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Designing early reflection patterns suitable for audio recordings by means of acoustic modelling

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ABSTRACT

The early reflection patterns of recording rooms strongly influence the subjective quality of stereo or multichannel recordings, especially when the microphones are situated at a distance from the source. The present paper investigates possibilities for the balance engineer to optimize the early reflection pattern at the microphone positions in a chamber music hall utilizing a computer based ray tracing model.

1. INTRODUCTION

Since the 1950's there has been great advance in the field of room acoustics. After the early discoveries of W.C. Sabine regarding the relation of reverberation time with room size and absorption, especially in the second half of the 20th century most of the objective criteria of architectural acoustics were defined and their relation to categories of subjective perception investigated. Relevant room acoustical literature clearly shows the great importance of proper early reflection design in concert rooms [1, 5]. A similar situation is found in the field of electroacoustic music reproduction, e.g. in listening control rooms. Taking care of strength and timing of early reflections at the listening position is an essential part of studio design.

Compared to this the amount of literature explicitly dealing with the role of early reflections during the recording process is little but – as the results of the research suggests – not less important.

This paper reports the attempt to investigate the possibilities of early reflection design during the recording process by the means of acoustic modelling. For this purpose a computer based room acoustical model was created and equipped with a simulated typical "spaced omni" recording configuration. After the "virtual recording" of various sources the early reflection pattern has been modified by simulated acoustical elements like absorbers, reflectors and diffusors. Auralization of these changes had been performed again. Listening tests were conducted to clarify which changes in the sonic image were caused by each configuration of acoustical elements.

2. THE EFFECTS OF EARLY REFLECTIONS – A SHORT OVERVIEW

As a starting point for the modifications of the virtual room acoustical situation a short overview of the various known effects is given, dealing with aspects of the early reflection perception.

2.1. The Masked Threshold

Different authors have examined yet the so called Masked Threshold as the lower limit of perceptibility of a single discrete reflection following the direct sound [8, 16, 13, 7]. Test conditions varied more or less from experiment to experiment but nevertheless the following conclusions can be drawn:

The perceptibility of a single discrete reflection following the direct sound is mainly dependant on

- the level of the direct sound,
- the direction from which the reflection reaches the listener's ears,
- the delay of the reflection and
- the character of the direct sound.

Buchholz [9] states, referring to Burgtorf [10], that for louder sounds a room reflection is perceived more easily than for a softer one which results in an overall lowering of the Masked Threshold.

Another important finding is that a reflection is easier perceived if it is coming from a different direction than the direct sound. Bergault [7] states in this context, that

> "Across all stimuli types and conditions, the lowest thresholds corresponded to stimuli with the maximum lateral difference between the direct sound and reflection."

As will be seen a variety of percepts caused by early reflections depend strongly on the lateral difference between the direct sound and the reflection.

Regarding the delay time it has been found that the bigger the delay of a reflection, the more easily it is perceived, and as Buchholz [9] remarks

> "Obviously the assumption can be made that both room masking and ordinary masking are based on the same perceptual mechanisms" ... as ... "the delay time dependency of the RMT [*Room Masking Threshold*] is in absolute agreement with investigations on ordinary masking and the Echo Threshold."

In this context the effect of strong, delayed reflections coming from the same direction as the direct sound has been examined by Seraphim. He found that a single strong reflection following the direct sound can lengthen its temporal masking effect (Seraphim after Kuttruff [12]).

Many of the experiments were performed with signals of different type and it has been found that the more transient a direct sound, the more easily a reflection is perceived [16, 7]. On the other hand, music as a direct sound of a rather continuous character normally led to the highest Masked Thresholds.

If decorrelated reverberation is added, the Masked Threshold increases between 5...10 dB for reflections arriving not later than 30 ms after the direct sound. For reflections later than 30 ms the Masked Threshold can raise even up to 20 dB [16, 7].

If the level of a reflection raises above the Masked Threshold, different effects on the auditory event are described in the literature as follows.

2.2. Tone Colouration

The sensation of tone colouration is mainly caused by reflections which arrive up to about 20 ms after the direct sound at the listener's ears. In this case the reflection interferes with the direct sound causing a spectral comb filter. Most authors state in accordance with each other that especially reflections from frontal directions cause the colouration and that it can be moderated if direct sound and reflection are coming from different directions. For architectural acoustics both Barron as well as Beranek [1, 5] point out that large flat surfaces above the listener are predestined to produce specular reflections causing colouration, and that

> "to reduce acoust ical glare [...] caused by flat sidewalls or flat suspended panels, irregularities of the order of $1-2$ in. ($2.5-5$ cm) deep should be embossed into the reflecting surfaces." [5]

2.3. Aspects of Spatial Perception in Reproduced Sound: Source Distance, Ensemble Depth and Source Width

Especially the advance in multichannel audio in the recent past led to increased research in this field. Various studies (Berg [6], among others) have shown the existence of several attributes to describe the spatial properties of a reproduced sonic image. Related to this, known correlations between these attributes and the causing physical factors are presented very thorough in the work of Neher [14]. Accordingly especially the spatial attributes "source distance" (and, closely related, ensemble depth) as well as "source width" are influenced by the characteristics of early reflections up to 80 ms.

Besides other cues for distance perception of a sound source like the high frequency roll off due to dissipation or simply the perceived loudness of a sound source, one of the more important cues for distance estimation in closed rooms is the direct to reverberant sound ratio as found by Nielsen [15].

Looking at the early part of the reflected energy both Griesinger [11] as well as Pellegrini [17] consider early reflections in the time range between 20 and 50 ms as the major cues for distance estimation. Regarding the direction of the reflections, Griesinger states that reflections should arrive from different directions than the direct sound in order to avoid masking and tone colouration.

Neher[14] remarks critically that an impression of distance also could be transmitted by monophonic recordings or by telephone, and concludes that the direction of early reflections support the distance perception only to a marginal degree.

Regarding the strength of the reflections between the 20 ms and 50 ms limit Griesinger states in the context with his concept of an "Ideal Reverberation Profile" that the total amount of energy in this range should be -4 to -6 dB relative to the direct sound.

As Theile [19] distinguishes between perception of distance and spatial depth, it is supposed that spatial depth is more related to extended sound sources like orchestras, and thus could also be described as ensemble depth. Nevertheless as ensemble depth and source distance are complementing spatial attributes, it is not surprising that similar characteristics of early reflections are made responsible for both effects. Theile states that

> "The dominant cue to create distance, spatial depth and apparent source width is the natural pattern of early reflections in the region 15. . . 50 ms."

And referring to Griesinger:

> "However a reflection pattern of about ten or twenty early reflections mainly laterally distributed are advantageous, also to avoid colouration effects due to combing."

According to Theile another spatial percept seems to be influenced by early reflections: The "source width" or "auditory source width" (ASW) which, as Blauert [8] remarks,

> "...denotes a characteristic spatial spreading of the auditory events."

Among others the investigations of Barron [2] as well as Barron and Marshall [3] have unraveled the relation between the spatial percept and objective characteristics of the sound field. An important finding of their work is that early lateral reflections up to 80 ms are responsible for the perception of source width or as they call it "spaciousness".

They could show that the degree of "spaciousness" is independent of the delay time of the reflections over a large time range (5. . . 80 ms)

Furthermore they showed that the magnitude of source width is strongly related to the angle from which the reflection reaches the listener's ears: While reflections from frontal directions cause no or only a small amount of ASW, the maximum is reached when the reflections arrive completely lateral. Finally their work led to the definition of the "Lateral Fraction" (LF) as an commonly acknowledged room acoustical criterion for the quality of concert rooms.

2.4. The Effects of Early Reflection on the Perceived Loudness of a Sound

In the field of room acoustics it is well–known that a room reflection could increase the perceived loudness of an auditory event [5]. The objective measure is the "Strength" G of the sound.

As this effect of early reflections seems to be meaningless for electroacoustic transmission due to the availability of amplifiers, on the other side it implies the possibility for level balancing between different parts of an ensemble in an acoustical way.

2.5. The Effects of Early Reflection on the Perceived Clarity of a Sound

As part of the energy arriving within the first 80 ms after the direct sound early reflections have a strong impact on the perceived "Clarity" C_{80} of a musical signal. According to Beranek the degree of horizontal and vertical definition of a music performance or reproduction is closely related to this percept [5]. Preferred values strongly depend of the kind of music performed or reproduced.

2.6. The Effects of Strong Early Reflections: Image Shift and Echo

Various authors have investigated the effect of strong early reflections on the auditory event. One of the most important effects is the well–known "precedence effect" as described first by Haas in 1951. As the phenomenon is regularly understood in the way that early reflections with a level up to 10 dB louder than the direct sound and a delay time of more than 0.6 and less than about 30 ms does not affect the perceived position of an auditory event, other authors like Bech [4] question the general validity of the precedence effect.

Bech states also that reflections in the time range between 1 and 15 ms and a level of -10 to -20 dB can cause the auditory event to shift horizontally. Furthermore he claims that the spectral content of the reflections above 2 kHz determines their influence on the perceived position of an auditory event. Increasing the delay time of a strong reflection usually results in the perception of an echo. For in–depth information about this phenomenon refer to Blauert [8].

3. INVESTIGATIONS

A listening test was employed to judge the effects of early reflection design by the means of acoustic modelling. For this purpose a virtual room acoustical model has been equipped with a typical stereo recording configuration. Auralization was used to perform "virtual recordings" of five sources: Bongo, Trumpet, Guitar, Cello and Voice. Based on this configuration the early reflection pattern was modified by the use of acoustical elements in the model. The changes were auralized again and rated by expert listeners in a randomized listening test as reproduced over loudspeakers, regarding different subjective criteria.

3.1. The Room Acoustical Model

The auralizations are based on a model of the chamber music hall of Detmold University of Music (Germany), the so called "Brahms–Saal". The room is mainly used as a room for chamber music performances, but also as lecture room and as a studio for productions as well as live recordings.

The hall offers space for 120 listeners and has an overall size of $8.1 \times 17.2 \times 5.7$ m (w × l × h) in a typical shoe–box shape. The total volume is about 800 m^3. The reverberation time at mid frequencies has been measured in the empty state as 1.49 s, and a calculation of the fully occupied room led to a value of 1.03 s.

Most of the surfaces are smooth plaster walls, the sidewalls covered with wallpaper. Except for the window niches at both sides of the room, there are no irregularities in the sidewalls neither in the ceiling, but in the rear wall of the stage (apsis with Brahms' bust). The room is equipped with a hollow wooden stage of 0.33 m height and 5.2 m depth. The floor is a hollow wooden floor on timber joists.

After collection of data about the dimensions of the hall and the properties of the surfaces, the room was modelled with the help of CATT–Acoustics software in two different states: one without audience and one fully occupied (Figure 1).

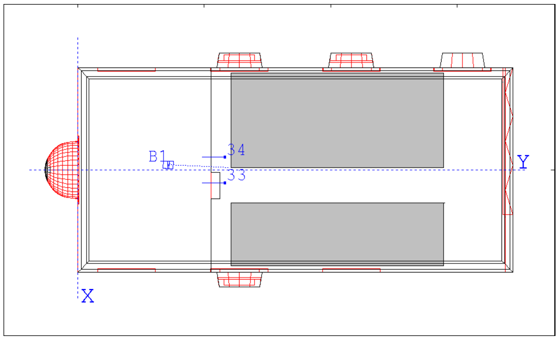

Fig. 1: Basic configuration of the model, B1: position of the sound sources; 33, 34: position of left and right omni microphone; audience area is coloured gray.

As the reverberation time of the empty room at mid frequencies is high, it was decided to use the occupied state of the room for the calculation of the stimuli. The virtual sound sources were placed on the stage at a position slightly out of the middle axis of the room to avoid perfect symmetry. Height, position on the stage and main direction of the sources were chosen appropriate to reality.

The five sources: Bongo, Trumpet, Guitar, Cello and Voice (represented by anechoic recordings) were implemented with their characteristic directivity patterns. As "recording system" a spaced pair of omnis with a base of 1 m was chosen. After Sengpiel the theoretical recording angle for such a configuration is about 31° [18].

Calculation of the critical distance and comparison of different virtual microphone positions by ear led to a position 2.2 m in front of the sound sources in a height of about 2.8 m above the stage level as shown in Figure 1.

3.2. Image Sources in the Basic Configuration

Every microphone system transforms a three–dimensional sound field into an image according to the chosen recording / reproduction configuration. It picks up not only the direct and diffuse sound (as one might believe according to most literature on recording engineering) but also the discrete reflections of the room boundaries.

These reflections can be modelled as image sources. As the strength of each single reflection depends also on the directional characteristic of the source, Fig. 8 shows exemplary the position of the image sources in the basic configuration (no absorbers, diffusors or reflectors in the room) for the Bongo, whose directivity pattern has been assumed to be omnidirectional:

One sees clearly the direct sound represented by the large circle in the middle, followed by strong first order reflections from the floor and the ceiling, respectively. Also the flat surfaces at both sides of the stage produce quite strong specular reflections. The smaller circle (the mirror source above the ceiling reflection) represents a second order reflection between floor and ceiling. All these reflections arrive earlier than 20 ms after the direct sound.

The floor reflection as well as the other reflections shown on the middle axis are supposed to be reproduced from the same direction than the direct sound (as the three–dimensional sound field is reproduced in two dimensions). As the recording angle of the chosen pair of omnis is about 31°, it is likely that the reflections from the side walls will be perceived mainly from one speaker.

3.3. Modifications

3.3.1. Absorbed Floor Reflection

As the floor reflection is the first reflection which reaches the microphones after the direct sound and is likely to be reproduced from the same direction, an absorber panel in front of the sound source was intended to reduce its level (Fig. 9).

3.3.2. Redirected Floor and Ceiling Reflection

By means of wedged reflector panels in front of the source and above, floor and ceiling reflections are redirected to the sidewalls. Thus more energy is arriving from the sidewalls, and the strong early reflections on the medial plane are eliminated (Fig. 10).

3.3.3. Reflector Panels on Both Sidewalls

With the intention to modify the sidewall reflections, four medium sized reflector panels ($1\text{m} \times 0.75\text{m}$) with different inclination were simulated on both sidewalls of the stage (Fig. 11).

3.3.4. Both Preceding Modifications Combined

Both of the preceding modifications (see 3.3.2, 3.3.3) were combined (Fig. 12).

3.3.5. Absorbed Sidewall Reflections

Two absorber panels on both sides of the stage are simulated in order to reduce the level of the specular sidewall reflections (Fig. 13).

3.3.6. Diffusor Panels Around the Stage

All the hard reflecting surfaces around the stage were intended to be "softened" utilizing large diffusor panels on both sides of the stage as well as on the floor and ceiling (Fig. 14).

3.4. Listening Test Design

Impulse responses at both microphone positions were calculated on the base of a improved ray tracing algorithm (randomized tail–corrected cone–tracing) for each combination of instrument (Bongo, Trumpet, Guitar, Cello, Voice) and each of the above mentioned room modifications. Anechoic recordings of the instruments were convolved with the impulse responses. The resulting monophonic sound files were level calibrated and combined to stereo files, taking into account the distance between the two microphone positions.

This resulted in a total amount of 35 stereophonic sound files with a duration of approx. 12 s each: 7 room configurations (including the basic configuration) × 5 instruments. An audio CD has been created consisting of two groups: the first with 10 stimuli, presented before the test to allow the test subjects to get familiar with the stimuli and the situation.

The second group contained 50 stimuli in random order (ten for each instrument: the seven cases under test as well as a control case and two forerunner "pad" cases) which had to be rated by the listeners. An excerpt from the questionnaire is given in Fig. 2.

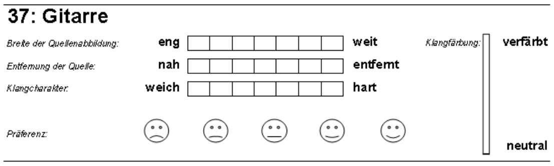

Fig. 2: Listening test excerpt

The listeners were asked to rate each sound sample regarding five aspects:

- Source Width (*Breite der Quellenabbildung*), 7–step scale, narrow (*eng*) — wide (*weit*)
- Source Distance (*Entfernung der Quelle*), 7–step scale, close (*nah*) — distant (*entfernt*)
- Sound Character (*Klangcharakter*), 7–step scale, hard (*hart*) — soft (*weich*).
- Preference (*Präferenz*): on a 5–step symbolical rating scale listeners were asked to express their preference.
- Colouration (*Klangfärbung*): on a graphical rating scale the listeners were asked to rate if the samples seem to be rather neutral or coloured (*verfärbt*).

As the time for the listening test was intended to not exceed half an hour, the stimuli were presented in sequence without breaks. The listeners had about 25 s to rate each sample and thus were instructed to give their judgement spontaneously.

The stimuli were presented to the listeners over a "high end" stereo loudspeaker configuration in a recording control room of Erich–Thienhaus–Institute. The listening panel consisted of eight students (between the 7th and the 10th semester) of the Detmold University of Music Tonmeister department and two professional Tonmeisters, and thus can be regarded as expert listeners.

4. RESULTS

Disregarding the pad and control cases, each room configuration had been rated five times by each listener (once for each instrument). Thus about 50 ratings of five different subjective parameters for each room configuration were obtained (sometimes listeners didn't rate a single aspect resulting in a missing case). For the purpose of analysis the five and seven step rating scales were coded numerically by numbers between -2 and $+2$ and -3 and $+3$ respectively. The ratings on the graphical scale were quantized in seven steps, where a value of 0 indicates a neutral, non–coloured perceived sound, and a value of 6 corresponds to a highly coloured sound. Mean values of each subjective parameter were calculated for the seven configurations.

4.1. Results for Perceived Source Width

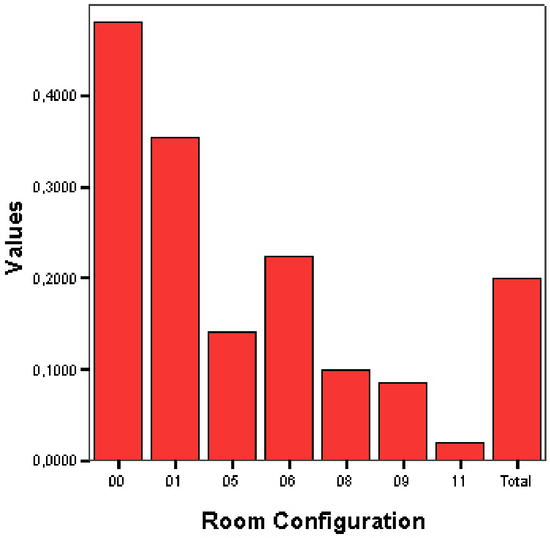

Fig. 3: **Perceived Source Width**. Mean values, left to right: Configs. 00–01–05–06-08–09–11, Total

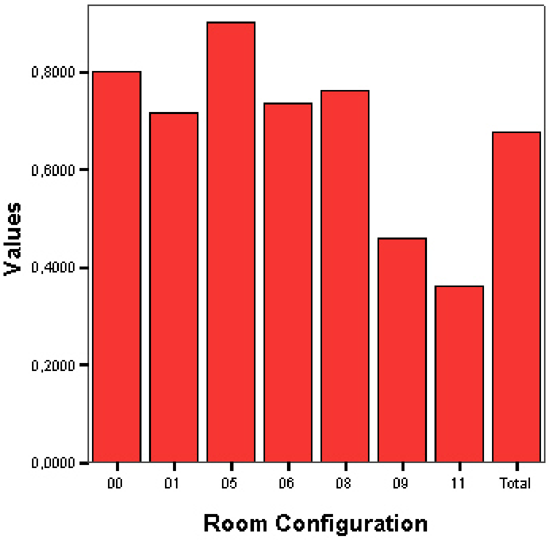

Fig. 4: **Perceived Source Distance**. Mean values, left to right: Configs. 00–01–05–06-08–09–11, Total

Fig. 3 shows the mean values of the listeners ratings for the parameter source width over the 7 room configurations. As the original scale has the range $-3 \ldots +3$, and the mean values vary in the range $0.02 \ldots 0.48$, the perceived differences between the configurations are obviously subtle. Similar observations hold true for the other parameters. Nevertheless such subtle differences in perceived sound quality can be quite important in the field of sound recording.

The room configuration 11 (with diffused reflections of the room boundaries thus reduced in level) shows the lowest mean value for the parameter source width: The auditory events seem to be perceived rather "narrow" with a rather precise localization of the phantom source, indicating that apparent source width in reproduced sound could be manipulated by the design of the lateral reflections. The original room configuration 00 without any modifications of early reflections shows the highest mean value (perception rather "broad").

4.2. Results for Perceived Source Distance

Fig. 4 shows mean values of the ratings of source distance. Mean values vary in the range $0.36 \ldots 0.9$.

The values for room configurations 09 and 11 (with sidewall absorber panels and diffusor panels respectively) indicate that the phantom sources seem to appear rather close. This is in agreement with former investigations as reported in section 2.3.

On the other hand, the wedged panels which redirect the floor and ceiling reflection to the sides (config. 05) seem to cause the auditory event to be perceived more distant.

4.3. Results for Perceived Sound Character

Fig. 5 shows the mean values of the listeners ratings for the parameter sound character over the 7 room configurations. Mean values for this parameter vary in the range $0.1 \ldots 0.4$.

Note that the configurations with lowest mean values (01, 08, 11), thus indicating that the sources were perceived "softer", are three of the four room configurations with manipulated floor reflection.

4.4. Results for Perceived Preference

Fig. 6 shows the mean values of the listeners preferences over the 7 room configurations. Mean values for this parameter vary in the range between $-0.21 \ldots 0.26$ (5–step scale, range $-2 \ldots 2$).

Mean values indicate that configurations 01 and 05 were least preferred, configurations 08 and 10 obtained rather positive ratings. All four configura-

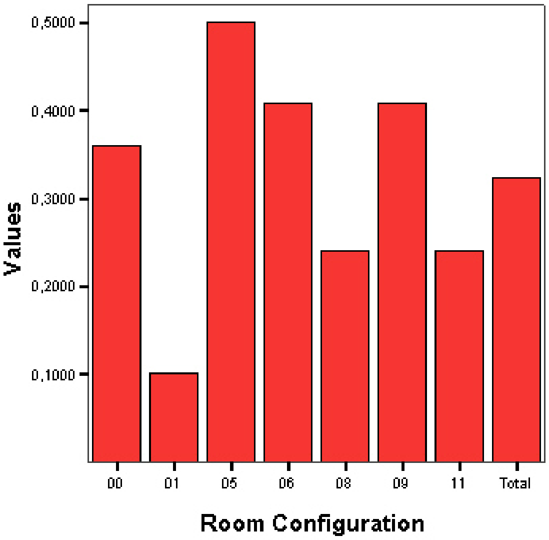

Fig. 5: **Perceived Sound Character**. Mean values, left to right: Configs. 00–01–05–06–08–09–11, Total

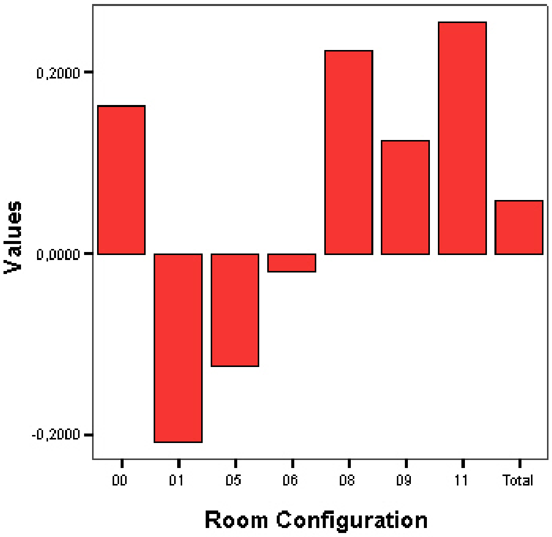

Fig. 6: **Preference**. Mean values, left to right: Configs. 00–01–05–06–08–09–11, Total

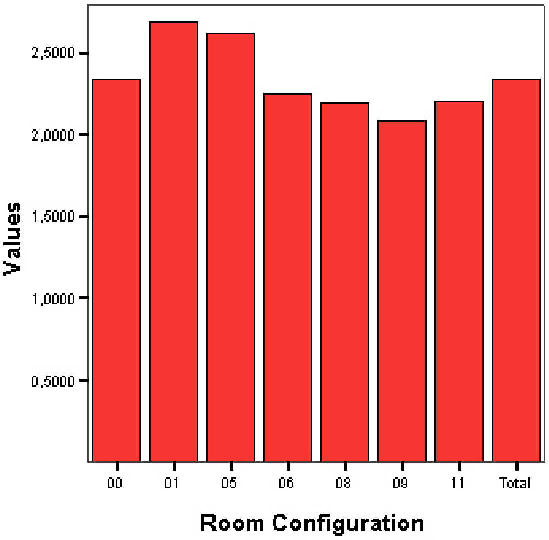

Fig. 7: **Perceived Colouration**. Mean values, left to right: Configs. 00–01–05–06-08–09–11, Total

tions have a manipulated floor reflection, but in configs. 01 and 05 the sidewall reflections are specular, and in configs. 08 and especially 11 sidewall reflections are diffuse.

Note that the configurations 01 and 05 also received the highest ratings for the parameter "colouration".

4.5. Results for Perceived Colouration

Fig. 7 shows the mean values of the listeners ratings for the perceived sound colouration over the 7 room configurations. The quantized scale allows ratings between 0 and 6. Mean values for this parameter vary in the range 2.1. . . 2.7.

Room configurations 01 and 05 received the highest ratings for this parameter. Both configurations have a manipulated floor reflection as well as prominent specular sidewall reflections. One might suppose that the negative ratings of the parameter preference is correlated to the higher values for the parameter colouration.

5. CONCLUSIONS AND OUTLOOK

The data obtained by the listening test indicate that various aspects of the reproduced sonic image can be influenced by the use of acoustical elements (i.e. reflectors, diffusors and absorbers) during the recording. Nevertheless further statistical analysis is needed to ascertain or reject the tendencies observed.

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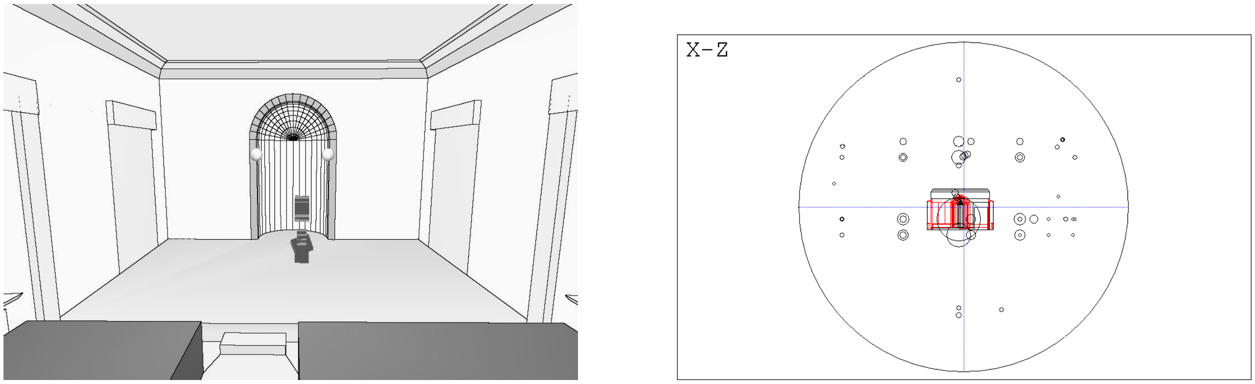

Fig. 8: **Configuration 00 (Basic Config.)**. Left: View to the stage of the basic configuration. The cluster of boxes represents the positions of the sound sources. The microphone positions are marked by white spheres. Note the hard flat surfaces around the stage. Right: Positions of relevant image sources up to third order, contributing to the sound field within the first 50 ms. The large circle indicates the 50 ms limit. The size of a circle indicates the level of the corresponding reflection.

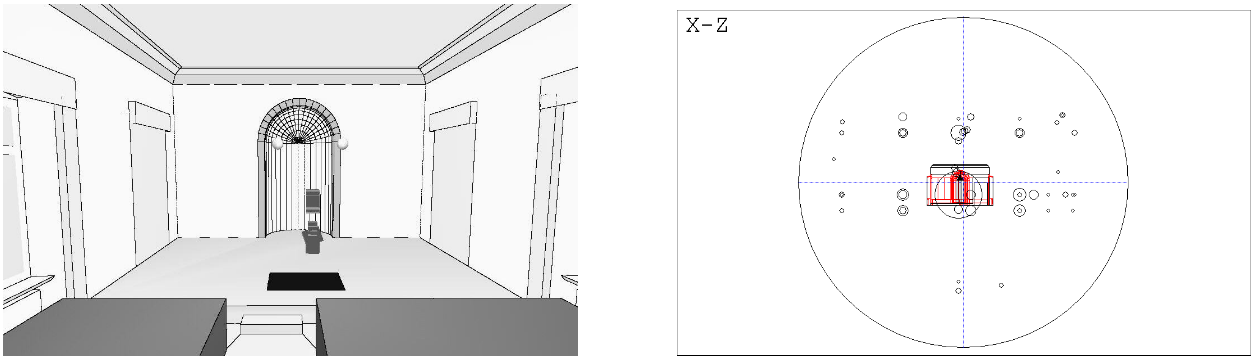

Fig. 9: **Configuration 01**. Left: An absorber was positioned on the stage. Right: The floor reflection (i.e. image source directly below the floor) is reduced markedly.

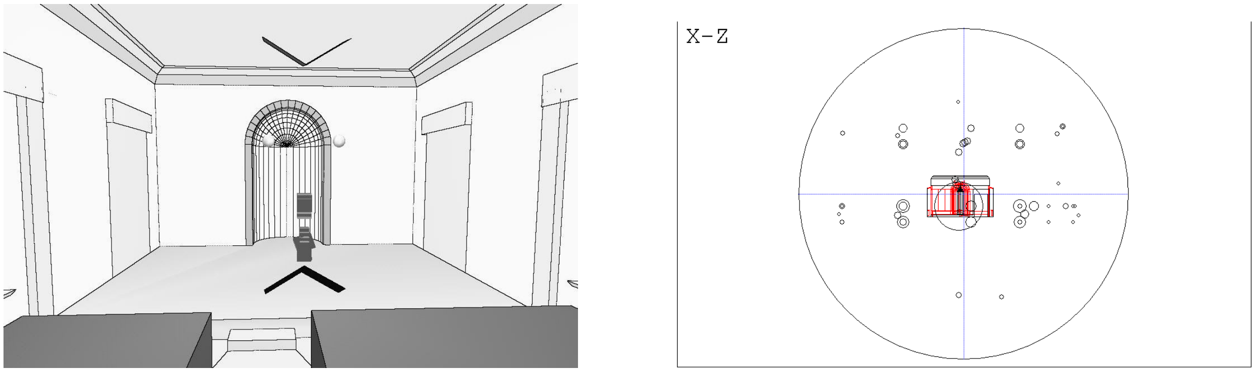

Fig. 10: **Configuration 05**. Left: Reflector panels to redirect the floor and ceiling reflections to the sides. Right: The floor and ceiling reflection are eliminated, while additional lateral reflections appear.

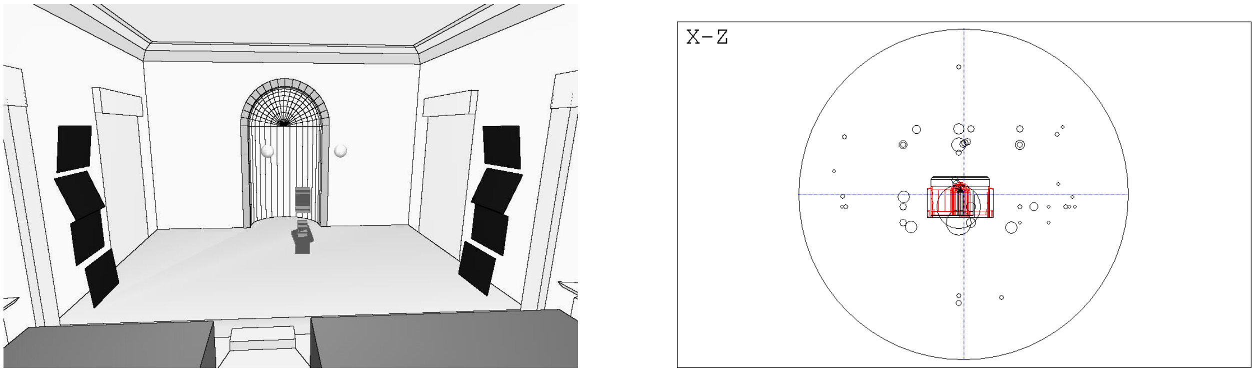

Fig. 11: **Configuration 06**. Left: Reflector panels to both sides of the stage. Right: Floor and ceiling reflection remain unchanged, but the lateral image sources are modified in timing and position.

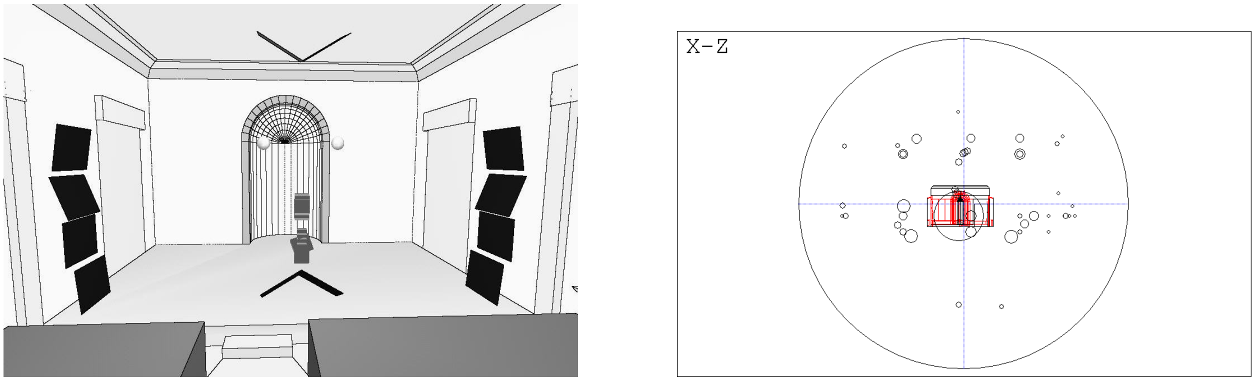

Fig. 12: **Configuration 08**. Floor and ceiling reflections are redirected to the sides, which are equipped with reflector panels. Right: First order floor and ceiling reflection are eliminated, lateral reflections are modified in timing and angle.

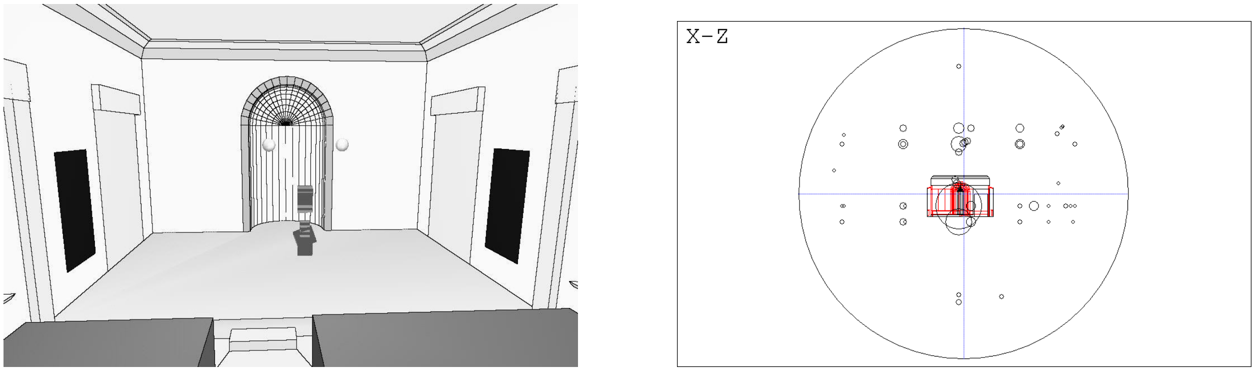

Fig. 13: **Configuration 09**. Left: Absorber panels to both sides of the stage. Right: Floor and ceiling reflection remain unchanged, lateral reflections are reduced in level.

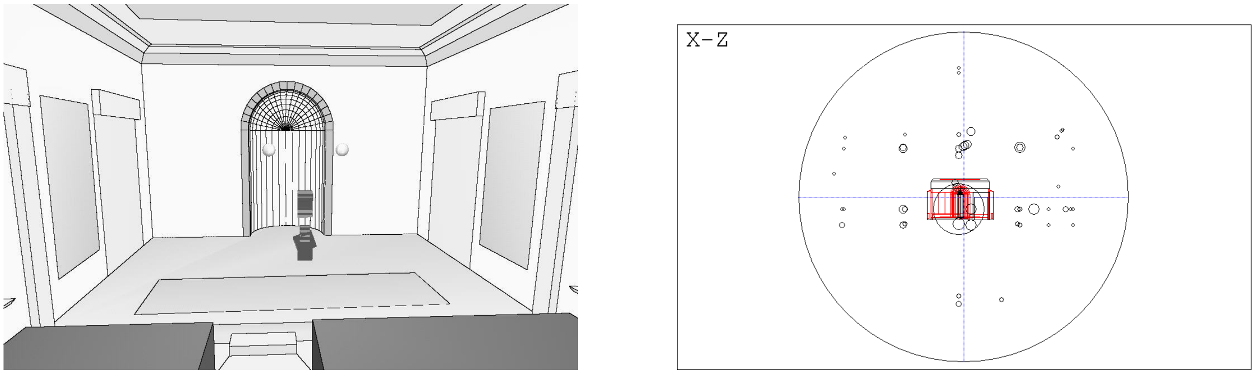

Fig. 14: **Configuration 11**. Left: Large diffusor panels around the stage. Right: The level of the specular early reflections is reduced.