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Binaural Performance and Aging

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Abstract

Binaural performance is a general term that can be applied to a wide range of paradigms that involve listening with both ears. This review samples from across the spectrum of binaural tasks by highlighting recent studies that encapsulate certain aspects of binaural function. Studies of the precedence effect and binaural unmasking suggest that temporal coding in elderly listeners is degraded relative to young listeners and that this decline is not simply a function of reduced audiometric sensitivity. For higher level tasks involving speech recognition in competing noise, the elderly show reduced binaural advantage, particularly when they also exhibit presbyacusic hearing loss. However, it should not be overlooked that the advantages of listening with two ears rather than one remain significant even in the presbyacusic listener.

Key Words: Aging, binaural, dichotic, masking level differences, precedence effect, presbyacusis

Almost a decade ago, Roush (1985) published a review of aging and binaural auditory processing. Much of what was covered in that review remains valid today, including the caveats concerning the complexity of factors, both auditory and nonauditory, that affect the performance of elderly listeners and that, therefore, influence the interpretation of specific test results. Nevertheless, much has been published in the intervening 10 years that could rightly be considered relevant to binaural processing in the elderly. How best to treat this newer material? Part of the difficulty is bound up with the plethora of paradigms that can be considered "binaural." These range from basic measures of localization ability to higher level tasks involving recognizing target speech material presented to one ear in the presence of competing, or distracting, speech material presented to the contralateral ear. Rather than attempt a complete coverage of these various levels, the approach taken in the following review is to sample from across the spectrum of binaural tasks, moving from "lower level" to "higher level" functions. This will be accomplished by highlighting particular studies that encapsulate certain aspects of binaural function. Where possible, common threads in the findings will be identified. The specific areas that will be examined are the precedence effect, binaural unmasking, and dichotic competition.

Precedence Effect

Most of the sounds that are heard in the natural environment are accompanied by echoes due to the reflection of the wavefronts off various surfaces en route to the ear. If the delay between the direct and reflected sound is reasonably short — less than a few milliseconds — the echo will generally not be perceived, although it may color the overall perception. Instead, the sound source will be localized entirely on the basis of the direct sound that arrived first. This general phenomenon, wherein the leading sound front plays the dominant role in localization, has been termed the precedence effect (Wallach et al, 1949) or the law of the first wavefront (Blauert, 1983). The phenomenon can be studied in the laboratory using very simple stimuli. In the most basic configuration, a listener can be seated in an anechoic room between two loudspeakers where one loudspeaker simulates the origin of the direct pathway and the other simulates the directional source of a reflection. A very brief click is delivered through one loudspeaker and a similar click (the "reflection") is delivered,

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after a variable delay, through the other loudspeaker. The listener's task is to indicate the location of the perceived sound. For interspeaker delays less than about 1 msec, the listener will perceive a single click (a fused image) originating from a phantom source somewhere between the two speakers, an effect sometimes called "summing localization." At the other end of the delay spectrum, interspeaker delays greater than about 5 msec will result in the listener hearing two distinct clicks, one associated with each speaker (i.e., the precedence effect has broken down). However, for interspeaker delays between these two limits, the listener will perceive a single click originating from the direction of the leading speaker.

Cranford et al (1993) examined the precedence effect in elderly listeners while controlling for the factor of hearing loss. Each listener was positioned in front of a loudspeaker array that included one speaker to the left (–45°), one speaker in front (0°), and one speaker to the right (+45°) of the listener. A series of trials was presented where a pair of clicks was delivered, one from the left speaker and one from the right speaker, with a variable delay between them. The listener had to indicate from which direction the (fused) click had originated. The judgments were scored as correct or incorrect and psychometric functions were generated that plotted percent correct as a function of interspeaker delay. Four groups of listeners were tested: two groups of elderly listeners (mean age ≈ 70 years) and two groups of young listeners (mean age ≈ 37 years). One of the elderly groups and one of the young groups were matched for high-frequency hearing loss. The other two groups were considered to have normal pure-tone sensitivity. The forms of the measured psychometric functions were somewhat similar for the four groups: all showed essentially chance performance for interspeaker delays around 0.1 msec and all showed near-perfect performance for delays around 2.0 msec, that is, the precedence effect was fully in effect by 2.0 msec for all listeners. Beyond 2.0 msec, the psychometric functions rolled off as the fused image of the click presumably began to break up. When the group-average psychometric functions up to 2.0 msec, as tabulated by Cranford et al (1993), are submitted to probit analysis and a threshold derived for each age group, then the data shown in Figure 1 are obtained. Here, the threshold interspeaker delay is plotted for each of the four listener groups. It is perhaps best to think of these thresholds as the delay at which the leading click begins to dominate the fused click image by drawing it towards its source of origin; thus, the thresholds appear to reflect summing localization rather than the precedence effect, per se. Two aspects of the data are particularly noteworthy: first, the two groups of young listeners, as a whole, performed better than the two groups of elderly listeners; second, within both age groups, hearing loss was detrimental to performance, though perhaps more so for the elderly listeners. Although the results of Cranford et al (1993) must be interpreted cautiously in light of potential response biases (cf. Silverman, 1963), the pattern of data supports the conclusion that elderly listeners are less able to process slight time-of-arrival differences than are young listeners. Moreover, this inability does not appear to reflect a simple decline in audiometric sensitivity. Cranford et al (1993) interpreted the results as indicating a breakdown in temporal processing in the elderly. This conclusion is not necessarily at odds with the findings of Schneider et al (1994), who also examined aspects of the precedence effect in elderly listeners. They found no difference between their elderly listeners (mean age ≈ 69 years) and a group of young adults (mean age ≈ 23 years) for the interaural time delay at which the perceptually fused image began to separate, that is, the delay at which the precedence effect broke down. Thus, detriments in summing localization, as found by Cranford et al (1993), do not necessarily lead to compromised echo suppression.

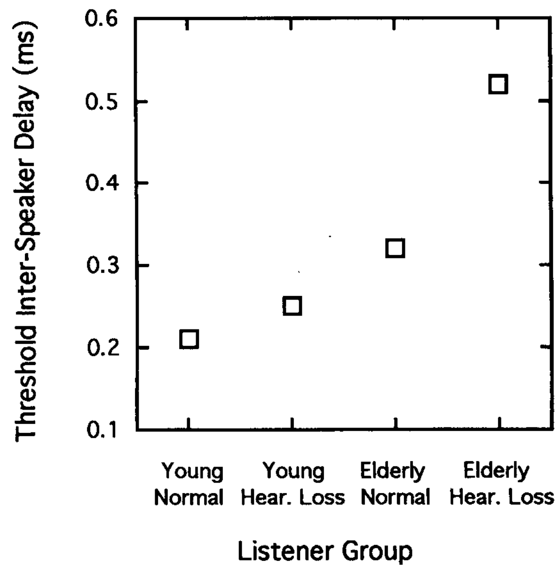

Figure 1 Mean thresholds for interspeaker delay for four listener groups. (Data derived from Cranford et al, 1993.)

Binaural Unmasking

In most acoustic environments encountered in everyday life there are multiple sounds present, each originating from a different source. This means that, when a particular signal is being attended to, there are usually other masking, or distracting, sounds present at the same time. However, by the same token, these extraneous sounds rarely originate from the same location as the target signal. These acoustic conditions highlight the benefits of listening with two ears since the binaural system is very adept at differentiating between sounds that can be separated on the basis of their location in space. Sounds that arrive at the head from one side or the other (i.e., off midline) result in interaural differences in time and interaural differences in intensity that are frequency dependent. By making use of these cues, the binaural system can differentiate with some success between sounds that are spatially separated, thus enabling the listener to attend to one sound and largely ignore the others. This binaural advantage is demonstrated by the contrived laboratory paradigm of masking level differences (MLDs) (Hirsh, 1948; McFadden, 1968; Durlach and Colburn, 1978). The MLD paradigm is contrived for two reasons: first, it is usually administered under headphones rather than in the free field; and, second, the interaural differences that are imposed often have characteristics that do not occur in natural environments.

The stimuli in MLD tasks usually consist of a masking noise (N) and a target signal (S). In one configuration, the N and the S are presented with no interaural differences (i.e., diotic), in which case they are designated N_0 and S_0 to indicate 0° phase difference between the ears. In another configuration, either the N or the S can be inverted at one ear relative to the other, that is, the stimulus is 180° — or π radians — out of phase at one ear relative to the other ear. In this configuration, the designation N_π or S_π is used. In a final configuration, either the N or the S can be delayed by some time value, τ, at one ear relative to the other ear, in which case the designation N_τ or S_τ is used. The configuration N_0S_0 is therefore analogous to the signal and noise coming from the same (midline) location, while other configurations, such as N_0S_π, are analogous to the signal and noise coming from different spatial locations. Signal thresholds for these latter configurations are generally lower than that for the N_0S_0 configuration, and the magnitude of this threshold reduction, or unmasking, is termed the MLD.

Pichora-Fuller and Schneider (1991) investigated a number of these configurations in a group of elderly listeners in the early stages of presbyacusis (mean age ≈ 69 years) and compared the results to a group of young adults (mean age ≈ 22 years). The elderly listeners had pure-tone thresholds no greater than 25 dB HL up to 2000 Hz. The signal was always a 500-Hz pure tone and the masker was a wideband noise. Some of the key configurations that they examined were N_0S_0, N_0S_π, $N_\pi S_0$, $N_{\pi\tau}S_\pi$, and $N_\tau S_0$, with the value of τ being 1 msec (i.e., half the period of 500 Hz). Figure 2 shows the results for the two listener groups for conditions where the noise and the signal were turned on and off synchronously when presented. The first, and expected, result is that, for both listener groups, thresholds in the diotic condition (N_0S_0) were higher than for any of the dichotic conditions. Thus, positive MLDs were observed for each group. However, the interesting points concern the comparative performance of the elderly listeners relative to the young listeners. First, the thresholds for the elderly listeners in the diotic condition were equivalent to those of the young listeners. However, thresholds for the elderly listeners in all four of the dichotic conditions were significantly higher than those of the young listeners. Second, the thresholds for the elderly listeners were essentially the same across the four dichotic conditions. For the young listeners, however, the thresholds in the N_0S_π and $N_{\pi\tau}S_\pi$

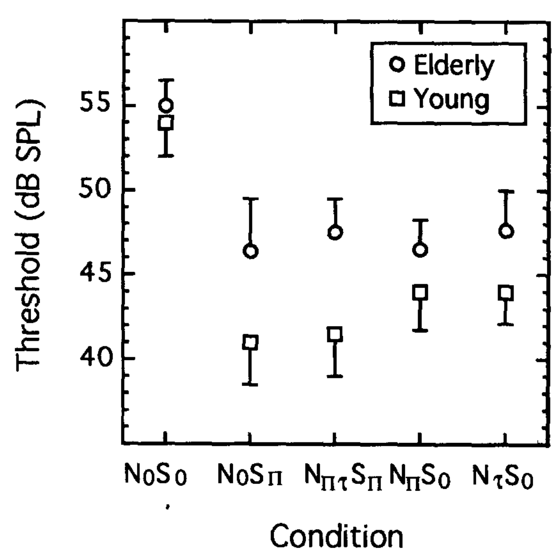

Figure 2 Mean thresholds for elderly (circles) and young (squares) listeners for five configurations of signal and masker. Error bars denote 1 standard deviation. (Data derived from Pichora-Fuller and Schneider, 1991.)

configurations were significantly lower than in the $N_\pi S_0$ and $N_\tau S_0$ configurations. This meant that the derived MLDs for the elderly listeners were, overall, smaller than for the young listeners but that they were equivalent across the four dichotic conditions. For the young listeners, the MLDs in the N_0S_π and $N_{\pi\tau}S'_\pi$ configurations were significantly larger than in the $N_\pi S_0$ and $N_\tau S_0$ configurations. Importantly, these differences between elderly and young listeners were robust even when hearing sensitivity in the 500-Hz region was statistically controlled. Pichora-Fuller and Schneider (1991) hypothesized that this pattern of results was due to a combination of two factors, both having to do with temporal aspects of binaural auditory processing. The first was that some sort of temporal jitter exists in the binaural system, which limits its performance. The assumed existence of this source of variability dates back to the original equalization/cancellation model that Durlach (1972) put forward to account for the MLD. The second assumption was that the binaural system can introduce some sort of internal delay to the input from one ear relative to the other ear. The hypothesized link between the two factors — which is key to the pattern of results — is that, in young listeners, the degree of temporal jitter is a function of the size of the internal delay, while, in elderly listeners, the degree of temporal jitter is constant across all internal delays. In a later study, Pichora-Fuller and Schneider (1992) tested this hypothesis more rigorously and showed that the differences in MLD between elderly and young listeners could be largely accounted for on the basis of differences in the amount of temporal jitter in the binaural system. Estimates of temporal jitter in the elderly listeners exceeded that for young listeners by factors of between 1.2 and 1.7. Thus, the differences between elderly and young listeners on the MLD task, as with the precedence effect task, appear to be due primarily to declines in temporal processing in the elderly.

A later study by Grose et al (1994) corroborated the essential results of the tonal MLD that Pichora-Fuller and Schneider (1991) had reported, namely, that there was no substantive difference between elderly listeners in the early stages of presbyacusis and young adult listeners for the diotic N_0S_0 condition, but that elderly listeners performed significantly worse in the dichotic N_0S_π condition, even when hearing sensitivity at 500 Hz was statistically controlled. The study by Grose et al (1994) went on to examine the comparative binaural performance of the elderly listeners (mean age ≈ 73 years) for a task where the target stimuli were spondee words and the masking noise was speech shaped. It was considered that the use of a task that involved speech recognition in a speech-shaped noise background would be a more realistic simulation of the natural competitive listening conditions that elderly listeners typically find most difficult. The background noise was always presented diotically, while the target spondee words were presented either in phase or 180° out of phase at the two ears. For each stimulus configuration, N_0S_0 and N_0S_π, a complete psychometric function was measured for each listener. The two panels of Figure 3 depict the raw data from the elderly listeners (upper panel) and the young listeners (lower panel). Within each panel, the circles indicate N_0S_0 thresholds while the crosses indicate N_0S_π thresholds. Triangular arrows on the abscissa indicate the speech level at which the particular listener group achieved an average score of 50 percent correct. The pattern of results mirrored that for the tonal MLD: there was only a slight difference between the elderly and young listeners on the diotic condition, but the elderly performed significantly worse than the young on the dichotic condition even when hearing sensitivity was statistically controlled. These results indicate that, for a suprathreshold recognition task, as for a detection task, the elderly display less of a binaural advantage than do the young adults.

The speech MLD task just described exemplifies how a laboratory test can be contrived relative to more realistic listening conditions. In particular, by presenting the broadband speech signal antiphasically at the two ears, each spectral component in the signal is, by definition, π radians out of phase across the two ears. In the free field, however, a constant difference in time of arrival translates to an interaural phase difference that depends upon the frequency of the sound: for a broadband signal, interaural phase differences will vary across the spectrum. Gelfand et al (1988) reported on a task that was, in some sense, an analog to the speech MLD described above. However, it differed in a number of respects: first, and most importantly, the stimuli were presented in the free field rather than under headphones; second, the masker was a 12-talker babble rather than a speech-shaped noise; and third, the signal was a complete sentence rather than a spondee word. When the signal and the masker originated from directly in front of the listener, the condition was analogous to N_0S_0; when the masker

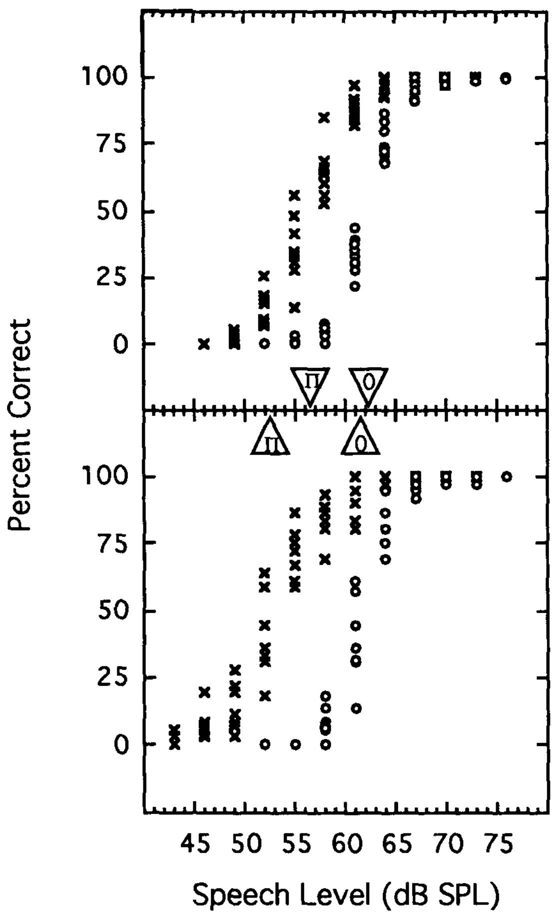

Figure 3 Individual psychometric functions showing spondee recognition in noise as a function of spondee level. Binaural spondee presentation was either homophasic (circles) or antiphasic (crosses). Upper panel is for elderly listeners, lower panel is for young listeners. Triangular arrows on the abscissa indicate thresholds for 50 percent correct recognition for the S_0 and S_π conditions. (Data derived from Grose et al, 1994.)

Figure 4 Mean signal-to-noise ratios for 50 percent correct sentence recognition for three listener groups. The parameter is speech and masker configuration in the free field: presentation was analogous to either N_0S_0 (squares) or N_0S_τ (circles), as described in the text. (Data derived from Gelfand et al, 1988).

originated from directly in front of the listener but the signal originated from one side, the condition was analogous to N_0S_τ, with concomitant interaural intensity differences due to head shadow effects. Gelfand et al (1988) measured the signal-to-noise ratio at which sentences could be correctly recognized 50 percent of the time for both of these conditions. Among their listeners were a group of young adults with normal hearing (mean age ≈ 29 years), a group of elderly listeners with normal hearing (mean age ≈ 61 years), and a group of elderly listeners with typical presbyacusic hearing loss (mean age ≈ 64 years). Figure 4 shows the mean N_0S_0 and N_0S_τ results for these three groups of listeners. Comparing first the two normal-hearing groups, it is apparent that the elderly listeners performed more poorly than the young listeners by about the same amount in both conditions. In terms of binaural advantage, this translates to an equivalent amount of unmasking. In contrast, the elderly presbyacusic group performed relatively more poorly in the dichotic condition than in the diotic condition, yielding a smaller binaural advantage. The equivalent degrees of unmasking in the two groups with normal hearing contrasts with the speech MLD data described earlier where the performance decline in the dichotic condition was markedly worse than in the diotic condition. In addition to the obvious differences in stimulus configuration between the two studies, these contrasting findings may also be influenced by differences in subject selection criteria. In the Gelfand et al (1988) study, the elderly normal group had a maximum age of 70 years with audiometric thresholds less than 25 dB HL even out to 8000 Hz. In the Grose et al (1994) study, the elderly group had a mean age of 73 years with audiometric thresholds less than 20 dB HL only out to 2000 Hz, with many listeners exhibiting loss either at or beyond 4000 Hz. Thus, there may be little overlap in the subject characteristics between these two studies. The Gelfand et al study shares with the Cranford et al (1993) study on the precedence effect the general similarity that, when comparing the three listener groups of normal-hearing young listeners, normal-hearing elderly listeners, and hearing-impaired elderly listeners, the most noticeable decline in performance occurs in the presbyacusic elderly group.

Dichotic Competition

The speech tasks described above exemplify measurements of speech recognition in a noisy background. Such listening conditions are analogous to many real-world environments where the elderly typically experience some communication handicap. Notice that the background noises are broadband and, even when they consist of "babble," the semantic content of the noise is usually not intelligible. In contrast, another competitive listening condition that is also typical of many real-world environments is one where multiple semantic messages are present, each one of which is intelligible if attended to, but only one of which is of interest to the listener. In this sense, the nontarget messages are distractors or competitors, rather than maskers in the traditional psychoacoustic sense. Given that the target message and the competing message are usually spatially separated, how do the elderly perform in these dichotic conditions, especially given the right-ear advantage often seen in dichotic tasks? In an attempt to address this question, Jerger and Jordan (1992) constructed a task in which the listener was seated in a sound field with a loudspeaker on either side. Discourse spoken by a single talker was presented continuously from each loudspeaker; there was no overlap of material coming from the two loudspeakers, although the talker was the same from each loudspeaker. The listener's task was to identify a target word in the ongoing discourse from either the left side or the right side, as indicated by a cueing light. Thus, on a particular trial, the discourse from one loudspeaker was considered the target message while the other was considered the competitor. A group of elderly presbyacusic listeners and a group of young, normal-hearing adults were tested and both groups showed better performance when the target was presented on the right side than when it was presented on the left side. However, this right-side advantage was markedly greater in the elderly group than in the young group and was not associated with interaural differences in audiometric sensitivity or monaural speech understanding. Although the factors of age and hearing sensitivity are confounded here, the implication was that these presbyacusic listeners experienced a greater left-ear (or, technically, left-side) decline with age and that this decline was associated with the highest levels of the neural pathway.

General Discussion

The studies described above exemplify the wide range of tasks that can be considered, at some level, to be measurements of binaural performance. Caveats concerning the influence of both auditory and nonauditory factors on the pattern of results must be re-emphasized. In particular, the confounding of age and hearing loss is apparent in many reports. In addition, while many studies compare the performance of elderly listeners with young listeners, it should not be overlooked that the term "elderly" is loosely used and may cover a wide age range. This is highlighted by the study of Welsh et al (1985), who undertook a number of dichotic speech tests on elderly listeners where the data were broken down into three age ranges: 60–69 years, 70–79 years, and 80–89 years. Welsh et al found that, even though the basic audiometric characteristics across the three groups were relatively similar, performance declined significantly with age. This emphasizes the heterogeneity of the elderly population.

While an attempt to force some global integration of findings across the various levels of binaural function would be nonsensical, certain commonalities exist among the findings from binaural tasks that probably represent more similar levels of processing. The findings of Cranford et al (1993) and Pichora-Fuller and Schneider (1991, 1992) highlight the probability that temporal coding in elderly listeners is degraded relative to young listeners and that this decline is not limited to temporal encoding in the auditory periphery (see paper by Fitzgibbons and Gordon-Salant in this issue). There have been attempts to confirm such degradations in (central) temporal processing by assessing neural conduction times electrophysiologically, but with little consensus. For example, Woods and Clayworth (1986) and Muchnick et al (1993) observed changes in auditory evoked potentials that were interpreted as indicating changes in neural conduction time with aging, whereas Martini et al (1991) did not (see paper by Chmiel and Jerger in this issue). While there may be some value in this approach, it would seem likely that, with the complexity of interneural connections within the central auditory system, neural conduction time is only one aspect of neural processing underlying the fidelity of the temporal code. The relation between perceptual and electrophysiologic measures in terms of binaural processing has been specifically investigated (see, for example, von Wedel et al, 1991), but the interpretation of such studies is difficult. For instance, Martin and Cranford (1991) found differences in binaural performance among elderly and young listeners in both behavioral and electrophysiologic measurement domains, but observed no correlation between the results from the two domains. This observation is consistent with the study of Kelly-Ballweber and Dobie (1984), which also found no correlation between behavioral and electrophysiologic measures of binaural interaction in elderly and young listeners. The suggestion that the fidelity of the temporal code that contributes to binaural processing is degraded in the aging auditory system has ramifications for the development of new generations of digital hearing aids designed to compensate for peripheral dysfunction. If the degradation has a central component, it places limits on the success that can be expected from preprocessing, particularly for monaural amplification.

Many of the studies that compare binaural function in young and elderly listeners naturally focus on the differences in performance between the two groups. While this is constructive, in that it helps to identify particular difficulties experienced by the elderly, it fails to draw attention to the fact that the elderly do, nevertheless, typically exhibit a significant binaural advantage in competitive listening conditions. The reminder that the benefits of listening with two ears rather than one remain to some extent even in the presbyacusic listener should be a factor in the consideration of monaural versus binaural amplification.

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