Externalization versus Internalization of Sound in Normal-hearing and Hearing-impaired Listeners

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Introduction

The externalization (i. e., the outside-of-the-head localization) of distant sound sources is a natural phenomenon and part of the sound localization process. Opposed to this, the internalization (i. e., the inside-the-head localization) of sound typically occurs during headphone playback. The investigation of these two effects with respect to hearing impairment is particularly interesting, as externalization is an aspect of *natural* hearing and might be affected by the hearing impairment itself or the impact of hearing aids on relevant acoustic cues.

The sensitivity of both normal-hearing listeners (NHL) and hearing-impaired listeners (HIL) to externalizing cues was tested in an intuitive listening test using headphones. The HIL group had mild to moderate hearing losses and the signals were amplified according to the 'Cambridge formula' [1], which ensured stimulus audibility at all frequencies of interest.

Auralization via headphones

A loudspeaker listening room at DTU according to the standard IEC 268-13 was used for the experiments. The room was equipped with two loudspeakers at about ±30° relative to the subject's median plane. A certain amount of lateralization ensured a sufficient amount of binaural cues (ITDs and ILDs) that enhance externalization. As the angle was not very large, the visual cues were maintained, i. e., the test subject could see the sound source without the need of head movements, which were restricted in these experiments. Figure 1 shows a photo of the experimental setup in the listening room.

Figure 1: Experimental setup in the listening room.

In order to create the virtual playback of a loudspeaker presented via headphones, the acoustical transfer functions from the loudspeaker to the listener's ears were measured using small hearing aid microphones in so-called 'open domes' (normally holding the receiver in open-fitting hearing aids). Likewise, the transfer function of each headphone driver was measured while being placed on the subject's ear. The division of the first transfer functions by the latter yields the cancellation of the microphone and headphone transfer functions. As a result, only the characteristics of true loudspeaker playback remain, namely the loudspeaker's characteristics and the room influence combined with the presence of the subject. The resulting transfer functions were converted into impulse responses, such that an arbitrary signal could be convolved with them. The resulting two-channel signal created the percept of a signal stemming from one of the loudspeakers, i. e. externalized, while actually being played back via the headphones.

Psychoacoustic listening test

In order to test a subject's sensitivity to externalization, two psychoacoustic experiments were conducted. They investigated:

1. How much externalizing information is necessary to perceive a deviation from complete internalization?
2. How much externalizing information has to be removed from the completely externalized state to perceive a deviation from complete externalization?

Both experiments required intermediate steps between the extremes (complete internalization/externalization). These were achieved by mixing internalized and externalized versions of the same stimulus in different ratios, see figure 2. The binaural impulse responses $h_{\text{ext}}(t)$ are the

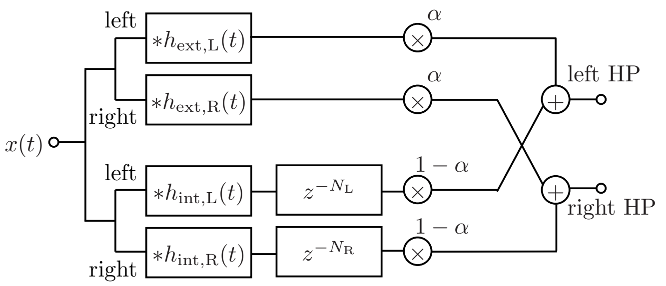

Figure 2: Mixing scheme to create headphone (HP) stimuli with different degrees of externalization.

externalizing impulse responses as described above, including headphone equalization. An internalized version of the same signal was created via the impulse responses $h_{\text{int}}(t)$, which were measured by placing the two omnidirectional microphones at the location of the listener's ears while the listener was absent. This ensured that a signal convolved with $h_{\text{int}}(t)$ had the same room reverberance and loudspeaker characteristics, i. e. no additional discrimination cues were introduced. The missing aspect was the directional filtering caused by the physical presence of the test subject's torso, head and pinnae. The lack of this filtering made the signal appear internalized. Finally, its channels were synchronized with those of the externalized version in order to maintain the ITD. Before the externalized and internalized signal versions were added, they were weighted with the factor α and $1-\alpha$, respectively. α reached from zero to unity and thereby determined the amount of externalized signal in the signal mix.

Using this technique, the two experiments stated above were implemented as discrimination tasks, using an adaptive 2-alternative forced choice method combined with a 1-up 2-down rule. In order to keep the task intuitive, the question to be answered was 'Which interval sounded more like coming from the loudspeaker?' in *both* experiments. Hence, the stimuli were set up as follows:

Experiment 1, 'int-to-ext': *Target* interval: $\alpha = 1$ (fully externalized) at the beginning, α was varied in the course of the experiment. The other interval was kept completely internalized ($\alpha = 0$).

Experiment 2, 'ext-to-int': *Target* interval: kept completely externalized ($\alpha = 1$). The other signal started internalized ($\alpha = 0$), α was varied in the course of the experiment.

The speech material of the 'Conversational language understanding evaluation' (CLUE) test [2] was used as the stimuli. In both experiments, the threshold was measured six times (interleaved runs) – each of them with a single sentence. In order to examine a possible dependence on source direction, three of them were determined using the left and right loudspeaker of the symmetrical stereo setup (see figure 1), respectively.

Results

The mean thresholds with the corresponding standard deviations for NHL are shown in figure 3. The across-subject averages (horizontal lines) reveal that the range of externalization perception is limited to α fractions of about 19 to 79 % of external signal in the mixed signal. This means that below 19 %, no further increase of internalization, and that above 79 % no further increase of externalization was perceived.

Figure 4 shows the mean thresholds and standard deviations for the HIL. There is a large spread of the data, i. e. the thresholds do not group closely to the across-subject averages, which are at 31 % for the int-to-ext condition and 69 % for the ext-to-int condition. The standard deviations vary considerably across subjects and partly also between the two experiments within a listener. Note however, that some HIL performed in the normal range.

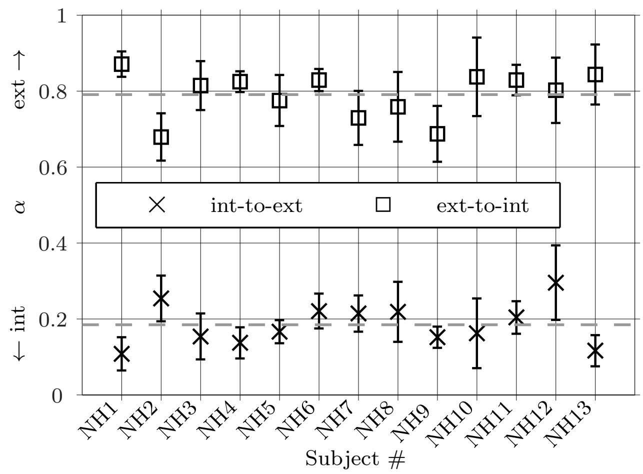

Figure 3: Average thresholds for the int-to-ext and the ext-to-int experiments for NHL.

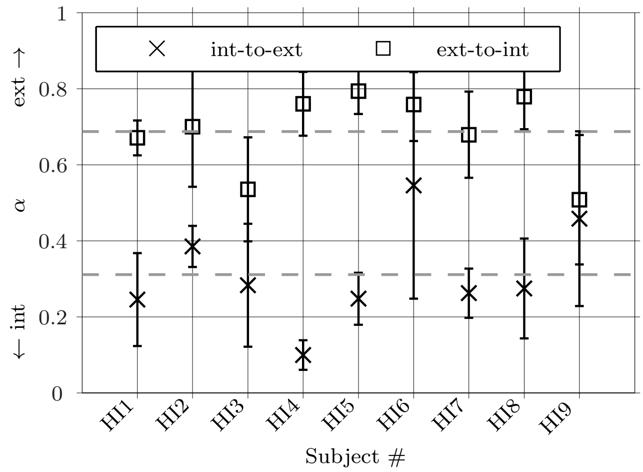

Figure 4: Average thresholds for the int-to-ext and the ext-to-int experiments for HIL.

Conclusion

Compared to NHL the results for the HIL were much less homogeneous. On average, the HIL were less sensitive to changes in externalization than NHL. The dynamic range limiting the perception of externalization was reduced by roughly 10 % on each side. Individual thresholds (not shown explicitly here) indicated some dependence on the direction of sound incidence, which only partly correlated with the individual listener's hearing loss and listening experience.

References

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