The Influence of Hearing-Aid Microphone Location and Room Reverberation on Better-Ear Effects

TOBIAS NEHER[1], CLAUDIA BREITSPRECHER[2], AND SØREN LAUGESEN[1]

[1] *Eriksholm Research Centre, Oticon A/S, Kongevejen 243, DK-3070 Snekkersten, Denmark*

[2] *Institute of Hearing Technology and Audiology, University of Applied Sciences Oldenburg, Ofener Str. 16, D-26121 Oldenburg, Germany*

This study quantified the influence of hearing-aid microphone location and room reverberation on so-called better-ear effects (BEEs), i.e. the ear-specific signal-to-noise ratio (SNR) changes brought about by head and pinna filtering in situations with spatially separated sound sources. Using an acoustic manikin, BEEs were measured for various target-masker constellations and for two microphone locations: above the outer ear (BTE) and at the ear-canal entrance (CIC). To determine the effects of reverberation, all measurements were made under anechoic and reverberant conditions.

Compared to the CIC position, the BTE position led to substantially lower high-frequency SNRs on the side of the masker when the target was in front and the masker to the side or the rear of the manikin. Furthermore, even though BEEs were found to decrease as the ratio of reverberant to direct sound increased, considerable BEEs remained even under fairly extreme reverberant conditions.

Altogether, these results demonstrate that, relative to the BTE position, hearing-aid microphones located at the ear-canal entrance are advantageous as far as head and outer-ear induced SNR changes are concerned. In addition, they indicate that BEEs of a noteworthy magnitude should be available in the reverberant listening situations experienced by typical hearing-aid users.

INTRODUCTION

In situations with competing noise sources, listeners are known to improve their speech recognition by exploiting BEEs (e.g. Bronkhorst and Plomp, 1988). These effects are due to the directional properties of the human head and pinnae. They can give rise to ear-specific SNR changes when the head and pinnae filter a target and masker signal differently. To give a simple example, consider the situation in which a target signal is coming from in front and a masker signal from the side of a listener. As a result of the listener's head acoustically shadowing frequencies above approximately 2 kHz (e.g. Blauert, 1997), the masker signal will have less energy on the far ("shadow") side than on the near ("baffle") side, leading to a high-frequency SNR improvement on the shadow side.

Proceedings of ISAAR 2009: Binaural Processing and Spatial Hearing. 2nd International Symposium on Auditory and Audiological Research. August 2009, Elsinore, Denmark. Edited by J. M. Buchholz, T. Dau, J. Cristensen-Dalsgaard, and T. Poulsen. ISBN: 87-990013-2-2. The Danavox Jubilee Foundation, 2010.

The directional filtering effects described above can be expected to be best preserved at a listener's ear-canal entrances where the microphones of a completely-in-the-canal (CIC) hearing aids are located. Nevertheless, a large number of hearing-aid wearers are in fact fitted with behind-the-ear (BTE) devices. Consequently, it is of interest to find out to what extent picking up the sound above the pinna – rather than at the ear-canal entrance – leads to modified BEEs. In addition to any microphone location effects, reverberant environments may also distort BEEs. This is because under reverberant conditions a source signal will reach a listener's ears not only via the direct path, but also via a multitude of indirect paths in the form of reflections. Since many of these reflections will effectively bypass the directional filtering exerted by a listener's head, they are likely to lead to reduced head shadowing (e.g. Kidd *et al.*, 2005). Given that most everyday listening takes place in reflective environments, it is therefore also of interest to find out to what extent BEEs are affected by the presence of reverberation. Hence, this study was designed to address the influence of both hearing-aid microphone location and room reverberation on BEEs.

MEASUREMENT AND ANALYSIS METHODS

Measurement set-up

To quantify the effects of hearing-aid microphone location, a Brüel and Kjær head-and-torso simulator (HATS) was fitted bilaterally with omnidirectional microphones (Knowles FG series). The microphones were placed at positions representative of CIC and BTE hearing aids. In order to obtain measurements suitable for speech intelligibility prediction, loudspeakers with directional properties similar to those of human talkers were used (Genelec 8030A). The loudspeakers were positioned at ear height at each of five source azimuths (0°, 45°, 90°, 135° and 180°), as shown in Fig. 1.

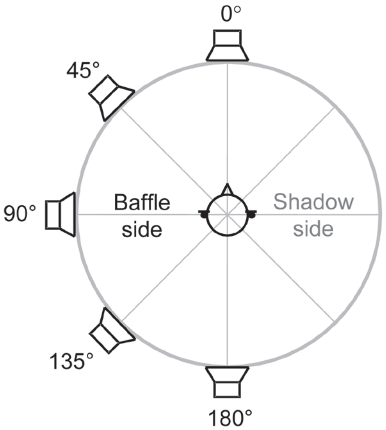

Fig. 1: Measurement set-up specifying HATS' baffle (black) and shadow (grey) side.

To quantify the effects of room reverberation, measurements were made in both an anechoic chamber and a reverberant auditorium. The auditorium was 11.6 m long by 10.8 m wide by 4.5 m high (volume ≈ 560 m3) and had a reverberation time of approx 0.7 s. Its side walls were made of glass, resulting in the arrival of strong lateral reflections at HATS, which was roughly positioned in the middle of the auditorium at a height of approx 1.7 m. In order to vary the relative amounts of reverberation at HATS, measurements were made at four loudspeaker distances (1 m, 1.9 m, 2.5 m and 4.1 m) for each source azimuth.

BEE estimation

To enable the estimation of BEEs, transfer functions, H(ω), were measured for all combinations of microphone, source azimuth and source distance. Next, an arbitrary input signal was filtered with each H(ω), and the resultant signal output levels were determined in one-third octave bands. A number of spatial target-masker constellations were then defined and the resultant SNRs determined using the same input signal for both target and masker (corresponding to a free-field SNR of 0 dB). Subsequently, the inner product of these one-third octave band SNRs and the one-third octave band importance weights from the articulation index (AI) (ANSI, 1997) was computed. This resulted in single-value SNR estimates, AI-SNRs, indicative of the intelligibility advantages offered by the head and pinna filtering effects effective for the various combinations of microphone location and target-masker constellation. The final BEE estimates could then be obtained by taking the difference between the one-third octave SNRs or AI-SNRs measured on HATS' shadow and baffle side. In what follows, however, the shadow- and baffle-side SNRs will be reported, since they are more informative than the BEEs and since the latter can easily be derived from the former.

Estimation of relative level of reverberation

Apart from estimating BEEs, the relative level of the reverberation at the receiver was also determined for all the measurements made in the auditorium. More precisely, for a given H(ω) the room impulse response, *h*(*t*), was found and the corresponding direct-to-reverberant sound ratio (DRR) computed as follows:

$$DRR = 10\log\left[\int_{0ms}^{2ms} h^2(t) \Big/ \int_{2ms}^{\infty} h^2(t)\right], dB \qquad \text{(Eq. 1)}$$

Estimating DRRs in this manner is very similar to the approach taken by other researchers (e.g. Devore *et al.*, 2007; Zahorik, 2002).

RESULTS

Anechoic one-third octave SNRs

The anechoic one-third octave band SNRs measured at the CIC and BTE locations on HATS' baffle and shadow side are shown in Fig. 2. For all measurements, the target was at 0°, whereas the masker was either at 45°, 90°, 135° or 180°. For a masker azimuth of 45°, it can be seen that the CIC and BTE locations generally lead to similar results. For masker azimuths of 90° and 135°, however, the BTE location leads to substantially smaller SNRs between 2-5 kHz, most notably so on HATS' baffle side. For a masker azimuth of 180°, in turn, the BTE location leads to smaller SNRs above approx 2 kHz on both sides of HATS, due to the lack of pinna-shadowing.

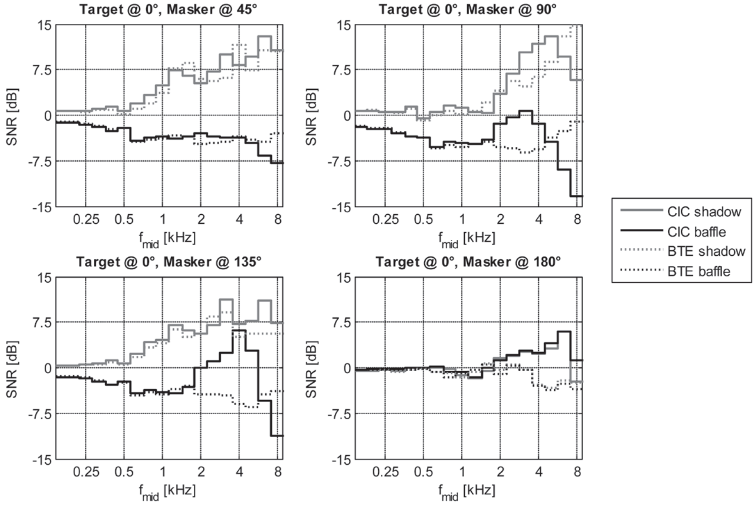

Fig. 2: Anechoic one-third octave SNRs measured at the CIC and BTE locations on HATS' baffle and shadow side. The target was at 0° and the masker at 45°, 90°, 135° or 180°.

Anechoic and reverberant AI-SNRs

Figure 3 shows the anechoic and reverberant AI-SNRs obtained for a target at 0° and a masker at 90°. As can be seen, the AI-SNRs at the "conversational" distances of 1 m and 1.9 m are largely unaffected by the presence of reverberation; at both distances, an across-ear AI-SNR difference – or AI-weighted BEE – of approx 8 dB can be observed, irrespective of microphone location. What is more, even at a distance of 4.1 m, an AI-weighted BEE of approx 5 dB remains. It is also apparent that, despite giving rise to very similar BEEs, the BTE location generally leads to lower AI-SNRs than the CIC location. The same holds true for masker azimuths of 135° and 180°, but not for a masker azimuth of 45°, for which the two microphone locations lead to highly similar AI-SNRs (results not shown). Altogether, the obtained AI-SNR results are in line with the unweighted one-third octave band SNRs shown in Fig. 2.

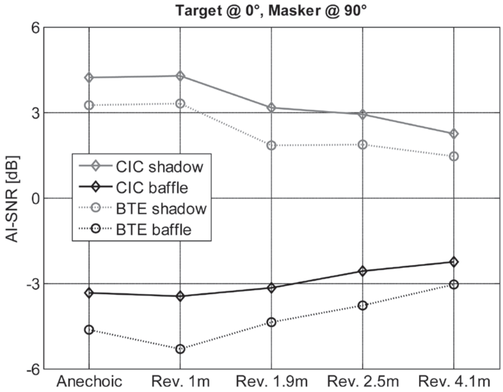

Fig. 3: Anechoic and reverberant AI-SNRs measured at the CIC and BTE locations on HATS' baffle and shadow side. The target was at 0° and the masker at 90°.

DRRs

Figure 4 displays the DRRs corresponding to the measurements made in the auditorium at source distances of 1 m and 4.1 m (results obtained for the two intermediate distances are in accordance with the findings reported below and will therefore not be shown). The first thing to note is that, for a given source azimuth, microphone location and side of HATS, a substantially smaller DRR is apparent for the 4.1 m distance than for the 1 m distance. This therefore confirms the expected relative increase in reverberation as the distance between source and receiver becomes larger.

More interestingly, it can also be seen that the DRR varies as a function of source azimuth, especially for the CIC measurements. For example, for the CIC location on HATS' baffle side, the largest DRR is apparent for a source azimuth of 45° and the smallest DRR for a source azimuth of 180°. These results can be traced back to the directional properties of the pinna. Due to its angular orientation relative to the surface of the head (the "pinna flare angle"; e.g. Algazi *et al.*, 2001) and its geometric shape, the pinna is particularly sensitive to high-frequency sound arriving from about 45° (cf. Mehrgardt and Mellert, 1977, Fig. 11). For high-frequency sound arriving from 180°, however, the pinna constitutes an obstacle and hence attenuates it (cf. Wightman and Kistler, 1997, Fig. 12). These effects can explain the pattern of DRRs observable in Fig. 4 for both the CIC location and the BTE location. The fact that the latter location leads to more homogeneous DRRs simply implies that HATS' directionality is less pronounced above the outer ear than at the ear-canal entrance.

The DRRs shown in Fig. 4 can also help explain the considerable (AI-weighted) BEE of approx 5 dB that was observed for the "extreme" source distance of 4.1 m (cf. Fig. 3). Even at that distance positive DRRs are apparent for source azimuths of 0° and, on the baffle side 90°, meaning that the energy contained in the direct sound outweighed the energy contained in the reverberant sound. Consequently, the directional filtering exerted by the head and pinnae on sound coming from these directions was still (partly) effective, resulting in the preservation of some BEE.

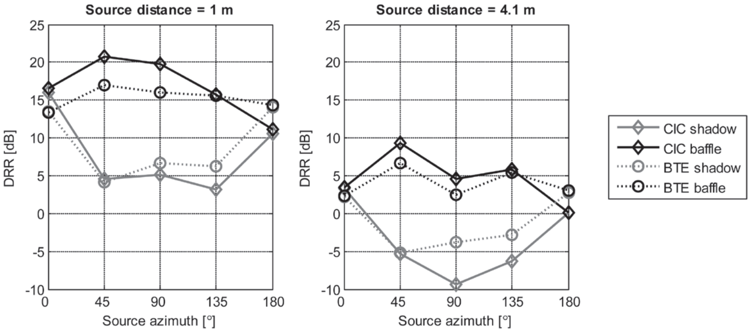

Fig. 4: DRRs computed on the measurements from the auditorium made at source distances of 1 m and 4.1 m for the CIC and BTE locations on HATS' baffle and shadow side.

SUMMARY AND CONCLUSIONS

This study investigated the effects of hearing-aid microphone location and room reverberation on BEEs, i.e. across-ear SNR differences. With the help of an acoustic manikin, BEEs were measured for a number of spatial target-masker constellations at both CIC and BTE microphone locations under anechoic and reverberant conditions. It was found that the BEEs observable at the CIC and BTE locations had comparable magnitudes. However, the ear-specific (local) SNRs brought about by head and pinna filtering were more favourable (i.e. positive) at the CIC location than at the BTE location when the target was at 0° and the masker at 90°, 135° or 180°.

Gradual increases in the level of reverberant sound relative to the level of direct sound were found to lead to reduced BEEs, as expected. Nevertheless, considerable BEEs remained even under comparatively extreme reverberant conditions. Since hearing-aid users in general are likely to avoid overly reverberant environments, considerable BEEs can be expected to be available to them in most listening situations.

Not only were the directional properties of the head and pinnae found to result in local SNR changes, they were also found to affect the ratio of direct to reverberant sound contained in a given microphone signal. This was particularly true for the CIC location, for which the computed DRRs showed a fairly large dependency on source azimuth. This dependency, in turn, was traced back to the pinna's comparatively high sensitivity in the 45° direction and its comparatively low sensitivity in the 180° direction.

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