudspeaker position does not reproduce the reflected wavefront itself.

The experiment therefore represents an initial step towards an in-situ methodology for investigating early reflection perception under real concert hall conditions. Future work should improve the isolation of the intended reflection modifications from the influence of the room. Possible approaches include dynamic binaural reproduction using head-tracked acoustically transparent headphones or local loudspeaker arrays positioned close to the listening region. Both approaches could reduce the contribution of the reproduced reflections to the unintended late reverberant field.

6. Acknowledgments

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