Effects of Long-Term Bilateral and Unilateral Fitting of Different Hearing Aid Types on the Ability to Locate Sounds

Denis Byrne*, William Noble†, Bernadette LePage‡

Abstract

Aided localization ability of 87 hearing-impaired listeners was tested for horizontal and vertical sound sources, at two signal levels, and for two orientations to the loudspeaker array (facing, sideways). Some listeners wore behind-the-ear (BTE) aids, others in-the-ear (ITE) aids. Some were bilaterally fitted, others unilaterally fitted. Listeners were tested only with types of aids and fittings that they were accustomed to wearing. The results strongly supported bilateral fitting for moderately and severely hearing-impaired listeners. However, for mildly impaired listeners, those fitted unilaterally performed as well, on average, as those fitted bilaterally. This suggests a need to consider individual listening requirements and also to provide such listeners with experience in unilaterally-aided listening before assessing the possible advantages of bilateral fitting. When hearing level was controlled, there was no overall difference in the performance of ITE and BTE aid wearers. This discrepancy with other research may be explained by measures (removal of intensity cues, permitting of head movement) designed to make the test situation more representative of real-life listening.

Key Words: Bilateral fitting, hearing aids, sound localization
The present research examined how auditory localization was affected by hearing impairment and by the wearing of hearing aids. The effects of hearing impairment (degree of hearing loss, type of loss, audiogram configuration) will be reported in a separate paper. Here, we note that, consistent with other studies (Hunig and Berg, 1990), there was a moderate correlation between localization performance and degree of hearing loss (greater hearing loss was associated with poorer localization). In this paper, we examine aided localization with particular reference to the effects of type of fitting and type of hearing aid. The specific research questions were: (a) Do listeners wearing two hearing aids localize better than listeners wearing only one? (b) Does the answer to the first question depend on degree of hearing loss or signal presentation level? (c) Is localization, with either unilateral or bilateral fittings, affected by type of hearing aid (BTE versus ITE)?

**METHOD**

**Listeners**

Eighty-seven hearing-impaired listeners participated in the study. They were nearly all clients of the National Acoustic Laboratories (NAL) and had, therefore, been fitted according to the NAL hearing aid selection procedure.
Aided Sound Localization/Byrne et al

(Byrne and Dillon, 1986). The mean age of the listeners was 65 years and 7 months (SD = 13 years, 5 months). They had worn hearing aids for periods ranging from 3 months to over 15 years. Only two had less than 6 months of aid usage experience and all except 11 had had their current fitting for over 6 months. In fact, the majority (53) had worn their current fitting for over 2 years. There were 43 men and 44 women.

All except three listeners had symmetric hearing losses, defined as no more than 15 dB difference between the four-frequency-average (4FA) hearing levels of the two ears and no more than 25 dB difference at any of the four frequencies (500 Hz, 1000 Hz, 2000 Hz, 4000 Hz) used in the average. Two listeners had interaural differences in 4FA hearing level of 18 dB and 19 dB. Another listener had an interaural 4FA difference of only 5 dB but a difference of 50 dB at 4000 Hz.

The listeners were divided into a number of groups according to type of fitting, type of hearing aid and, for some types of analysis, severity of hearing impairment. The number of listeners in each group and the group mean 4FA hearing levels are shown in Table 1. The 4FA levels shown in Table 1 and used in the analyses, are the averages for each person of the better hearing levels (i.e., not necessarily the same ear) at each of the four frequencies.

### Hearing Aids

The listeners were wearing various BTE and ITE hearing aids and, as indicated in Table 1, some fittings were bilateral, others unilateral. One listener had bilateral BTEs with directional microphones. All the other hearing aids had omnidirectional microphones. Aided testing was performed with the listeners wearing their own hearing aids. The hearing aids were checked and, if necessary, repaired, but were otherwise not altered during the study.

#### Localization Testing Procedure

Details of the localization testing procedure have been presented in Noble and Byrne (1990). Briefly, each block of trials consisted of one presentation of a signal, in a random order, from each of 20 loudspeakers that were visible to the listeners and identified by a number. The listener's task was to nominate, by number, which loudspeaker had been the source of the signal. The sound used was a pulsed pink noise (equal level per 1/3 octave from 200 Hz to 12,500 Hz) of about 0.9 sec duration. It consisted of four 150-msec pulses with rise and fall times of 10 msec and 50 msec interpulse intervals. This stimulus was considered to be broadly representative of speech and other sounds encountered in real life, including the high-frequency components of some consonants.

The testing arrangement is shown in Figure 1. The loudspeaker array comprised two intersecting arcs of 1.22-m radius, one spanning 180 degrees in the horizontal plane and the other 160 degrees in the vertical plane (there was no loudspeaker directly beneath the listener). Two testing arrangements were used—one in which the listeners sat facing the loudspeaker at the intersection of the two arcs and the other facing one of the extreme loudspeakers of the horizontal arc. This sideways arrangement placed the loudspeakers to the listener's right hand side except for the three loudspeakers that were directly in front of, directly behind, or directly above him or her. The listeners were instructed to remain seated but were permitted to move the head and torso while trying to localize each sound. They were required to resume the position facing the intersecting (or extreme) loudspeaker in time to await the next signal presentation.

The difficulty of the task is such that listeners with normal hearing achieve near perfect identification of sounds from horizontal sources and about 70 percent correct identification of sounds from vertical sources. Specifically, for a control group of six normally hearing listeners the unaided scores (number of correct responses) were for MCL and ½ MCL respectively: horizontal forward = 98 percent and 98 percent, horizontal sideways = 95 percent and 87 percent.

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**Table 1** Mean 4FA Hearing Levels for Groups of Listeners

<table>
<thead>
<tr>
<th>Group</th>
<th>No.</th>
<th>Mean 4FA HL (dB)</th>
<th>SD (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4FA HL &lt;50 dB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bil. BTE</td>
<td>15</td>
<td>40.4</td>
<td>6.7</td>
</tr>
<tr>
<td>Uni. BTE</td>
<td>10</td>
<td>39.9</td>
<td>4.1</td>
</tr>
<tr>
<td>Bil. ITE</td>
<td>8</td>
<td>37.7</td>
<td>7.2</td>
</tr>
<tr>
<td>Uni. ITE</td>
<td>13</td>
<td>39.1</td>
<td>5.1</td>
</tr>
<tr>
<td>4FA HL &gt;50 dB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bil. BTE</td>
<td>20</td>
<td>61.8</td>
<td>9.1</td>
</tr>
<tr>
<td>Uni. BTE</td>
<td>13</td>
<td>63.8</td>
<td>9.6</td>
</tr>
<tr>
<td>Bil. ITE</td>
<td>4</td>
<td>52.8</td>
<td>6.7</td>
</tr>
<tr>
<td>Uni. ITE</td>
<td>4</td>
<td>54.1</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Listeners were classified by type of fitting and degree of impairment.

* Bil = bilateral; BTE = behind-the-ear; Uni = unilateral; and ITE = in-the-ear.
vertical forward = 70 percent and 55 percent, vertical sideways = 87 percent and 70 percent. Test-retest reliability data for a subsample (22) of the hearing-impaired listeners of the present study has been reported for tests repeated on the same day and 1 year apart (LePage et al, 1991). These showed test-retest correlations of .5 to .9 for most conditions. The exceptions were for some of the vertical conditions, where performance was almost random.

**Equipment**

The equipment consisted of the loudspeaker array, a personal computer (an AT type IBM compatible), a custom-built multiplexer (for switching), an amplifier (Technics, SU 7300), and an attenuator (Marconi TF 2162) with 1-dB steps. The presentation levels were determined manually using the attenuator, but the switching and sequence of stimuli were under computer control. An intercom system was used to communicate with the listener and to hear his or her responses. A video camera and monitor were used for visual monitoring of the listener’s activities. Testing was conducted in an anechoic room containing only the loudspeaker array and video camera.

**Signal Levels**

The signals were presented at two levels, designated MCL and ½ MCL. To determine MCL, the listener sat facing the loudspeaker in the centre of the array while the experimenter presented a series of signals and adjusted the level until the listener indicated that it was at the preferred level for listening over an extended period of time. Threshold of audibility for the signal was measured using a bracketing procedure and ½ MCL was taken to be the mean of that threshold and MCL levels. For all aided testing and for determining the signal presentation levels, the hearing aid volume control was on the setting usually used by the listener. MCL and threshold were determined for aided and unaided listening conditions.

Although the presentation levels were nominally MCL or ½ MCL, the actual level of successive signals within any test block was varied randomly among the nominal level, 3 dB higher and 3 dB lower.

**Scoring**

The localization results were expressed as error scores that reflect both the number and size of errors. The error score for each presentation is the number of loudspeakers by which the response differs from the source. When there were confusions between horizontal and vertical sources, the error score was the product of the amounts of error in the horizontal and the vertical directions.

**RESULTS**

**Analysis of Variance**

An analysis of variance (ANOVA) was performed to determine which factors significantly affected localization performance. As the main factors of interest were type of fitting and type
of aid, the effects of differences in hearing level were controlled by including this factor as a covariate. Table 2 shows the results of this analysis.

The first factor, type of fitting, is significant at the 5 percent level. Specifically, there is an overall advantage for bilateral fitting when all test conditions are considered. Type of aid is not significant (at the 5% level) when the effect of hearing level is removed. The other four factors are all significant at very high levels. Performance was better when facing the loudspeaker array, rather than sideways. It was also better for the higher presentation level, for horizontal sources, and for unaided listening. The analysis also showed a number of significant two-way and three-way interactions. Type of fitting (bilateral, left, right) interacted significantly with aid type (BTE, ITE), orientation (forward, sideways), and level (MCL, 1/2 MCL). Aid type interacted significantly with type of fitting and orientation. There were also interactions between orientation and direction (horizontal, vertical), level and direction, unaided/aided and orientation, and unaided/aided and direction.

Bilateral Fitting Advantage

Figures 2 and 3 show bilateral advantage by comparing unilateral and bilateral aided performance. For clarity of presentation, the listeners have been divided into two levels of hearing loss. This means that, unlike in the

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Results of ANOVA with 4FA HL Included as a Covariate Effect of Hearing Level Controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect</td>
<td>F</td>
</tr>
<tr>
<td>--------</td>
<td>-----</td>
</tr>
<tr>
<td>1. Type of Fitting (L, R, Bil)</td>
<td>3.44</td>
</tr>
<tr>
<td>2. Type of Aid (BTE, ITE)</td>
<td>1.65</td>
</tr>
<tr>
<td>3. Orientation (For, Side)</td>
<td>83.64</td>
</tr>
<tr>
<td>4. Level (MCL, 1/2 MCL)</td>
<td>24.11</td>
</tr>
<tr>
<td>5. Direction (Hor, Vert)</td>
<td>550.10</td>
</tr>
<tr>
<td>6. Unaided/aided</td>
<td>42.03</td>
</tr>
<tr>
<td>1 x 2</td>
<td>4.22</td>
</tr>
<tr>
<td>1 x 3</td>
<td>3.45</td>
</tr>
<tr>
<td>2 x 3</td>
<td>6.80</td>
</tr>
<tr>
<td>1 x 4</td>
<td>7.38</td>
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<td>3 x 5</td>
<td>8.69</td>
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<td>4 x 5</td>
<td>5.35</td>
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<td>3 x 6</td>
<td>15.72</td>
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<tr>
<td>5 x 6</td>
<td>4.60</td>
</tr>
<tr>
<td>2 x 3</td>
<td>4.41</td>
</tr>
</tbody>
</table>

Table shows all main effects and significant (p < .05) interactions.
L = left; R = right; Bil = bilateral; BTE = behind-the-ear; ITE = in-the-ear; For = forward; Side = sideways; Hor = horizontal; and Vert = vertical.

Figure 2 Average error scores in locating signals from horizontal sources for groups of listeners classified according to type of fitting (unilateral, bilateral), degree of hearing impairment (less than vs greater than 50 dB 4FA HL), and type of hearing aid (BTE, ITE), for two presentation levels (MCL, 1/2 MCL). Bilateral advantage (or lack of it) can be determined by comparing the corresponding unilateral and bilateral groups, as indicated by connecting lines.

Figure 3 Bilateral advantage in locating signals from vertical sources (same format as Fig. 2).
analysis of variance, the results are affected by differences in degree of hearing loss among the groups of listeners that are compared. The significance of these results (but not the ANOVA or the regression analyses reported later) is also affected by the number of listeners in each group. In particular, the numbers are small for the over 50 dB ITE groups (see Table 1).

The top two panels (labelled a and b) of Figure 2 show performance in localizing signals from horizontal sources when the listeners were facing the loudspeaker array. The zero line (no errors) indicates perfect performance. For the listeners with 4 FA HLs of less than 50 dB (panel a) performance is relatively good for both the unilateral and bilateral conditions and there is no indication of bilateral advantage. By contrast, panel b shows a clear bilateral advantage for the more severely impaired groups. Bilateral advantage is least for the ITE wearers and is not statistically significant. The S on this and later figures indicates that the difference between two conditions is significant at the 5 percent level, as shown by planned comparison tests. The absence of notable bilateral advantage for the over 50 dB ITE fittings is explained by the fact that, on the average (see Table 1), the ITE groups were less impaired than the corresponding BTE groups. Consequently they had better performance with the unilateral fittings. The results for the sideways orientation (panels c and d of Figure 2) are less clear-cut. They are generally consistent with the view that, on the average, there is no bilateral advantage with less impairment whereas there is such an advantage with greater impairment. (In fact, the only significant result for the under 50 dB group suggests a unilateral advantage.) Figure 2 also shows that, for both the less impaired and the more impaired groups, horizontal plane localization was substantially poorer for the sideways than for the forward orientation. This is largely due to the occurrence of front/rear (cone of confusion) errors in the sideways position.

Figure 3 shows the results for the vertical plane. The scale has been expanded, compared with Figure 2, because the vertical performance was much poorer than the horizontal performance for all conditions. Panels a and b of the figure show that there is no bilateral advantage for the under 50 dB listeners but that there is a substantial advantage for the more impaired listeners except for the ITE wearers at the higher presentation level.

Interpretation of the sideways data (c and d of Figure 2) is complicated by our scoring method that may not give a true picture, particularly of vertical localization. Errors between vertical and horizontal planes become common in the sideways orientation because of cone-of-confusion effects (Blauert, 1969/70). Thus, we note these results only in general terms and reserve further analysis for a treatment of data separate from the present paper.

Bilaterally versus Unilaterally Aided Disadvantage

Another way to compare bilateral with unilateral fittings is to consider the disadvantage that results from wearing a hearing aid when listening to sounds that are sufficiently intense to be heard unaided. This disadvantage is shown by comparing the aided with the unaided scores for each condition.

Figure 4 shows the results for horizontal forward localization. For the under 50 dB groups (panels a and b), performance is good for all conditions; there is a small but consistent trend for aided to be worse than unaided and there is no difference between unilateral and bilateral performance. For the over 50 dB groups (c and d), there appears to be a slight (but not significant) disadvantage for bilateral fitting but this contrasts with a substantial (significant) disadvantage for unilateral fitting.

**Figure 4** Aided disadvantage as shown by comparing unaided with aided error scores, for the various listener groups (see Fig. 2), for horizontal localization in the forward orientation.
Figure 5 Aided disadvantage for horizontal localization in the sideways orientation.

Figure 5 shows the horizontal sideways results. Although the picture is less clear than for the forward results, it is generally consistent with the conclusion that, for the over 50 dB groups, unilateral fitting incurs a disadvantage that is not present (or is much less) with bilateral fitting.

Figure 6 shows the vertical forward results, which tell the same story and, indeed, are clear-cut.

Bilateral Advantage versus Hearing Level

The above analyses clearly show that bilateral advantage is related to hearing level. A further analysis was conducted to elucidate this relationship more precisely. For each aid type, presentation level, and orientation, regression analyses were conducted to determine how localization error score was related to 4FA HL, for the unilaterally-fitted listeners and for the bilaterally-fitted listeners. The results for horizontal localization for the forward orientation are shown in Figure 7.

The data points show error score as a function of 4FA HL. Separate symbols distinguish the listeners who were fitted unilaterally from those who were fitted bilaterally. The regression lines indicate how localization perform-

Figure 6 Aided disadvantage for vertical localization in the forward orientation.

Figure 7 Detailed comparison of performance of bilateral versus unilateral listeners for horizontal forward localization. Data are shown separately for BTE and ITE fittings and for the MCL and ½ MCL levels. The regression lines show how aided localization deteriorates with increases in hearing level. Bilateral advantage, for the greater hearing levels, can be seen by comparing the bilateral regression functions (solid lines) with the corresponding unilateral regression functions (broken lines).
ance varied with hearing level. The four panels present data for BTE fittings at MCL; BTEs at 1/2 MCL; ITEs at MCL; ITEs at 1/2 MCL. Although there is considerable scatter among the data points (i.e., localization is not perfectly correlated with hearing level), there is a clear trend for aided localization to deteriorate as hearing level increases. In the present context, the major point is that the rate of deterioration is much more pronounced for unilateral fitting than for bilateral fitting. For small hearing losses, bilateral and unilateral performance is similar (on average) whereas for greater losses, there is a bilateral advantage that increases as hearing level increases. The point at which bilateral advantage first appears (i.e., where the bilateral and unilateral regression slopes intersect) is about 40 dB HTL for signals presented at MCL and about 30 dB HTL for signals presented at 1/2 MCL.

Corresponding analyses were made for vertical localization and for the sideways orientation. The related graphs are not presented, as the broad trends (although not the fine details) can be deduced from the information shown in Figures 2 and 3. The most relevant characteristics of the complete data set are summarized in Table 3.

The aided slope values in Table 3 confirm the trend, illustrated in Figure 7, that the deterioration of localization with hearing level is more pronounced for unilateral than for bilateral fittings. For all four comparisons, horizontal and vertical aided, for BTEs and ITEs, the slope values are greater for unilateral fitting than for the corresponding bilateral fitting.

### Table 3  Mean Values for Various Conditions with Levels and Orientations Combined

<table>
<thead>
<tr>
<th></th>
<th>BTE Bil</th>
<th>BTE Uni</th>
<th>ITE Bil</th>
<th>ITE Uni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hor Aided</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0.21</td>
<td>0.77</td>
<td>0.08</td>
<td>0.51</td>
</tr>
<tr>
<td>(Error score)</td>
<td>(16)</td>
<td>(23)</td>
<td>(13)</td>
<td>(16)</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.27</td>
<td>0.64</td>
<td>0.09</td>
<td>0.38</td>
</tr>
<tr>
<td>Hor Unaided</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0.34</td>
<td>0.70</td>
<td>0.00</td>
<td>-0.49</td>
</tr>
<tr>
<td>(Error score)</td>
<td>(16)</td>
<td>(14)</td>
<td>(9)</td>
<td>(12)</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.42</td>
<td>0.66</td>
<td>0.11</td>
<td>0.21</td>
</tr>
<tr>
<td>Vert Aided</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0.22</td>
<td>0.55</td>
<td>0.03</td>
<td>0.24</td>
</tr>
<tr>
<td>(Error score)</td>
<td>(43)</td>
<td>(57)</td>
<td>(44)</td>
<td>(44)</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.21</td>
<td>0.31</td>
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<td>Vert Unaided</td>
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<tr>
<td>Slope</td>
<td>0.31</td>
<td>0.48</td>
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<tr>
<td>(Error score)</td>
<td>(42)</td>
<td>(42)</td>
<td>(37)</td>
<td>(39)</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.24</td>
<td>0.43</td>
<td>0.11</td>
<td>0.16</td>
</tr>
</tbody>
</table>

BTE = behind-the-ear; Bil = bilateral; Uni = unilateral; ITE = in-the-ear; Hor = horizontal; and Vert = vertical.

The mean error scores for unaided listening are included to show that there are no large differences in unaided performance for the groups of unilaterally and bilaterally fitted listeners. A surprising and unexplained finding is that the unaided slope values are higher for the unilateral BTE group than for the bilateral BTE group. Given that the mean error scores are equivalent, this implies that the less impaired members of the unilateral group had superior unaided performance to the less impaired members of the bilateral group whereas the opposite was true for the more impaired members of these two groups.

For the ITE listeners, the table contains one slope value, namely -.49 for the horizontal unaided condition for the unilaterally fitted group, which suggests that performance improved as hearing level became greater. Further analysis, in which the group was divided into left and right ear fittings, showed that this was true only for left fittings for the sideways orientation at the 1/2 MCL level. For all other conditions, horizontal localization was either close to perfect across all hearing levels or there was a small positive correlation (up to .35) between error score and hearing level. Thus, it was only when the usually aided ear (not aided during this unaided testing) was away from the speaker array and when signals were presented at the lower level, that the more impaired members of the group performed better.

The correlations are included in Table 3 to indicate the strength of the relationship between localization and hearing level for each condition. Where the correlations are low, the regression slope values should be interpreted cautiously. In fact, this is true of all the individual slope values, as the associated confidence limits tended to be large. The values in the table should be regarded, therefore, only as indicating the broad trends discussed above.

### Effects of Hearing Aid Type on Localization

Aided localization was compared for the BTE and ITE groups of listeners. Altogether there were 24 conditions in which the scores for a BTE group were compared with the scores for a corresponding ITE group (3 types of fitting [bilateral, unilateral right, unilateral left] x 2 orientations [forward, sideways] x 2 levels [MCL, 1/2 MCL] x 2 directions [horizontal, vertical]). However, some of the groups were unequal in hearing level and the differences could
be expected to affect localization scores, both aided and unaided, thereby distorting any comparison of aid types. Specifically, the ITE groups could be expected to have better localization simply because they were, on average, less severely hearing impaired. To compensate for this biasing effect, we adjusted the BTE scores in each comparison by the difference between the unaided BTE and ITE scores of the two groups that were being compared. This assumes that any differences other than the type of hearing aid have had the same effect on unaided scores as on aided scores.

The above calculations indicated that for about half of the 24 conditions, the BTE error score was lower, whereas the ITE error score was lower for the other half. The details of this analysis do not permit specific conclusions because, when broken down to this level, some of the listener groups were very small. However, it is clear that there was no overall superiority for either aid type. This conclusion agrees with the ANOVA result that did not show a significant main effect for hearing aid type. However, the ANOVA did show a significant interaction between aid type and type of fitting and, therefore, some further analysis in terms of unilateral versus bilateral fitting seems justified.

In Figure 8, scores are compared for each aid type for each type of fitting for each direction; levels and orientations have been combined. The results are expressed as difference scores and are arranged so that the bars above the zero line mean that the ITE was better whereas the bars below the line mean that the BTE was better. The left panel shows that, averaged over all conditions, there is very little difference between aid types for horizontal localization. However, the BTE tends to be better for the bilateral fittings whereas the ITE tends to be better for the right unilateral fittings. The results for vertical localization (right panel) are similar.

Any superiority for the ITEs could be expected to become evident only in the sideways orientation because this allows for the possibility of frontward/rearward confusions. To permit this to be examined, the results for the sideways conditions only are presented in Figure 9.

The horizontal results are very similar in Figures 8 and 9, which implies that the effect of aid type is the same for both the sideways and the forward orientations. We might conjecture that the superiority of the ITE for the right ear fittings is somehow related to that ear's being closer to the loudspeakers for the sideways conditions. However, this supposition is weakened by the fact that the same aid effects occur in the forward conditions. For vertical localization, the aid effects (i.e., ITE superior for right unilateral fittings, BTE superior for bilateral fittings) do appear to be stronger in the sideways conditions than in the forward conditions. This is consistent with the fact that the ANOVA showed a significant interaction between aid type and orientation.

**DISCUSSION**

**Features of Present Study**

In this paper, we have examined how auditory localization is affected by type of hearing aid fitting (unilateral vs bilateral) and by type of
hearing aid (BTE vs ITE). Although both of these issues have been investigated previously, the present study has some distinctive features and has, in some respects, produced different findings. A major difference, between the present and other studies, is that we have tested listeners only with the types of aids and types of fittings that they had been used to wearing. Thus, the comparisons have been between groups of listeners who wore different types of aids or fittings rather than between different aid types or fittings tested on the same listeners. Our choice of design was prompted by the evidence, discussed earlier, that optimal performance with any type of aid or fitting may not be achieved until after experience with that particular fitting. Thus, comparisons between familiar and unfamiliar fittings may not necessarily give a true indication of their relative merits. This view is supported, indirectly, by the present study in that the less impaired unilaterally fitted listeners performed better than would be expected on the basis of previous studies in which unilateral fittings were tested on listeners who did not normally wear this type of fitting (e.g., Dermody and Byrne, 1975).

A second distinctive feature is that this study included localization of sounds from vertical sources. This has helped to complete the picture of localization ability although the information has been somewhat limited because many listeners performed very poorly in the vertical conditions.

A third difference between this study and others of aided localization is the use of sounds that were unpredictable in level to avoid providing an intensity cue that would not usually be present in real life situations. A further distinctive feature is that head movement was permitted during the presentation of signals.

Hearing Level Effects

Probably our most significant finding is that the effect of type of fitting is strongly dependent on hearing level. For moderate to severe hearing losses, the bilaterally fitted listeners could localize much better than those fitted unilaterally. Furthermore, when listening to sounds that would be audible unaided, the unilaterally aided listeners were distinctly disadvantaged, compared with unaided listening, whereas the bilaterally aided listeners suffered only a minimal, if any, disadvantage. We regard this as strongly supporting the use of bilateral fittings for hearing-impaired clients who have moderate or severe hearing losses. In this respect, our finding is in keeping with the general evidence favoring bilateral fittings (Markides, 1977; Byrne, 1981). Here we may point out that we assume localization to be an important aspect of human functioning, although we acknowledge that its full significance for everyday living remains to be elucidated. Furthermore, we regard evidence of localization as evidence of binaural functioning that presumably will affect other aspects of auditory performance, possibly including speech recognition in noise.

If bilateral advantage depends on hearing level, then it is likely also to depend on signal level. Our study shows such a trend and is in keeping with previous research (Dermody and Byrne, 1975). The hearing level at which bilateral advantage begins is about 10 dB lower for signals at ½ MCL than for signals at MCL (see Fig. 7). Any conclusions about bilateral advantage will depend on the choice of signal level which is, therefore, a critical methodologic issue in localization testing. As a hearing aid wearer will be exposed to signals of various levels, we consider it desirable to sample a range of levels. In the present study, this range was restricted to two levels for the aided testing and two for the unaided testing. The rationale for choosing MCL for the aided testing is that this is the most typical speech input level and we are thus most likely to sample how well the listener can locate which person is talking and, possibly, differentiate among simultaneous speech signals. The ½ MCL level was chosen to represent one that was clearly audible but relatively soft and which, by presenting a more difficult listening situation, might show differences among aid or fitting types that would not be evident at the higher level. The unaided MCL condition samples unaided performance at high signal levels whereas unaided ½ MCL represents levels that are audible and typically of moderate intensity (varying as a function of hearing level). Although arguments could be made for choosing other levels, we consider that this set provides a reasonable basis for predicting localization performance over a realistic range of listening conditions.

A distinctive finding, which would not be predicted from previous studies, is that the less impaired, unilaterally fitted clients performed relatively well, at least in horizontal localization. Indeed, for 4FA hearing levels less than 50 dB, the unilaterally fitted listeners performed, on average, as well as the bilaterally fitted
listeners. Although this could mean that either unilateral or bilateral fitting would be equally effective for all such listeners, a more likely interpretation is that unilateral fitting would be better for some listeners whereas bilateral fitting would be better for others. Presumably, this means that, for some mildly impaired listeners, the signal received in the unaided ear can contribute as much or more to localization performance than would be obtained if that ear were also aided. In other words, for such listeners, unilateral fitting may result in equally good, or even better binaural functioning. This is not unreasonable considering the limitations of current hearing aids, particularly the restriction in frequency range and the elimination, or reduction, of the opportunity to use pinna reflections.

In addition to the possibility of combining information received in the unaided and aided ears, there is another possible explanation for why mildly impaired, unilaterally fitted listeners may be able to localize relatively well. This is that, for these listeners, the head shadow effect may lead to the signal always being heard more loudly on the side that is nearer to the sound source. When the source is on the aided side, the signal will be louder in the aided ear; when the source is on the unaided side, the signal may be louder in the unaided ear because the signal at the aided side will be reduced by head shadow and will be amplified by only the small amount of gain that is used by most mildly impaired hearing-aid wearers. For the more severely impaired, the higher gain that is used will have more effect than the head shadow and will result in the signal being heard more loudly in the aided ear irrespective of the sound source. There is some support for an explanation along these lines in the finding that the performance of unilaterally aided listeners varied, not only in precision, but also qualitatively, and such variations were related to hearing level (Noble and Byrne, 1991). Specifically, the pattern of errors showed a bias toward the unaided ear for some listeners but a bias toward the aided ear for other listeners. Those in the first category were significantly less impaired (mean of average HL [250 - 2000 Hz] = 29 dB) than those in the second category (mean HL = 41 dB) (Noble and Byrne, 1991). However, there is also evidence against the theory that the mildly impaired unilaterally aided listeners always hear the signal more loudly on the side of the sound source. If this were true, we would expect performance to show little change with the signal level provided it were audible. This expectation is contradicted by the present study and others (e.g., Dermody and Byrne, 1975) that have consistently shown that unilaterally aided performance is strongly influenced by the signal sensation level. We suspect that the localization performance of unilaterally aided listeners is determined in a complex manner with a variety of factors operating for different listeners or for the same listener under different conditions.

Considering the generally poorer performance of unilaterally aided listeners in other studies, it may be inferred that our listeners have learned to make better use of the signal received by the unaided ear even though it may be considerably softer than the signal in the aided ear. It appears that, with experience, the better quality but softer signal received in the unaided ear may contribute as much or more than would be obtained if that ear were also aided. It has been known for many years that a loud but poor quality (restricted bandwidth) signal in one ear can be combined with a soft, good quality signal in the other ear to provide better speech recognition than is possible with either of these signals alone (Bocca, 1955). That finding seems noteworthy in the present context, although it has not been linked with localization or listening experience.

In the present study, bilateral advantage was just as pronounced for vertical as for horizontal localization (compare Figures 3 with 2, and 6 with 4). This is, in fact, surprising because binaural cues are generally considered to play little part in vertical localization, although head/torso movement does introduce an increased contribution from interaural differences in the sideways orientation (Wallach, 1940). On the theoretic grounds that vertical localization depends mainly on pinna transformations of high frequency sounds, we might expect to find the best localization for the less impaired groups when unilaterally aided. A likely factor in explaining the bilateral advantage in the more severe group, is that horizontal and vertical performance were correlated. Specifically, if bilateral fitting improves the localization of horizontal sources, there will be less likelihood of judging vertical sources to be horizontal and this will reduce the vertical error score. For the forward orientation, the correlations between horizontal and vertical error scores were .73 and .68 for the MCL and ½ MCL levels, respectively.

Hearing Aid Fitting

What are the implications of the foregoing for hearing aid fitting practices? As indicated
above, we consider that, for moderate and severe hearing losses (HTLs exceeding about 40 dB), the already substantial case for bilateral fitting is strongly supported by our results. With regard to mild losses, the situation is more complicated. Our results serve as a caution that bilateral fitting may not necessarily be advantageous. It would seem that many such clients will, after experience, get equally good and possibly even better binaural functioning if only one ear is fitted except, perhaps, when listening to very low level signals. However, the advantages of bilateral fitting are not exclusively related to binaural functioning. In many situations, the avoidance of head shadow, by always having a microphone on the same side as the talker, may be important. Therefore, even in the absence of improved localization, we might consider bilateral fitting to be desirable for some mild hearing loss clients, depending on their listening requirements. We would also predict that such clients might find it beneficial to wear both aids in some situations but only one aid at other times. Experience in NAL suggests that this is, in fact, a common usage pattern (Byrne and Dermody, 1975b) and some of our previous experimental results support such a possibility (LePage et al, 1991; Noble and Byrne, 1991).

From the above argument, we suggest that bilateral fitting for mild hearing losses may often be unnecessary, perhaps even undesirable, from the viewpoint of binaural functioning, but that it may be desirable to avoid head shadow. What would be optimal to restore or preserve binaural functioning, while at the same time avoiding head shadow? It is possible (but by no means certain) that any adverse effects of bilateral fitting, for mild hearing losses, could be avoided or reduced by using open earmolds. These would permit unamplified sound to enter the ear although they would still preclude pinna reflections. In our study, some of the BTE wearers used open molds or large vents but this information was not recorded and, therefore, the results for these listeners cannot be analyzed separately. The issue seems worthy of further investigation.

In our study, all except three listeners had symmetric hearing losses, defined as no more than 15 dB difference between the 4FA hearing levels of the two ears and no more than 25 dB difference at any of the four frequencies. We have no direct evidence of the aided localization performance of listeners with asymmetric losses, but to a limited extent, some inferences can be made from our data. On logical grounds, it is possible that substantial asymmetry may preclude benefit from bilateral fitting even when the hearing loss is moderate or severe. However, our data suggest that this view may not necessarily be correct, or at least not for all clients. Apparently, it is possible, after experience, to achieve good binaural functioning by combining signals from each ear that differ substantially in loudness. Another implication is that when unilaterally fitting mild and probably moderate, hearing loss clients, the poorer ear should usually be chosen as this should maximize the possibilities for obtaining binaural functioning through the combination of signals received in the unaided and aided ears. This agrees with some of the older, audiogram-based rules for choosing the ear to fit but disagrees with the advice of some texts that give priority to the ear with the better speech discrimination, although most frequently this is the ear with less hearing loss.

Our study has not shown any overall difference in the aided localization performance of ITE versus BTE wearers, when differences in hearing loss are taken into account. This general lack of superiority for ITEs is in conflict with other studies that have demonstrated fewer front/back confusions for this type of aid. We think that the difference in results may be explained by differences in test procedures. In other studies, the signal presentation level was constant from trial to trial whereas we varied this in a random fashion. Head movement was permitted in the present study, not in previous ones. However, there were significant interactions between aid type and other variables. For the right ear unilateral fittings, the ITE wearers tended to perform better than the corresponding groups of BTE wearers, but for bilateral fittings the BTE wearers tended to perform better.

In looking for explanations of the aid effects, one factor could be that, for unilateral fittings, an ITE provides less disturbance of interaural cues because there is less delay in the signal passing through the aid than for a BTE. This argument would be much stronger if the left, as well as the right, unilateral fittings had shown this effect. It is even more difficult to explain the apparent superiority of the BTE for bilateral fittings. Possibly this aid type may provide a better signal at some frequencies because of a more suitable frequency response. Also, because there were significant interactions between type of fitting and hearing loss
and between type of aid and hearing loss, it is possible that these results may be distorted by the correction we made for differences in unaided scores. It is also possible that the aid effects actually reflect differences among the listener groups, which cannot be accounted for by differences in hearing level. This supposition tended to be supported by an analysis of some sub-groups of listeners who were carefully matched for hearing levels. Therefore, we would urge caution in drawing any conclusions about the specific aid effects noted above unless they can be replicated.

In this paper we have examined two issues, namely the effects of aid type and type of fitting on localization of sounds. Our results do not support other research that claims that ITEs are clearly superior. At the most, our data suggest that ITEs may be preferable when unilateral fittings are used. This is not proposed as an argument against ITE fittings that may be justified on grounds other than localization. Rather, the implication is that in hearing aid design we need to do more than move the aid from behind the ear to in the ear if we are to improve localization substantially. This conclusion should not be surprising as many aspects of localization depend primarily on cues from frequencies higher than are passed by current hearing aids. Further work is needed to determine how important this is in terms of its possible relationship to speech recognition in noise, and to determine to what extent improved aided localization is possible in view of the limitations imposed by hearing impairment. In the latter respect, our work has been rather discouraging in that we have been generally unsuccessful in improving vertical plane localization by shaping the signal to ensure that all of its frequency components, especially the high frequencies, were audible. The data will be reported in a further article. Considerably more work is required to define the inherent limitations of hearing impairment on localization abilities.

Our data have clear implications for bilateral fitting candidacy. This is important in view of the paucity of validated guidelines for determining this issue (Byrne, 1981). Although there are complex issues to be considered, the data suggest that degree of hearing loss could provide a good starting point. Other things equal, we should expect bilateral fitting to be advantageous if hearing level exceeds a value of about 40 dB, whereas a unilateral fitting may be equally effective, or even better, for lesser hearing losses. There is room for debate about the best dividing value. The regression analyses suggest that binaural advantage begins to become evident, on average, for HTLs of 30 or 40 dB for low or average signal levels, respectively. One might argue that the criterion should be pushed a little higher than these values because they indicate only marginal advantage. In any event, we are not proposing a rigid criterion but we suggest that the benefit of bilateral fitting may be regarded as relatively certain for the more impaired clients, whereas it needs to be individually assessed for the less impaired clients. Such assessment would involve consideration of individual listening requirements particularly the extent to which problems would be likely to arise from head shadow if a unilateral fitting were used. Binaural summation could also be a factor although its relevance to different listening situations and degrees of hearing loss is not clear. In addition to the localization data, there is other support for the view that not all clients can benefit from bilateral fitting. Surveys by Hickson et al (1986) and Dillon et al (1991) indicated that about 25 percent of NAL clients who had been fitted bilaterally were using only one aid.

A comparison of the present study with other published research suggests that optimal performance with a unilateral fitting may not be evident until after the listener has had experience using that type of fitting. Direct evidence of the role of experience is the finding that listeners tended to localize better when tested with their own hearing aids than with foreign hearing aids (Noble and Byrne, 1990, 1991). This adaptation appears to occur not simply to a type of fitting but rather to a specific hearing aid (Noble and Byrne, 1991). Therefore, if bilateral fitting is being considered for a client with a mild hearing loss, it seems desirable that the client should first be given experience with a unilateral fitting before attempting to assess whether bilateral fitting would be advantageous. Furthermore, any comparative testing that includes a unilateral fitting should be done with the specific aid that the client has been wearing. We have no data on how much experience is required but the study by Gatehouse (1991) suggests that 12 weeks of regular aid usage might be appropriate.

In summary, our study has implications for hearing aid fitting, especially for bilateral fitting candidacy, and to a lesser extent and less directly for the design of hearing aids to improve localization and possibly to achieve other binaural advantages.
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REFERENCES


