Perception of spatiousness in rooms in dependence of the strength of the absorption at the side walls

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Introduction

The perception of sounds in a room is highly depending on the characteristics of that room. Thereby the reverberation caused by the room can be a desired part of the perceived sound. In a concert hall e.g., the reverberation is a vital part of the experience of a musical performance and such a room is perceived as pleasant. The room influences mainly the spatial perception of sounds. Thereby perception of spaciousness is influenced by single and multiple reflections of the sound at the walls, the floor and the ceiling. The reflections increase the perceived width of sound sources within rooms and cause a stronger envelopment by sounds in rooms, which both is highly desired for the perception of sound in concert halls [2].
The reverberation in rooms affects different physically measurable room acoustical parameters which can be linked to the spatial impression of sounds in rooms [3] and also to the acoustical quality of concert halls [4]. For the perceived listener envelopment (LEV) and the apparent source width (ASW), it has been shown, that both are strongly affected by the interaural cross-correlation (IACC) [5] and slightly by the level of the early reflections [6]. Also the reflections at the side walls (lateral fraction, LF) are assumed to be important for the perception of source width [1] and also for the envelopment.

This study shows the results of a psychoacoustic experiment, where the perception of source width and envelopment were rated by subjects. The stimuli were anechoic music signals convolved with simulated binaural room impulse responses (BRIR) of a shoe-box room. They were presented with headphones. The BRIRs were simulated with a mirror image model. The simulation of the BRIRs allowed to alter the absorption coefficients of the side walls separately from the other surfaces of the room. This was used in two different ways. Either the other four surfaces of the room were not altered, therefore the reverberation time (T_{60}) was directly depending on the manipulation of the absorption at the side walls and was unconstant. Or the other four surfaces were altered in a way that they compensated for the additional or missing absorption at the side walls and the T_{60} was independant of the manipulation. By systematically varying the strength of the side reflections within the simulated rooms, the dependency of the perception of spaciousness on lateral fraction was investigated.

Method

For this study subjects had to rate acoustical stimuli with regard to the perceived spatiousness in a psychoacoustic experiment. Thereby the strength of the reflection at the side walls of a room, was altered as a parameter in the experiment. The stimuli were generated by convolving anechoic music signals with BRIRs and were presented via headphones. Since it is not possible to identify the original direction of all the reflections in a real BRIR, the BRIRs used in this experiment were simulated with the “Razr-Engine” [7], a computationally-efficient hybrid simulation engine which simulates BRIRs with direction-depending reverberation. The simulated BRIRs were based on real rooms in their size and their frequency-depending absorption coefficients (α_f).

Stimuli

The BRIRs were simulated with the “Razr-Engine” with a third-order mirror-image model and a feedback delay network for the diffuse reverberant tail. The early part of the BRIRs was calculated geometrically exact and the reverberant tail was simulated with a direction-depending diffuse sound field. Thereby the third and even the second order reflections may occur concurrently to the beginning of the diffuse sound field, so that the cross-over between the early part and the reverberant tail of the BRIR extends to a certain period of time. The feedback delay network, as it is implemented in the “Razr-Engine”, includes inputs of the mirror-image model and also takes the absorption coeffiecients of the different walls into account. Therefore the origin of the diffuse sound field is direction-dependant.
The simulated rooms based on real rooms in size and the mean frequency depending absorptions coefficients over all walls. To simplify the simulations, the rooms were simulated shoe-box shaped and for the reference condition (see Fig. 1), all six walls had the same frequency-dependant absorptions coefficients (α_f). The source and the receiver were set on an axis in the middle of the rooms, so that the distance from the source and the receiver to the sidewalls was the same for both sides. The source was placed at a height of 1.8 m in the frontal part of room and the receiver was placed at a heigt of 1.3 m in the back of the room. As receiver the head-related transfer functions (HRTF) of a “Cortex MK2” artificial head were used.
To investigate the effect of the strength of the reflections

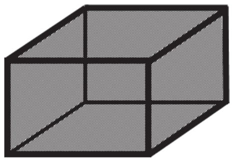

Figure 1: Pictogram of the simulated shoe-box room corresponding to the reference condition with identical frequency dependant aborption coefficients α_f at all six walls.

at the side walls on the perception of spatiousness, the absorption coefficients of the side walls were used as a parameter in the experiment. Therefore the absorptions coefficients (α_f) of the left and the right wall were simply multiplied by a factor k (see Eq. 1).

$$\alpha_f(k) = k \cdot \alpha_f \quad (1)$$

The faktor k was set to 0, 0.1, 0.4, 1, 2, 4, or 10, in which $k = 10$ practically meant full absorption at the side walls, since it was always ensured, that the absorption coefficients could not get bigger that one. Hence $k = 0$ corresponds to no absorption at the side walls at all and $k = 1$ to the reference condition. Figure 2 shows two pictogramms of the simulated rooms with manipulated absorption at the side walls. The left panel corresponds to the conditions with $k < 1$ and the right panel to $k > 1$. By enhancing or reducing the absorption

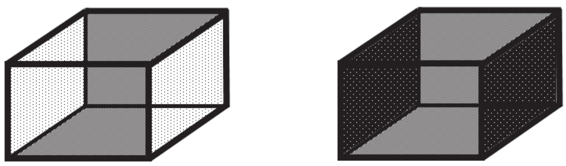

Figure 2: Pictograms of the simulated shoe-box rooms correspondig to the conditions where only α_f of the side walls were altered. On the left side the absorption of the side walls is reduced, which leads to a larger T_{60} in the room. The right side shows exemplarily an increased absorptions at the side walls, which leads to fewer reverberation and a smaller T_60 in the room.

at the side walls, the overall reverberance of the rooms is of course affected. The T_{60} therefore increases if the side walls are less absorbing and it is reduced, if the absorption coefficients of the side walls are increased.
To investigate the influence of the reflections at the side walls independently of the T_{60}, a second manipulation is surveyed in the experiment. In this case, not only the absorption at the side walls was altered but also the absorption at the other four surfaces of the room. The front and the back wall as well as the floor and the ceiling were used to compensate for the additional or missing absorption at the side walls. The T_{60} of the simulated BRIRs could be kept the same as for the reference condition by multiplying the other four surfaces with $\frac{N}{k}$. N is a scaling factor ($N < 1$), which is calculated with respect to the proportion of the size of the surfaces of the side walls compared to the other four surfaces of the shoe-box room. Figure 3 shows two exemplary pictograms of the second manipulation. The left panel shows less absorption at

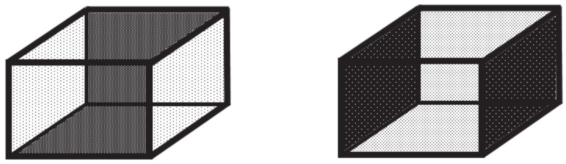

Figure 3: Pictograms of the simulated shoe-box rooms correspondig to the conditions where α_f was altered at the side walls and contrariwise at the other four surfaces. On the left side the absorption of the side walls is reduced and the absorption at the other surfaces is increased in such a way that the T_{60} was kept constant. The right side shows exemplarily an increased absorption at the side walls, which is compensated by less absorption at the other walls.

the side walls which is compensated by slighty stronger absorption at the other four surfaces. The right panel shows stronger absorption at the side walls and slightly weaker absorption at the other four walls.
All simulations were done for three different rooms, which were based on real BRIRs of a lecture hall, a seminar room and a concert hall.
The simulated BRIRs were convolved with excerpts of anechoic recordings of either a guitar, a violin or a snare drum play. The excerpts had a length of four seconds and were taken out of longer recordings of the sounds at a random starting point for each stimulus used in the experiment. The convolved signals were cut after four seconds and flanked with Hann ramps. The stimuli were presented with headphones at 65 dB SPL.

Procedure

The stimuli were presented to the subjects in a random order and had to be rated with regard to the perceived width of the source (ASW) and the perceived envelopment (LEV). At the beginning of each run of the experiment the subjects had to listen to a training phase which included the stimuli with the strongest manipulations. Additionally some anchor stimuli were included in each run of the experiment. As anchors the BRIRs of the underlying three real rooms were cut after 10 ms and convolved with the anechoic music signals, so that only the direct sound is used.
The ratings of the stimuli were done with a graphical user interface in Matlab. The LEV was rated with a single slider and the subjects were asked: “How much do you feel enveloped by the sound?”. The subjects could adjust the slider continuousliy between the extrema “Not at all” and “Completely”. For the rating of the ASW a mirror symmetric double slider was used. The subjects were asked: “How wide was the source” and the extrema were “wide” on the left and right end of the double slider and “small” in the middle of it.
ASW and LEV were rated in different runs of the experiment. Four expert listeners participated in the experiment and each subject repeated the experiment twice.

Results

The results of the subjective ratings are shown in figures 4 and 5 as a function of the multiplication factor k. The data of the three different rooms and the three instruments are summarized and the graphs show the mean values over the subjects with inter-individual standard errors. The blue squares show the data, when only the side walls are manipulated and the T_{60} varies with the strength of the manipulation. The green diamonds show the results for the conditions, when the enhanced or extenuated absorption at the side walls is compensated by the absorption at the other surfaces, which means that the T_{60} is constant for all values of k. The black circle shows the ratings for the anchor stimuli, where only the direct sound of the real BRIRs was convolved with the music signal.
Figure 4 shows the ratings of the ASW for the different manipulations. It can be seen, that the ASW decreases, when the absorption at the side walls is increased. With

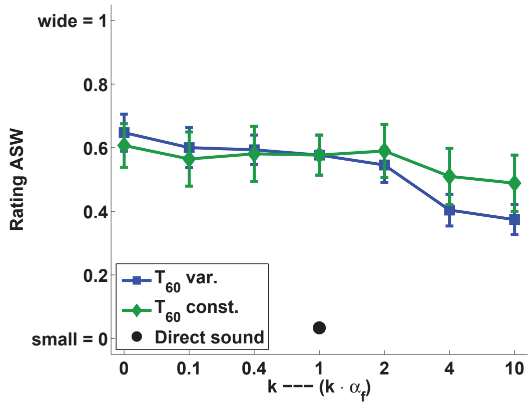

Figure 4: Rating of the perceived width of source as a function of the factor k, by which the absorption coefficients of the side were multiplied. Error bars show inter-individual standard errors. Blue squares show the results for the conditions with changing T_{60} (see Fig. 2) and green diamonds for a constant T_{60} (see Fig. 3). The black circle corresponds to the anchor-condition.

decreasing overall reverberance of the room, the source is perceived clearly smaller. When the overall reverberance stays the same ($T_{60} = const.$), the reduction of the rating of ASW is quite small. For less absorbing side walls, the perceived source width increases slightly with increasing overall reverberance ($T_{60} = var.$). The effect of the manipulated absorption at the side walls on the ASW is small compared to the difference between the reference condition ($k = 1$) and the anchor condition (Dircet sound).
Figure 5 shows the ratings of the LEV for the different manipulations. If only the side walls are manipulated ($T_{60} = var.$), the perceived envelopment is increasing with decreasing absorption ($k < 1$) and it strongly decreases when the absorption at the side walls is stronger ($k > 1$). For the conditions in which the manipulated absorption at the side walls is compensated at the other surfaces ($T_{60} = const.$), the LEV is hardly affected by the manipulation. The differences between the reference con-

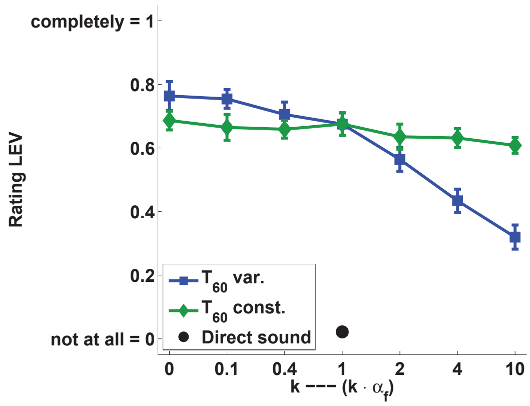

Figure 5: Rating of the perceived envelopment as a function of the factor k, by which the absorption coefficients of the side were multiplied. Error bars show inter-individual standard errors. Blue squares show the results for the conditions with changing T_{60} (see Fig. 2) and green diamonds for a constant T_{60} (see Fig. 3). The black circle corresponds to the anchor-condition.

dition ($k = 1$) and the maximum manipulation ($k = 10$) is much bigger than for the ASW ratings, but still not as big as the difference between the reference and the anchor condition. The changes in the overall reverberance of the room have a strong impact on the perception of envelopment.

Discussion

The results show that the perception of ASW and also of LEV is influenced by the strength of the lateral reflections. However, the effect of the altered absorption at the side walls on the perceived source width and envelopment was rather small, compared to the expectations from the literature. Especially the lateral fraction of the early reflections is supposed to be a good predictor for the perception of source width, which could not be confirmed by this study. However the simulations in this study altered the lateral fraction for the complete BRIR and not only for the early part, which may have an influence on the perception of source width.
Additionally, some subjects which participated in this study mentioned difficulties in the externalisation of the stimuli simulated with the used HRTF set. Therefore the sources might have been perceived closer than they should have been. This would lead to a generally high rating in source width because close sources are always perceived as rather broad. Thus, the resolution of the ASW rating could be not high enough to clearly see the effects of altering the lateral fraction.
The strong influence of the overall reverberance of the room on the LEV fits quite well with the literature, since the perception of envelopment is strongly connected with the perception of reverberance. Nevertheless, it is surprising that the additional or missing absorption at the side walls could virtually completely be compensated by the other surfaces without having a clear effect on the perceived envelopment.
This study of course, only included simulated BRIRs

with source and receiver position on the middle axis of the surveyed rooms. The influence of the reflections of the side walls might increase clearly, when the BRIRs are simulated with the source or the receiver position closer to the side walls. It would also be more difficult to compensate for the manipulated absorption at the side walls in more realistic rooms, which have different materials at the surfaces and are not shoe-box shaped.

Conclusion

The stronger the absorption at the side walls within a room is, the smaller a source is perceived and the less enveloping a sound is. If the side walls are less absorbing, the reflections from the side are stronger and the ASW and LEV are rated higher. The LEV is stronger affected by changes in the overall reverberance of a room than the ASW is.
For the perception of envelopment it seems possible to compensate for stronger absorption at the side walls, by decreasing the absorption at the other surfaces, without altering the LEV too much. At least for the simple simulated shoe-box rooms which were surveyed in this study and a source-receiver lay-out on the center axis of the room, the LEV seems to only depend on the overall reverberance of a room and not directly on the strength of the reflections at the side walls.

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