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Perceptual Relevance of Location of Reverberation in a Concert Hall

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The Stockholm Concert Hall, a historic shoebox hall from the first half of the 20th century, is the resident hall of the Royal Stockholm Philharmonic Orchestra as well as hosting space for the yearly Nobel Prize Ceremony. Concerns with the acoustic quality of the hall provided an interesting case study regarding the perception of reverberation. The acoustic shortcoming of the hall that concerns us here was a lack of "bloom" and insufficient reverberation time. It turned out that the problem was due to a semitransparent technical ceiling, which was installed under the lighting bridges for practical and esthetic reasons. This semitransparent expanded-metal ceiling created a slight transmission loss both on the "way in" for sound into the volume under the roof and on the "way out." As a consequence no reverberation was heard coming from the top of the room, and the acoustic volume above the semitransparent metal ceiling was acoustically absent. First as a tryout and then as a solution, an electro acoustic enhancement system based on the multiple channel reverberation principle was installed in the volume above the semitransparent ceiling, with microphones picking up the sound under the stretched-metal ceiling and loudspeakers enhancing the sound above the stretched-metal ceiling. During tuning of the system, the location of reverberation—in this case, the gain of individual loudspeaker channels—had very strong perceptual effects. Some locations had a very strong positive effect while others had a negative impact on the acoustic result. The negative impact found in Stockholm Concert Hall is compared with the perceptual effects of excessive frontal background noise, observed in another concert hall.

Keywords: room acoustics, perceptual aspects of room acoustic quality, spatial aspects of sound fields, electro-acoustic enhancement systems, perceptual effects of background noise

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Standard reference texts as well as the International Organization for Standardization (ISO) standard on room acoustic quality (see, e.g., Beranek, 2004; Barron, 2010; and ISO3382-1:2009–focus on temporal distribution of energy [e.g., reverberation time T, G, and C80] and binaural aspects [lateral energy]. Kahle (2013) suggested that this description is insufficient when working with concert halls and that spatial aspects of sound fields need to be taken into consideration beyond binaural aspects. Furthermore, spatial aspects should be considered independently and separately for the foreground stream ("source presence") and the background stream ("room presence"; see, e.g., Kahle, 1995, for details on source presence and room presence). For source presence, lateral reflections have different effects than ceiling reflections; this difference is taken into account by the objective criterion of lateral energy and the subjective factor of apparent source width. For room presence, listeners prefer to be fully enveloped by room sound; when talking to musicians and experienced listeners it is clear that this must not be limited to the frontal hemisphere and the question of lateral energy. All of the room around the listener should be "acoustically active" and this includes the parts of the room above us and behind us. Finally, when accepting the concept of stream segregation into a "foreground source stream" and a "background room stream," a generalization of the cocktail party effect suggests that stream segregation is facilitated when the center of gravity (or direction of arrival) of the source stream is spatially separated from the center of gravity (or direction of arrival) of the room stream. Room reverberation should hence ideally be spatially homogeneous or come from a different direction than the source stream. In this paper, case studies are examined that show how spatial aspects of late sound can influence the perception of early sound and how frontal noise can influence the perception of both source presence and room presence. This suggests that spatial direction of arrival can strongly influence the perception of room acoustic quality.

Case Study: Electro Acoustic Enhancement System in Stockholm Concert Hall

F1 The Stockholm Concert Hall (*Konserthuset*, see Figure 1 for a photo of the hall) had been plagued with acoustic problems for decades (Dahlstedt, 1974) and has undergone several renovations. During the 1972 renovation, an electro-acoustic enhancement system was installed in the hall, but apparently decommissioned after few months of use (Dahlstedt, 1974). The reasons for the decommissioning of the system are unknown, but probably the increase of natural reverberation during the renovation was at the time considered as being sufficient. Further renovations in 2000 and 2005 decreased reverberation time and as a consequence the audibility of the late room response was significantly below optimum after 2005.

AQ: 3 As already indicated, it was found that one of the main reasons for the insufficient reverberance (what musicians described as

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Figure 1. View from the balcony to the stage, Stockholm Concert Hall. See the online article for the color version of this figure.

"lack of bloom") was the presence of a semitransparent technical ceiling installed under the lighting bridges for practical and esthetic reasons. The semitransparent expanded-metal ceiling (which can be seen at the top of Figure 1; Figure 2 shows a more detailed side view) created a slight transmission loss both on the "way in" for sound into the volume under the roof and on the "way out." As a consequence, no reverberation could be heard coming from the top of the room and the ceiling was felt as being acoustically absent.

F2

First as a tryout and then as a final solution, an electro acoustic enhancement system based on the multiple channel amplification of reverberation (MCR) principle (de Koning, 1983–1984; Mulder, 2001) was installed in the volume above the semitransparent ceiling, with microphones picking up the sound under the stretched-metal ceiling and loudspeakers enhancing the sound above the stretched metal ceiling. MCR was developed by Philips in the 1960s and is now freely available and can be considered as a system principle: There are an equal number of microphones and loudspeakers, each microphone being connected to a single loudspeaker, passing through a digital mixing console for equalization and gain control as well as delay (to avoid preechoes). Each pair of microphone and loudspeaker can be thought of as "negative absorption," as the loudspeaker acts like a virtual reflector without taking any of the incoming sound away. With adapted settings of the system, the "insertion loss" of the stretched-metal ceiling can be compensated, and at the same time, reverberation time is increased. Please note that no digital convolution reverberation or similar is introduced; only gain from a single microphone to a single loudspeaker creating a single reflection, feedback occurs through the acoustic path in the room.

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Figure 2. Acoustically semitransparent metal mesh ceiling, partly horizontal (far left and far right), partly angled in section (center left) in order to reveal lighting bridges (center right). The semitransparent metal mesh ceiling creates a transmission loss between the main acoustic volume of the hall and the volume below the ceiling. See the online article for the color version of this figure.

Location of the microphones and loudspeakers are detailed in Figures 3, 4, and 5, where Figure 3 shows the loudspeakers are pointed across the room and toward the ceiling, avoiding the creation of early reflections down to the audience.

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Stockholm *Konserthuset* Electro-Acoustic System, the Initial Setting

During the setup and tuning of the final system, a negative acoustic effect was observed in Stockholm *Konserthuset*: When compared to the temporary system, the initial setting of the final system created a clear decrease of clarity of the orchestral sound, a "veil" over the orchestra, an increased acoustic distance, a decrease of openness (Lokki, Pätynen, Kuusinen, Vertanen, & Tervo, 2011) and a decrease of source presence. What had happened? While the test system had 12 channels and no loudspeakers above the stage, the final system has 14 channels, that is, seven loudspeakers on the left side and seven on the right side, including loudspeakers above the stage. The loudspeakers are spread evenly along the side walls, all mounted on the side technical catwalk railing, aimed horizontally and tilted slightly upward toward the middle of the room under the ceiling (see Figure 3). For technical reasons, the loudspeakers above the brass and percussion instruments at the rear of the stage were placed on a transversal lighting bridge, facing the organ wall (so facing away from the audience, as

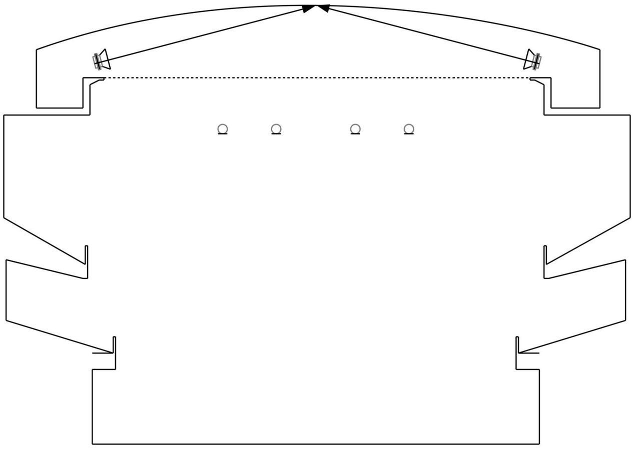

Figure 3. Short section, location of the microphones and loudspeakers of the MCR system.

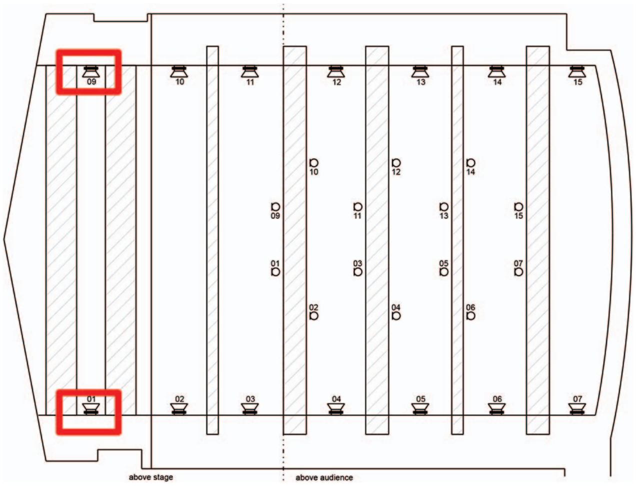

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Figure 4. Plan of ceiling attic showing the locations of loudspeakers and microphones of the multiple channel reverberation system. The stage is on the left side of the plan, rear balconies on the right side of the plan. Loudspeakers that were finally switched off are indicated by rectangles. See the online article for the color version of this figure.

those loudspeakers were supposed to send reverberant energy back to the musicians on stage). The microphones feeding those loudspeakers were in the middle of the hall, and a 20-ms delay was added to the channels, approximately corresponding to the travel path length between the microphone in the middle of the hall and the loudspeaker. In acoustic terms, what was created with those couples of microphones and loudspeakers above the stage corresponds to a strong reflection from a reflector panel approximately above Row 8, sending an acoustic reflection toward the upper organ wall. The level setting of the loudspeakers above the stage was the same as for the other loudspeakers.

During listening tests, it was found that it was those two loudspeakers above the stage, facing the organ wall, that created the negative acoustic effect. Muting the loudspeakers instantly suppressed the negative effect—and reflections from the rear of the hall could suddenly be heard while clarity improved, envelopment increased and subjective distance was reduced. The difference was very strongly audible even when seated in the rear balconies, more than 30 m away from the organ wall.

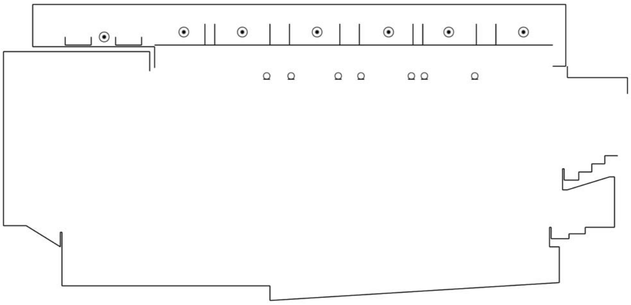

Figure 5. Long section, location of the microphones and loudspeakers of the multiple channel reverberation system (stage on the left).

Various tests and trials were conducted concerning the loudspeakers above the rear part of the stage (orienting them down, sideways or toward the audience) and with various delays and levels—but in the end, there was a single clear conclusion: What sounded best was to completely switch off these loudspeakers.

This experience suggests that reverberation in certain parts of the room (or from certain directions) that are spatially close to the sound sources can have negative acoustic effects on both source presence and room presence, decreasing source clarity and audibility of room sound. Reverberation spatially located further away from the sources, on the other hand, has no negative influence on source presence and clarity while having a positive effect on room presence and envelopment.

Case Study: *Bozar*, Brussels: Frontal Background Noise Masks Rear Reflections

In 2014, we (acousticians and expert listeners) attended a concert at the *Salle Henry LeBoeuf* at the *Palais des Beaux-Arts*, now called *Bozar*, the main 2,200-seat concert hall in Brussels. The concert started about 30 min after the end of a speech by United States President Barack Obama in the same room that had been televised internationally. A large additional lighting truss with several large moving lights was still hanging in the room above the main floor parterre, and while the lights were no longer in use, they were still powered "on" for cooling, creating a strong background noise of the order of NR-40 (i.e., noise rating, corresponding to approximately 45 dB), already audible during the tuning of the orchestra. Figure 6 shows a view of the hall and the lighting truss F6 in question. During the first movement, the background noise from the lights was no longer audible as the level of the music was

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Figure 6. View of the stage of *Bozar*, Brussels, from the balcony. After the speech by United States President Barack Obama, the front lighting truss was significantly lower and equipped with several large moving lights, with fans still in operation. See the online article for the color version of this figure.

higher than the background noise from the cooling fans—but at the same time, we found the acoustic quality of the hall significantly altered and decreased. Listening from the center of the first balcony, facing the stage, clarity and dynamics were decreased (the latter a known negative influence of background noise), orchestral colors deteriorated, and the sound was much more frontal than usual. Furthermore, there was a notable decrease of acoustic clarity. During the second, slow movement, the background noise from the fans was clearly audible even during running music.

Then, during the third movement, the moving lights were powered off and the fans stopped. As this happened during the music—and during relatively loud music—the absence of background noise was not instantly noticeable, but what was instantly noticeable was the improvement in the room acoustic quality. Most striking was the sudden ability to hear acoustic reflections coming from behind the listener that had previously been masked by the noise. The room "behind" the listener suddenly became alive and audible, and at the same time, a clear increase in clarity and dynamics was observed—even before noticing the absence of background noise!

This experience indicates that noise sources located in front of the listener can strongly decrease the perception of reflections from behind, what can be called an effect of spatial masking: sound from the front masking sound and reflections from the back. This effect of spatial masking goes beyond—but can be considered as an extension of—the temporal masking effects described by Zwicker and Feldtkeller (1967) and Seraphim (1961). Furthermore, the case study seems to confirm that the presence of background noise influences perceptual aspects of room acoustical quality even when the background noise is not audible as such. The perceptual effects of the background noise observed in *Bozar* are similar to the perceptual effects of reverberation observed in *Konserthuset*, suggesting that similar masking effects come into play in both cases.

Stockholm *Konserthuset* Electro-Acoustic System, the Final Setting

After switching off the loudspeakers above the rear of the stage in Stockholm Concert Hall, further tests were performed to find out how the suppressed energy should be distributed among the remaining loudspeakers. The result was, once again, very clear and the differences quite strong: The best acoustic result was not obtained with an equal distribution of energy, but rather with an "adapted gain" setting—less gain for loudspeakers above the stage and close to the stage and more gain for loudspeakers further away from the stage, toward the rear of the room.

When objectively comparing the "initial setting" and the "final setting" for the electro-acoustic system, the total gain (sum of all loudspeaker gains) was basically identical. Yet the subjective acoustic result is very different: One setting sounds significantly better than the other setting, including differences in source clarity. The experience therefore strongly suggests that distribution as well as direction of arrival of late sound is highly significant in the perception of room acoustic quality.

An interesting side thought here is to discuss the relationship between these observations and acoustic diffusion (surface roughness) and scattering. Loudspeakers facing across the room have a behavior similar to Lambert's law, as loudspeakers radiate sound independent of angle of incidence to the microphone. Barron (2015, p. 3097) observed that in concert halls, "high rates of decrease with distance of early sound tend to be associated with highly scattering ceilings" (p. 3097) or walls: Surfaces close to the sound sources receive more energy; with Lambert scattering most sound is reflected normal to the surface irrespective of the angle of incidence. The consequence is a relative reduction of late reverberant sound levels further away from the sources. Decreasing the gain of the loudspeakers close to the stage while increasing the gain for loudspeakers far away from the sources can be thought of as increasing projection from the stage to the hall. Furthermore, increasing the sound level at the rear of the hall increases the "hall response" for the musicians on stage, giving them better feedback than a response from above the stage.

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Table 1 and Figure 7 show the measured reverberation times for various settings of the room, all in the unoccupied state of the room. It is interesting to note that the final setting is well below the maximum possible reverberation increase; this setting was found to be the most natural-sounding setting. Reverberation from under the ceiling is now audible and the hall correspondingly sounds 3 m taller than without the system in place, while definition and clarity as well as openness, bloom and reverberation are increased. The system is now in operation as a permanent system during all rehearsals and concerts.

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Future Work

The effects and observations described in this paper will need to be verified and quantified under controlled listening conditions. The effect of direction of arrival and level of background noise shall be studied, as well as the influence of delayed energy and reverberation from locations close to the sound sources. The final aim should be to develop a model for spatial masking and to study the influence of spatial direction of arrival of late sound (or noise) on the perception of early sound and source presence, studying the interactions between the early and late room responses and the perception of source and room presence.

Conclusions

A strong negative effect of background noise and late reverberation coming from directions close to the direction of arrival of the direct sound was observed during critical listening in two concert halls. The observations indicate that the direction of arrival is highly relevant beyond the question of lateral sound and interaural cross correlation. In addition, the observations indicate that late

Table 1
Reverberation Time (T30, mid), as Well as Bass Ratio (BR) and Gain, for Different Settings of the Electro-Acoustic Enhancement System

Setting (measured T)	T30, mid (s)	*BR* (–)	Gain, mid (dB)
Passive	1.70	1.06	—
Temporary system, active	2.15	1.10	1.0
Final system, maximum	2.20	1.17	1.1
Final setting	2.00	1.16	.6

Note. All measurements correspond to the unoccupied room.

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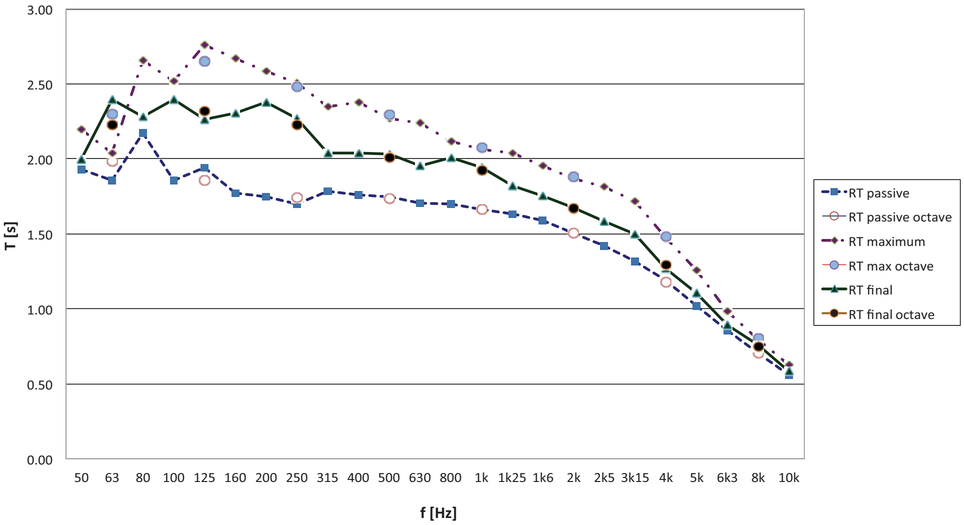

Figure 7. Measured reverberation times (T30) for various settings of the room (all measurements unoccupied), *Konserthuset*, Stockholm. The lowest curve (dotted) is without electro-acoustic system, the top line (dashed) the maximum setting (originally preferred) and the intermediate (solid) line the final setting of the system. The lines indicate the results for third octave bands; dots give the values for full octave bands. RT = reverberation time. See the online article for the color version of this figure.

sound can have a strong influence on the perception of source presence, subjective distance and clarity, depending on the direction of arrival of the late sound.

References

Barron, M. (2010). *Auditorium acoustics and architectural design*. New York, NY: Spon Press.

Barron, M. (2015). Theory and measurement of early, late and total sound levels in rooms. *The Journal of the Acoustical Society of America, 137,* 3087–3098. http://dx.doi.org/10.1121/1.4919655

Beranek, L. L. (2004). *Concert halls and opera houses: Music, acoustics, and architecture*. New York, NY: Springer. http://dx.doi.org/10.1007/978-0-387-21636-2

Dahlstedt, S. (1974). Electronic reverberation equipment in the Stockholm concert hall. *Journal of the Audio Engineering Society, 22,* 627–631.

de Koning, S. H. (1983–1984). The MCR system: Multiple-channel amplification of reverberation. *Philips Technical Review, 41,* 12–23.

Kahle, E. (1995). Validation d'un modèle objectif de la perception de la qualité acoustique dans un ensemble de salles de concerts et d'opéras [Validation of an objective model of the perception of acoustic quality in a collection of concert halls and opera houses]. (Unpublished doctoral thesis) Université du Maine, Le Mans, France.

Kahle, E. (2013). Room acoustical quality of concert halls: Perceptual factors and acoustic criteria: Return from experience. *Proceedings of the International Symposium on Room Acoustics, ISRA 2013,* Toronto, Canada.

Lokki, T., Pätynen, J., Kuusinen, A., Vertanen, H., & Tervo, S. (2011). Concert hall acoustics assessment with individually elicited attributes. *The Journal of the Acoustical Society of America, 130,* 835–849. http://dx.doi.org/10.1121/1.3607422

Mulder, C. (2001). Variable acoustics using multiple channel amplification of reverberation (MCR), *International Congress of Acoustics (ICA) Rome, 5,* 384–385.

Seraphim, H. P. (1961). Über die Wahrnehmbarkeit mehrerer Rückwürfe von Sprachschall [Regarding the perceptibility of multiple reflections in speech sound]. *Acustica, 11,* 80–91.

Zwicker, E., & Feldtkeller, R. (1967). *Das Ohr als Nachrichtenempfänger* [The ear as a receiver of information]. Stuttgart, Germany: Hirzel.

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