The precedence effect for speech and hearing impairment

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The "precedence effect" - the dominance of the onset when localizing sounds - is a fundamental part of spatial hearing. It enables a listener to make a decision on the direction of a source using only the first-arriving (direct) sound while ignoring subsequent echoes and reverberation. Any difficulties with the precedence effect may thus be of practical importance as they will interfere with the perception of sounds in rooms. This may be especially true in complex, dynamically-changing backgrounds in which the direct sound and echo may be occasionally hidden. Here we report two experiments on the effectiveness of the precedence effect, measuring (1) localization dominance for speech targets (single words) in quiet and partially masked by diffuse speech babble, and (2) the effective onset duration needed to localize a sound. The results showed that, in general, the precedence effect worked less well for the more impaired listeners, but there was a fair amount of inter-individual differences.

INTRODUCTION

The phenomena of the "precedence effect" has been well studied in normal-hearing listeners but surprisingly rarely in hearing-impaired listeners. Moreover, many of the experiments have used clicks as stimuli; these methods undoubtedly gain experimental control over the stimuli but they may well be less effective than stimuli such as speech in informing how the precedence effect might benefit someone in everyday life. In two experiments we measured the performance of hearing-impaired adults on the precedence effect. The first measured how well listeners could ignore a reflection in localizing a speech sound (a single word), whereas the second experiment measured how long an onset listeners needed to have to be able to decide on its location. Taken together, the results characterize the effectiveness of the precedence effect in hearing-impaired adults.

In the typical precedence-effect paradigm the listener is presented with two clicks, almost-simultaneous in time (for reviews, see Blauert, 1997; Litovksy *et al*., 1999). Provided the gap between the two clicks is sufficiently short — less than about 10 ms, though it does differ if other stimuli are chosen — then the listener only reports hearing one click. This effect is known as "fusion". If asked to report the direction or location of what has been heard, the listener will usually reply with the direction of the first ("lead") click as the directional informational in the second ("lag") click is barely acknowledged; this is known as "localization dominance". It is as though the spatial information in the first click dominates over spatial information in the second

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click. When extended to other stimuli, this notion becomes that spatial information at the onset of a sound dominates over spatial information in subsequent parts of the sound. If instead the gap between the two clicks is far longer, then listeners do report hearing two sounds, and each has the direction of the individual clicks. The gap at which the percept changes from one sound to two is known as the "echo threshold" or "lag burst threshold".

Localization dominance would be useful to listening in rooms. The walls, floor, and ceiling in most rooms generate reflections of any sound produced in the room. These will be further reflected, again and again, by any objects present within the room. The result is that even a single source in the room will produce sound that arrives at a listener from every conceivable direction. Many of these will be far reduced in intensity compared to the direct sound from the source to the listener —usually, only the earliest reflections in a room have any substantial intensity — but they all contribute to the complexity of the auditory scene. But the only sound that marks the true direction of the source is the direct sound. This always arrives first; thus an auditory system that could extract the spatial information of the onset of a sound and then use that to determine the direction of the whole, while ignoring any subsequent parts to the sound (which mark the direction of the reflective surfaces, not the source) would be able to avoid the complication of all the reflections. This is precisely the effect of localization dominance. Any reduction in localization dominance should lead to a reduction in the ability to determine direction in a reverberant environment; if so, this would affect someone's auditory disability, and, if they then start avoiding reverberant situations, lead to an increase in their auditory handicap.

Some studies have found that localization dominance is reduced in hearing-impaired listeners (e.g., Goverts *et al*., 2002; Cranford *et al*., 1993). Schneider *et al*. (1994) found significant correlations between echo thresholds and pure-tone audiometry, and Roberts *et al*. (2002) found an overall effect of hearing impairment on lag-burst thresholds. But other studies have failed to find an effect of hearing-impairment on performance (e.g., Cranford *et al*., 1990; Roberts *et al*., 2003; Lister and Roberts, 2005). The variation in results may be due, at least in part, to individual variations in performance — many of those studies have reported substantial individual differences. Moreover, the results of the only large-scale study to have been conducted — albeit one that used young college students as participants — demonstrated a very wide variation across listeners in performance on a task of detecting changes to the spatial parameters of the lag click (Saberi and Antonio, 2003; Saberi *et al*., 2004).

Accordingly, in our first experiment we measured localization dominance for a large number of normal-hearing and hearing-impaired adults. We used single words as stimuli, either in quiet or partially-masked by a background of spatially-diffuse babble. We also asked them to complete nine questions from the "Speech, Spatial, and Qualities of Hearing Questionnaire" of auditory disability (Gatehouse and Noble, 2004), in order to determine how well the laboratory measurements matched listener's self-reports of how well they performed in situations likely to involve the precedence effect.

EXPERIMENT 1

Methods

The design of the experiment was taken from Agus (2008). Two copies of a single word were presented almost simultaneously, as a "lead-lag" pair. They were separated by 4 ms in time and by 60° in angular separation, but were equal in level (other conditions, not considered here, used stimuli separated by 30°). The stimuli were presented using a circular ring of 24 loudspeakers (each was 15° apart), in which the listener sat at the center (Akeroyd *et al*., 2007). The listener's task was to report the perceived direction of the sound. If localization dominance was perfect, then this would be the actual direction of the lead copy of the word, but if there was no localization dominance then it would be the average of the actual directions of the lead and the lag. The results were averaged across various choices of direction of the lead and whether the lead was on the left or right of the lag, in order to avoid any potential biases to one particular direction. In the babble condition the experiment was repeated, except that the words were presented in a background of a spatially-diffuse multi-sentence babble, at a signal-to-noise ratio (SNR) of either 0, 6, or 12 dB (whichever was used was based on a short pre-test of speech identification). This was constructed by playing streams of sentences from all 24 loudspeakers. In a control condition, only one copy of the word was presented, i.e., the lead alone; this was done to determine each individual's baseline accuracy in locating sounds in isolation.

The data is reported for 93 listeners. Their ages were between 40 and 78 years (mean 63); their hearing loss — taken as the average of 0.5, 1, 2, and 4 kHz in the better ear — between 4 and 61 dB (mean 29 dB). Age and hearing loss were significantly correlated at $r = 0.37$ ($p < 0.05$).

Results

The results for the stimuli in quiet are shown in Fig. 1. It shows the localization of the precedence-effect stimuli for each listener as a function of their hearing loss. "Localization" is the average location of the stimuli, averaged across all lead-lag separations and whether the lead was on the left or the right of the lag. It is measured relative to the reported location of the control (lead-alone) stimuli, and so it represents the amount of localization dominance: for instance, a value of 0° means that the listener thought the lead-lag stimulus was in the same place as the lead-alone stimulus (perfect localization dominance), a value of 30° means the lead-lag stimulus was located on the average of the lead and lag directions (no localization dominance), and a value of 60° means that the whole stimulus was located at the lag (in effect, a localization "lag-dominance").

The results show that the amount of localization dominance clearly depended upon hearing loss: listeners with no or minimal losses give near-perfect localization dominance, but some listeners with moderate losses give results near 30°, or effectively no localization dominance. The solid line is the regression line; the slope was 0.37 degrees per dB. There was also a substantial variation across listeners, even for some of the normal-hearing listeners. The correlation of performance with hearing loss was r = 0.60 ($p < 0.01$); given that the corresponding correlation with age was only r = 0.19 (p = 0.07), it is likely that performance was primarily mediated by hearing loss rather than age.

Figure 2 shows the performance in the babble conditions plotted against the performance in quiet. The data is the same in the two panels; in the left panel the symbols represent the hearing loss of each listener, grouped by < 25 dB, 25-40 dB, or > 40 dB, but in the right panel the symbols represent which SNR was used in the babble condition. The solid line is the regression line: $y = 0.59x + 11.4°$. The diagonal dashed lines plot 1:1 performance. It can be seen that most of the data points lay above the 1:1 lines: i.e., performance was worse in the babble conditions, so indicating that localization dominance was weaker in babble than in quiet. That the slope of the regression line was substantially less than 1 showed that the strength of the effect interacted with overall performance: even those listeners who showed near-perfect localization dominance in quiet (around 0°-5°) showed a much reduced dominance in babble (around 10°-20°), but those listeners who showed minimal localization dominance in quiet (e.g., 20°-30°) were about the same in babble.

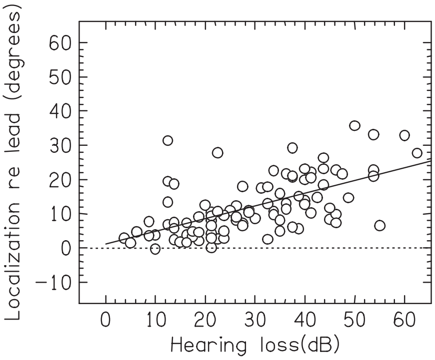

Fig. 1: Results from Experiment 1. The localization of the in-quiet lead-lag sounds, relative to the location of the lead, is plotted against hearing loss.

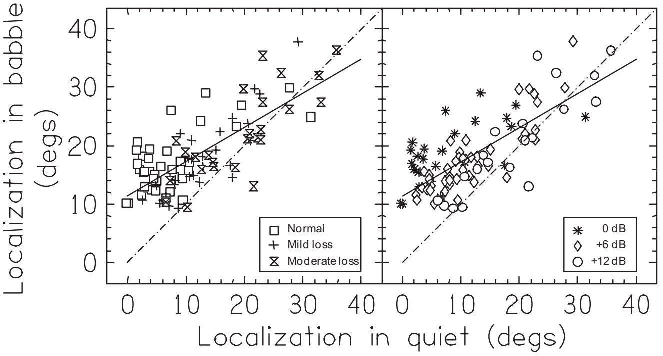

Fig. 2: Further results from Experiment 1. The localization of the lead-lag sounds in babble is plotted against the localization in quiet. The data is the same in two panels; the symbols mark the overall hearing loss (left) or the SNR used in the babble conditions (right).

The nine Speech, Spatial and Qualities (SSQ) questions (Gatehouse and Noble, 2004) were made-up of two from the Speech section (#7, #11), four from the Spatial section (#2, #3, #8, #17), and three from the Qualities section (#9, #18, and #19). These were chosen as it seemed reasonable that they would be related in some way to either the precedence effect, location, suitably complex listening situations, or to the effort of listening. The responses were averaged across category and then correlated with the experimental data. It was found that the average Speech score did not correlate significantly with the localization-dominance measure in quiet

($r = -0.15$), but the average Spatial score did correlate ($r = -0.43$, $p < 0.01$), while the average Qualities score did too, but to a lesser extent ($r = 0.29$, $p = 0.01$). The correlation with average Spatial score was the only one to remain after correcting for hearing loss in a partial correlation

($r = -0.31$, $p < 0.01$). For the results in babble, the correlations were reduced to about a half of those; only the correlation with average Spatial score remained significant ($r =-0.22$; $p = 0.04$), but it did not survive the partial correlation.

Discussion

This experiment has confirmed the existence of an effect of hearing impairment on the precedence effect: the amount of localization dominance reduces as hearing impairment increases (e.g., Goverts *et al.*, 2002). The value of localization dominance is reasonably close to the "textbook" value — 0°, or perfect localization dominance to the lead sound alone — for normal-hearing listeners, but approaches no localization dominance (an average of the lead and lag directions) for listeners with moderate hearing losses. The experiment has also confirmed the substantial individual variation in performance: many listeners, even some with normal hearing, perform relatively poorly. This is summarized in Fig. 3, which shows the distribution of results for a lead-lag separation of 60°. Although the modal value was 6°, the tail was quite broad, with about one-fifth of the listeners giving a value of 20° or more. If one takes the range of 25°-35° as an (arbitrary) criterion for absent localization dominance, then 8 listeners — almost 10% of our sample — fall within it.

When the SSQ data was considered, it was primarily the responses to the Spatial questions that demonstrated significant correlations with the experimental data. This suggests that the listeners with poor localization dominance may indeed notice some difficulties in everyday aspects of spatial listening. This would be expected to affect someone's auditory disability; it may therefore be of interest to determine if their auditory handicap is changed as a consequence.

By concentrating upon localization dominance, however, these results do not touch on the other facets of the precedence effect. In particular, does a listener with a substantially-reduced localization dominance perceive a compact source at the average of the locations of the lead and lag sounds, or a broad image extending as far as both, or two separate images of the lead and lag, or some variation or mix of these? This is a fundamental question that should offer insight into the resulting auditory disability. Some help in answering it would be obtained if a reduced localization dominance could be induced in normal-hearing listeners. For instance, one could increase the intensity of the lag sound so that it begins to override the lead sound; here, introspection suggests that the percept depends on the intensity difference, but in some circumstances one can hear a broad image in which the extremes are emphasized. But it is not certain if such an approach is a fair representation of what a reduced-dominance listener may perceive. Instead, it may be necessary to develop tests that directly ask what someone hears; for instance, Huang *et al.* (2008) reported the number of "one compact image" vs. "one broad image" vs. "two images" judgments for sentence stimuli presented at various lead-lag separations from 0 to 64 ms. They found that, on average, a small group of older listeners gave relatively less "two images" responses than a small group of younger listeners, but only at separations of 16 or 32

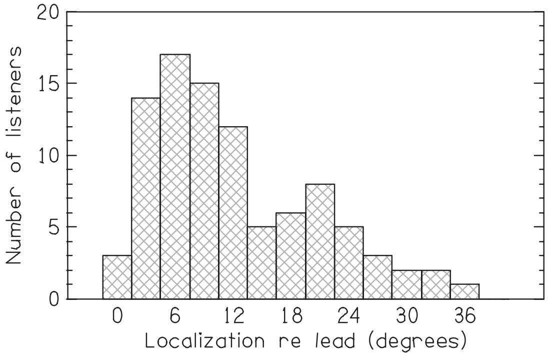

Fig. 3: The distribution of localization dominance in quiet for lead-lag sounds separated by 60°.

ms. Given this small effect of age, it would be of interest to study the responses of hearing-impaired listeners and those with reduced localization dominance.

A full model of what listeners perceive would also account for which aspects of a speech stimulus underlie localization dominance. It is well-known that speech is a semi-continuous sound whose instantaneous intensity varies by as much as 30 dB and which has inherent gaps, such as pauses by the talker or within stop consonants. A reverberant environment will tend to mask these variations. But localization dominance is the dominance of an onset, and an onset is defined by the gap — or at least a dramatic reduction in intensity — before it. One can then ask the question of whether localization dominance requires the gaps in speech to define onsets, or if it can somehow use the full, ongoing stimulus? A first corollary is what happens in hearing-impaired listeners: given the difficulties that hearing-impaired listeners have in identifying speech in noise, one might well expect a substantial effect. A second is what do the compression algorithms usual in modern hearing-aids do to the onsets? The overall issue is but part of a wider problem: how is the spatial information extracted from real sounds, given that they generally occur in backgrounds of other sounds and so will be partially masked to a greater or lesser extent? Moreover, the characteristics of the sounds change dynamically from moment-to-moment, and any movements by the listener — such as reflexive head movements towards a new sound — will affect the actual ITDs or ILDs that occur (Brimijoin *et al.*, 2009). The problem has attracted much computational modeling (see Blauert, 1997) but a truly general solution is proving elusive.

It is almost-certain that such models will need to incorporate some form of onset dominance in order to account for the precedence effect. This mechanism will have to process the start of a sound but then ignore what comes almost-immediately afterwards. This naturally leads to the question of how long is "almost immediately afterwards"? Are some listeners able to process localization information from just the first few milliseconds of a sound and then ignore the rest, but others unable to ignore information within even the first tens of milliseconds? Our second experiment was designed to study this, by measuring how long the start of a sound had to be.

EXPERIMENT 2

In a real room, the direct sound always arrives first, and its direction is that of the source. It is quickly followed by reflections from the walls and other reflective objects; their direction marks that of the surface from which the reflection occurred. It is then followed by reflections of reflections, and so on. The resulting reverberation will, eventually, come from every conceivable direction. For the auditory system to only use the first-arriving sound in determining the direction of the whole sound, it must ignore all the reflections: that is, it must operate quickly enough that the processing to the direct sound can be completed before any of the reflections arrive. We reasoned that listeners with good localization dominance would be better at this, in that they could exclude any reflections that arrived within, for example, 5 ms, but listeners who showed poor localization dominance could not avoid including reflections that arrived that early; instead they could only exclude reflections that arrived after, say, 20 ms. We therefore set out to measure this "effective onset duration" for normal and hearing-impaired adults.

The stimulus was designed as a caricature of the room impulse response. It was split into two parts, each being a burst of speech-shaped noise concatenated together: the first had a "proper" interaural time delay (ITD), which represented the direct sound, but the second was interaurally uncorrelated, so it represented the reverberation from every direction (see Fig. 4). If a listener's effective onset duration was longer than the duration of the first burst, then they could not avoid including some of the second burst in determining the direction of the start of the sound. But a listener whose effective onset duration was shorter than the duration of the first burst would be able to locate the sound as though the second burst was not there.

Methods

The stimulus was constructed from two bursts of noise concatenated together to form a single sound, presented over headphones. The noises were taken from track 1 of the ICRA set (unmodulated; Dreschler *et al.*, 2001). The first burst was given an ITD, which varied across trials between ±45 to ±340 µsecs. Its duration was also varied across trials: 10, 20, 40, or 80 ms. The second burst was interaurally uncorrelated, with a duration of 600 ms. A short onset gate (2 ms) and a far longer offset gate (100 ms) were applied. Note that the stimulus is equivalent to a "backward fringe" stimulus that has been used in other experiments (e.g., Akeroyd and Bernstein, 2001), though with a interaurally-uncorrelated backward fringe that is remarkably long.

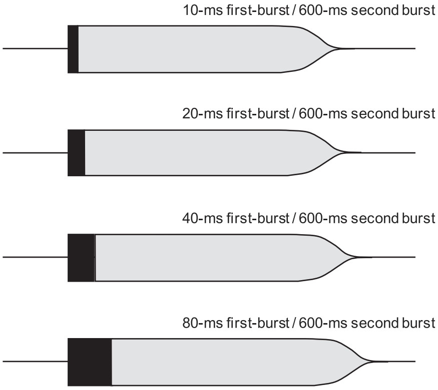

Fig. 4: Schematic illustration (not to scale) of the stimuli used in Exp. 2. The first burst (solid) has a proper ITD, the second burst (shaded) is interaurally uncorrelated. The task was to report whether the start of the sound is to the left or right. The long offset gate was applied as it was found that listeners sometimes had their attention taken by the end of the sounds that finished in short gates.

The listener's task was to listen to the stimulus and report if it was on the left or right side of the head. Psychometric functions were measured for accuracy (marked as the real ITD of the first burst) as a function of the ITD and duration of the first part. Figure 5 shows an example dataset from one listener; as would be expected, performance increased with both the duration of the first burst (parameter) or the ITD applied to it (abscissa). Analytic functions were fitted to the data (solid curves); these assumed that d′ was proportional to ITD with a constant-of-proportionality that depended on duration.

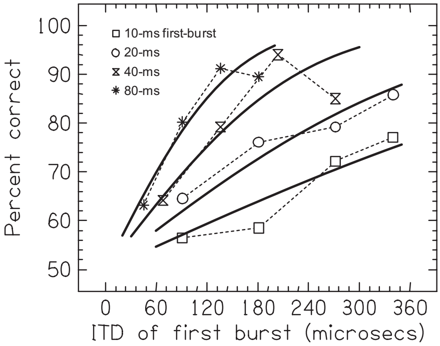

Fig. 5: Illustrative results for one listener from Exp. 2. The smooth curves plot analytic fits to the data. The effective onset duration for this listener was 9.2 ms.

From these functions, we calculated (1) the ITD needed to perform the task to criterion (d′ = 1) for each duration of the first burst, (2) the duration for which an ITD of 260 µsecs gaves a d′ of 1 (chosen as ±260 µsecs corresponds to ±30° and so a spatial separation of 60°, which is a common choice of loudspeaker separation in precedence-effect experiments). This second statistic is the "effective onset duration".

Nineteen listeners completed the experiment satisfactorily. They were aged between 34 and 73 years (mean 59), and with hearing losses between 3 and 50 dB (mean 26 dB).

Results

Figure 6 shows the threshold ITDs as a function of the duration of first burst. As would be expected given the ubiquity of temporal integration in auditory processing, the threshold ITD reduced as the duration increases. The mean rate of reduction taken as the slope of a straight line fit to the log-log plots was -0.6. If no temporal integration occurred, the slope would have been 0.0; if temporal integration had been perfect it would have been 1.0 (i.e., if the duration had doubled, the threshold would have halved). That the value is somewhere in-between demonstrates the dominance of the onset of the sound over subsequent information. This has often been observed in studies of ITD vs. duration without the presence of the second, uncorrelated burst (e.g., Houtgast and Plomp, 1968; Hafter and Dye, 1983), so its demonstration here shows that the presence of the second burst has not interacted with performance — although if one desired to be truly sure of this, one would want to measure performance without the second burst and compare it.

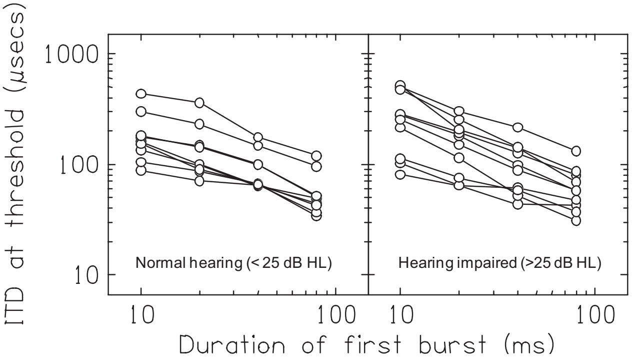

Fig. 6: Results from Exp. 2: threshold ITD as a function of the duration of the first burst of noise. The left panel is for listeners with hearing losses < 25 dB, the right panel for those with hearing losses > 25 dB.

Figure 7 shows the derived values of the effective onset duration as a function of hearing loss. There was a substantial variation across listeners, especially amongst those with some level of hearing loss (we are presently testing more listeners with minimal hearing losses to determine if the variation is loss-dependent). Indeed, some of the listeners show remarkably long values: if the assumptions underlying the experiment are valid, then they should demonstrate minimal localization dominance. Curiously, other listeners show remarkably small values, of a few milliseconds or less. The accuracy of the actual values as small as these could be questioned — remember that the shortest duration used in the experiment was 10 ms — but it is clear that these listeners have an emphasized ability to extract information from the onset of a sound that is apparently mostly absent in other listeners.

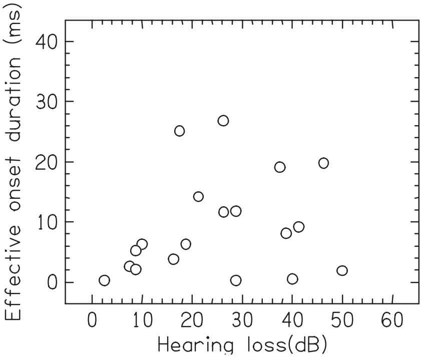

Fig. 7: Results from Exp. 2: the derived value of effective onset duration for each individual.

SUMMARY

This work has emphasized the wide variability seen in localization dominance across listeners as well as a general reduction of localization dominance seen with hearing impairment (e.g., Goverts *et al*., 2002; Saberi *et al*., 2004). It has also shown links with self-reports of auditory disability. It remains for further work to determine (1) how hearing impairment affects how spatial information is obtained from the onsets in continuous sounds, (2) what, if any, effect compressive hearing aids have on that, and then (3) whether listeners with reduced localization dominance have had their auditory handicap affected by their relatively ineffective precedence effect.

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