The effect of hearing impairment on localization dominance for single-word stimuli

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Localization dominance (one of the phenomena of the “precedence effect”) was measured in a large number of normal-hearing and hearing-impaired individuals and related to self-reported difficulties in everyday listening. The stimuli (single words) were made up of a “lead” followed 4 ms later by an equal-level “lag” from a different direction. The stimuli were presented from a circular ring of loudspeakers, either in quiet or in a background of spatially diffuse babble. Listeners were required to identify the loudspeaker from which they heard the sound. Localization dominance was quantified by the weighting factor $c$ [B.G. Shinn-Cunningham et al., J. Acoust. Soc. Am. 93, 2923–2932 (1993)]. The results demonstrated large individual differences: Some listeners showed near-perfect localization dominance ($c$ near 1) but many showed a much reduced effect. Two-thirds (64/93) of the listeners gave a value of $c$ of at least 0.75. There was a significant correlation with hearing loss, such that better hearing listeners showed better localization dominance. One of the items of the self-report questionnaire (“Do you have the impression of sounds being exactly where you would expect them to be?”) showed a significant correlation with the experimental results. This suggests that reductions in localization dominance may affect everyday auditory perception.

I. INTRODUCTION

The extensive experimental work into the “precedence effect” has revealed much about how the auditory system deals with the presence of reflections (for reviews, see Blauert, 1997; Gardner, 1968; Litovsky et al., 1999; Zurek, 1987). In a typical experimental paradigm two almost-simultaneous clicks are presented to a listener. The first is termed the “lead,” representing the direct sound, and the second is termed the “lag,” representing a reflection. If the delay from the lead click to the lag click is about 10 ms or less then listeners report hearing only one sound, not two, an effect termed “fusion.” The location of the sound is close to the location of the lead click. This phenomenon is known as “localization dominance.” It is likely that localization dominance is due to an emphasis on the first-arriving sound because the auditory system is particularly sensitive to spatial information at the onset of a sound (e.g., Zurek, 1980; Akeroyd and Bernstein, 2001). Any impairment that compromises localization dominance could lead to a reduced ability to locate sounds when listening in rooms, as few of the sounds would appear to come from the correct direction. One can imagine that if a person had no localization dominance then they would report either a punctuate image at the average direction of all the reflections or a broad diffuse image given by the sum of all reflections. Prior work has mostly, although not always, demonstrated that hearing-impaired listeners show reduced performance in various precedence-effect experiments (see the following). But the across-listener distribution of reduced performance is unknown, as is how it relates to hearing in everyday life. Accordingly, this study (1) measured localization dominance for a large number of normal-hearing and hearing-impaired adults and (2) correlated localization dominance with self-reported difficulties using a questionnaire on auditory disability.

Localization dominance is rarely perfect. A convenient measure of the amount of localization dominance is the weighting factor $c$, introduced by Shinn-Cunningham et al. (1993). They postulated that the effective interaural delay (ITD) of a lead–lag stimulus is equal to $c \tau_{\text{lead}} + (1 - c) \tau_{\text{lag}} + \alpha$, where $\tau_{\text{lead}}$ is the ITD of the lead, $\tau_{\text{lag}}$ is the ITD of the lag, and $\alpha$ is an error term. The value of $c$ is 1 for perfect localization dominance, 0.5 for none, and 0 for “opposite” localization dominance, corresponding perceptually to the direction of the lead, midway between the lead and lag, and the direction of the lag, respectively. Reported values of $c$ are generally close to 1.0, but only occasionally reach it (Litovsky and Macmillan, 1994; Chiang and Freyman, 1998; Litovsky and Shinn-Cunningham, 2001; Zurek and Saberi, 2003).

There are only a few previous studies of localization or lateralization dominance in hearing-impaired listeners. Crawford and Romereim (1992) tested a group of older adults ($N = 22$; mean age $= 70$; mean hearing loss $= 33$ dB) on left vs center vs right localization for 40 dB sensation level click pairs presented from loudspeakers. They did not find any significant differences in performance between this group and a control group of younger, normal-hearing listeners for lag localization dominance.

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delays between 0.7 and 8 ms—i.e., there was no effect on localization dominance. They did find worse performance than controls at shorter lag delays of 0.5 ms or less, but these delays are far shorter than those typically used in localization-dominance experiments and instead are in the “summing-localization” region, where the reported direction is based on a weighted average of the directions of the lead and lag clicks (Litovsky et al., 1999). Similar results were subsequently obtained by Cranford et al. (1993), who tested four groups of 15 listeners, crossing age (approximately 37 or 70 yr) vs hearing loss (normal or moderate losses). Again they did not find an effect at lag delays of 0.7 ms or longer, but did at shorter delays, with both age and hearing loss leading to reduced performance. Goverts et al. (2002) measured localization dominance for headphone-presented 5 ms noise bursts, in which one ITD was applied to the first half of the burst and the opposite ITD applied to the second half (see Goverts et al., 2000). With this stimulus, someone with strong lateralization dominance would report a position of the noise that was in accord with the ITD of the first half. At signal levels of 60–70 dB sound pressure level (SPL), they found that normal-hearing listeners did this at least 90% of the time, but six hearing-impaired listeners, with mild hearing losses, did this only about 60% of the time. Further testing with different levels, durations, and in the presence of masking noise showed that the performance of the hearing-impaired listeners in quiet was similar to that of normal-hearing listeners at a target-to-masker ratio of about 0 dB. There was a wide individual variation across listeners. Finally, a study of the effects of hearing aids on localization dominance was reported in an abstract by Seeber et al. (2008). They found that localization dominance occurred for six out of seven aided listeners with a speech stimulus, but for four out of seven for a noise stimulus. They did not find any distinction between compressive and linear hearing aids, despite their expectation that the compressive hearing aids would interfere with the binaural cues.

Other experiments on the effects of hearing impairment on the precedence effect have instead measured “echo thresholds”: the shortest lag delay at which listeners report hearing two sounds. Such delays are considerably longer than those used in studies of localization dominance, reaching as much as 50 ms (Litovsky et al., 1999). Schneider et al. (1994) found that echo thresholds for Gaussian pips, presented over headphones, correlated significantly with audiometric thresholds. A set of experiments by Roberts et al. (2002) used 4 ms segments of noise presented over headphones, either as is or with virtual-acoustic simulations of anechoic or reverberant environments. They reported a wide variation in echo thresholds for hearing-impaired listeners, but whether the hearing-impaired individuals, as a group, showed longer echo thresholds than normal-hearing individuals depended on the study: Roberts et al. (2002) found an overall effect, but Roberts et al. (2003), Roberts and Lister (2004), and Lister and Roberts (2005) did not. Some of these echo-threshold experiments have also considered the effect of age. Roberts and Lister (2004) found that performance for 4-ms noise bursts, processed to simulate reverberation, depended on age and hearing loss. A similar study by Lister and Roberts (2005) did not find an effect of age. Schneider et al. (1994) failed to find an effect of age on echo thresholds for Gaussian pips. Huang et al. (2008) measured the number of “one-image” and “two-image” responses made in an echo-threshold task for sentences. They found more one-image responses to a longer lag delay for a group of older listeners than for younger listeners.

A few other studies have also reported precedence-effect experiments for other populations. Hochster and Kelly (1981) tested a small group of children with temporal lobe epilepsy. They found that localization dominance was as good for this group as in normal-hearing controls for a lag delay of 1 ms, but, in contrast to normal hearing, it was effectively nonexistent at a lag delay of 16 ms. Cornelisse and Kelly (1987) found that brain-damaged patients, with discrete right temporal-parietal lobe lesions, responded incorrectly on a left vs right localization task with click pairs when the lead click was on the left, even though they performed normally with single clicks. The effect was strongest at a lag delay of 16 ms but was also apparent at 2 and 8 ms. Patients with lesions in other areas performed normally on all the tasks. Cranford et al. (1990) measured left vs center vs right localization of click pairs for a group of 24 patients diagnosed with multiple sclerosis. As a group the patients showed a substantial reduction in performance for lag delays of 0.7 ms or less (i.e., the summing-localization region), but no significant difference at longer delays (i.e., the localization-dominance region). Some patients performed normally at all delays but others performed poorly at all delays.

Many of these experiments have found substantial variations across individuals. This key result was also found by the only large-scale study to have reported distributions of performance in a precedence-effect task. Saberi and Antonio (2003) measured thresholds for the ITD of the lag click of a lead–lag click pair and also for single clicks acting as controls. An adaptive task was used to measure thresholds. 127 listeners participated across multiple conditions of level and lag delay. All were young college students, aged 18–22, with self-reported normal hearing. They were effectively untrained, being given only minimal practice to understand the task. Saberi and Antonio found that both the mean performance and the variability were notably higher for the lag conditions than for the single-click control conditions. For instance, at a level of 73 dB, the lag threshold was 535 μs and the single-click threshold was 247 μs; the across-listener distribution of lag thresholds was broadly spread across delays over the range of about 10–1000 μs, whereas it was much more tightly drawn around 100–300 μs for the single-click thresholds. Some of these listeners, however, gave lag thresholds near those of two highly trained listeners, which were around 100 μs. Saberi and Antonio also reported a case study of very-long-term learning effects: one listener undertook 66 h in the task using a 2-ms lag delay. The threshold ITD reduced from around 300 μs, among the worst of all, to around 150 μs, among the best of all, but even with this remarkably lengthy training there was no indication of learning reaching a plateau. A subsequent study of interaural level thresholds (ILDs) for the lag click with a further group of 91 untrained listeners was reported by Saberi et al. (2004).
Thresholds were overall higher and more variable than for single-click control conditions. These two studies provide clear evidence of substantial individual differences for laboratory measurements of the precedence effect, even in young, normal-hearing students.

The present study measured localization dominance for speech sounds, in quiet and in a background of spatially diffuse babble, for a large group of listeners. The choice of words as stimuli (instead of the more-usual click pairs) and the choice of localization dominance as the method (instead of the other phenomena of the precedence effect, such as echo thresholds or threshold ITDs of the lag) were both made as they would give most relevance to real-world experiences in locating sound. To quantify this possible relationship between localization dominance and everyday listening, we also ran a shortened version of a self-report questionnaire of auditory disability, the Speech, Spatial, and Qualities of Hearing questionnaire (“SSQ”) (Gatehouse and Noble, 2004; Noble and Gatehouse, 2004, 2006). It includes many items that would be expected to relate to the precedence effect (see the Appendix).

II. EXPERIMENTAL METHOD
A. Design

The experiment was an extension of a design developed by Agus (2008). The listener sat at the center of a circular ring of 24 loudspeakers, placed at 15° intervals. In all cases the target stimuli were single words presented from one of the front loudspeakers. The listener had to identify the loudspeaker from which the word came and respond accordingly.

A randomly chosen word was used on each trial.

In the “lead–lag” conditions the target was presented from two loudspeakers nearly simultaneously. There were 28 combinations of lead–lag conditions: seven lead directions crossed by four lead–lag angular separations (see Table I). The lag was either +60° or +30° to the right of the lead or −60° or −30° to the left of the lead. The conditions are termed Δ + 60, Δ + 30, Δ − 30, and Δ − 60, respectively. These directions and lead–lag separations were chosen to give an approximate counterbalancing of whether the overall sound was perceived to the left or right and whether it was near the midline, just to one side, or further across. Following Freyman et al. (1999), the lag was always presented at a delay of 4 ms from the lead and at the same level. Given that this value is far shorter than the echo threshold for words, which is at least 30 ms (e.g., Lochner and Burger, 1964, Litovsky et al., 1999), listeners would not perceive the lag separately. In control conditions for overall localization performance, the target was presented from just one of the loudspeakers in the front half of the loudspeaker ring (Table I).

In separate blocks the stimuli were presented in quiet or in the presence of a continuous, spatially diffuse background “babble.” The signal-to-noise ratio (SNR) of the target word to the babble was 0, +6, or +12 dB; to avoid audibility issues the SNR for each individual was determined by their performance in a short speech-identification pretest. Within each block the stimuli were presented in a random order, with the lead–lag conditions and the single-presentation conditions being randomly intermingled. Each block thus contained a randomly ordered mix of lead–lag or single-speaker stimuli, various values of lead–lag separation, and various values of lead direction. It was entirely unpredictable what type of sound or what direction would occur on any given trial.

B. Listeners

All the participants were from the pool available to the MRC Institute of Hearing Research, sourced primarily from attendees at clinics of the local hospital and postal surveys, but also from hospital staff and local university students. Data were collected on 100 listeners, but, of these, four were excluded on the basis of poor left/right discriminability in the control stimuli, and three were excluded on the basis of poor straight-ahead accuracy. The analyses below are therefore based on the remaining 93. They were aged between 40 and 78 yr (mean 63 yr), and with hearing levels of between 4 and 61 dB (mean 29 dB); here “hearing level” was defined as the average at 500, 1000, 2000, and 4000 Hz, in the better ear. For some of the analyses we divided the listeners into three sets by their hearing level. The sets were “normal hearing” (a hearing level less than 25 dB), “mild loss” (between 25 and 39 dB), and “moderate loss” (40 dB or greater). The numbers of listeners in each set were 39, 29, and 25, respectively; the mean hearing losses were 16, 33, and 47 dB. More listeners had a better right ear than left ear, but most were reasonably symmetric: 17 listeners had a right–left difference in hearing levels of at least 10 dB in

<table>
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<tr>
<th>Condition</th>
<th>Sounds</th>
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<tr>
<td>Control</td>
<td>Lead only</td>
<td>−90° −75° −60° −45° −30°</td>
</tr>
<tr>
<td>Δ + 60</td>
<td>Leading</td>
<td>−75° −60° −45° −30°</td>
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<td></td>
<td>Lagging</td>
<td>−15° 0° +15° +30°</td>
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<td>Δ − 60</td>
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favor of the right ear, 67 listeners were symmetric to within \( \pm 10 \text{ dB} \), and nine listeners had a difference in favor of the left ear of \( 10 \text{ dB} \) or more. The mean right–left difference was \( 2.9 \text{ dB} \), with a standard deviation of \( 14 \text{ dB} \).

Figure 1 shows each individual’s hearing loss as a function of their age. The symbols mark which SNR each listener did: 0 dB (squares; \( N = 28 \)), +6 dB (hourglasses; \( N = 45 \)), or +12 dB (stars; \( N = 20 \)). As would be expected from the general population, there was a link between age and hearing level (\( r = 0.37 \)).

C. Stimuli

The stimuli were recordings of single words taken from the 80-word “FAAF” corpus, spoken by a native British–English male (Foster and Haggard, 1987). The average word duration was 450 ms.

The background was constructed by playing 24 streams of sentences, one from each of the loudspeakers. Each stream consisted of a sequence of about 370 sentences, joined one after the other without any gaps in between, and all chosen at random from a male-talker recording of the BKB (Bench, Kowal, and Bamford) corpus (Bench et al., 1979). The overall percept was therefore of a continuous, diffuse babble whose direction was everywhere, but in which none of the individual words of any sentence could be identified. For all the stimuli, the sampling rate was 44.1 kHz.

D. Apparatus

The sounds were presented using a 0.9 m radius circular ring of 24 loudspeakers, placed in a small, acoustically treated room that was 2.5 m wide by 4.4 m long by 2.5 m high (see Fig. 1 of Akeroyd et al., 2007). The loudspeakers (Phonic Sep207) were placed at \( 15^\circ \) intervals, with \( 0^\circ \) being directly ahead, and had their azimuthal direction marked on a label. Negative directions were to the left of straight ahead, positive directions were to the right. The listener sat in the center of the ring, with a small table in front of them upon which was placed a touch-screen monitor for collecting responses. The loudspeakers and their labels were visible.

Although listeners were free to move their head, they were recommended to always face straight ahead.

The loudspeaker feeds were derived from a PC computer, equipped with a 24-channel digital audio interface (Mark of the Unicorn MOTU 2408), whose output was fed into three 8-channel digital-to-analog converters (Fostex VC-8), monitored via three 8-channel VU meters (Behringer Ultralink Pro), and then passed through three computer-controlled gates (custom-programmed DSP chips) before being sent to the loudspeakers. The presentation of each sound was controlled by a custom-written software package.

E. Questionnaires

Each listener completed a shortened version of the SSQ questionnaire (Gatehouse and Noble, 2004; Noble and Gatehouse, 2004, 2006). This measures auditory disability by asking how well a listener would do in many complex listening situations illustrative of real life. The questions used are reported in the Appendix. They were chosen as those that could be expected to be related in some way to the precedence effect, either because they asked about the auditory processing of location, reflected complex listening situations in which the precedence effect might be useful, or targeted the effort of listening. The questionnaire was administered by interview, and responses were obtained using a computerized visual-analog scale ranging from 0 (“not at all”) to 10 (“perfect”).

F. Procedure

A source-identification method was used (e.g., Hartmann et al., 1998). The listener’s task was to listen to the target word and then to identify from which loudspeaker it came. A circular 24-button interface was provided (via a computer touch-screen); each button corresponded to one of the loudspeakers and was labeled with its azimuthal direction. No feedback was provided. The task was relatively simple to explain to listeners, and was complemented by a structured practice/training procedure. For this, they completed 13 trials of the control stimuli in quiet, and then 27-trial and 54-trial mixtures of the control and \( \Delta + 60 \) and \( \Delta + 60 \) stimuli, presented in a much-reduced level of background babble. This was done so that the listeners could get used to its presence without it interfering with their performance. Next, they completed six blocks of the main experiment. Each block had 164 stimuli, being four presentations each of all the conditions in a random order, and lasted about 10 min. In separate blocks the stimuli were presented in quiet or in babble. Quiet and babble blocks alternated, starting in either the quiet or the babble condition. After the fourth block of trials listeners were given a break from listening, during which they completed the reduced SSQ questionnaire. Twelve responses were obtained for each of the conditions. In all of the blocks the trials were separated by 3.5 s. If a listener took longer than about 2.25 s to respond to a given trial, then the control software paused the experiment (including the background babble, if present) to wait for a response to be made. When it was, the experiment
immediately restarted. On average, about 1/3 of the trials were paused.

Before data collection began, listeners performed a short speech-identification test in order to determine which SNR to use in the babble conditions. In this test a single word, chosen at random from the FAAF corpus, was presented from the 0° loudspeaker. Listeners made their identification from the four possible choices specified for the target by Foster and Haggard (1987), which were shown on the touch-screen monitor. The target word was partially masked by the continuous, spatially diffuse babble from all loudspeakers at a SNR of 0 dB. Initially, 20 words were presented at a SNR of 0 dB. If the listener scored at least 15 out of 20, then they were assigned to the 0 dB SNR condition, but otherwise the test was re-run at a SNR of +6 dB. If the score there was 15 or more, then they were assigned to the +6 dB SNR condition, but otherwise they were assigned to the +12 dB SNR condition. The whole experiment was completed during one visit to the laboratory.

G. Analysis of localization responses

As all the stimuli were presented from in front of the listener, we first corrected for any front–back errors. On average, this was required for 10% of the responses. Next, we calculated the mean of the 12 responses made for each condition. For the control conditions, the difference between this mean response and the actual direction of the stimulus was calculated. This is the mean error, \( E \) (Hartmann, 1983). It was chosen in preference to the root-mean-square error as it is sensitive to whether responses are to the left or right of the stimulus. For the lead–lag conditions, the mean error was taken from the mean response in the control condition corresponding to the direction of the lead, not the actual direction of the lead itself. This is termed the corrected mean error, \( E^\ast \). It ensures that the localization of the lead–lag pair was measured relative to the localization a listener reported for the lead had it been presented alone, and so measures the effectiveness of localization dominance, in degrees. Perfect localization dominance to the lead would give a \( E^\ast \) value of 0°; no localization dominance would give \( E^\ast \) values of either 30° or 15° for lead–lag separations of 60° or 30°, respectively, and an opposite localization dominance to the lag would give \( E^\ast \) values of 60° or 30°. In all cases a positive value of \( E^\ast \) indicates a mean response to the right of the direction of the leading sound. Values of the weight \( c \) (Shinn-Cunningham et al., 1993) were found by transforming \( E^\ast \) to a scale from +1 through 0.5 to 0, corresponding to perfect, none, and opposite localization dominance. Note that \( c \) is a normalized scale and does not depend on the separation between the lead and the lag.

III. RESULTS

It was found that listeners differed substantially in response variability. To quantify this, we calculated the standard deviation of a listener’s 12 responses to each of the 28 lead–lag conditions and then averaged across all to form a composite value. Figure 2 plots this value against their hearing loss. The dashed line marks a criterion of 15°, chosen as it was equal to the spacing of the loudspeakers. Approximately two-thirds (61/93) of the listeners fell below this. This group of listeners was therefore termed “low-variability listeners.” There were 21 mildly impaired and 10 moderately impaired listeners in this group; the mean hearing levels were 15, 32, and 45 dB. The remaining listeners gave higher variabilities, and so are termed “high-variability listeners.” The numbers per hearing-loss set were, respectively, 9, 8, and 15. A \( \chi^2 \) test indicated that there was a significant difference in hearing loss between the low-variability and high-variability groups (\( \chi^2 = 10.0, \ df = 2, p = 0.007 \)). Inspection of the contingency table indicated that there were considerably fewer moderate-loss listeners found in the low-variability group but considerably more in the high-variability group than would be expected on the null hypothesis. The mean hearing losses in the two groups were 26 and 36 dB, respectively. The data from the two groups are reported separately in subsections A and B in the following.

A. “Low-variability” listeners

1. In-quiet conditions

Figure 3 plots the mean error \( E \) in the control conditions as a function of the direction of the stimulus. The parameter is the classification of listeners by hearing level. The noticeable upward and downward curves at the extreme directions were due to a bias toward responding in front of ±90°. Within the central part of the range listeners were, on average, quite accurate: the across-listener mean value of \( E \) between −60° and +60° was less than 1°. A repeated-measures analysis of variance (ANOVA) demonstrated a significant effect on \( E \) of target direction [F(1.6*, 92*) = 28.0, \( p < 0.001 \)] but an insignificant effect of listener set [F(2, 58) = 1.2; \( p = 0.3 \)] and an insignificant target direction × listener set interaction [F(3.2*, 92*) = 1.3; \( p = 0.3 \)]. The standard deviations of the responses increased with hearing loss, being 6°, 10°, and 10° for the normal, mild-loss, and moderate-loss sets, respectively. The standard deviations also depended on the direction of the target, increasing from 3° to 14° for directions from 0° to
this is consistent with the well-known result that the resolution for changes in angle—the minimum audible angle—is poorest at extreme azimuths (e.g., Mills, 1958).

Figure 4 plots the corrected mean error $E^*$ for the lead–lag conditions as a function of the direction of the lead. The four panels are for the four values of lead–lag separation; the parameter is the listener set. Note that the left-hand axis is $E^*$, but the right-hand axis is $c$, and the direction of $c$ is up if the lag was on the left and down if the lag was on right of the lead.

Overall, it can be seen that (1) for the conditions in which the lag was on the left of the lead ($\Delta = 60$ and $\Delta = 30$), the value of $E^*$ was always negative, i.e., toward the lag; (2) conversely, for the conditions in which the lag was on the right of the lead ($\Delta + 60$ and $\Delta + 30$) the value of $E^*$ was always positive; (3) there were some variations in $E^*$ across lead direction; (4) the value of $E^*$ was generally smallest for the normal-hearing set (circles) but larger for the two impaired sets (diamonds and asterisks); (5) the value of $E^*$ was generally greater for the $\Delta = 60$ and $\Delta = 60$ conditions than for the $\Delta = 30$ and $\Delta = 30$ conditions. To determine the statistical significance of these effects, a repeated-measures ANOVA was conducted on $E^*$ using a between-subject factor of listener set and within-subject factors of whether the lag was on the left or right of the lead (“lag-side”), whether the angular separation between the lead and lag was $30^\circ$ or $60^\circ$ (“lead–lag separation”), and what the direction of the lead was (“lead-direction”). It was found that the main effect of set was significant [F(2, 58) = 15.4, p < 0.001]: the mean values of $E^*$ were $4^\circ$, $9^\circ$, and $10^\circ$ for the three sets of normal, mildly impaired, and moderately impaired, respectively. The main effect of lag-side was not significant [F(1, 58) = 0.1]. The main effect of lead–lag separation was significant [F(1, 58) = 128, p < 0.001], in that the value of $E^*$ was $9^\circ$ when the separation was $60^\circ$ but $6^\circ$ when the separation was $30^\circ$. The
interaction of lead–lag separation × listener-set [F(2, 58) = 18.2, p < 0.001]; the difference in $E^*$ for 60° separation vs 30° separation was 7° for the moderately impaired set but only 1° for the normal-hearing set. The main effect of lead direction was significant [F(3.6*, 209*) = 10.1, p < 0.001], ranging from 6° to 9° across directions. The interaction of lag-side × separation was not significant. The other interactions of separation × lead-direction, lag-side × lead-direction, and lag-side × separation × lead-direction were significant [respectively, F(4.1*, 237*) = 12.6, p < 0.001; F(4.3*, 250*) = 5.4, p < 0.001; F(5.0*, 291*) = 15.0, p < 0.001]; the largest $E^*$ was observed for the $\Delta + 60$ condition with the lead at 60° ($E^* = 13^\circ$), the lowest for the $\Delta + 30$ condition with the lead at 0° ($E^* = 4^\circ$).

Finally, the full interaction of separation × lag-side × lead-direction × set was significant [F(10*, 291*) = 1.9, p = 0.04]; here, the largest value was found for the $\Delta - 60$, 0°-lead condition in the moderately impaired set ($E^* = 20^\circ$), but the lowest for the $\Delta - 30$, 45°-lead condition in the mildly impaired set ($E^* = 40^\circ$).

To give an overall measure of localization dominance, we collapsed the values of $E^*$ and $c$ across the various lead directions and whether the lead was on the left or right of the lag. Table II reports the values for each listener set. The increase in the value of $E^*$ as the hearing loss increases is clear. This corresponded to a decrease in the value of $c$; i.e., a reduction in the strength of localization dominance. The overall mean value of $c$ was 0.83.

Figure 5 shows the individual values of $c$ for each listener as a function of their hearing level. The values are collapsed across both lag side and lead direction. The results showed a clear dependence of $c$ on hearing level and a smaller dependence on whether the lead–lag separation was 60° or 30°. It was also found that there was a substantial variability across listeners. This variability depended on hearing loss: the deviation from the linear regression lines for hearing losses less than about 20 dB was considerably less than the deviation for hearing losses more than about 30 dB. The two regression lines had effectively the same slope: $-0.0049$ and $-0.0044$ per dB for the 60° and 30° separations. The constant differed, however, at 0.98 and 0.92. The correlations of $c$ with hearing level were $-0.62$ and $-0.49$; both were statistically significant at $p < 0.001$. The values of $c$ in the two panels were themselves correlated at $r = +0.90$. They were also correlated significantly with the composite standard deviation (see Fig. 2) at $r = 0.45$. The average values of $c$ across all listeners were 0.85 and 0.81 for 60° and 30° separations; these two were significantly different [paired-sample $t(92) = 6.3, p < 0.001$].

To look for any effect of right–left asymmetry, we calculated the differences in the values of $c$ for $\Delta + 60$ vs $\Delta - 60$ and then for $\Delta + 30$ vs $\Delta - 30$. These right–left differences represent the asymmetry in localization dominance, so that a positive value meant that $c$ was larger for lags that were to the right of their leads than for lags to the left. The right–left differences were then correlated with the right–left difference in hearing level for each individual. It was found that neither correlation was significant ($r < 0.1$), although the right–left differences in $c$ for 60° and 30° separations were correlated highly with each other ($r = 0.87, p < 0.001$).

### 2. Background-babble conditions

The average values of $c$ for the background-babble conditions are shown by the filled circles in Fig. 6. The data are averaged across lag side. The parameter is the SNR group;
the numbers of listeners in the three SNR groups of 0, +6, and +12 dB were 20, 32, and 9 respectively. Their average better-ear hearing levels were 17 dB, 28 dB, and 38 dB; this dependence was expected given that the choice of SNR was based on a simple pre-test of speech understanding in noise. The open circles in Fig. 6 show the corresponding values of c for the in-quiet conditions, calculated with listeners divided into the same SNR groups (note that the apparent effect of SNR on the in-quiet data is due to the “between-subjects” effect of listener group, not the SNR itself). It was found that the use of the babble background led to reduced values of c, provided the SNR was 0 or +6 dB. Six paired-sample t-tests confirmed that the average value of c in babble was less than in-quiet for both 60° and 30° separations at SNRs of 0 or +6 dB (all t > 8.4; p < 0.001), but there was no significant babble vs quiet difference for either 60° and 30° separations at +12 dB (t < 3.2, p > 0.008, which is the conventional value of p = 0.05 with a Bonferroni-correction for 6 tests). A repeated-measures ANOVA demonstrated that there was a significant effect on the in-babble values of c of lead–lag separation [F(1, 58) = 4.6; p < 0.04], but no effect of SNR group or the lead–lag-separation x SNR-group interaction [F(2, 58) = 0.08; F(2, 58) = 0.74]. The mean values of c in babble for the two separations, averaged across SNR, were 0.73 and 0.71.

3. SSQ

Across all the low-variability listeners, the average score of the shortened SSQ questionnaire was 6.4. For each question, the mean scores ranged between 4.5 and 8.8, with across-listener standard deviations of 1.6 to 2.5. Table III reports the correlations between the individual SSQ corrections and the hearing level, the value of c in quiet, the value of c in babble, and a partial correlation with c in quiet after controlling for hearing level. After applying a Bonferroni correction for 40 tests—giving a critical value of r = 0.404—only three correlations were statistically significant: Space #3 and Space #17 with c in quiet, and Space #17 with c after controlling for hearing level. Inspection of the table indicates that the correlations of the four spatial questions with c were generally substantially higher than those for the other questions.

TABLE III. The correlations between the various SSQ items and hearing level, localization dominance in quiet or babble, and the partial correlation with localization dominance after controlling for hearing level. The boldfaced entries were statistically significant after applying a N = 40 Bonferroni correction.

<table>
<thead>
<tr>
<th>SSQ question</th>
<th>Hearing level</th>
<th>c (quiet)</th>
<th>c (babble)</th>
<th>Partial correlation with c (quiet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average of all nine items</td>
<td>−0.37</td>
<td>0.34</td>
<td>0.16</td>
<td>0.17</td>
</tr>
<tr>
<td>Speech #7</td>
<td>−0.04</td>
<td>0.11</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>Speech #11</td>
<td>−0.12</td>
<td>−0.06</td>
<td>−0.16</td>
<td>−0.16</td>
</tr>
<tr>
<td>Space #2</td>
<td>−0.30</td>
<td>0.27</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>Space #3</td>
<td>−0.37</td>
<td><strong>0.41</strong></td>
<td>0.14</td>
<td>0.30</td>
</tr>
<tr>
<td>Space #8</td>
<td>−0.35</td>
<td>0.40</td>
<td>0.19</td>
<td>0.25</td>
</tr>
<tr>
<td>Space #17</td>
<td>−0.39</td>
<td><strong>0.58</strong></td>
<td>0.38</td>
<td><strong>0.45</strong></td>
</tr>
<tr>
<td>Qualities #9</td>
<td>−0.17</td>
<td>0.04</td>
<td>−0.01</td>
<td>−0.07</td>
</tr>
<tr>
<td>Qualities #18</td>
<td>−0.39</td>
<td>0.22</td>
<td>0.11</td>
<td>−0.05</td>
</tr>
<tr>
<td>Qualities #19</td>
<td>−0.09</td>
<td>0.10</td>
<td>0.09</td>
<td>0.02</td>
</tr>
</tbody>
</table>

B. Other listeners

The other 32 listeners showed substantial variability in their responses (Fig. 2). Of these, three listeners were clear outliers, with composite standard deviations of over 45°. For the remaining 29 listeners, we limited the statistical analyses to only the most-important comparisons. In general the relationships supported those reported above, although the values of c were lower. The correlation between these listeners’ average value of c (across lag side and lead direction, for the in-quiet conditions) with their hearing level was statistically significant for both 60° and 30° separations (r = −0.63 and −0.58; p < 0.001). The average value of c for the 60°-separation was significantly higher than that for the 30° separation (c = 0.69 & 0.66; paired-samples t(28) = 2.6, p = 0.014). The corresponding values for the in-babble data, averaged across SNR, were 0.61 and 0.60, which did not differ significantly from one another. Note that all of these mean values of c were substantially less than the corresponding means found for the low-variability group. There was a significant partial correlation of r = 0.41 (p = 0.03) between the average value of c and the average SSQ score after controlling for hearing level.

IV. DISCUSSION

The results of this Experiment clearly demonstrate that some listeners show reduced localization dominance whereas others showed strong localization dominance. There was a strong effect of hearing loss, with localization dominance reducing with increasing hearing loss (Fig. 5). We also found that substantially more listeners with a moderate impairment gave high-variability responses than low-variability (Fig. 2).

An effect of hearing impairment on localization dominance was previously observed by Goverts et al. (2002), an effect on echo thresholds by Schneider et al. (1994) and Roberts et al. (2002), and an effect on summing localization by Cranford and Romereim, (1992), Cranford et al. (1990), and Cranford et al. (1993). Also, the precedence effect is also less well developed in young children than in adults (Litovsky and Godar, 2010). But effects of hearing impairment are not always found in either localization-dominance tasks (Cranford and Romereim, 1992; Cranford et al., 1990,
1993) or in echo-threshold tasks (Roberts and Lister, 2004; Lister and Roberts, 2005; Roberts et al., 2003). The reasons for these capricious results are not certain, but it is likely that individual differences between listeners will play a major role. The present results have confirmed the wide individual differences observed in prior precedence-effect experiments with large groups of young students (Saberi and Antonio, 2003; Saberi et al., 2004), with small groups of normal-hearing individuals (e.g., Litovsky and Shinn-Cunningham, 2001), and with small groups of hearing-impaired individuals (e.g., Goverts et al., 2002). Individual variability is also a feature of many studies of other aspects of binaural hearing in hearing-impaired listeners, such as threshold ITDs or ILDs (Koehnke et al., 1995), minimum audible angles (Häusler et al., 1983), and localization accuracy (Lorenzi et al., 1999). We also found that the individual variation in response variability was sufficient for us to classify our listeners into “low-variability” and “high-variability” groups. The low-variability group was the larger (61 vs 31 listeners) and had a lower mean hearing level (26 vs 36 dB). The results showed that they gave a larger mean value of \( c \) (0.83 vs 0.67) but about the same mean score on the shortened SSQ (9.3 vs 9.0). Nevertheless, inspection of Fig. 2 indicates that listeners fell on a continuum of variability, and defining the groups by a criterion of less than 15° is convenient but arbitrary. Similarly, our data suggest that the distribution of localization dominance across the population is continuous rather than dichotomous, though it is skewed toward the high-dominance end. This can be demonstrated by counting the number of listeners who fall into divisions of the localization-dominance scale \( c \). For the 60°-separation data measured in quiet, the numbers were 25, 30, 14, 16, and 8 for, respectively, values of \( c \) between 1 and 0.90, 0.899 and 0.80, 0.799 and 0.70, 0.699 and 0.60, and 0.599 or less. Two-thirds (64/93) of all of the listeners gave a value of \( c \) that was at least 0.75. It is clear that the majority of listeners gave a high value of \( c \). One would expect that these listeners would notice few problems in dealing with reflections in rooms, but the other listeners may have difficulties. This is discussed further below.

Values of \( c \) have been previously reported by Shinn-Cunningham et al. (1993), Litovsky and Macmillan (1994), Chiang and Freyman (1998), Litovsky and Shinn-Cunningham (2001), and Zurek and Saberi (2003). In general, the values are close to 1.0, although they only occasionally reach it. The present results are thus in qualitative accord with these prior measurements. Precise comparisons are complicated by experimental differences, but two comparisons are of interest. First, Shinn-Cunningham et al. (1993) noted a trend for the value of \( c \) to increase as the difference between the ITDs of the lead and lag stimuli increased; Litovsky and Shinn-Cunningham (2001) observed a similar effect. As a larger difference in ITD for headphone-presented stimuli corresponds to a larger angular separation for loudspeaker-presented stimuli, it would therefore be expected that that the value of \( c \) for a 60° separation would be larger than for a 30° separation. This was found in the present data (Fig. 5). Second, Chiang and Freyman (1998) compared \( c \) for brief bursts of noise presented in quiet vs in a background of spatially specific broadband noise. They did not observe a statistically significant effect of quiet vs noise on \( c \) (although several listeners did show a trend), but follow-up experiments on time-intensity trading and on echo threshold did find an effect of noise. In contrast, however, Leakey and Cherry (1957) found that the presence of a background noise on a speech stimulus led to a much-reduced localization dominance of the lead. Our data accord with Leakey and Cherry’s data rather than Chiang and Freyman’s: we found a clear effect of background noise, in that \( c \) was lower in babble than in quiet, for our 0 and 6 dB SNR groups, although not for our 12 dB SNR group. These groups were based on a short pretest of speech understanding, such that those listeners who performed best in the pretest were assigned to the 0 dB group, but those who did worst were assigned to the 12 dB group. The groups can therefore be characterized as “good speech” and “poor speech.” As would be expected, hearing impairment varied with group: the mean hearing level was 17 dB for the good-speech group and 38 dB for the poor-speech group. We found that the values of \( c \) were similar across groups in babble, but dropped markedly in quiet (Fig. 6; said equivalently, there was an interaction such that \( c \) was much reduced by the presence of babble in the good-speech group but was unaffected in the poor-speech group). This implies that localization dominance at 0 dB SNR in the good-speech group is approximately equivalent to localization dominance in quiet in the poor-speech group. Given the strong dependence on hearing loss in our groups (see Sec. II B), it is likely that it is hearing loss that is mediating localization dominance, not speech understanding per se. The result therefore confirms that of Goverts et al. (2002), who found that the localization dominance of a group of hearing-impaired listeners in quiet was similar to that of a group of normal-hearing listeners at a SNR ratio of about 0 dB.

Our results also demonstrated some links between the experimental measures of localization dominance and self-reported ability in spatial hearing. This broadly agrees with other studies that have measured correlations between experiment and questionnaire for other localization tasks: they gave \( r = 0.18 \) (Boymans et al., 2008; AVETA questionnaire), −0.34 (Tyler et al., 2009; SHQ questionnaire), and 0.46 (Kramer et al., 1996; Amsterdam Inventory). One prior study used the SSQ questionnaire on auditory disability, i.e. “the actual auditory consequences of the impairment for the affected person” (Stephens and Héut, 1991, p. 188). Noble et al. (2008) measured localization performance for an everyday sound from one of eight locations using 49 cochlear-implanted listeners. They found statistically significant correlations of \(-0.35\) and \(-0.31\) for two subscales of the SSQ (“localization” and “distance & movement”), but non-significant correlations with the other eight subscales of the SSQ (\( r = -0.26 \) to \(-0.02 \)). In our data for the high-variability listeners, we found a significant partial correlation between \( c \) and the average SSQ score (\( r = 0.41 \)) (Sec. III B). In our data for the low-variability listeners, only two of the nine SSQ questions gave a significant correlation with the value of \( c \), and only one of those returned a significant partial correlation after controlling for hearing level (see Sec. III A 3). This question was Space #17: “Do you have the...
impression of sounds being exactly where you would expect them to be?" It would seem reasonable that this question would be related to localization dominance. The partial correlations for the other three Spatial questions (see the Appendix for their text) were between 0.19 and 0.30, but the correlations for the two Speech questions and the three Qualities questions were all lower, at 0.16 or less. One Speech question was explicitly about echoes (Speech #7: “You are talking to someone in a place where there are a lot of echoes, such as a church or railway terminus building. Can you follow what the other person says?”) and one Qualities question could have been interpreted to include broadness or diffuseness of the image (Qualities #9 = “Do everyday sounds that you can hear easily seem clear to you (not blurred)?”)

Both of the correlations of these with c were effectively zero (|r| < 0.1). Overall, it is encouraging that one can demonstrate a correlation between an experimental measure of localization dominance and someone’s self report of their listening difficulties, even if it is somewhat disappointing that many of the self-report questions did not give a substantial value of the correlation. Nevertheless, the correlations of the nine individual questions with hearing level were surprisingly small. For the low-variability listeners, the values ranged between −0.39 and −0.04; for the high-variability listeners they ranged between −0.32 and 0.04. The corresponding correlations in the first SSQ paper were between −0.51 and −0.28 (Gatehouse and Noble, 2004). We are unsure of the reasons for these differences.

The present findings do have some procedural limitations, however. First, we used only one value of lag delay, 4 ms, as we chose to include multiple lead directions instead of including multiple choices of lag delay (e.g., Dizon and Litovsky, 2004). We therefore do not know the degree to which the results will generalize to other values of lag delay, and especially to lag delays short enough to give summing localization or long enough to give the percept of a separate echo. It is quite unlikely that our listeners heard the lag sound as a separate echo, as a lag delay of 4 ms is considerably shorter than the echo threshold for speech (Litovsky et al., 1999), but then there is the question of what those listeners with reduced localization dominance actually perceived (who, given that we found a strong link between hearing level and localization dominance, were primarily hearing-impaired listeners). One possibility is a punctate percept, whose direction was somewhere in-between the lead and the lag; the alternative is a diffuse percept that has substantial width and whose location was somewhat indefinite.

Our data do not resolve this question, although the data of Huang et al. (2008) partially does. They measured the number and perceptual width of the percepts with sentence stimuli. For a 4-ms lag delay, they found that the number of listeners who reported one compact image was slightly higher than those who reported one broad image. They did not find any two-image reports at lag delays of 8 ms or less, as would be expected as the echo threshold for continuous speech is generally reported as being at least 30 ms (Lochner and Burger, 1964, Litovsky et al., 1999). Listeners with low localization dominance would be expected to hear reflections to a greater extent than others. This may interfere with the ability to process the direct sound from the source and therefore may contribute to the general difficulties of listening in rooms. It should also be noted that we used a lag that was equal in level to the lead. This situation is unlikely—although not impossible—to occur in a real environment, where generally the lag sounds will be reduced in level due to absorption at each surface they have reflected from and an inverse-square effect from having traveled farther. It would therefore be of interest to extend the experimental results to conditions in which the lag was less intense than the lead.

Second, we allowed our listeners only a small choice of possible responses. These were limited to 15° intervals to correspond to the directions of the loudspeakers. This “source-identification” method has been used elsewhere in free-field studies of localization dominance (e.g., Dizon and Litovsky, 2004; Litovsky and Godar, 2010), as well as in localization per se (e.g., Noble et al., 1994; Lorenzi et al., 1999; van den Bogaert et al., 2008). It has the advantage of being an easy method to implement and to explain to listeners, but it has the disadvantage of not allowing a response in between two loudspeakers (see Hartmann et al., 1998, for a full discussion and analysis of the source-identification method). This disadvantage may have affected our 30°-separation conditions, as there was only one intermediate response allowed between the actual directions of the lead and the lag. In future research with such small separations it might therefore be preferable to obtain an entirely open response via head pointing (e.g., Seeber, 2002; Brungart and Simpson, 2009; Kopčo et al., 2010; Brimijoin et al., 2010).

Third, we did not extensively train our listeners. We used a structured practice/training procedure designed to teach them the task, as it would have been practically unfeasible to give lengthy training for such a large number of listeners (note also that Saberi and Antonio, 2003, and Saberi et al., 2004, did not give extensive training). Listeners can show significant training in binaural experiments, such as in tasks measuring the ITD or ILD thresholds of simple or modulated tones (e.g., Wright and Fitzgerald, 2001; Rowan and Lutman, 2007). In their precedence-effect experiment, Saberi and Antonio (2003) reported that one listener’s performance in a task measuring the threshold ITD of a lag click improved by a factor of about 2 after about 66 h of training. They also found that two highly experienced listeners gave thresholds that, at lag delays near that used here, were at least 4 × lower than the mean of a large group of untrained listeners. But these were all adaptive-track measurements of threshold ITDs, not constant-stimuli measurements of localization like we used. It is arguable that the amounts of learning seen in one method may not be linked to those in the other or even be of the same magnitude as each other. It is therefore a question for future research whether our “low-dominance” listeners would have performed better had we extensively trained them. If they did learn, it would be of further interest to know whether it is the initial performance or the fully trained performance that is the better predictor of their listening to reflected sounds in the real world.
We measured localization dominance for single words, using a 4 ms lead–lag delay, for a group of 93 adults aged between 40 and 78 and with hearing levels between 4 and 61 dB. On average, we found that the amount of localization dominance reduced as hearing level increased. We also saw a substantial individual variation. These results accord with those of earlier studies with either small numbers of hearing-impaired listeners (e.g., Goverts et al., 2002) or large numbers of normal listeners (e.g., Saberi et al., 2004): the precedence effect is reduced, on average, for hearing-impaired listeners, but there is a large variability across listeners. The distribution was skewed toward high localization dominance: for the 60°-separated lead–lag stimuli presented in quiet, two-thirds (64/93) of all of our listeners gave a value of c that was at least 0.75. We also measured self-reported auditory disability using a shortened SSQ questionnaire (Gatehouse and Noble, 2004). We found a statistically significant link between one question and localization dominance, suggesting that the effectiveness of the precedence effect may well affect everyday auditory perception.

ACKNOWLEDGMENTS

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APPENDIX

We used these questions from the SSQ questionnaire (Gatehouse and Noble, 2004):

Speech #7 = “You are talking to someone in a place where there are a lot of echoes, such as a church or railway terminus building. Can you follow what the other person says?”

Speech #11 = “You are in conversation with one person in a room where there are many other people talking. Can you follow what the person you are talking to is saying?”

Space #2 = “You are sitting around a table or at meeting with several people. You cannot see everyone. Can you tell where any person is as soon as they start speaking?”

Space #3 = “You are sitting in between two people and one of them starts to speak. Can you tell right away whether it is the person on your left or your right, without having to look?”

Space #8 = “In the street, can you tell how far away someone is, from the sound of their voice or footsteps?”

Space #17 = “Do you have the impression of sounds being exactly where you would expect them to be?”

Qualities #9 = “Do everyday sounds that you can hear easily seem clear to you (not blurred)?”

Qualities #18 = “Do you have to put in a lot of effort to hear what is being said in conversation with others?”

Qualities #19 = “Can you easily ignore other sounds when trying to listen to something?”

Note that onset information is not necessary for localization dominance, as the effect can still be demonstrated if the onset information is removed and only the ongoing portion is available (Dizon and Colburn, 2006).

Another precedence-effect phenomenon, “lag discrimination suppression,” is the just-noticeable differences for changes in the spatial characteristics of the lag sound are much larger than for the lead sound. There appears to be no studies of this for hearing-impaired listeners. The left/right test was based on the ability to report the correct hemifield for control stimuli presented in quiet. In detail, (1) a listener’s responses across the control, in quiet conditions, at −90°, −75°, −60°, −45° had to be negative (i.e., on the left), and (2) their responses across the corresponding +45°, +60°, +75°, and +90° conditions had to be positive (i.e., on the right). The straight-ahead test was that the mean error across the −15°, 0°, and 15° control, in quiet conditions had to be 15° or less.

The asterisks on the degrees of freedom mark where a Greenhouse–Geisser correction was applied to correct for sphericity.

In Fig. 4 it can be seen that values of $E^*$ in the $\Delta + 60$ and $\Delta − 30$ conditions are generally opposite in sign to those in the $\Delta − 60$ and $\Delta − 30$ conditions. But both correspond to responses slightly toward the lag and are therefore equivalent. To avoid the negative values of $E^*$ cancelling out the positive values of $E^*$, the values for the $\Delta − 60$ and $\Delta − 30$ conditions were multiplied by −1 before the ANOVA. This is equivalent to reflecting the $\Delta − 60$ and $\Delta − 30$ data about the y=0 line of Fig. 4.


