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Published in:
Proceedings of DAGA 2014

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Cubick, J., Santurette, S., Laugesen, S., & Dau, T. (2014). Influence of High-Frequency Audibility on Distance Perception. In Proceedings of DAGA 2014 (pp. 576-577). German Acoustical Society (DEGA).

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Influence of High-Frequency Audibility on Distance Perception

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Introduction

When listening in natural environments, normal-hearing (NH) listeners usually perceive sounds at the place of their origin outside their head. This phenomenon is referred to as externalization. The opposite phenomenon of sounds being perceived inside the head is called internalization. For NH listeners, internalization typically occurs when listening to recordings through headphones. In a recent study [1], some hearing-impaired (HI) listeners were reported to externalize sounds less than NH listeners in an experiment where a virtual auditory space technique with individual binaural room impulse responses (BRIRs) was used. However, it was also found that the average externalization rating of NH listeners dropped to the level of HI listeners when the stimuli were lowpass-filtered at 6.5 kHz to simulate a typical hearing aid bandwidth. A slight reduction of the externalization rating compared to broadband speech for NH listeners was also found in [2] in a similar experiment for stimuli lowpass-filtered at 4 kHz. These findings suggested that HI listeners perceive sounds less externalized than NH listeners and that reduced audibility at high frequencies might be the main reason for this degradation.

The current study investigated whether the perceived distance of sounds in HI listeners differs from that in NH listeners and, if so, whether this difference can be accounted for by reduced audibility at high frequencies in the HI listeners. It was assumed that a reduction of the externalization percept should also reduce the perceived distance of the auditory event. Instead of degrading a single BRIR, BRIRs were measured for different loudspeaker distances similar to [3]. The listeners were asked to rate the perceived distance on an absolute scale in metres according to visual markers in the room, either for signals filtered with the measured BRIRs or lowpass-filtered versions to reduce high-frequency audibility. If high-frequency audibility is crucial for externalization, it was expected to see reduced distance ratings in the conditions with lowpass-filtered stimuli.

Methods

Individual BRIRs were measured for ten NH listeners (one female) at nine log-spaced egocentric distances (0.43, 0.61, 0.86, 1.22, 1.72, 2.44, 3.45, 4.88 and 6.9 m) at an angle of 25°. The listeners were blindfolded before being guided into the experiment room, a workshop of about 12.65 x 6.75 x 3.10 m with an acoustic ceiling and an average reverberation time T_{30} of about 0.6 s. During the measurement, the listeners were seated in a listening chair and provided a small headrest to help keep-

ing the position of the head fixed. The BRIRs were measured at the entrance of the open ear canal with DPA 4060 lapel microphones attached to the pinna with a wire hook, using six repetitions of a 5 s logarithmic sine sweep and a deconvolution method according to [4]. After the BRIR measurements, the listeners put on a pair of Sennheiser HD 800 headphones and the headphone impulse response (HPIR) was measured with 10 repetitions of a 2 s sine sweep. After the measurement, the microphones remained in the ears and the headphones were not moved throughout the experiment.

For each experimental run, a random sentence from the Danish HINT speech test corpus [5] was convolved with the measured BRIRs and the inverse of the HPIRs. The resulting auralized signals were band-limited between 50 and 15000 Hz with 6th order Butterworth filters (Broadband condition). Apart from the broadband condition, two conditions were tested with lowpass-filtered stimuli, either with a cutoff-frequency of 6 kHz to simulate the limited bandwidth of a hearing aid or with a cutoff-frequency of 2 kHz to simulate a hearing loss. Both lowpass-filters were realized as 32 tap Hamming-window based FIR filters. The listeners were instructed to judge



Figure 1: Photograph of the listening test setup in the workshop room with visual markers at 2, 4, 6, and 8 m.

the distance of the auditory event on an absolute scale in m provided by visual markers at distances of 2, 4, 6, and 8 m in the workshop room (see Fig. 1 for a photograph of the experimental setup). The rating was done in a modified MUSHRA (ITU-R BS.1534-1) Matlab user interface with a playback button for each stimulus and a slider with the same scale as provided in the room to rate the perceived distance. In each run, stimuli with the same bandwidth for all nine measured distances were assigned to the sliders randomly. All bandwidth conditions

were tested once to train the listeners and repeated four times in the actual experiment.

Results and Discussion

Fig. 2 shows the mean value and standard deviation of the perceived distance for all listeners in the broadband condition (squares) and for the stimuli lowpass-filtered at 6 kHz (triangles) and 2 kHz (circles). For the two shortest distances, the auditory image was perceived closer to the listener than the auralized distance. For medium distances between about one and five metres, the average distance estimates were fairly close to the veridical values (light grey, dash-dotted line in Fig. 2) whereas the sounds were perceived slightly closer than the actual loudspeaker position in the BRIR measurement for the farthest distance.

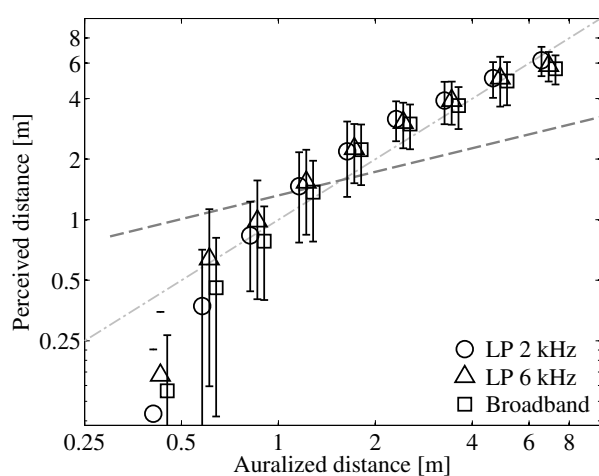


Figure 2: Mean perceived distance over ten NH listeners for the three test conditions. The error bars indicate \pm one standard deviation. For clarity the symbols are slightly shifted around their values on the abscissa. The grey dashed line indicates the average perceived distance found in [3].

These findings are clearly in contrast to the average data presented in [3], indicated by the grey dashed line in Fig. 2, where the listeners typically overestimated the distances at short source distances and underestimated the farther distances, a behaviour that was also found in most other studies about auditory distance perception (see summary table in [3]). One reason for this discrepancy might be that the measurements in [3] were conducted in an auditorium, whereas the experiment was performed in a listening booth without visual cues. In contrast, the listeners in the present study performed the task in the *same* room where the BRIRs had been measured and visual cues were provided. The experimental conditions in the present study were thus much closer to those of a recent study investigating the influence of visual anchors on auditory distance perception [6]. Comparing our results to the ones from [6], the data are consistent in the case where visual markers were present. This suggests that auditory distance perception is strongly influenced by, and much more precise, in the presence of visual cues.

Comparing the distance ratings for the different bandwidth conditions, no systematic influence of the lowpass-filtering could be found. This seems to be in contradiction with [1] and [2], where even moderate lowpass-filtering caused a significant reduction of the externalization rating. It is possible that the method used here is less sensitive to slight degradations of the percept, because the available distance range is subdivided into many steps by the different measurement distances, whereas the entire distance between the (visible) loudspeaker and the listener's position was available to judge the externalization rating in [1, 2].

Conclusion

In the presented distance experiment, the listeners were able to rate the perceived distance of the auralized speech stimuli consistently. The procedure yielded average distance ratings fairly close to the auralized distances for medium distances and did not produce the highly compressive behaviour commonly observed in experiments on auditory distance perception. Unlike in earlier investigations on externalization, lowpass-filtering of the signals did not cause any systematic change in the distance rating, even within listeners. Conducting the same experiment with HI listeners will reveal potential differences in the perception of auditory distance compared to NH listeners. Should such differences be found, other effects of hearing impairment besides the loss of audibility will need to be considered as the limiting factors for distance perception and externalization in HI listeners.

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