Horizontal localization with pinna compensation algorithm and inter-ear coordinated dynamic-range compression

PETRI KORHONEN*

Widex, Office of Research in Clinical Amplification (ORCA-USA)

Many hearing-aid users show poorer aided than unaided localization performance even when audibility is accounted for. One source of potential disruption of aided localization include the use of wide dynamic range compression circuits operating independently at each ear in bilateral fittings, which can compromise the interaural-level-difference (ILD) cues used for left-right localization. The natural ILD cues can be restored by coordinating the gain between the two hearing aids wirelessly. Another potential source of disrupted localization include the absence of pinna-shadow when using behind-the-ear (BTE) hearing aids with omnidirectional microphones. A pinna shadow compensation feature that restores the natural attenuation for sounds originating from behind was developed. This study examined the localization performance of hearing-impaired listeners in the horizontal plane when using a BTE hearing aid incorporating inter-ear coordinated compression and a pinna-shadow compensation algorithm. Fifteen listeners who had previously participated in a localization study were recruited. The data demonstrated that the use of the pinna-shadow compensation algorithm improved the localization accuracy over a BTE hearing aid with an omnidirectional microphone. A modest improvement in localization performance was measured for some listeners when using the coordinated inter-ear compression.

INTRODUCTION

The physical presence of pinna attenuates high-frequency sounds that originate from the back and sides by an average of 5 dB from 2 kHz to 8 kHz. This attenuation provides an important acoustic cue for normal-hearing individuals to localize sounds along the median plane. The use of behind-the-ear (BTE) hearing aids with an omnidirectional microphone placed on top of the pinna eliminates the pinna shadow used for front-back localization, because an omnidirectional microphone has the same sensitivity to sounds from all directions. This lack of difference in sensitivity between sounds arriving from the front and the back may reduce front-back localization performance. The absence of the pinna shadow can be corrected so that, despite using a BTE with an omnidirectional microphone, the wearer will still have the ‘normal’ localization cues. The Digital Pinna (DP) hearing-aid feature was developed to compensate for the difference in input measured between an unaided ear and an aided ear with an omnidirectional BTE hearing aid. The DP algorithm sets the microphone system to a fixed hypercardioid polar pattern above 2000 Hz,

*Corresponding author: petri.korhonen@iki.fi

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while keeping an omnidirectional mode below 2000 Hz. This simulates the natural pinna attenuation for sounds originating from the back.

For sounds arriving from the side of the listener the difference in the acoustic path from the source to the two ears results in a difference in the signal amplitude and phase characteristics at the two ears. This interaural level difference (ILD) and interaural time difference (ITD) provide the cue for left-right localization in the horizontal plane (Blauert, 1997). The use of wide-dynamic-range-compression (WDRC) circuits operating independently at each ear in bilateral fittings may compromise the ILD cues. The WDRC circuit provides more gain to low-level signals, and less gain to high-level signals. Sounds that arrive from the incident side will measure a higher sound pressure level at the microphone opening than the opposite ear because of the head shadow. In this case the WDRC hearing aid applies less gain on the side of the sound source than on the opposite side. As a result, the use of two independently operating WDRC hearing aids at each ear may result in output levels between the two ears such that the natural ILD is not preserved. The coordination of the gain between the two hearing aids can restore the natural ILD. The hearing aid used in the current study included functionality where each input received by one hearing aid was shared wirelessly with the other hearing aid. The gain calculated for the target sound side was used in both hearing aids.

While the inter-ear coordinated compression and digital pinna can restore the natural cues that hearing-aid processing may have distorted, it is possible that listeners may not be able to interpret these new localization cues immediately. In fact, the effect of distorted ILDs on localization has been reported to be rather small in hearing-impaired listeners (Keidser *et al.*, 2006; Musa-Shufani *et al.*, 2006). Maybe the reported small impact of distorted ILDs on localization has been a result of the listeners' inability to fully utilize the ILD cues. For that reason, it would be worthwhile to examine the effects of WDRC on localization with listeners that have participated in auditory localization training.

Keenan (2013) developed and evaluated a training program that focused on localizing sounds in the horizontal plane. The training included both computerized laboratory-based and take-home programs. These programs provided immediate feedback and learning opportunities, and were designed to motivate the participants for greater success by adaptively changing the difficulty of the stimuli by varying the duration of the stimuli, and by exaggerating the pinna-shadow attenuation for sounds that originated from the back. The laboratory-based training utilized a 12-loudspeaker array distributed evenly at 360° separated by 30°. The take-home training used two loudspeakers located at 0° and 180°. The trainee's task was to indicate from which loudspeaker they perceived the stimulus. The trainee was given an opportunity to compare the perception between the correct loudspeaker direction and their indicated loudspeaker direction after each stimulus presentation.

The listeners who have received localization training may be more sensitive to changes caused by the inter-ear coordinated WDRC and the digital pinna. To test this hypothesis, the current study recruited the participants that had received localization training previously in the Keenan (2013) study. The current study examined the horizontal localization performance of these listeners when using a BTE hearing aid incorporating the digital pinna feature and the inter-ear coordinated compression.

METHODS

Subjects

Fifteen participants (7 males and 8 females) with bilateral sensorineural hearing loss were recruited. The averaged pure-tone averages were 48.6 dB HL (standard deviation, SD = 11.8) for the right ear and 50.1 dB HL (SD = 12.0) for the left ear. The symmetry of hearing loss was within 15 dB between ears at any frequency. One subject had a threshold difference of 20 dB at 6000 Hz and another a difference of 25 dB at 8000 Hz. Participants' ages ranged from 28 to 83 yr (mean = 71 yr, SD = 12.9). Ten participants had received one month of home-based training and one month of laboratory-based training as a part of a separate study. Five participants had received six days of laboratory-based training. Participants signed informed consent and were financially compensated for their participation in the study.

Hearing aids

Participants were fitted bilaterally with Widex C4-m-CB BTE hearing aids using custom earmolds. This 15-channel wide-dynamic-range-compression micro-BTE hearing aid uses a relatively long attack time of up to 2 s and a long release time of up to 20 s in each of the 15 channels for most situations. This hearing aid includes a pinna-compensation algorithm called Digital Pinna which was designed as a directional microphone with a hypercardioid pattern above 2000 Hz, which approximates the unaided in-situ directivity below 1.5 kHz and has a directivity index (DI) of 4 dB above 2 kHz. This hearing aid also includes wireless functionality where input received by one hearing aid is shared with the other aid of the bilateral pair wirelessly at a rate of 21 times per second using near field magnetic induction (NFMI). The data exchange coordinates the gain parameters so that the gain at each ear corresponds to the gain calculated for the side of the more intense sound.

Testing

Testing was conducted in a double-walled sound-treated test booth with internal dimensions of 3 × 3 × 2 m (W × L × H). The target stimulus was a three-second female speech sample presented in quiet at a 30 dB sensation level (SL). The stimulus was presented using twelve loudspeakers (KRK-ST6) distributed evenly (30° spacing) on a horizontal plane around the listener (1-m distance) at one-meter height from the floor. The participants were asked to keep their heads fixed towards the loudspeaker at 0°. Four hearing-aid settings were compared: omnidirectional microphone (Omni), omnidirectional microphone with digital pinna (DP), omnidirectional microphone with inter-ear coordinated compression (IE), and omnidirectional microphone with IE and DP (IE+DP). In addition, the unaided performance was measured. The test conditions were counterbalanced across participants. The participants indicated the perceived location of the target by touching a touch-screen computer monitor placed in front of them. The stimulus was presented from each azimuth three times during each test trial.

RESULTS

The current study reported the error characteristics of sound-localization performance using a 'centre of mass' (CoM) method pioneered and presented in detail by Edmondson-Jones *et al.* (2010). The CoM method examines the proportion, direction, and size of errors simultaneously. The CoM analysis is represented visually with a unit circle centered at the origin in the Cartesian coordinate system in the Euclidean plane. The planar Cartesian coordinates for a single response are defined as (sin θ, cos θ) (Fig. 1, left). The CoM is the mean location of all the 'mass' in a group of bodies (Fig. 1, right). Each data point is assumed an equal weight of a unit mass. For a sample of N observations the sample mean is defined as

$$\overline{X} = (xCoM, yCoM) = \left(\frac{1}{N}\sum_{i=1}^{N}\sin\theta_i, \frac{1}{N}\sum_{i=1}^{N}\cos\theta_i \right)$$

When the responses are perfectly correct the yCoM will be 1 while xCoM will be 0. Thereby, yCoM is a measure of the target accuracy indicating how close the responses are from the perfect responses, and xCoM is a measure of lateral accuracy indicating the response distance from the origin. Applying the standard Multivariate Analysis of Variance (MANOVA) methods, Edmondson-Jones *et al.* (2010) demonstrated that the CoM method performs well in the control of Type I errors and showed its power to detect significant changes in localization responses. Post-hoc methods are also appropriate to investigate the front-back location effects or effects in different quadrants.

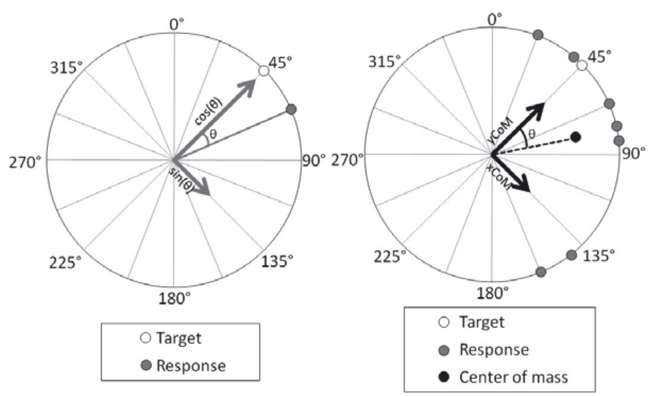

Fig. 1: Visual representation of center of mass (CoM) analysis method for a single response (left), and a group of seven responses (right) for a stimulus at 45°.

Figure 2 shows the averaged localization performance (target-accuracy) for all participants under the five test conditions. Again, the target accuracy of 1 suggests localization performance is perfect. The performance was 0.51 with Omni, 0.58 with IE, 0.68 with DP, with 0.64 IE+DP, and 0.66 unaided. The localization performances between each of the listening conditions were compared pair-wise with one-way ANOVA. The condition pairs with a significant difference are shown with connectors. There was a significant difference ($p < .05$) between the Omni condition and all other conditions. There was no significant difference between unaided condition, and the DP or IE+DP conditions.

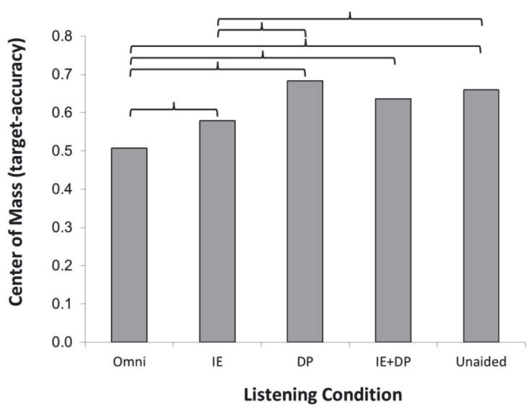

Fig. 2: Averaged localization performance for all participants (N = 15). Test conditions included Omni, IE, DP, IE+DP, and unaided. Comparisons where statistical significance was reached ($p < .05$) are shown with connectors.

Figure 3 compares the unaided and the Omni conditions. Note that the more accurate the performance, the closer the location of the CoM was towards the edge of the unit circle. Statistical significance in the difference in performance between the evaluated conditions was analyzed for front (330°, 0°, 30°), right (60°, 90°, 120°), back (150°, 180°, 210°), and left (240°, 270°, 300°) quadrants separately using one-way ANOVA. The quadrant where there was a significant ($p < .05$) difference between the conditions is indicated with gray shading. With the Omni condition the listeners had difficulties localizing in front-back dimension. A significant difference ($p < .05$) in performance between the unaided and Omni conditions was observed in the back quadrant. This demonstrated that the use of omnidirectional microphone in a BTE hearing aid distorted the natural pinna cue used for front-back localization. No significant difference was observed for the other three quadrants.

Figure 4 compares the Omni and the DP conditions. Digital pinna was designed to correct for the absence of the pinna shadow in a BTE hearing aid with an omnidirectional microphone. In fact, the localization performance was significantly better ($p < .05$) with the DP than with the Omni condition in the front and the back quadrants. No significant difference was observed for the right and left quadrants.

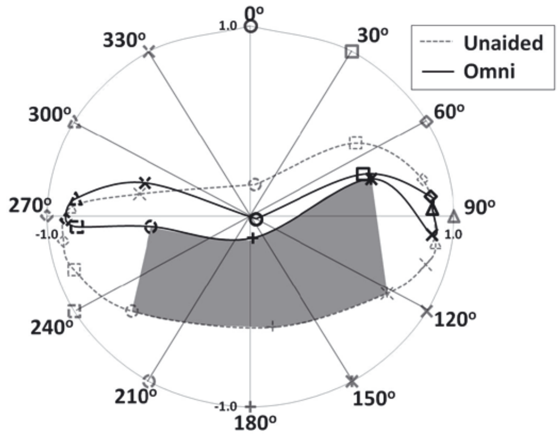

Fig. 3: Localization performance with Unaided (dashed) and Omni (solid). The gray area indicates the quadrant with significant ($p < .05$) difference between the test conditions.

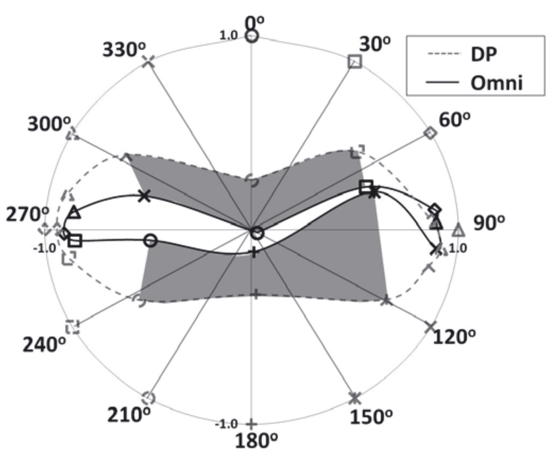

Fig. 4: Localization performance with DP (dashed) and Omni (solid). The gray area indicates the quadrant with significant ($p < .05$) difference between the test conditions.

With both the Omni and the IE conditions the listeners reached a high level of accuracy for sounds arriving from the left or the right, and there was no significant difference between the two conditions for any quadrant. While most participants reached a high level of accuracy for sounds arriving from the sides, individual differences existed. Variation in individual localization performance among participants prompted us to investigate whether the effect of IE compression was dependent on the localization ability. For the participants with the poorest localization performance (yCoM < 0.87) the target accuracy was better with the IE than the Omni condition ($F(1,14) = 5.81$, $p = 0.03$, $\eta^2 = 0.29$, power = 0.6) (Fig. 5).

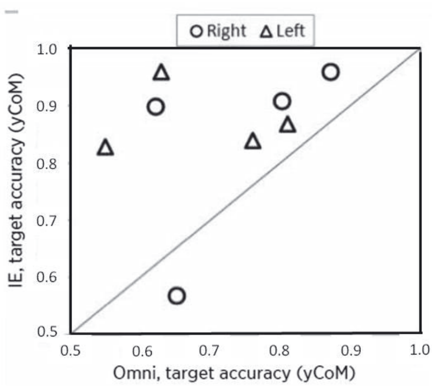

Fig. 5: Scatter-plot comparing individual localization performance between the Omni (x-axis) and IE (y-axis) condition for sounds arriving from the sides (left quadrant: triangles; right quadrant: circles) for the four poorest performers (yCoM < 0.87).

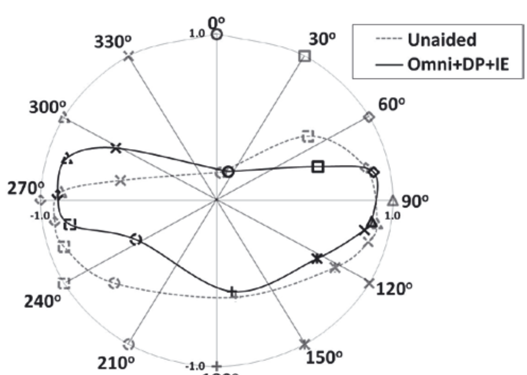

Fig. 6: Localization performance with Unaided (dashed) and IE+DP (solid). The gray area indicates the quadrant with significant (p < .05) difference between the test conditions.

Figure 6 compares unaided performance and the IE+DP conditions. Unlike in the Omni condition, no difference ($p < .05$) was seen in performance between unaided and the IE+DP conditions for any quadrant. In other words, the unaided localization performance was retained when using the digital pinna and inter-ear coordinated compression.

CONCLUSIONS

We demonstrated that the use of the digital pinna feature, as implemented on the hearing aid in the current study, improved front-back localization accuracy in the horizontal plane over a BTE hearing aid with and omnidirectional microphone. We also demonstrated that inter-ear coordinated compression was providing a helpful cue for localization for those listeners who had poorer localization performance for sounds arriving from the sides. The unaided localization performance was better than aided performance when using an omnidirectional microphone alone. However, the use of the digital pinna feature together with inter-ear coordinated compression was successful in restoring the compromised aided performance.

All participants in the current study had received localization training prior to participating in the current study. Also no one wore the hearing aid during the study. We can therefore expect that differences in performance among test conditions reflected the efficacy of the technology and not listener experience or technology alone.

It is worth noting that the effect of the coordinated compression on localization may have been lessened by the slow-acting compression used in the studied hearing aid. In a quiet or in a diffuse sound field, the onset of a sound originating from the side will quickly adjust the gain at each ear in response to changes in the input in a fast-acting WDRC hearing aid. On the other hand, a slow-acting WDRC takes longer to adjust to the final gain setting. Consequently, the natural ILD cues may be interrupted more rapidly in a fast-acting WDRC than a slow-acting WDRC hearing aid, such as the one used in the current study.

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