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Interaural Discrimination and Localization of Cross-Frequency Stimuli in Normal-Hearing and Impaired-Hearing Listeners.

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INTERAURAL DISCRIMINATION AND LOCALIZATION OF CROSS-FREQUENCY STIMULI IN NORMAL-HEARING AND IMPAIRED-HEARING LISTENERS

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ABSTRACT

The ability to discriminate interaural differences in complex signals and to localize those signals was examined in listeners with normal hearing (NH) and with bilateral high frequency sensorineural hearing impairment (IH). In Experiment I just noticeable differences for interaural time and intensity were obtained using 1/3-octave narrow band noise (NBN) stimuli centered at 500 and 4000 Hz in three conditions: (1) the NBNs played in isolation; (2) the NBNs played simultaneously with congruent interaural information across frequency; and (3) the NBNs played simultaneously with either (a) the 500 Hz band dichotic and the 4000 Hz band diotic or (b) the 500 Hz band diotic and the 4000 Hz band dichotic. The best interaural time discrimination for the IH listeners is observed when the 500 Hz NBN contained the relevant information (conditions 1, 2, and 3a) and the best intensity discrimination for the IH listeners was seen when both bands contain congruent interaural information (condition 2). Results indicate reduced sensitivity to interaural time differences for all subjects when the 500 Hz band is diotic and discrimination is based on the 4000 Hz band (3b). The IH listeners also demonstrate poorest interaural intensity discrimination for this condition (3b). Results suggest that IH subjects may benefit from congruent interaural information in more than one frequency region.

In Experiment II a measure of localization accuracy was obtained in three conditions: (1) the NBNs played in isolation; (2) the NBNs played simultaneously with one as the target and the second (interferer) at a fixed location; and (3) the NBNs played simultaneously with the interferer at a random location. The NH subjects performed similarly on all tasks with each target band, although accuracy was reduced with a 4000 Hz NBN target. Best performance by the IH subjects was seen with a 500 Hz NBN target, whether or not the interferer was present. The IH subjects performed most poorly with a 4000 Hz NBN target and a random interferer. Results suggest that in IH subjects, localization is most difficult when forced to rely on interaural information in the higher frequency region with competing interaural information at low frequencies.

INTRODUCTION

The ability to efficiently use binaural cues is important in many tasks listeners perform on a daily basis, such as locating a sound source or listening to speech in the presence of background noise. However, it is well established that individuals with sensorineural hearing loss often have difficulty with binaural processing tasks including: interaural time discrimination (Hawkins and Wightman, 1980; Häusler *et al.* 1983; Smoski and Trahiotis, 1986; Gabriel *et al.*, 1992; Koehnke *et al.*, 1995; Koehnke and Besing, 1995); interaural intensity discrimination (Häusler *et al.* 1983; Gabriel *et al.*, 1992; Koehnke *et al.*, 1995); localization (Jonkgees and Veer, 1957; Tonning, 1975; Colburn *et al.*, 1982; Noble *et al.*, 1994); and binaural detection (Koehnke *et al.*, 1995; Koehnke and Besing, 1995). However, to date these studies of binaural processing in listeners with impaired hearing have used a single target signal, either simple (pure tones) or complex (narrow or wide band noise, speech). In most everyday listening situations the signals, such as speech, music, etc., include relevant binaural information in more than one portion of the frequency spectrum. Also, in natural listening situations other sounds unrelated to the target signal may interfere with the reception of relevant binaural information in the target signal. The situation is further complicated by the fact that the target signal and interfering signal may have

similar spectral components. While the binaural information from the individual target or interferer will provide reinforcing information across frequency, when the target and interferer are combined they may have reinforcing or conflicting binaural information across frequency. There have been a limited number of studies of cross-frequency binaural processing in listeners with normal hearing (McFadden and Pasanen, 1976; Wenzel and Hafter, 1985; Trahiotis and Bernstein, 1990; Heller, 1992; Buell and Hafter, 1991; Buell and Trahiotis, 1993); however, these studies have not included individuals with impaired hearing, whose most common complaint is understanding speech in the presence of interfering noise.

Therefore, the overall goal of this study was to investigate the effects of sensorineural hearing loss on binaural processing of complex signals. Specifically, this research was designed to: (1) measure interaural time and intensity discrimination of complex stimuli (a) when the interaural information in two widely separated frequency regions is congruent and (b) when the interaural information in those two frequency regions is incongruent; and (2) measure the perceived location of a target signal in the presence of an interfering signal, i.e. one with a different frequency and contradictory interaural information. These data will provide insight into how listeners combine interaural information across frequency. It is important to

study the combination of interaural information across frequency in order to determine why binaural processing is more difficult in some situations than others and is more difficult for some listeners than others.

In order to achieve these goals, individuals with normal hearing and with impaired hearing were used as subjects and interaural time and intensity discrimination and localization were measured in various listening conditions. Specifically, interaural discrimination and localization ability were measured with and without an interfering narrow band noise present in a different spectral region. Performance on these tasks was measured to provide information to help understand difficulties encountered by all listeners when interaural information is available in more than one frequency region, which is true of virtually all listening situations.

Experiment I examined how listeners combine interaural information across frequency. Results of this experiment provide information to evaluate the contribution of binaural processing across frequency by investigating the ability of listeners to process binaural stimuli in isolation, i.e., with no conflicting information present (quiet conditions), and binaural stimuli that overlap temporally but are spectrally distinct (noise conditions). The combination of interaural information across frequency was investigated in two ways, (1) by presenting signals with congruent cues and (2) by presenting signals with incongruent cues. It has been

demonstrated that discrimination of interaural time differences improves when congruent interaural information is present at more than one frequency within low or high spectral regions for listeners with normal hearing (Buell and Trahiotis, 1993; Buell and Hafter, 1991; Wenzel and Hafter, 1985). Improved interaural time discrimination may not result when the congruent interaural information is present at low and high frequencies, however. McFadden and Pasanen (1976) designed an experiment to examine the combining of information for interaural time differences across low and high frequencies. Subjects performed so well with only the low frequency signal the researchers could not assess the possible contribution of the high frequency information. Therefore, the researchers did not determine whether interaural time information across low and high spectral regions combines to result in improved interaural time discrimination.

The first portion of Experiment I was designed to address the question regarding interaural discrimination with congruent interaural information available in more than one spectral region. Specifically, does interaural time or intensity information combine across low and high frequency regions to enhance interaural discrimination? To address this question, interaural time and intensity just noticeable differences (JNDs) were measured using 1/3-octave narrow band noise (NBN) signals centered at 500 and 4000 Hz. The JNDs

were obtained at each center frequency and with a complex signal that was a combination of the 500 and 4000 Hz NBN signals.

In the second part of Experiment I, the combination of interaural information across frequency was measured in a "binaural interference" paradigm. In this paradigm interaural time and intensity JNDs of a target signal were measured when the interaural information in the 500 and 4000 Hz NBNs was incongruent across those components. Binaural interference, reported thus far only in listeners with normal hearing, is a phenomenon in which the interaural time JND increases for a target signal when it is presented simultaneously with a second signal which is lower in frequency and (usually) diotic (McFadden and Pasanen, 1976; Heller, 1992; Buell and Trahiotis, 1993). Interaural intensity JNDs in listeners with normal hearing increase whether the interfering signal is higher or lower in frequency than the target signal (Heller, 1992). The work of Buell and Hafter (1991) and Heller (1992) suggests that combination of interaural information is obligatory, even if it degrades interaural discrimination. The second portion of Experiment I was designed to assess whether listeners must combine all cross-frequency interaural information across low and high frequency regions, even if interaural discrimination is degraded, or whether there are some situations in which

irrelevant interaural information can be ignored, thus leaving interaural discrimination unaffected.

Experiment II was designed to examine the effects of an interfering signal (i.e., one differing in frequency and location from the target) on the perceived location of a target signal. Localization in listeners with impaired hearing is important to study because it provides data which may indicate how they handle temporally overlapped signals in actual localization situations, such as determining the direction of an oncoming vehicle.

Previous localization research has established that listeners predominantly use interaural timing information to localize low frequency signals (Yost *et al.* 1971) and interaural intensity information to localize high frequency signals (Sandel *et al.*, 1955). Localization is a complex task that requires the use of both time and intensity information simultaneously (e.g., Mills, 1960; Rayleigh, 1907). It is reasonable to assume, then, that one's performance on a complex listening task, such as localization, is related to performance on the simpler time and intensity discrimination tasks. That is, if a person has good interaural time and/or intensity discrimination ability, it is likely he will also be able to localize accurately. Conversely, if a listener demonstrates poor interaural discrimination, localization may be less accurate.

Theoretical evidence also supports the idea of a relationship between performance on simple and complex binaural tasks. Zurek (1993) extended a model first proposed by Levitt and Rabiner (1967) to account for improved speech intelligibility in noise when using two ears compared to one. Zurek proposed two underlying factors in his model, binaural interaction (or capitalizing on the interaural differences in a sound source) and the head-shadow effect. One measure of binaural interaction is the masking level difference (MLD), a simple psychoacoustic task of detecting a tone in noise binaurally. The MLD is the difference in dB between detection thresholds of a signal in noise with both the noise and signal in phase at each ear versus with the noise in phase at each ear and the signal 180° out of phase at the two ears. The MLD is largest for low frequency signals and is apparently based primarily on detecting interaural time differences. The head-shadow effect refers to the interaural differences that result in a signal being more intense at the ear closer to the sound source. Head-shadow occurs primarily with high frequency signals that have short wavelengths and therefore do not diffract around the head. Because the MLD and head-shadow effect included in Zurek's model are based on sensitivity to interaural time and intensity differences, it is reasonable to expect a relationship between performance on the interaural time and intensity discrimination tasks in

Experiment I and the complex localization task in Experiment II.

Localization studies in quiet (i.e., signals presented in isolation) using subjects with impaired hearing have demonstrated that they are, on the whole, less accurate than subjects with normal hearing (Jongkees and Veer, 1957; Tonning, 1975; Colburn *et al.*, 1982; Noble *et al.*, 1994). The addition of an interfering signal which has different spatial and spectral information from the target signal would presumably disrupt the localization accuracy of all listeners, potentially even more so in individuals with impaired hearing than those with normal hearing. Effects of an interfering signal on the localization of a target signal may be dependent on the spectral characteristics of the two; however, any such effects are unknown since these localization experiments have been conducted in quiet (e.g., Colburn *et al.*, 1982).

Heller (1992) explored the effects of an interfering signal differing in interaural time or intensity from the target signal on lateralization in subjects with normal hearing. In a lateralization experiment a signal is presented to both ears with the signal leading in time at one ear, more intense at one ear or both of these. The listener's task is to indicate whether the signal appears to be to the right or left of midline. If the signal leads in time or is more intense in the right ear, for example, then

a NH listener hears the signal to the right of midline. How far away from midline a signal is heard depends on the time or intensity difference between the ears; the greater the difference, the further away from midline. Heller (1992) reported that a target's perceived location within the head shifted towards the interfering signal's location, and the amount of the shift was dependent on the magnitude of the interaural time or intensity difference. Similarly, in a localization task where interaural time and intensity differences occur simultaneously, moving the interferer further away from the target is likely to result in greater localization error.

In the present localization experiment, two primary questions are addressed: (1) how do the relative spectral characteristics of the target and interferer affect localization accuracy, and (2) is localization accuracy affected differently when the interfering signal is in a fixed versus a random location? The results of this experiment provide data to assess the localization accuracy of listeners with impaired hearing in quiet and in the presence of interference with interaural information distinct from the target. In addition, the combination of interaural information across frequency regions can be examined, including whether combination of interaural information is obligatory or if there are instances in which it is not combined.

Overall, this study is important because it provides information on the ability of listeners to localize and/or process interaural cues in complex listening situations when there is conflicting information in different spectral regions, as often occurs in everyday listening situations. This extends our understanding of binaural processing in listeners with normal hearing and impaired hearing. In addition, the data can be used to refine and extend models of binaural hearing in normal-hearing and impaired-hearing listeners.

BACKGROUND

The advantages of using two ears instead of one have been recognized for over a century. Rayleigh (1907) was among the first to investigate systematically how the binaural system exploits signals to allow enhanced performance over one ear on localization tasks. His "duplex" theory of localization, timing information is used to localize low frequency signals while intensity information is used to localize high frequency signals, still stands for pure tones, though it has been shown to be inadequate for complex signals (e.g., Neutzel and Hafter, 1976). It is clear now that the binaural system takes advantage of small differences in time of arrival and intensity of signals reaching the two ears in order to localize sound sources and enhance speech reception in noisy situations.

Relevant research pertinent to issues in the current study can be divided into three areas: (1) combination of interaural information across frequency; (2) measures of interaural time and intensity just noticeable differences (JNDs) in normal-hearing and impaired-hearing listeners; and (3) localization of sound sources in normal-hearing and impaired-hearing individuals. The following discussion will include a review of the research in each of these areas, followed by a brief examination of a model originally developed by Levitt and Rabiner (1967) and extended by Zurek (1993). This model posits two underlying factors, the head-

shadow effect and binaural interaction, i.e., "making use of interaural differences in the received sounds" (p. 255, Zurek, 1993), as the bases for improved speech intelligibility in noise and localization. The argument will be made that the interaural time and intensity discrimination measured in this study can reasonably be substituted for binaural interaction and head-shadow effect, respectively. Thus it should be possible to predict localization performance based on interaural time and intensity discrimination performance.

Combination of Interaural Information Across Frequency

Binaural Enhancement

Studies by Bernstein and Trahiotis (1982) and Yost *et al.* (1971), suggest that information in low frequency regions of wideband complex stimuli is the most important for interaural time discrimination. There is evidence for listeners with normal hearing, however, that when signals with spectrally distinct (in separate "critical bands") components reside completely within either the high frequency, i.e. >1500 Hz (Buell and Trahiotis, 1993; Wenzel and Hafter, 1985), or low frequency, i.e., <1500 Hz (Buell and Hafter, 1991; Dye, 1990), regions, there is "facilitation" of interaural time discrimination; that is, a combination of interaural information across frequency occurs and discrimination of interaural time differences improves. It should be noted that in the Dye (1990) study some of the

components of the complex stimuli were in the same critical band. However, in Dye's study as well as the other studies cited, only those components which were in separate critical bands yielded facilitation of interaural discrimination.

Buell and Hafter (1991) measured interaural time discrimination for 5-component tone complexes centered near 750 Hz and interaurally delayed one component, then two, etc. They reported increased sensitivity to interaural time differences when more components were delayed, i.e., the JND was smaller when congruent interaural information occurred across frequency. Buell and Trahiotis (1993) measured interaural time JNDs of sinusoidally amplitude modulated (SAM) tones with 2000 and 4000 Hz carriers. These researchers also reported increased sensitivity when congruent interaural information was carried in more than one spectral region.

Binaural Interference

McFadden and Pasanen (1976) employed 1/3-octave narrow band noise (NBN) signals centered at 500 and 4000 Hz to determine whether facilitation of discrimination occurs when interaural information is in low and high spectral regions. In contrast to the other studies cited, McFadden and Pasanen did not report improved interaural time discrimination. Instead, they encountered a "ceiling effect" with the 500 Hz NBN signal; that is, their subjects performed so well at 500 Hz that essentially no improvement was possible with the

addition of the high frequency signal. Therefore, if additional information was available from the 4000 Hz NBN, its contribution was not detectable due to the ceiling effect at 500 Hz. JNDs for the 4000 Hz NBN signal alone were elevated compared to both the 500 Hz NBN alone and the 500+4000 Hz NBN signals, consistent with the idea that the binaural system is more sensitive to interaural time information in the low frequencies.

The reasons for the different results obtained by McFadden and Pasanen (1976) and Buell and Hafter (1991) and Buell and Trahiotis (1993) may be explained by differences in procedures and stimuli. First, the spectral characteristics of the stimuli were different; McFadden and Pasanen's stimuli were in low and high frequency regions while the other two studies used stimuli within low or high frequency regions (i.e., below or above 1500 Hz). Second, the types of signals employed differed; McFadden and Pasanen used NBNs, Buell and Hafter used tone complexes, and Buell and Trahiotis used sinusoidally amplitude modulated tones. Third, the task required of the subjects differed; McFadden and Pasanen's subjects were instructed to indicate the direction of lateralization (i.e., whether the perceived image moved right or left of midline inside the head) of the target signal while the other two studies employed oddity paradigms in which subjects were instructed to indicate the "different" interval, i.e., a discrimination task.

Stellmack and Dye (1993) examined the two experimental procedures (i.e., direction versus discrimination) and postulated that the easier task of these two should yield smaller JNDs. They reported time JNDs of low frequency pure tone complexes in these two tasks. In one task, subjects indicated the different interval and in the other task, they indicated the direction of perceived movement of a complex binaural stimulus. Unfortunately, Stellmack and Dye's results were equivocal, as two of the three subjects demonstrated smaller JNDs with the oddity paradigm and the third had smaller JNDs in the movement task. Although it is possible the task in the McFadden and Pasanen study adversely influenced subjects' discrimination of the 4000 Hz signal, this explanation is inadequate, because their subjects demonstrated good discrimination of the 500 Hz signal using the perceived movement task.

A second phenomenon involved in the combination of interaural information across frequency is binaural interference. McFadden and Pasanen (1976) reported increases in interaural time JNDs for a 4000 Hz NBN when a diotic 500 Hz NBN was presented simultaneously. However, time JNDs did not increase for the 500 Hz NBN when a diotic 4000 Hz NBN was also presented. Buell and Trahiotis (1993) (using 2000 and 4000 Hz SAM tones) and Trahiotis and Bernstein (1990) (using NBNs in a wideband notched noise interferer) described similar results; that is, when the 2000 Hz signal was the

target, no decrement in time discrimination performance was noted, but when the 4000 Hz signal was the target, the time JND increased. These results suggest that upward spread of masking by an interfering signal, which is lower in frequency than the target signal, may permit peripheral disruption for reception of information in the target signal. Interestingly, Heller (1992), using narrow bands of noise, also found spectrally asymmetric interference when measuring interaural time JNDs, but no spectral effects when measuring interaural intensity JNDs. That is, the intensity JND increased slightly (1-2 dB) whether the interfering signal was higher or lower in frequency than the target signal. Heller's finding of no spectral effects in an interaural intensity discrimination task refutes the idea of upward spread of masking as an adequate explanation for the results of these binaural discrimination studies.

Time and Intensity Just Noticeable Differences

Several investigators have measured JNDs for interaural differences of time and intensity in normal-hearing listeners (e.g., Klumpp and Eady, 1956; Zwislocki and Feldman, 1956; Hershkowitz and Durlach, 1969; Bernstein and Trahiotis, 1982; Buell and Hafter, 1991; Mills, 1960; Grantham, 1984; Heller, 1992), but there are fewer measurements for impaired-hearing listeners (e.g., Koehnke *et al.*, 1995; Koehnke and Besing, 1995; Gabriel *et al.*, 1992; Häusler *et al.*, 1983; Smoski and Trahiotis, 1986; Hawkins and Wightman, 1980). Interaural

time JNDs of less than 20 μsec for low frequency tones (500 Hz) in normal-hearing listeners have been reported (Klumpp and Eady, 1956; Hershkowitz and Durlach, 1969). However, JNDs cannot be measured for high frequency tones, due to the insensitivity of listeners to cycle-by-cycle changes at frequencies greater than about 1500 Hz. Accordingly, NBN stimuli have been used to measure high frequency JNDs for interaural time differences in normal-hearing and impaired-hearing listeners. In normal-hearing subjects the interaural time JND of a NBN centered at 500 Hz is similar to that for tones, i.e. less than less than 20 μsec, while the JND of a NBN centered at 4000 Hz is slightly elevated compared to the 500 Hz NBN, about 60-90 μsec (Hawkins and Wightman, 1980; Smoski and Trahiotis, 1986; Koehnke *et al.*, 1986).

Impaired-hearing subjects demonstrate more variability in sensitivity to interaural time differences than normal-hearing subjects; almost without exception these subjects exhibit interaural time JNDs which are greater than those of normal-hearing subjects, even when measured in a frequency region in which the impaired-hearing person has audiometrically normal hearing (Koehnke *et al.*, 1995; Koehnke and Besing, 1995; Hawkins and Wightman, 1980; Smoski and Trahiotis, 1986; Gabriel *et al.*, 1992).

A possible explanation for decreased sensitivity to interaural time differences in listeners with impaired hearing is based on traveling wave mechanics which dictate

that all signals first cross the high-frequency, basal end of the cochlea where synchronization of neural impulses is greatest (Bekesy, 1960). With damage to the basal portion of the cochlea synchronization decreases and timing information is diminished. Therefore, if individuals with hearing impairment have damage in the basal portion of the cochlea, it may affect the auditory system's ability to process high and low frequency signals. Additionally, the effect of cochlear damage may be different in the two ears. If so, then the relevant interaural information reaching the portions of the brainstem which mediate binaural processing (e.g., superior olivary complex) may be inaccurate, and inaccurate to different degrees depending upon the type and amount of damage in each cochlea. Thus, listeners with hearing impairment may have impaired binaural processing, even in spectral regions where they have "normal" audiometric thresholds.

In normal-hearing subjects the intensity JND for tonal stimuli is relatively constant across frequency with JNDs ranging from 1-3 dB (Mills, 1960; Grantham, 1984). There have apparently been no studies in which interaural intensity JNDs of tones were measured for listeners with hearing impairment, so comparison on this task between normal- and impaired-hearing listeners is not possible. The intensity JND for NBN signals in listeners with normal hearing is also relatively constant at less than 1 dB at octave frequencies

from 250-4000 Hz (Gabriel *et al.*, 1992). Several researchers (Hawkins and Wightman, 1980 [NBN]; Koehnke *et al.*, 1986 [pure tone]; Hershkowitz and Durlach, 1969 [pure tone]; Grantham, 1984 [pure tone]) have reported an intensity JND of less than 1-3 dB for a 500 Hz signal in normal-hearing subjects.

As a group, impaired-hearing listeners have demonstrated greater sensitivity to interaural intensity differences than interaural time differences. However, simply because a listener with impaired hearing displays good interaural intensity discrimination of a signal does not provide evidence that listener will also demonstrate good interaural time discrimination of that same signal or vice versa (Hawkins and Wightman, 1980; Gabriel *et al.*, 1992). Hawkins and Wightman (1980) reported data for two impaired-hearing subjects using equal sound pressure level signals across subjects and frequencies; the subjects' interaural time JNDs could not be measured, but their interaural intensity JNDs were similar to the normal-hearing subject run on the same task with the 500 and 4000 Hz NBNs. Gabriel *et al.* (1992) reported results similar to those of Hawkins and Wightman (1980) for four impaired-hearing subjects who demonstrated variable interaural intensity JNDs at 500 and 4000 Hz; two subjects had smaller JNDs at 500 than at 4000 Hz while the other two had smaller JNDs at 4000 than 500 Hz. In this experiment, stimuli were at least 30 dB sensation level for each subject at each frequency, but otherwise were kept at

equal sound pressure level. All subjects with hearing impairment had interaural intensity JNDs of 8 dB or less, even if their interaural time JNDs were very large (greater than 1000 μsec). Based on these data, it is unlikely that an individual's ability to use one cue can be predicted from their sensitivity to the other cue. In order to understand better how hearing impairment affects binaural processing, it is important to measure sensitivity to both interaural time and intensity differences.

Localization Studies

Although many investigations have examined the ability of normal-hearing listeners to localize sound sources, there have been relatively few studies of the localization ability of impaired-hearing listeners. One of the few comprehensive studies of localization by listeners with hearing impairment was done by Jongkees and Veer (1957). Most of their subjects had conductive hearing losses resulting from various medical conditions, e.g., chronic otitis media or otosclerosis, but they also tested some persons with sensorineural hearing loss ranging from mild to moderate loss. Nordlund (1964), Tonning (1975), and Häusler *et al.* (1983), employed subjects with a wide variety of hearing loss configuration and degree: unilateral and bilateral conductive, sensorineural, mixed, and retrocochlear losses, ranging from mild to severe. Colburn *et al.*'s (1982) subjects had bilateral sloping or flat sensorineural hearing loss. Noble *et al.* (1994) used

subjects with bilateral sensorineural and unilateral and bilateral conductive losses ranging from mild to moderately severe losses.

The goals of the earliest localization studies of impaired-hearing individuals were to (1) describe the effect of different medical conditions resulting in auditory disorders on localization ability (Jongkees and Veer, 1957) and (2) develop a differential diagnostic test based on pathology and localization ability (Nordlund, 1964).

Jongkees and Veer (1957) used a 1000 Hz pure tone target signal and reported localization performance of subjects with (cochlear) hearing impairment was poorer than subjects with normal hearing. Nordlund (1964) employed 500, 2000, and 4000 Hz pure tones and a low-pass noise. In contrast to Jongkees and Veer, he reported localization performance of subjects with (cochlear) hearing impairment was similar to that of subjects with normal hearing.

The general method these investigators applied was similar; both seated subjects in an anechoic chamber and presented stimuli through a speaker mounted on a graduated arc with a $\pm 90°$ (Jongkees and Veer) or $\pm 70°$ (Nordlund) range of motion at a distance of 50 cm and 100 cm, respectively, in front of the subject. Subjects were instructed to indicate where the sound originated. Possible methodological differences including instructions, response mode, and eye and head position, as well as subject differences including

degree of hearing loss, etiology, and age, may account for the disparate findings. Interestingly, both studies concluded that the audiogram was not correlated with an impaired-hearing listeners' ability to localize sound sources.

In contrast to the conclusions regarding the relevance of the audiogram to localization ability of the two previously mentioned studies, Noble *et al.* (1994) reported that type and degree of hearing loss does correlate with the ability to localize sound. The source locations used in this study were more numerous than the earlier studies and included measures of vertical plane localization and front-rear discrimination. The stimuli were bursts of "pink noise"; subjects were seated within hemicircumferential loudspeaker arrays which permitted vertical plane and front-back measures. Normal-hearing subjects localized sound sources more accurately than the impaired-hearing subjects in both the vertical and horizontal planes, and in front-rear discriminations. The researchers concluded that the degree of hearing loss in various frequency regions for listeners with sensorineural hearing loss is moderately predictive of auditory localization function and that conductive loss produces more localization difficulty than that attributable to degree of impairment.

Tonning (1975) and Colburn *et al.* (1982) also reported subjects with hearing impairment performed more poorly on

localization tasks than their normal-hearing counterparts. Tonning and Colburn *et al.* both used a white noise stimulus for the stated purpose of making the task as easy as possible, yet the impaired-hearing subjects still performed more poorly than the normal-hearing subjects. Stevens and Newman (1936) reported that pure tones are more difficult to accurately localize than are wideband signals. Given that pure tones are more difficult to localize than wideband noises, it is interesting to contrast results of the Tonning and Colburn *et al.* studies with those of Nordlund, who reported no differences in localization accuracy between his subjects with normal hearing and those with impaired hearing. One would expect that Nordlund's subjects with impaired hearing would perform even more poorly than those in Tonning's or Colburn *et al.*'s study, given the differences in stimuli. However, at least some of Nordlund's normal-hearing subjects "...had noise-induced losses at the frequencies 2000 and 4000 cps..." (p. 5). Although he excluded their data for these frequencies, any effect of their hearing loss on their performance with the other stimuli was ignored, thus calling into question the representativeness of his "normal" data.

Generalizations regarding the localization abilities of impaired-hearing listeners are difficult to state, due to the variety of stimuli and methods which have been employed to investigate this question. However, in general, studies examining localization ability of listeners with impaired

hearing indicate their performance is not as accurate as listeners with normal hearing. It seems likely that since localization ability is based at least in part on recognition of differences in time and intensity of signals reaching the ears, if a listener has difficulty distinguishing those differences he or she should also have difficulty localizing sounds.

It is not possible to ascertain the individual contribution of interaural time and intensity cues to localization because all cues occur simultaneously. However, if we measure listeners' performance on interaural time and intensity discrimination and localization tasks using similar stimuli, it seems reasonable to compare performance on the interaural discrimination tasks to the localization task.

It is well established that for simple or complex low frequency sounds interaural time is the predominant cue for localization while interaural intensity is used for localizing simple high frequency signals (e.g., Mills, 1960). Researchers have also determined that interaural time cues are available in complex high frequency signals (e.g., Henning 1974; Neutzel and Hafter, 1976). Interaural intensity is not a good cue in low frequency signals, whether the signal is simple or complex, because below about 1200 Hz interaural intensity differences are negligible due to the size of the human head relative to the wavelength of sound. Nevertheless, listeners can discriminate small interaural

intensity differences in low frequency signals under headphones, which suggests that the auditory mechanism is capable of using interaural intensity differences for low frequency signals, but is prevented from doing so due to the lack of usable cues. Thus, interaural time and intensity cues may both be used to localize high frequency sounds, but interaural time is the predominantly useful cue for localization of low frequency signals.

Most localization studies have been performed with the target signal in isolation, rather than with a target in noise. A localization task using a target signal in isolation does not allow examination of the effects of combining interaural information across frequency. In the current study a target signal and an interfering signal, which differed in spectral and spatial information from the target, were used in order to examine localization skills and to examine the effects of combining interaural information across frequency in localization of listeners with normal hearing and impaired hearing.

All tasks in the current study were measured for the same subjects to enable comparison of binaural abilities across tasks. This is particularly important as it has been suggested that binaural performance cannot be predicted (e.g., Jongkees and Veer, 1957; Koehnke and Besing, 1995) or only moderately so (e.g., Noble *et al.*, 1994) from audiograms for individuals with hearing loss. Additionally, there is

only limited ability to predict performance on one binaural task based on results of a different binaural task (Gabriel *et al.*, 1992; Koehnke *et al.*, 1995; Koehnke and Besing, 1995). Therefore, it is important to measure performance across tasks for the same listener.

Model for Speech Intelligibility and Localization

Levitt and Rabiner (1967) presented a model for predicting binaural gain in intelligibility of speech and release from masking for detection of speech in broadband Gaussian noise. Reports published before the Levitt and Rabiner model had shown that under certain conditions a release from masking could occur (e.g., Licklider, 1948) and that speech intelligibility in noise was better with binaural than monaural listening (e.g., Cherry, 1961). No one had attempted to quantitatively relate these two phenomena, although it was clear that they were connected in some way. The primary purpose of the Levitt and Rabiner paper was to quantitatively relate binaural release from masking and binaural gain in intelligibility, with all stimuli presented under headphones, not in the sound field. When Levitt and Rabiner applied the model to the data from normal-hearing subjects, the model fit the data reasonably well except in the 200 Hz region.

Zurek (1993) was interested in extending the Levitt and Rabiner model to include a free-field environment. He wanted to use a limited number of factors which might quantitatively

predict a listener's ability to understand speech in a noisy situation. An integral part of his argument is that separate source locations for the speech and noise allow for better speech understanding by the listener. Inherent in this statement is the assumption that the listener is performing localization, at least to the extent of recognizing there are two source locations for the speech and noise. Therefore, while his model is put forth primarily as one for predicting speech intelligibility in noise, the same factors may well be adequate to predict a listener's localization ability.

The two factors that Zurek sets forth for predicting speech intelligibility in noise are head-shadow effect and binaural advantage, or exploiting interaural differences of a sound reaching the two ears. The head-shadow effect operates primarily on high frequency signals, because high frequency sounds will be reflected off the head due to the relative size of wavelength and the size of the head. Therefore, except for a midline sound source, one ear will always have a better signal-to-noise ratio, or greater signal intensity, which the binaural system can use to help the listener localize that sound source. The explanation provided for the second factor of "binaural interaction" (i.e., using interaural differences) could include both time and intensity differences. However, because high frequency interaural intensity information is conveyed through the phenomenon of head-shadow, binaural interaction will be used

to explain low frequency processing, which is based primarily on timing information. One of the best demonstrations of using low frequency interaural timing information is a psychoacoustic phenomenon known as the masking level difference (e.g., Licklider, 1948). We have, then, two factors available to listeners for localizing sound sources: "head-shadow" for intensity differences contained in high frequency signals and "binaural interaction" for time differences contained in low frequency signals.

In the current study listeners' ability to discriminate interaural time and intensity differences in high and low frequency signals was measured in Experiment I. The high frequency intensity discrimination measures of Experiment I can reasonably be associated with the head-shadow factor and the low frequency time discrimination measures can be associated with binaural interaction because head-shadow and binaural interaction are based on interaural intensity and time information, respectively. Therefore, it seems reasonable to expect that performance on a complex binaural localization task may be predicted by the basic psychoacoustic measures of interaural time and intensity discrimination.

METHODS

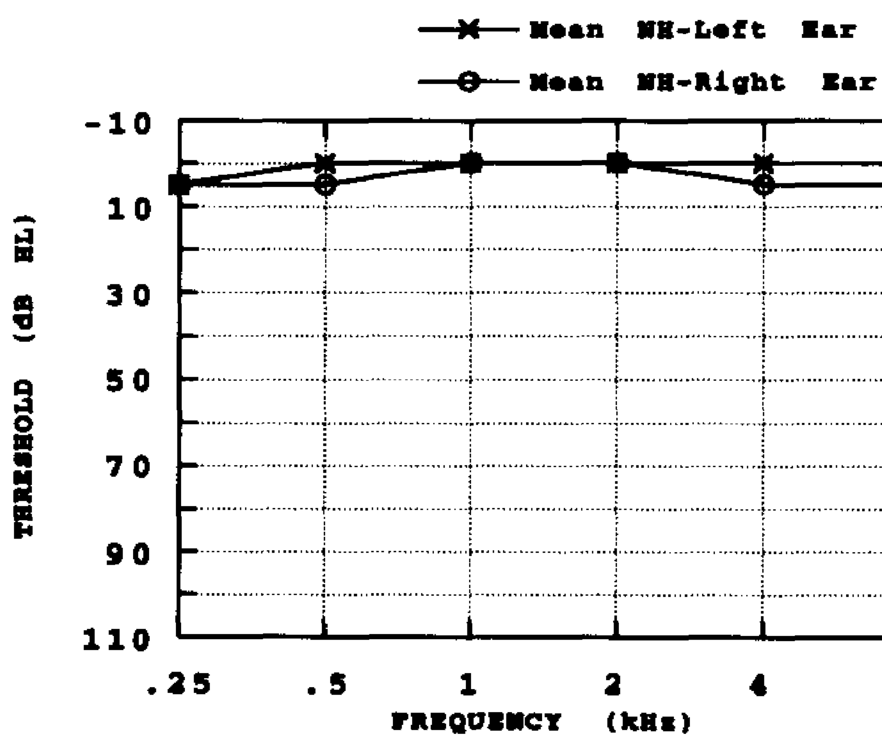
The following section describes the methods used in Experiments I and II for the interaural discrimination and localization tasks, respectively. The discrimination tasks were designed to measure listeners' interaural just noticeable differences (JNDs) for time and intensity using the stimulus configurations described below. The localization task was designed to measure listeners' ability to locate a narrow band noise (NBN) source either alone or with a second, interfering, NBN present.

Subjects

Two groups of subjects participated in the experiments: one group with normal hearing (NH) and one with impaired hearing (IH). There were three subjects with normal hearing whose age ranged from 23 to 36 years. Audiometric testing indicated bilateral audiometric thresholds ≤ 5 dB HL at octave frequencies from 250 through 8000 Hz (re: ANSI 1969). Figure 1 includes the mean thresholds for the NH subjects.

There were six subjects with impaired hearing ranging in age from 32 to 64 years. Audiometric evaluations included pure tone air and bone conduction thresholds, tests of word recognition performance, tympanometry, and acoustic reflex testing. Audiograms for the IH subjects are shown in Figure 2. Pure tone thresholds for each subject were bilaterally symmetric (within 10 dB between ears). As shown in Figure 2, all but one subject had normal thresholds at 500 Hz, one of

Figure 1. Mean audiometric thresholds for the three subjects with normal hearing. The abscissa represents the octave frequencies tested, in kHz, while the ordinate specifies listener thresholds in dB HL. The X's represent left ear thresholds and the O's represent right ear thresholds.

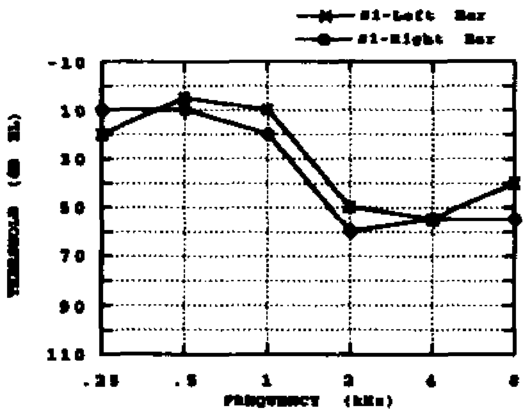

Mean NH-Left Ear
Mean NH-Right Ear
THRESHOLD (dB HL)
-10
10
30
50
70
90
110
.25
.5
1
2
4
8
FREQUENCY (kHz)

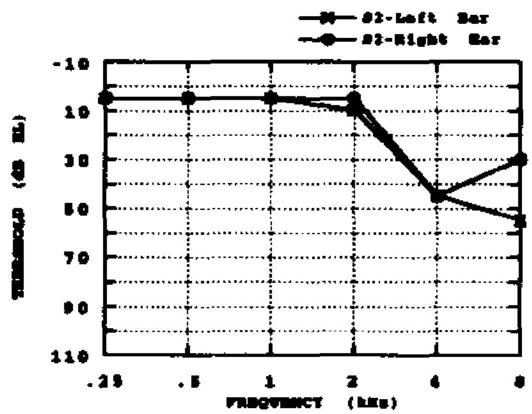
the test frequencies in both experiments. All subjects in the experimental group had sensorineural hearing loss as evidenced by equivalent air conduction and bone conduction thresholds and normal tympanograms. None of the IH subjects presented with medical diagnoses of the etiology of their hearing loss. However, reported history from these subjects suggested presbycusis as the etiology for subjects 1 and 5, noise exposure for subjects 2 and 4, and either presbycusis or noise exposure for subjects 3 and 6.

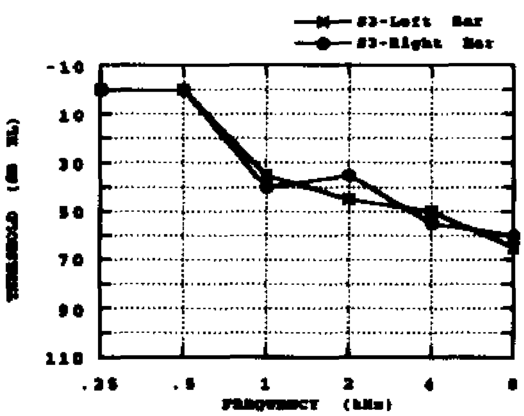
Persons with sensorineural hearing loss were used as subjects in order to compare the data of this study with previously published reports and because the greatest proportion of people with a hearing loss have sensorineural hearing loss. Audiometric testing was performed on a Grason-Stadler model 16 audiometer, a Grason-Stadler model 10 audiometer, or a Madsen model OB 822 audiometer. Impedance testing was done on a Grason-Stadler Model 33 impedance bridge.

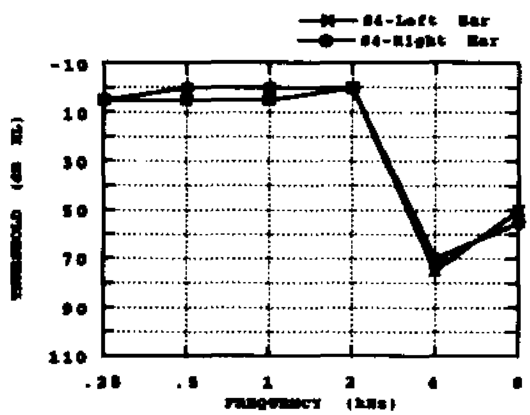
The IH subjects were recruited through the Speech and Hearing Clinic at Louisiana State University (Baton Rouge) and by referral from area audiologists. None of the IH subjects had any previous experience in psychoacoustic experiments. Each IH subject was paid for his/her participation in the study. The NH subjects, including the author, were students in the Department of Communication Sciences and Disorders at Louisiana State University (Baton

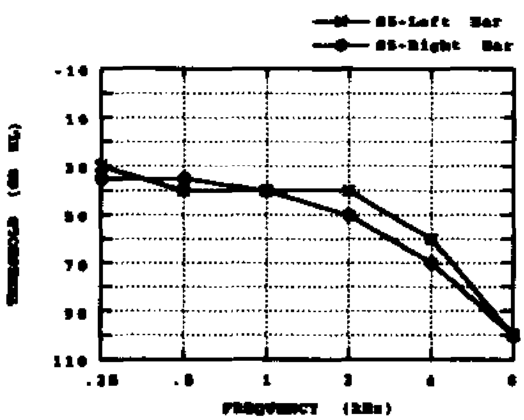
Figure 2. Pure tone audiogram for each subject with impaired hearing. The abscissa represents the octave frequencies tested, the ordinate represents the pure tone threshold in dB HL, the X's denote left ear thresholds, and O's right ear thresholds.

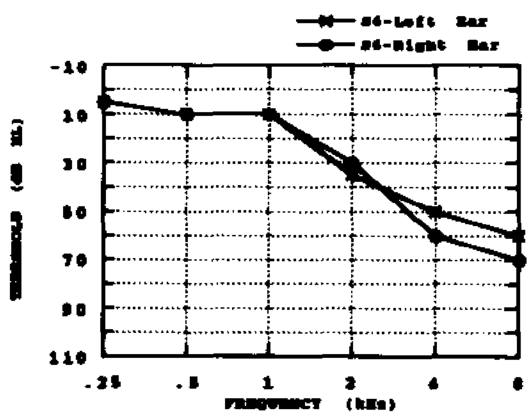

S1-Left Ear
S1-Right Ear
THRESHOLD (dB HL)
-10
10
30
50
70
90
110
.25
.5
1
2
4
8
FREQUENCY (kHz)


S2-Left Ear
S2-Right Ear
THRESHOLD (dB HL)
-10
10
30
50
70
90
110
.25
.5
1
2
4
8
FREQUENCY (kHz)


S3-Left Ear
S3-Right Ear
THRESHOLD (dB HL)
-10
10
30
50
70
90
110
.25
.5
1
2
4
8
FREQUENCY (kHz)


S4-Left Ear
S4-Right Ear
THRESHOLD (dB HL)
-10
10
30
50
70
90
110
.25
.5
1
2
4
8
FREQUENCY (kHz)


S5-Left Ear
S5-Right Ear
THRESHOLD (dB HL)
-10
10
30
50
70
90
110
.25
.5
1
2
4
8
FREQUENCY (kHz)


S6-Left Ear
S6-Right Ear
THRESHOLD (dB HL)
-10
10
30
50
70
90
110
.25
.5
1
2
4
8
FREQUENCY (kHz)

Rouge). All had previously participated in psychoacoustic experiments, including binaural tasks, for at least two years. See Appendix A for the consent form each subject read and signed before participating in this study.

Equipment

The equipment used during both the discrimination and localization experiments included a CompuAdd 386/33 computer, Tucker-Davis Technologies (TDT) QDA2 digital-to-analog board (D/A) and AP2 array processor board mounted in the computer, and Tucker-Davis Technologies free-standing modules, as shown in Figure 3. Right and left channels from the internal D/A board were connected to two TDT PA3 digital attenuators, then routed to a TDT FLT3 2-channel, 6-pole 10 kHz anti-aliasing filter, and then to an HBUF3, a 2-channel headphone buffer. The outputs of the HBUF3 were then connected to a set of TDH-49P phased and matched headphones mounted in MX-41/AR cushions. All subjects were seated in an IAC single-walled sound-treated room.

Experiment I - Discrimination

Method

Interaural time and intensity JNDs were measured using 1/3-octave NBNs centered at 500 Hz, 4000 Hz and 500+4000 Hz. All time and intensity JNDs were obtained using an adaptive, 2-cue, 2-interval, 2-alternative forced choice (2C, 2I, 2AFC) procedure with feedback. The JND was defined as the 70.7% correct level using the 1-up/2-down Transformed Up-Down

Figure 3. Equipment set-up for the discrimination and localization experiments.

CompuAdd 386/DX
(TDT AP2)(TDT 16 D/A)

TDT PA3 Atten

TDH-49P

TDT HBUF3

TDT FLT3

method (Levitt, 1971). In this procedure, the variable (e.g., interaural time difference) is decreased after a subject chooses the correct interval on two consecutive trials and is increased after a subject chooses the incorrect interval on any trial. The adaptive procedure for time and intensity discrimination consisted of eight reversals with the mean of the last four calculated as the JND. Hawley (1994) completed computer simulations with a locally developed software program on three binaural experiments, interaural time discrimination, interaural intensity discrimination and binaural detection, to determine over what range of reversals one could obtain similar results. Her results indicated that employing 8 reversals in 5 or 6 runs with 30-40 trials each with the Transformed Up-Down method, provided the (statistically) same estimate of JND as 12 reversals in 4 runs with 40-45 trials in each. In the present experiment each JND was measured five times for each subject in each condition. The average number of trials on a given run was between 30 and 40; therefore, each estimate of JND consisted of between 150 and 200 trials. The interquartile range of the interaural differences presented was constrained to ensure relatively stable performance. If the interquartile range of the levels for all trials during the last four reversals was greater than the difference between the levels one step above and below the median level

visited by the subject, the data were considered unreliable and the experimental condition was repeated.

For all conditions, intervals one and four were diotic and served as a reference within and across trials. Interaural differences occurred in either interval two or three with a 0.5 *a priori* probability. The paradigm was subject-paced in that a response was required before a new trial could begin.

Interaural time and intensity JNDs were obtained for four signal configurations for the two NBN signals (see Table 1): (1) individual noise bands (**.5 kHz, 4 kHz**); (2) combined 500 Hz and 4000 Hz NBN with the same interaural information in both bands (**cong**); (3) dichotic 500 Hz NBN and diotic 4000 Hz NBN (**5hd**); and (4) dichotic 4000 Hz NBN and diotic 500 Hz NBN (**4kd**). Interaural time and intensity JNDs for the noise bands in isolation were obtained first, then the JNDs for the 500 and 4000 Hz NBNs played simultaneously were obtained in a random order across frequency and time/intensity.

Before any JNDs were obtained, NBN thresholds for each of the two stimuli were measured. Subjects' thresholds for the 500 and 4000 Hz NBN signals for each ear were measured using a two-interval forced-choice (2IFC) adaptive paradigm, controlled by locally developed software. The adaptive procedure consisted of 14 reversals and targeted the 70.7% correct level (Levitt, 1971). The stepsize for threshold estimation began at 4 dB and was reduced to 2 dB after the

fourth reversal. The threshold was calculated from the average of the fifth through the fourteenth reversals. Two

Table 1. Signal Configurations in the Interaural Time and Intensity Discrimination Experiments.

NBN Conditions	Interaural Time		Interaural Intensity	
Isolation	500	4000	500	4000
Congruent	500 + 4000		500 + 4000	
Target Signal/ Interfering Signal	500/4000	4000/500	500/4000	4000/500

estimates of each NBN threshold for each ear were obtained with the stipulation they be ±4 dB, to ensure consistency of performance across runs. If the second run was not within 4 dB of the first run, a third NBN threshold estimate was obtained. The average of the two which fell within 4 dB was used as the NBN threshold and is the reference level for all subsequently discussed sensation levels. The paradigm was subject-paced in that a response was required before a new trial could begin. The mean of the NH subjects' NBN thresholds and each IH subject's NBN thresholds are listed in Table 2. Subjects were instructed to inform the experimenter if the level of the signal was uncomfortably loud. On no trial did any subject indicate the signal was too loud, so it

is assumed that listeners' uncomfortable levels were never exceeded.

Table 2. Mean NBN Thresholds (dB SPL) for Normal-Hearing Subjects; Individual NBN Thresholds (dB SPL) for Impaired-Hearing Subjects.

		Right		Left		
Subj	Freq	Run 1	Run 2	Run 1	Run 2	Bin. Avg
Mean NH	500 4000	8.0 7.4	8.3 5.4	7.6 3.8	5.1 3.1	7.0 7.0
IH S1	500 4000	16.8 58.1	14.4 58.1	7.8 58.1	9.2 57.7	12.0 58.0
IH S2	500 4000	8.8 41.5	11.6 41.9	8.4 36.3	8.4 33.7	9.0 38.0
IH S3	500 4000	12.4 62.6	11.8 63.4	11.4 56.6	9.6 57.4	11.0 60.0
IH S4	500 4000	13.4 34.0	10.2 33.4	10.2 30.6	9.0 28.8	11.0 32.0
IH S5	500 4000	32.6 69.4	34.6 69.4	37.2 57.0	35.6 56.8	35.0 **
IH S6	500 4000	18.0 51.0	15.2 49.4	8.6 58.0	11.6 58.2	13.0 54.0

** There was a 12 dB difference between ears (R = 69, L = 57); therefore, 28 dB SL was referenced to the poorer threshold (right ear).

For individual NBNs, overall signal levels for the NH listeners were 77 dB SPL. For IH subjects the signal level was either 77 dB SPL or 28 dB SL, whichever was higher, to ensure audibility of the signals. Table 3 lists the specific SPL levels for each subject for both the 4 kHz and .5 kHz

NBNs. The SPL values of both NBNs were always equivalent for any given listener. Note that impaired-hearing subject 4 (IH S4) had 4000 Hz NBN thresholds which should have allowed him to be run at 77 dB SPL (see Table 2); however, he reported he had difficulty hearing the 4 kHz NBN signal at that level on certain conditions, but could hear the signal in all conditions with an added five dB. Therefore, to be consistent for this subject across experiments, all conditions were run with each NBN at 82 dB SPL. Also IH S5 had 4000 Hz NBN thresholds in each ear which differed by 12 dB (see Table 2). Signal levels used with this subject were 28 dB SL relative to her poorer threshold (right ear) rather than to the average binaural threshold.

In the double-band conditions the overall level was set to 77 dB SPL or 28 dB SL, whichever was higher, referenced to the poorer binaural threshold of 500 Hz or 4000 Hz. In this study all IH subjects presented with poorer thresholds at 4000 Hz than at 500 Hz. For example, IH S3 had a 500 Hz NBN binaural threshold of 11 dB SPL but a 4000 Hz NBN binaural threshold of 60 dB SPL; for this subject, the level used was 88 dB SPL for each NBN. No signal exceeded 110 dB SPL at anytime and the 28 dB SL criterion was met at levels well below that which might be uncomfortable for the subjects. In all three double-band measures, the unattenuated output level of both bands played simultaneously was measured on a Quest

Table 3. SPL Levels for both NBNs for the Normal-Hearing Group and Each Impaired-Hearing Subject in Both Experiments.

Subject(s)	NBNs SPL Level
NH	77
IH S1	86
IH S2	77
IH S3	88
IH S4	82
IH S5	97
IH S6	82

Sound Level Meter. Greater detail regarding the calibration of the signals is presented in the description of the interaural time experiment below.

Training can be an important factor in binaural listening experiments. The NH listeners used in the present study all had extensive experience listening to binaural tasks; therefore, they required only a few runs before their JND estimates reached asymptotic levels. The JNDs for the NH subjects also matched JNDs previously reported by other researchers. The subjects with impaired hearing needed more training than the subjects with normal hearing. Each IH subject completed training runs for at least one half of an hour, but in most cases at least one hour, for time and intensity discrimination with each of the NBNs in isolation.

To ensure that subjects had reached stable performance, the standard deviation of the final five runs was compared to that for the five runs immediately preceding those. The comparison of the standard deviations indicated the standard deviation was reduced by at least half (and more than half) in most instances. In a few cases the standard deviation of the final five runs did not decrease to half that of the previous five. In these instances, it was felt intrasubject variability would not be reduced with further data collection, and the final five runs were used as the estimate of the JND. In the double-band runs both the NH and IH listeners usually needed only a few practice trials before data collection began.

Interaural Time Discrimination

The signals used in the interaural time discrimination experiment were 400 msec bursts of 1/3-octave NBN geometrically centered at 500 or 4000 Hz with 10 msec rise and 10 msec fall $\cos^2$ ramps. The individual noise signals were generated on a 386/33 computer at a 40 kHz sampling rate prior to data collection and were stored for on-line retrieval. Twenty samples of each NBN were generated. During the experiment one sample, presented to both ears, was chosen randomly for each of the four intervals of every trial.

Interaural time differences ranging from 0 to 1000 μsec were created by imposing a phase delay equivalent to the

desired μsec time difference. The time difference was present as an ongoing delay with no interaural onset or offset envelope differences. Implementation of the time delay was controlled by computer algorithm.

Calibration of the NBNs used in the time discrimination experiment was accomplished using the Quest Sound Level Meter, model 215, connected to an external octave filter band, model OB-45. The average unattenuated signal levels were determined by measuring the output SPL of each noise sample through each headphone with no attenuation. The (average) unattenuated level for both the .5 kHz and 4 kHz NBN signals was 109 dB SPL (See Appendix B). The unattenuated level was also measured for the combined bands (.5 + 4 kHz); the unattenuated level for the combined bands was 111 dB SPL. Because the NBN samples had less than a 2.5 dB between-channel difference, the output from each of the two channels was averaged to obtain a single value for the unattenuated level of the combined bands. The resulting value served as the reference for setting presentation levels for each subject.

Initially, the step-size in the time discrimination experiment was changed by a factor of two; after the fourth reversal the step-size was changed by a factor of $\sqrt{2}$. Decrements in the interaural time difference in μsec (τ) were calculated as $\tau/2$ and $\tau/\sqrt{2}$ during the first four and the fifth through the eighth reversals, respectively. Increments

were calculated as $\tau \times 2$ and $\tau \times \sqrt{2}$ for the first four and the fifth through the eighth reversals, respectively. The initial stepsize was used so the subjects would approach the region of threshold rapidly, while the smaller stepsize concentrated later trials near threshold. The interaural time delay was presented to only one ear on any run; however, the ear which received the delay was randomly assigned from one run to the next. For each condition each subject performed the task with the delay in the right and left ears approximately an equal number of times.

Interaural Intensity Discrimination

The same 20 samples of NBN used in the time discrimination experiment were used in the intensity discrimination experiment. During the experiment one sample, presented to both ears, was chosen randomly for each of the four intervals of every trial.

There is an important consideration when running an interaural intensity discrimination experiment which is not a concern in an interaural time discrimination experiment. In an interaural intensity discrimination test, if the overall intensity of the signals remains constant on all but the odd interval, it is possible for listeners to use the monaural increment or decrement of the signal intensity as the salient cue rather than the interaural intensity difference. To reduce this possibility, the overall intensity of the signals was varied randomly on each of the

four intervals, a procedure called a "roving level". The overall intensity varied randomly over a 10 dB range. With a 10 dB rove range, monaural intensity cues could not be used when the interaural difference was 5 dB or less (Koehnke *et al.*, 1995). The rove was always applied as a decrement in the overall level to insure the signal was never uncomfortably loud for listeners; that is, the overall signal intensity levels varied between 28 dB SL and 18 dB SL. IH S4 could not perform the task with a 10 dB rove; in his case an 8 dB rove was used. The overall intensity for the roving level varied together in each ear. Rove levels from 1 to 10 dB in 1 dB increments were chosen by the computer program and the appropriate attenuation values were sent to the external digital attenuators.

Interaural intensity differences ranged from 0.4 dB to 10 dB. The interaural intensity differences were created by presenting half the total interaural difference to each ear, according to Eqs. (1) and (2):

$$SI_R = I + \Delta I/2 \qquad (1)$$

$$SI_L = I - \Delta I/2 \qquad (2)$$

where SI_R equals the right ear stimulus intensity, SI_L equals the left ear stimulus intensity, I equals the overall intensity of 77 dB SPL or 28 dB SL, and ΔI equals the total interaural difference. For example, to achieve an interaural intensity difference of 4 dB, 2 dB was added to SI_R and 2 dB

was subtracted from SI_L or 2 dB was subtracted from SI_R and 2 dB was added to SI_L. The more intense signal (based on the ΔI level) was presented to only one ear on any run; however, the ear which received the more intense signal was randomly assigned from one run to the next. For each condition each subject heard the more intense signal in each ear approximately an equal number of times. The overall intensity levels were set using the PA3 attenuators and the interaural intensity difference was imposed by adding ΔI/2 to one channel and subtracting ΔI/2 from the second channel.

The initial step size was 2 dB, but after the fourth reversal the interaural intensity differences (IID) became smaller as ΔI decreased, in order to make more precise measurements of subjects' intensity JNDs. The PA3 attenuators were capable of delivering equivalent IID to each of the two channels so long as the ΔI/2 value was evenly divisible by two. The values in Table 4 were chosen as the interaural intensity differences for the fifth through the eighth reversals.

During the intensity discrimination experiment, monaural intensity JNDs were first determined for the individual NBNs in both ears of every IH subject. Obtaining the monaural intensity JNDs served the dual purpose of allowing the subject to practice performing intensity discrimination and providing a measure of baseline intensity discrimination. Next, the interaural intensity JND for the individual NBNs

Table 4. Interaural Intensity Differences for the Fifth Through the Eighth Reversals.

IA difference (dB)	Stepsize (dB)
≥ 5.0 and ≤ 1.0	2.0
≥ 2.0 and < 5.0	1.0
≥ 1.0 and < 2.0	0.6
≥ 0.1 and < 1.0	0.4

was obtained with no rove. Finally, the rove was added to the individual NBN task to obtain the reported interaural intensity JNDs.

Experiment II - Localization

Experimental Conditions

The localization experiment was controlled by locally developed software. Subjects pressed a key (1-9) on a response terminal to indicate which one of nine possible locations they thought to be the source of the signal. The paradigm was subject-paced in that a response was required before a new trial could begin. All signals were presented via headphones, with the source locations and environment simulated using signal processing. Figure 4 shows that signals for each ear were processed according to source-to-eardrum transfer functions, and then presented to the subject via headphones.

Signals were processed in two steps. First, 20 samples of 300 msec NBN geometrically centered at 500 or 4000 Hz were generated with a 20 kHz sampling rate and 10 msec cos^2 rise and 10 msec cos^2 fall ramps. Second, these noise samples

were convolved with source-to-eardrum transfer functions measured using the Knowles Electronic Manikin for Acoustic Research (KEMAR; Burkhard and Sachs, 1975). Impulse responses were measured at each of KEMAR's eardrums from nine locations spaced 22.5° apart in an arc of 180° in the horizontal plane for a total of 18 impulse responses. Each of the 40 (20 .5 kHz and 20 4 kHz) original noise files was convolved with each of the 18 impulse responses for a total of 720 NBN signals, 360 for the right ear (180 of .5 kHz and 180 of 4 kHz) and 360 for the left ear (180 of .5 kHz and 180 of 4 kHz). See Figure 5 for an example of the convolution. The top two panels of Figure 5 are one sample of the original NBN time waveforms used in Experiment II. The second pair of panels is a representation of the two impulse responses from location 5; the left side is the KEMAR impulse response for the right ear and the right side is the KEMAR impulse response for the left ear. The bottom two panels are the result of convolution; again, the signal shown in the left panel was played to the right ear and the signal shown in the right panel was played to the left ear.

After convolution the absolute value of the amplitude peak of each set of 18 signals was determined. Using that peak value, a scaling factor was calculated for that set of 18 signals so that none of the 18 signals would be clipped. The scaling factor preserved all interaural intensity differences. Each signal of the set of 18 was then

Figure 4. Block diagram showing the signal processing scheme for the localization experiment.

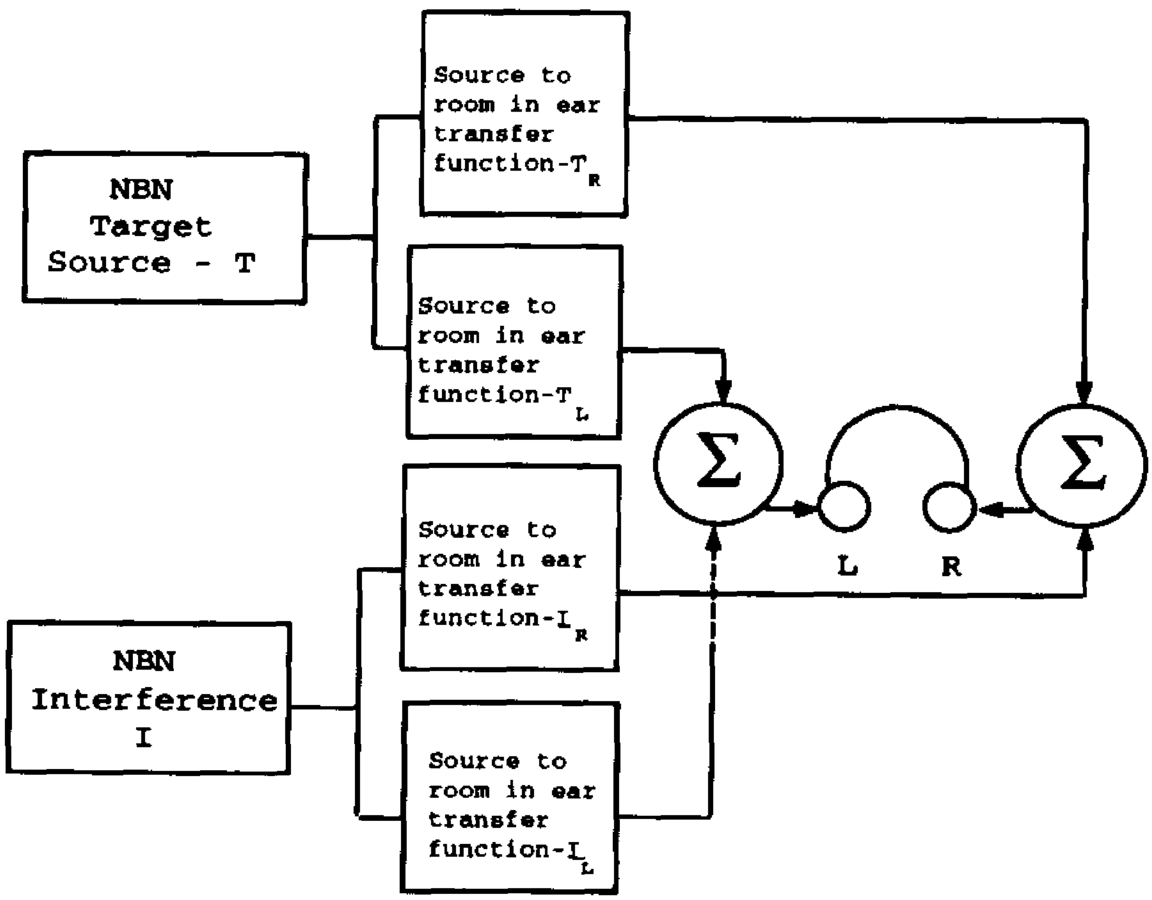
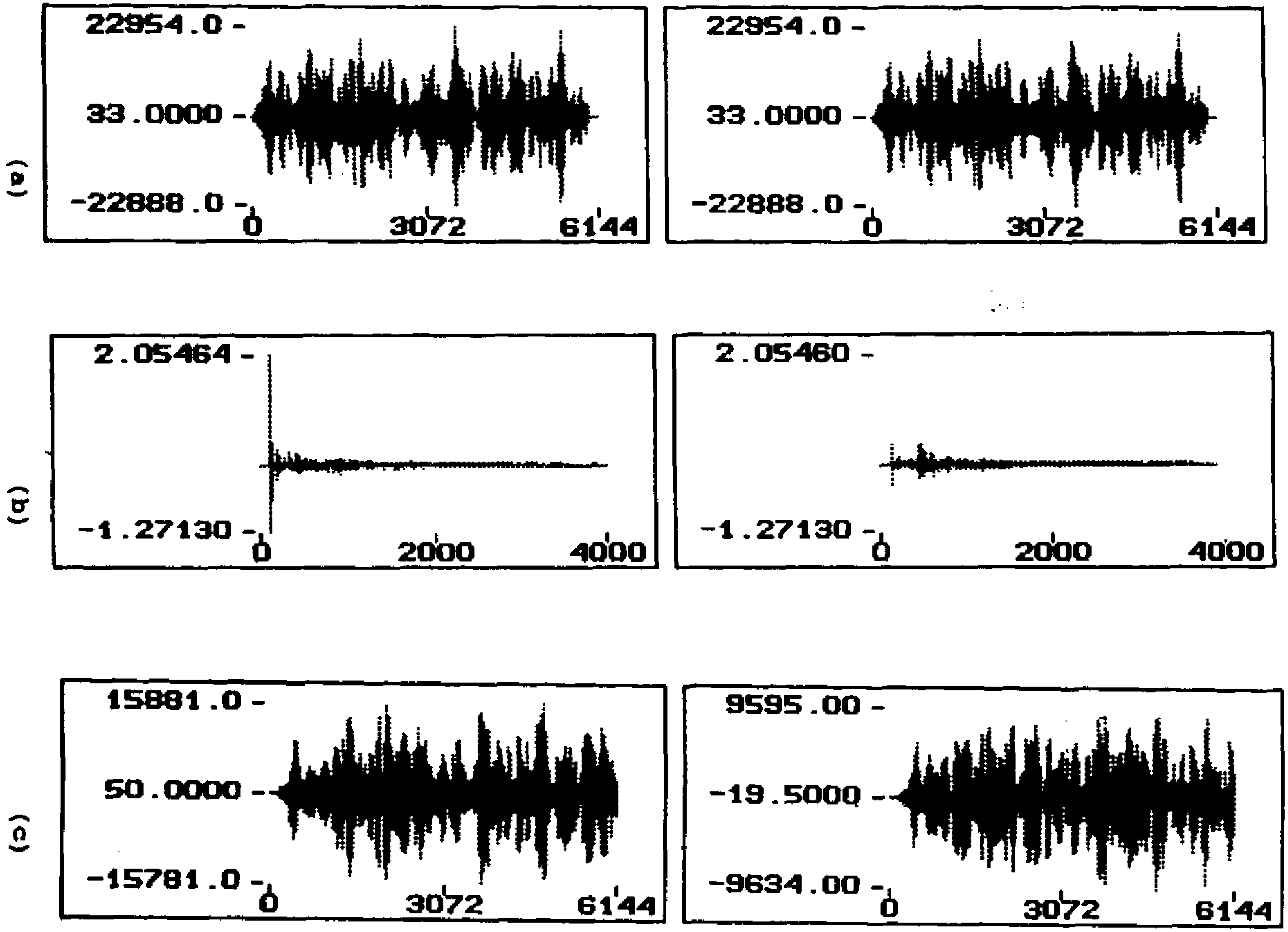

NBN
Target
Source - T
Source to
room in ear
transfer
function-T_R
Source to
room in ear
transfer
function-T_L
NBN
Interference
I
Source to
room in ear
transfer
function-I_R
Source to
room in ear
transfer
function-I_L
Σ
Σ
L
R

Figure 5. Steps of processing a pair of signals for the localization experiment. (a) One original noise band sample; (b) Impulse responses measured with KEMAR for the right ear (left-hand panel) and left ear (right-hand panel); (c) Convolved signals for the right ear (left-hand panel) and left ear (right hand panel).


(a)
22954.0
33.0000
-22888.0
0
3072
6144
22954.0
33.0000
-22888.0
0
3072
6144
(b)
2.05464
-1.27130
0
2000
4000
2.05460
-1.27130
0
2000
4000
(c)
15881.0
50.0000
-15781.0
0
3072
6144
9595.00
-19.5000
-9634.00
0
3072
6144

multiplied by that scaling factor and the products were the signals used in the localization experiment. The 500 Hz NBN signals had to be increased in amplitude while the 4000 Hz NBN signals had to be reduced in amplitude relative to one volt. This amplitude scaling of the localization signals was performed to eliminate any inter-location loudness differences which were not related to interaural differences of the signals. For example, location 4 was not recognizable because it was softer or louder than all other locations but because of its perceived location only. Signal convolution and scaling were accomplished with the DADiSP® Signal Processing program run on a 486/33 computer. The resultant noises were 1000 msec in duration. The reverberation time was 0.25 sec for frequencies below 800 Hz and 0.4 sec above that frequency. All of the processed NBN signals were stored on the computer for on-line retrieval.

The simulated locations for the sources were spaced 22.5° apart in an arc around the subjects' heads from +90° to -90° azimuth (+90° right, 0° straight ahead, -90° left) in the horizontal plane. The perceived location of the stimuli varied with each listener, although most subjects indicated the noises appeared in distinctly different locations along an arc somewhere between the horizontal plane and directly above the head. The exception was IH S6 who indicated that many of the noises appeared to emanate from locations behind his head. The NBNs were presented at 77 dB SPL or 28 dB SL

with the source at 0°. Levels at each ear of the subjects with the source at other locations varied depending on location of the source relative to the listener's ears. Three experimental conditions were included in the localization experiment: (1) localization of individual NBNs; (2) localization of each NBN as the target with the second NBN as the interferer, presented randomly from the ±90° and 0° locations; and (3) localization of each NBN as the target with the second NBN as the interferer, presented in a fixed location at +90°, 0°, or -90°, for a total of 10 conditions. Table 5 provides a list of all signal configurations in the localization experiment. A "set" of runs in the localization experiment was comprised of 10 runs and consisted of each of the experimental conditions run in each of the two possible spectral configurations. On each set of 10 runs the individual NBN conditions were run first followed by the fixed and random interfering conditions in random order.

Method

For signal condition (1) the task was a single-interval, 9-alternative, forced choice (1I, 9AFC), as listeners heard only the NBN. For condition (2) and condition (3) the task was a cued, single interval forced-choice (1C, 1I, 9AFC). In these conditions the target NBN for the run was presented as a cue at the 0° location followed by the target plus the

interfering sound. A drawing of the possible locations relative to the head was mounted in front of the subjects.

Subjects received only one training run for each of the 10 signal configurations, with two exceptions. Because of difficulty with a particular signal condition, IH S4 had two practice runs with the 4 kHz NBN alone, and IH S6 had three practice runs on the condition with a 4 kHz target and a .5 kHz fixed interferer. In addition to the training run, all conditions were run twice. Each run included six presentations of the target from each location for a total of 54 trials. When the interferer was in a random location, the target was presented from each combination of target and interferer location twice, resulting in 18 trials with the interferer in each location on any one run. Therefore, the individual NBN and fixed interferer conditions include a total of 108 trials each (54 trials X 2 repetitions) while the random interferer conditions include 36 trials each (18 trials X 2 repetitions). Seven of the nine subjects performed a total of 30 runs and IH S4 performed 31 runs. IH S6 performed 35 runs, due to his initial difficulty with perceived target location.

On any particular localization run the target sound was always a specific noise sample, e.g., number 5, while the interfering noise was randomly chosen from the 20 noise samples. Five 500-Hz NBN samples and five 4000-Hz NBN samples were chosen to be used as targets. These five were

Table 5. Signal Configurations in the Localization Experiment.

500 Hz						4000 Hz					
No Int	With Interferer					No Int	With Interferer				
	Fixed			Random			Fixed			Random	
	-90	0	+90	-90 0 +90			-90	0	+90	-90 0 +90	

chosen on the basis that the average intensity of the 0° NBNs for these samples were closest to the average intensity of all the 0° location 500 Hz NBN and 4000 Hz NBN samples, respectively. Each target noise was used only once in each set of 10 conditions, and no target was used for the same condition across repetitions.

Calibration for the localization experiment was done with acoustical and electrical measurements. On the equipment used in the current experiments, 108 dB SPL was equivalent to 1 volt. One set of noises for each frequency (e.g., right and left ear noises from each location for the 6^{th} sample of 500 and 4000 Hz NBNs) was measured acoustically on the Quest Sound Level Meter. All noise samples (right and left ears) for the 500 and 4000 Hz sets located at the 0° (straight ahead) position were also measured on the Quest Sound Level Meter. The root mean square amplitude value for

every signal was calculated (See Appendix C) and the SPL of each signal at location 5 relative to 108 dB SPL (1 volt) was determined (See Appendix D). The levels of the signals at location 5 varied between 106 and 110 dB SPL (See Appendix E).

RESULTS

Results of the experiments will be presented in several ways. The group data from Experiment I (discrimination) will be presented first, then the individual data for the impaired-hearing (IH) subjects will be presented. The same format will be followed for Experiment II (localization). The last method of data presentation will be an analysis of the relationship of the localization data with respect to various aspects of the interaural time or intensity data. Because the normal hearing (NH) subjects performed similarly, their data will be presented only as average (group) data. Individual data will be shown for the IH listeners because such individuals typically show disparate results, even those with similar audiograms (e.g., Koehnke *et al.*, 1995). Little, if any, performance homogeneity among listeners with hearing loss has been reported (e.g., Jongkees and Veer, 1957; Häusler *et al.*, 1983). In addition, we cannot assume that all IH listeners use similar strategies to perform the same task. See Appendices F and G for individual raw data from all subjects for Experiment I and Experiment II, respectively.

Experiment I - Discrimination

Group Data

The group interaural time and interaural intensity discrimination data are presented in Figures 6-9. There is ample evidence in the literature that listeners generally

demonstrate larger time JNDs for higher frequency signals than lower frequency ones. In contrast, very little difference in performance has been reported for intensity discrimination as a function of frequency, at least in normal-hearing listeners. Interaural time and intensity JNDs of the subjects in both groups in the current study held to these patterns for the NBN in isolation signals. Therefore, no comparisons are made between conditions of targets with different frequencies.

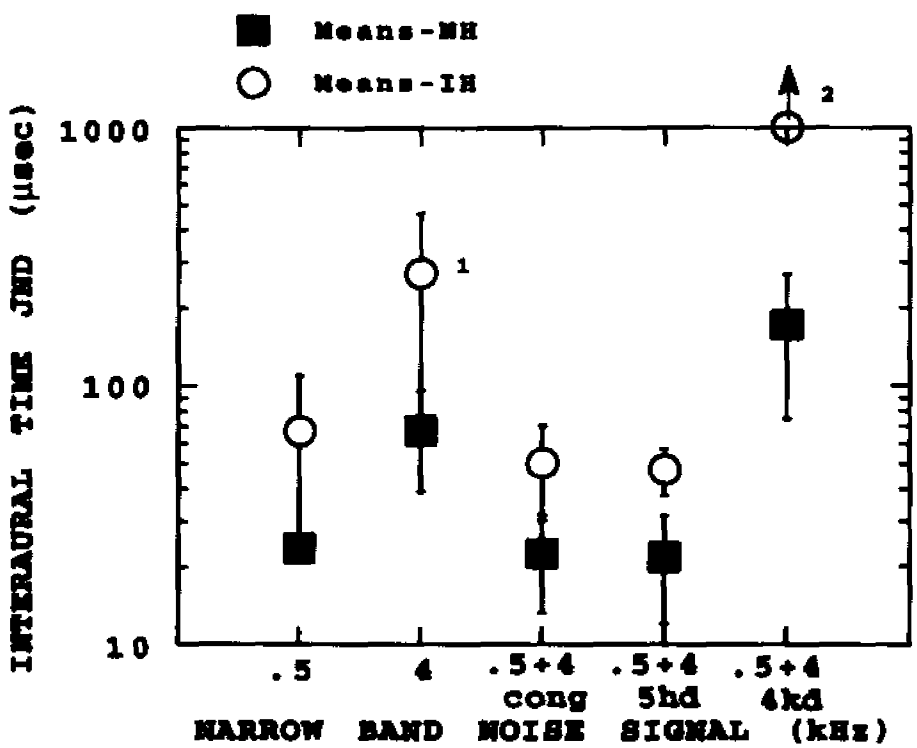
Interaural Time Discrimination

In general, performance of the NH listeners for interaural time discrimination is consistent with reported results from other studies which have employed similar signals (Klumpp and Eady, 1956; McFadden and Pasanen, 1976; Hawkins and Wightman, 1980; Smoski and Trahiotis, 1986; Koehnke *et al.*, 1986; Koehnke *et al.*, 1995). Figure 6 contains the group means for the interaural time discrimination task. There were four signal configurations in the discrimination experiment: (1) individual noise bands (.5 kHz, 4 kHz); (2) combined 500 Hz and 4000 Hz narrow band noise (NBN) with the same interaural information in both bands (cong); (3) dichotic 500 Hz NBN and diotic 4000 Hz NBN (5hd); and (4) dichotic 4000 Hz NBN and diotic 500 Hz NBN (4kd). Notice in Figure 6 that although the absolute JND values for each group differ, the pattern of the JNDs is similar across groups. That is, both groups perform most

Figure 6. Mean interaural time JNDs for the NH and IH subjects. The abscissa represents the signal conditions and the ordinate (logarithmic scale) represents the interaural time JND in μsec. The solid squares represent the means of the NH listeners and the open circles represent the means of the IH listeners. The error bars represent the standard deviation for each signal condition across listeners.

1: Represents mean of four IH subjects who could perform interaural time discrimination with the 4 kHz NBN in isolation. The other two could not perform the task with the maximum interaural difference of 1000 μsec.

2: Five of the six IH subjects could not perform the task with a 1000 μsec interaural time difference (indicated by the arrow). The one subject who could perform the task had a JND of 228 μsec.



Means-NH
Means-IH
INTERAURAL TIME JND (μsec)
1000
100
10
1
2
.5
4
.5+4
cong
.5+4
5hd
.5+4
4kd
NARROW BAND NOISE SIGNAL (kHz)

poorly in the condition in which both NBNs are present and only the 4 kHz NBN signal is dichotic (**4kd**). This result is consistent with the literature (e.g., Trahiotis and Bernstein, 1990).

There are three questions of interest for the interaural time discrimination data. First, is there an effect of training? Second, is there a difference between the NH and IH groups on the interaural time discrimination tasks? Third, is there an effect on interaural time discrimination when a second noise band is added to the task?

To address the questions of a possible training effect and differences between the two groups, a 3-factor ANOVA (group X signal condition X repetition, 2 X 3 X 5, between-within-within) was performed. The **4k** and **4kd** signal conditions are not included in this ANOVA due to the missing data in the IH group in these two signal conditions. In the **4k** condition four of six IH subjects can perform the task. That number drops to one of six in the **4kd** condition.

In the 3-factor ANOVA a significant difference due to group ($F=24.34$, $df=1,105$, $p<.05$) and non-significant differences due to signal condition ($F=1.37$, $df=2,105$, $p>.25$) and repetition ($F=0.33$, $df=4,105$, $p>.8$) were obtained. This result indicates that there is no effect of training, and no differences among the signal conditions with a .5 kHz dichotic signal, but there is a difference between subject groups. None of the tests for interaction were significant

(p>.36), which indicates that the three factors are independent. (Appendix H contains all ANOVA tables.)

The third question, whether there is an effect of a second noise band, was examined using a within-group ANOVA (signal condition X subject, blocked on subject). ANOVAs were used to test for differences among the three signal conditions when the .5 kHz signal was dichotic on the odd interval in each group. Additionally, the NH group's performance was measured on the signal conditions when the 4 kHz signal was dichotic on the odd interval. The signal conditions were: (1) **.5 kHz** versus **cong** versus **5hd** (both groups), and (2) **4 kHz** versus **cong** versus **4kd** (NH group). No significant differences for condition or subject are observed in either test for the NH subjects. For the IH subjects, however, a significant difference due to subject is observed in the .5 kHz ANOVA (F=5.92, df=5,10, p<.05). Results of the ANOVA indicate there is no change in the performance for the NH group with the addition of the second NBN with either frequency as the target signal. The performance of the IH subjects is not changed when a second NBN is added to the .5 kHz target signal. Although no statistical test was run on the 4 kHz target signal conditions for the IH group, it is clear that group performance of interaural time discrimination is degraded with the addition of a low frequency interfering signal to a high frequency target.

A *post-hoc* Duncan's test on IH subjects for the ANOVA with the .5 kHz target signals divides the IH listeners into two groups. The means of the IH subjects on the .5 kHz signal conditions are used to list subjects in ascending order from left to right ($p<.05$):

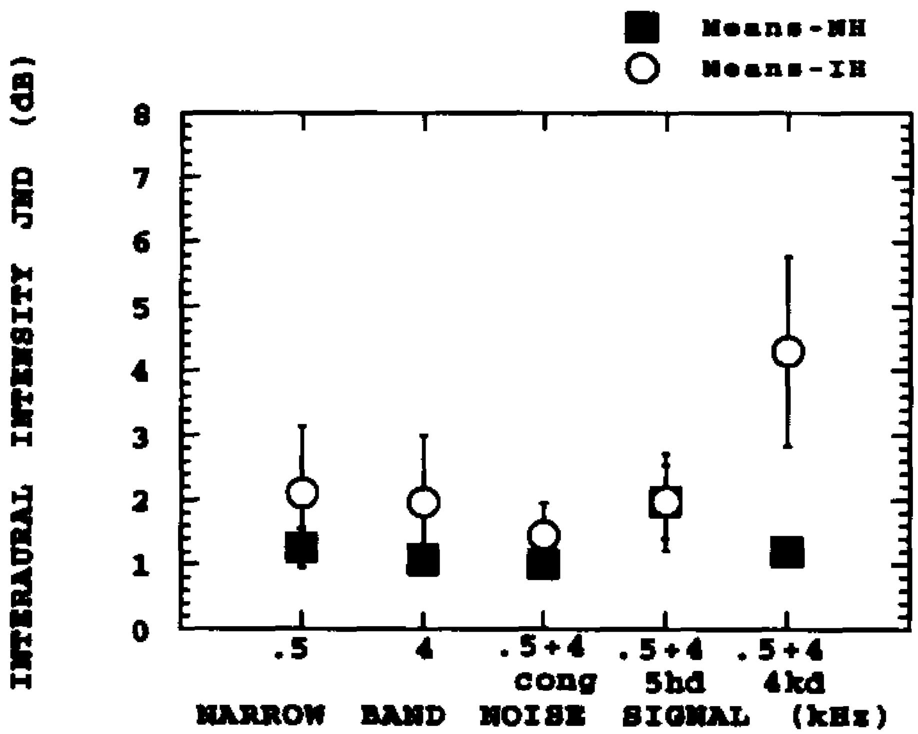
4	1	2	5	3	6
______	______	______	______	______	
				======	======

Subjects 1, 2, 3, 4, and 5 are not significantly different from one another. Impaired-hearing subject 6 (IH S6) performed significantly more poorly than IH Ss 1, 2, 4, and 5, while he performed similarly to IH S3 (See Appendix I for all Duncan's Multiple Range tests).

Interaural Intensity Discrimination

In general, performance of the NH listeners on interaural intensity discrimination is consistent with reported results from other studies which have employed similar signals (Gabriel *et al.*, 1992; Koehnke *et al.*, 1986; Koehnke *et al.*, 1995). Figure 7 contains the group means for the interaural intensity discrimination task. The pattern of interaural intensity discrimination varies between the NH and IH groups. For 4 of the 5 conditions, the NH group demonstrates smaller JNDs than the IH group. The exception is the **5hd** condition in which the mean JND for each group is equal. This result for the **5hd** condition among the NH subjects may be an anomaly because one of the three NH

Figure 7. Mean interaural intensity JNDs for the NH and IH subjects. The abscissa represents the signal conditions while the ordinate represents the interaural intensity JND in dB (linear scale). The solid squares represent the means of the NH listeners and the open circles represent the means of the IH listeners.


Means-NH
Means-IH
INTERAURAL INTENSITY JND (dB)
8
7
6
5
4
3
2
1
0
.5
4
.5+4
cong
.5+4
5hd
.5+4
4kd
NARROW BAND NOISE SIGNAL (kHz)

subjects exhibited great difficulty with this signal condition. While the NH group exhibits similar JNDs in all conditions except 5hd, the IH group exhibits a smaller JND in the condition when the same interaural information appears in both NBNs (cong), and a larger JND when both NBNs are present but the dichotic information is present only in the higher frequency signal (4kd). The 4kd result in the IH group for interaural intensity discrimination mirrors the 4kd result for both groups in interaural time discrimination; both groups exhibit larger JNDs for the 4 kHz signal with a low frequency interfering signal than for the 4 kHz signal in isolation. Recall that with a 10 dB rove, those JND estimates which are one-half or less than one-half of the rove range are considered to be based on the subject's use of interaural information. Although all subjects could perform intensity discrimination with all signals, in a few cases some of the subjects may have used monaural rather than interaural intensity information. These cases include those JND estimates which are $\geq$5 dB.

The same questions posed above for the time discrimination data are also of interest for the intensity discrimination data. First, is there an effect of training? Second, is there a difference between the NH and IH groups on the interaural intensity discrimination tasks? Third, is there an effect on interaural intensity discrimination when a second noise band is added to the task? A 3-factor ANOVA

(group X signal condition X repetition, 2 X 5 X 5, between-within-within) indicated a significant difference due to group ($F=36.38$, $df=1,175$, $p<.05$) and signal condition ($F=8.91$, $df=4,175$ $p<.05$), and a non-significant difference due to repetition ($F=0.57$, $df=4,175$, $p>.6$). There was a significant interaction indicating differences between groups across signal conditions ($F=9.55$, $df=4,175$, $p<.05$). This, combined with visual inspection of the data, indicate that the NH group perform better on some tasks while both groups perform similarly on other tasks. These results for the main effects indicate that there is no significant effect of training, but there is a significant difference between subject groups and among signal conditions.

A *post-hoc* Duncan's was performed on the interaction of group and signal condition. The results are shown below, again in ascending order of the means from left to right ($p<.05$). The 'N' denotes the normal-hearing group means and the 'I' the impaired-hearing group means:

congN 4kN 4kdN .5kN congI 4kI 5hdN 5hdI .5kI 4kdI

The **4kd** condition in the IH group is significantly different from each of the other signal conditions. All other signal conditions from both groups are statistically similar.

Further analyses were conducted for each group on within-group questions; specifically, (1) "Do subjects in the

same group perform similarly to one another?"; and (2) "Are there differences in performance on signal conditions when a second noise band is added?" To examine questions (1) and (2), ANOVAs (signal condition X subject, blocked on subject) were run on two sets of conditions: (1) **.5 kHz versus cong** versus **5hd**, and (2) **4 kHz versus cong versus 4kd**. The ANOVAs reveal no significant differences in the NH group for signal condition or subject in either test. The IH group data demonstrate significant differences due to signal condition ($F=4.98$, $df=2,10$, $p<.05$) and subject ($F=6.92$, $df=5,10$, $p<.05$) for the .5 kHz test and due to signal condition ($F=32.98$, $df=2,10$, $p<.05$) and subject ($F=4.97$, $df=5,10$, $p<.05$) for the 4 kHz test.

Post-hoc Duncan's tests were performed on all four contrasts in the IH group. The Duncan's test performed on the **.5 kHz**, **cong**, and **5hd** signal conditions indicates no significant differences among the means. The mean JND for each IH listener on interaural intensity discrimination with the .5 kHz signals is listed below (ascending order left to right). The following overlapping groups are indicated ($p<.05$):

```
4        5        2        3        1        6
____________________________________
         ==============================
                  *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
```

IH S6's performance is significantly poorer than that of IH S4 and IH S5. Also, IH S1 is significantly different from IH S4. Performance among the other subjects is similar.

The signal condition Duncan's test with the **4 kHz** NBNs indicates a significant difference between the congruent condition and each of the other two:

cong	4 kHz	4kd
______	______________	______________

The **4 kHz** Duncan's test run on subject showed the following significant differences. The numbers represent subjects listed on the basis of mean JND in ascending order from left to right ($p<.05$):

2	3	1	5	4	6
______	______	______	______	______	======

IH S6 performs more poorly than each of the other subjects, while the other five perform similarly in the **4 kHz** signal conditions. This result is in contrast to the Duncan's test for subject in the **.5 kHz** signal conditions (p. ??). Recall the three overlapping groups formed by the means of the IH subjects in that test. While there is quite a bit of variability in the IH subjects' ability to use the interaural information in the .5 kHz NBN for intensity discrimination, with the exception of IH S6, they appear to make equivalent

use of the interaural information in the 4 kHz NBN for interaural intensity discrimination.

Individual Data

The data in this section are presented in terms of the signal conditions for which the IH subjects could perform the interaural time and intensity discrimination tasks. Figures 8 and 9 contain graphs of the individual interaural time JNDs and intensity JNDs, respectively, for each IH subject. These two figures show the JNDs of each IH subject which are within one standard deviation of the normal subjects. Every IH subject, except subject 2, exhibits interaural time JNDs much larger than those of the NH subjects for the **4 kHz** NBN in isolation (but consistent with the literature, e.g., Smoski and Trahiotis, 1986). Additionally, none of the IH subjects, except IH S2, can perform the interaural time discrimination task even with a 1000 μsec interaural difference in the **4kd** condition. There is greater variability among the IH subjects than among the NH listeners on interaural intensity discrimination. All subjects exhibit fairly small JNDs on all interaural intensity conditions except **4kd**. IH subjects 4, 5, and 6 have JNDs equal to or larger than one-half the rove range (8 dB for IH S4 and 10 dB for IH S5 and IH S6) in the **4kd** condition. This indicates that the subjects may have been using monaural intensity information rather than interaural intensity information.

IH S1 has time JNDs of less than 100 μsec in the conditions when the dichotic information is present in the .5 kHz NBN. Her time JND for the 4 kHz NBN is between 100 and 200 μsec. On interaural intensity discrimination IH S1 has a smaller JND with the 4 kHz NBN than with the .5 kHz NBN. Overall, her time and intensity JNDs are only slightly larger than normal except in the **4kd** condition in each task.

IH S2 can perform the interaural time discrimination task in all signal conditions, including **4kd**. His JNDs for 4 of the 5 signal conditions are comparable to the NH subjects' on the interaural intensity discrimination task, although his **4kd** intensity JND is larger than the NH subjects.

IH S3 has interaural time JNDs <100 μsec in all conditions containing .5 kHz dichotic information. His interaural time JNDs are much larger than the NH listeners for the conditions in which the dichotic information is in only the 4 kHz NBN, regardless of whether a second noise band is present. His interaural intensity JNDs are elevated for **.5 kHz**, **5hd** and **4kd** compared to the **4 kHz** and **cong** conditions.

IH subjects 4, 5, and 6 present similar interaural time JNDs (<100 μsec) in all conditions with the dichotic information in the .5 kHz NBN. IH subjects 4 and 6 cannot perform interaural time discrimination with the 4 kHz NBN, while IH S5 has a JND almost a factor of 10 larger than the

Figure 8. Individual interaural time JNDs (and standard deviations) for each IH subject and the group JNDs for the NH subjects. The abscissa on each panel represents the narrow band noise conditions. The ordinate represents the interaural time JND in μsec. The error bars represent the within-subject standard deviation of the five estimates of JND. For comparison, the group mean data for the NH subjects (with standard deviation) is displayed on each panel. The solid squares represent the mean of the JNDs of the NH subjects and the open circles represent the JNDs of each IH subject.

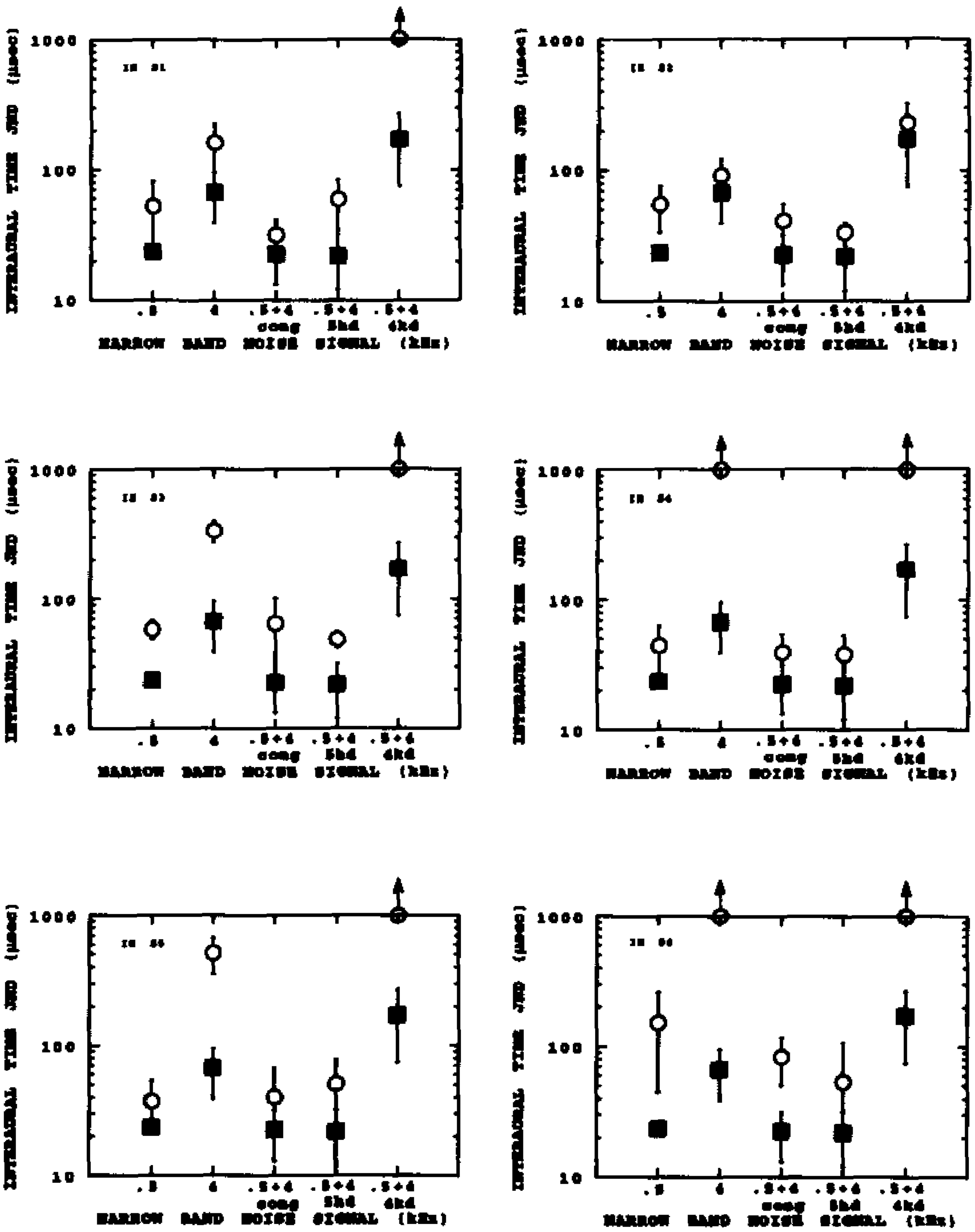
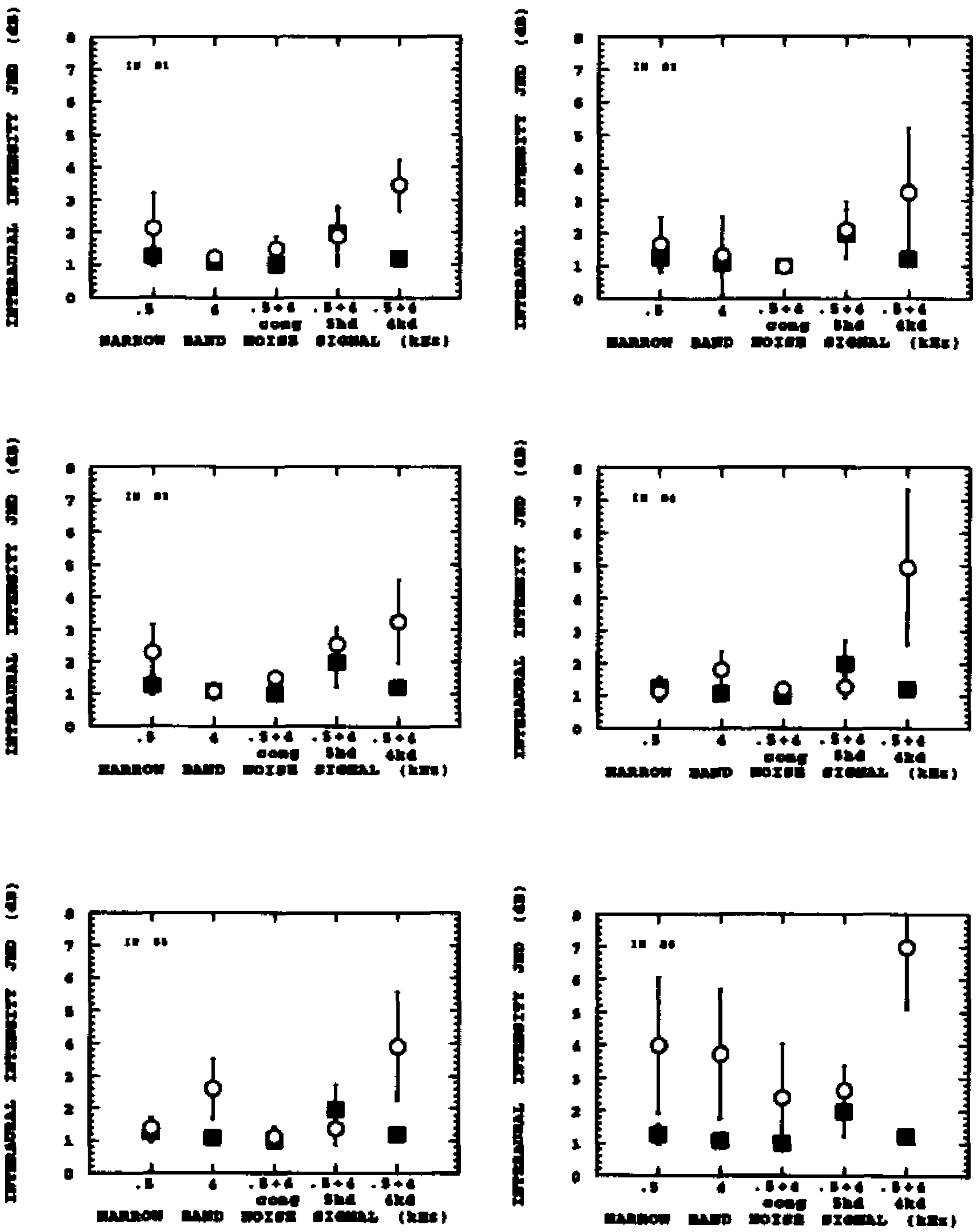

INTERAURAL TIME JND (µsec)
1000
100
10
.5
4
.5+4 cong
.5+4 5hd
.5+4 4kd
NARROW BAND NOISE SIGNAL (kHz)

Figure 9. Individual interaural intensity JNDs (and standard deviations) for each IH subject and the group JNDs for the NH subjects. The ordinate represents the interaural intensity JND in dB. The error bars represent the within-subject standard deviation of the five estimates of JND. For comparison, the group mean data for the NH subjects (with standard deviation) is displayed on each panel. The solid squares represent the mean of the JNDs of the NH subjects and the open circles represent the JNDs of each IH subject.


INTERAURAL INTENSITY JND (dB)
.5
4
.5+4 cong
.5+4 5hd
.5+4 4kd
NARROW BAND NOISE SIGNAL (kHz)

NH listeners in this condition. IH subjects 4, 5, and 6 cannot perform interaural time discrimination in the **4kd** condition, even with a 1000 μsec interaural difference. Interaural intensity JNDs for IH S4 are between 1 and 2 dB for all conditions except **4kd**; for IH S5 the JNDs are between 1 and 2.5 dB; and for subject IH S6 the JNDs are between 2.5 and 3.5 dB. In the **4kd** condition, where the JNDs were >5 dB, IH subjects 4, 5 and 6 may have been using monaural intensity information rather than interaural intensity information.

<u>Summary of Discrimination Results</u>

For the signal conditions in the interaural time discrimination task (Figure 8) the IH listeners have larger JNDs than the NH listeners. On the interaural intensity discrimination task both groups of subjects exhibit similar JNDs on all signal conditions except **4kd**. All listeners demonstrate binaural interference for the **4kd** signal condition for interaural time discrimination; however, only the IH subjects demonstrate binaural interference for that signal condition for interaural intensity discrimination.

Experiment II - Localization

<u>Group Data</u>

The localization data are presented in Figures 11-14. (Appendix G contains the raw data in the form of confusion matrices for each subject in Experiment II.) Two indices of localization performance were determined: (1) root mean square (RMS) error and (2) percent correct. The RMS error is

a measure of accuracy of a subject's response compared to the actual stimulus location without regard to direction. RMS error is used in all statistical analyses and is calculated as follows:

$$RMS = \sqrt{\left[\sum_{i=1}^{n}(s_i - r_i)^2/n\right]} \qquad (3)$$

where n equals the number of trials per run, s_i equals the stimulus location and r_i equals the response location. A sample confusion matrix is shown in Figure 10. The subject responses are indicated in the columns, and the rows indicate the actual stimulus location. For example, when the stimulus location was #5 the subject indicated that the source location was #2 once, #4 two times and #5 three times.

Figures 11 and 12 show the RMS error group means for the NH (solid squares) and IH (open circles) subjects on all signal conditions in the localization task. RMS error in degrees was determined by multiplying the RMS error calculated using Equation 3 by 22.5 (the angle between adjacent stimulus locations.) In Figure 11 the signal conditions (left to right) are:

- .5 kHz NBN in isolation (**.5 kHz**);
- .5 kHz NBN target with 4 kHz NBN fixed at location 1 (**.5T/4F1**);
- .5 kHz NBN target with 4 kHz NBN fixed at location 5 (**.5T/4F5**);
- .5 kHz NBN target with 4 kHz NBN fixed at location 9 (**.5T/4F9**);
- .5 kHz NBN target with 4 kHz NBN presented randomly from location 1 (**.5T/4F1**);

.5 kHz NBN target with 4 kHz NBN presented randomly from location 5 (.5T/4F5);
.5 kHz NBN target with 4 kHz NBN presented randomly from location 9 (.5T/4F9).

In Figure 12 the signal conditions are:

4 kHz NBN in isolation (**4 kHz**);
4 kHz target with .5 kHz NBN fixed at location 1 (**4T/.5F1**);
4 kHz target with .5 kHz NBN fixed at location 5 (**4T/.5F5**);
4 kHz target with .5 kHz NBN fixed at location 9 (**4T/.5F9**);
4 kHz target with .5 kHz NBN presented randomly from location 1 (**4T/.5R1**);
4 kHz target with .5 kHz NBN presented randomly from location 5 (**4T/.5F5**);
4 kHz target with .5 kHz NBN presented randomly from location 9 (**4T/.5F9**).

Figure 11 shows that the NH listeners localize more accurately (by roughly 10°) than the IH listeners in every signal condition with a .5 kHz target signal. Likewise, Figure 12 shows the NH group is more accurate than the IH listeners in all conditions with a 4 kHz target signal. When **4 kHz** is localized in isolation, the two groups have comparable performance. However, when the interfering noise band is introduced, the IH group's RMS error increases while the NH group's RMS error remains about the same, regardless of the interference condition. Comparison of Figures 11 and 12 indicates that both groups perform more accurately with the .5 kHz NBN target than with the 4 kHz NBN target.

In examining these data the questions of interest are: (1) "Is there a training effect?"; (2) "Are there differences in localization error between the groups?"; and (3) "Are there differences in localization error based on signal

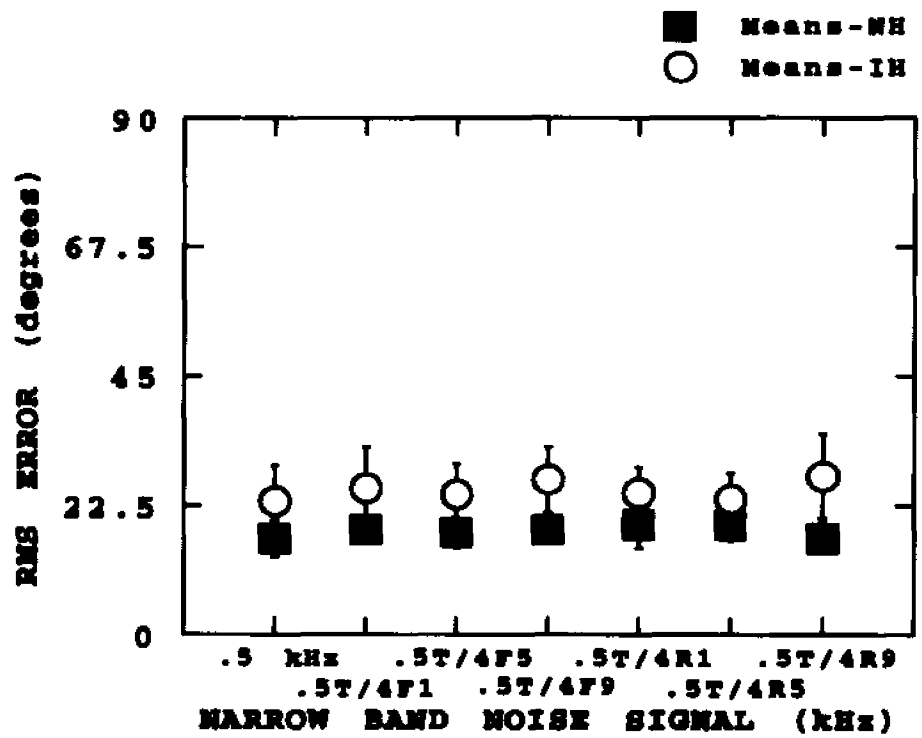
Figure 10. A sample confusion matrix generated during one localization run.

RESPONSE LOCATION

			1	2	3	4	5	6	7	8	9
		1	0	0	5	1	0	0	0	0	0
S	L	2	1	3	1	1	0	0	0	0	0
T	O	3	0	0	4	2	0	0	0	0	0
I	C	4	0	2	2	2	0	0	0	0	0
M	A	5	0	1	0	2	3	0	0	0	0
U	T	6	0	0	0	0	0	3	3	0	0
L	I	7	0	0	0	0	0	4	2	0	0
U	O	8	0	0	0	0	0	0	4	2	0
S	N	9	0	0	0	1	0	5	0	0	0

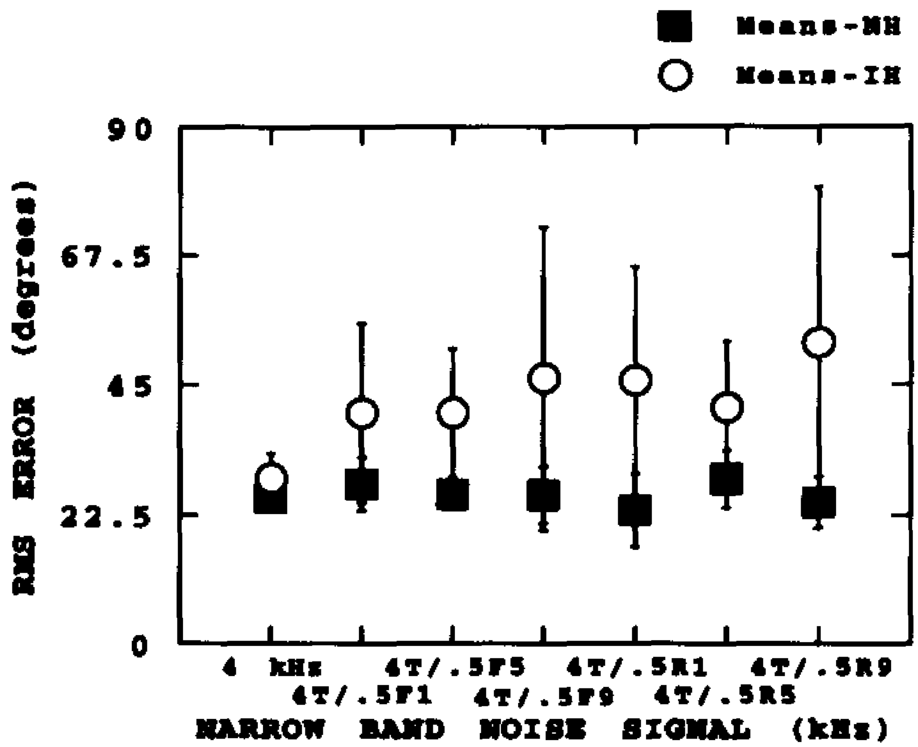
RMS ERROR = 1.604 % CORRECT = 35.19

Figure 11. NH and IH group RMS error means on signal conditions with a .5 kHz NBN target. The abscissa in each figure represents the signal condition and the ordinate the RMS error in degrees. The solid squares represent the mean of the JNDs of the NH subjects and the open circles represent the JNDs of each IH subject.



Means-NH
Means-IH
90
67.5
45
22.5
0
RMS ERROR (degrees)
.5 kHz
.5T/4F1
.5T/4F5
.5T/4F9
.5T/4R1
.5T/4R5
.5T/4R9
NARROW BAND NOISE SIGNAL (kHz)

Figure 12. NH and IH group RMS error means on signal conditions with a 4 kHz NBN target. The abscissa in each figure represents the signal condition and the ordinate the RMS error in degrees. The solid squares represent the mean of the JNDs of the NH subjects and the open circles represent the JNDs of each IH subject.


Means-NH
Means-IH
90
67.5
45
22.5
0
RMS ERROR (degrees)
4 kHz
4T/.5F1
4T/.5F5
4T/.5F9
4T/.5R1
4T/.5R5
4T/.5R9
NARROW BAND NOISE SIGNAL (kHz)

condition?" To answer these questions, a 3-factor ANOVA (group X signal condition X repetition, between-within-within, 2 X 14 X 2) was completed. This analysis indicates a significant difference due to group ($F=51.74$, $df=1,196$, $p<.05$), a significant difference due to signal condition ($F=5.21$, $df=13,196$, $p<.05$), and a non-significant difference due to repetition ($F=0.44$, $df=1,196$, $p>.5$). All interactions were non-significant ($p>.13$). This result indicates that there is no effect of training, but there is a difference between subject groups as well as differences among signal conditions.

A *post-hoc* Duncan's test was run on the 14 signal conditions. Results indicate that significant differences occur primarily between conditions with a .5 kHz target and those conditions with a 4 kHz target. All conditions with a .5 kHz target have statistically similar means. The conditions with a 4 kHz target have means statistically similar to one another, except that 4 kHz in isolation is significantly different from 4T/.5R9 (4 kHz target and the .5 kHz interferer random from location 9). Additionally, performance with the 4 kHz signal in isolation is statistically similar to all conditions with a .5 kHz target. (See Appendix I for all Duncan's test results complete with all significant contrasts.)

The significant difference between groups is expected, based on localization studies in the literature which suggest

that IH listeners are less accurate than NH listeners at localizing sound sources (e.g., Noble *et al.*, 1994; Colburn *et al.*, 1982; Jongkees and Veer, 1957; Tonning, 1975). Therefore, the remainder of the analyses were performed within-group. Two questions were examined within-group: (1) "Are there differences in subject's abilities to indicate source location when there is no interference versus when the interference is in a fixed or a random location?", and (2) "Within each of the three interference conditions (none, fixed, random), is there a difference in localization accuracy based on the frequency of the target signal?"

Before these questions could be addressed it was necessary to determine whether the location of the interferer within the random and fixed conditions caused a difference in localization ability among listeners. Within-group ANOVAs (interferer location X subject, blocked on subject) were run comparing interferer Location 1 versus Location 5 versus Location 9 within the random and fixed cases. There are no significant differences ($p<.05$) for either subject group due to interferer location.

Because there is no effect of interferer location, the fixed runs for the interferer locations (1, 5, 9) were collapsed and the random runs for the interferer locations (1, 5, 9) were collapsed for each listener. The RMS error was then recalculated from the resultant matrices for each listener. Because several of the signal conditions were

collapsed across interferer location, the notation employed to this point (**.5T/4F1**, **.5T/4R5**, **4T/.5F5**, **4T/.5R1**, etc.) will be changed to reflect that collapsing. The notation will now be **.5T/4F**, **.5T/4R**, **4T/.5F**, and **4T/.5R**. Figure 13 represents the group means for each of these collapsed conditions.

In the IH group the ANOVA indicates a significant difference due to subject for two of the four signal configurations: (1) .5 kHz NBN as target with 4 kHz NBN interferer in fixed locations (**.5T/4F**) and (2) 4 kHz NBN as target with .5 kHz NBN interferer in random locations (**4T/.5R**).

Post-hoc analysis of IH subject differences in the **.5T/4F** condition using Duncan's test reveals the following groupings among the IH subjects (p<.05):

3	2	5	4	1	6

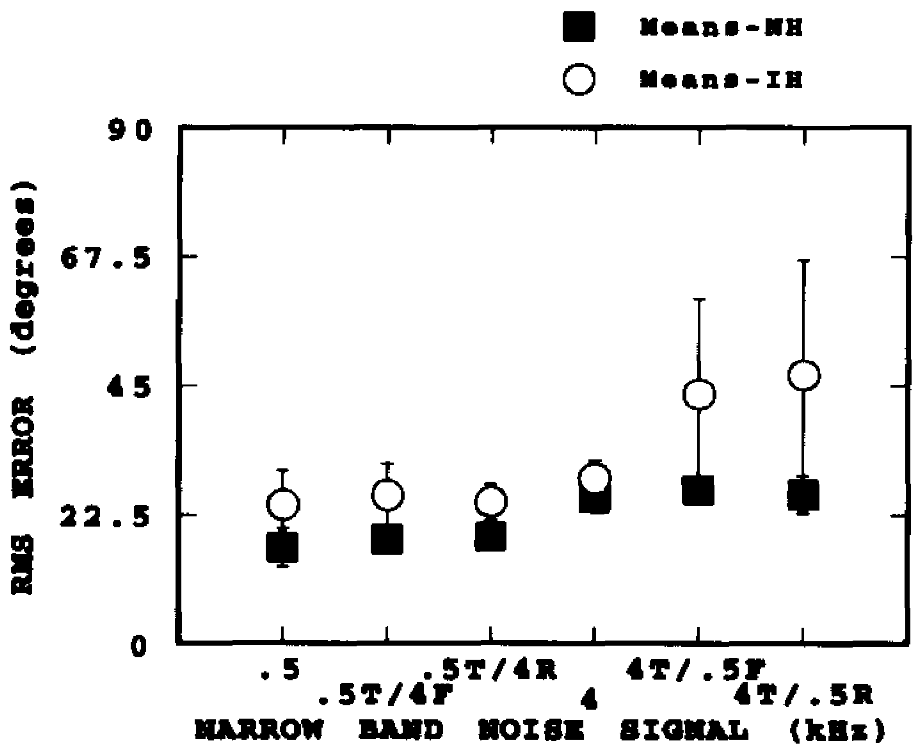
	====	====	====	====	====

While 5 of the 6 subjects performed similarly, IH S3 is significantly better than each of the others. For the **4T/.5R** condition the Duncan's test indicated two non-overlapping groups:

3	2	5	4	1	6
----	----	----	----		
				====	====

IH S1 joined IH S6 in this signal condition to form a group whose performance is consistently poorer than the other

Figure 13. NH and IH group RMS error means for the six signal conditions collapsed across interferer location. The ordinate represents the RMS error in degrees and the abscissa the signal conditions. The three signal conditions with a .5 kHz target are to the left side of the panel, and the three with a 4 kHz target are to the right side of the panel. The open circles represent the means for the IH group and the solid squares the means for the NH group.



Means-NH
Means-IH
90
67.5
45
22.5
0
RMS ERROR (degrees)
.5
.5T/4F
.5T/4R
4
4T/.5F
4T/.5R
NARROW BAND NOISE SIGNAL (kHz)

four IH subjects. Note that the order of the subjects' mean performances is the same for both Duncan's analyses (the .5T/4F and 4T/.5R signal conditions).

The NH group performed similarly for all three conditions at each frequency, suggesting that performance is unaffected by the addition of an interfering signal. The same is true of the IH group for the .5 kHz target conditions. It is interesting that although five of six IH listeners had 500 Hz audiometric and 1/3-octave noise detection thresholds within the normal range, they are still less accurate at localizing a .5 kHz NBN than the NH group. When an interfering sound is introduced with the 4 kHz NBN as target, the IH group RMS error increases notably compared to the 4 kHz signal in isolation. However, this result may be explained by subject variability, as will be presented shortly.

To test for any significant differences between the groups and among the signal conditions, a 2-factor ANOVA was run on group X signal condition (2 X 6, between-within) collapsed across interferer location (no interferer, fixed interferer, random interferer). The results indicate a significant difference between groups ($F=31.16$, $df=1,96$, $p<.05$), a significant difference among signal conditions ($F=9.48$, $df=5,96$, $p<.05$), and a non-significant interaction of group and task ($F=2.28$, $df=5,96$ $p>.05$).

A *post-hoc* Duncan's test to examine differences among the means of the six signal conditions indicate the following groupings ($p<.05$):

```
.5 kHz    .5T/4R    .5T/4F    4 kHz     4T/.5F    4T/.5R
______________________________
          ============================
                                        *-*-*-*-*-*-*-*-*
```

Subjects perform more poorly on conditions when 4 kHz is the target and there is an interferer present than in any condition in which .5 kHz is the target. Also, subjects could locate a 4 kHz NBN signal in isolation as accurately as they could the .5 kHz NBN with any interferer. Otherwise, localization performance is not significantly different for the three conditions with .5 kHz as the target and for the two conditions with a 4 kHz target and .5 kHz interferer. Notice in Figure 13 that the mean RMS errors for any two like conditions with different target frequencies (e.g., **.5T/4R** versus **4T/.5R**), the .5 kHz target signal conditions are smaller than the 4 kHz target signal conditions. This result suggests there is a difference in localization ability based on target frequency. Paired *t*-tests (Appendix J) indicate that for each group of subjects, within-group RMS localization error with the **.5 kHz** signal is significantly smaller than that for the **4 kHz** signal; RMS error with the **.5T/4F** signal is significantly smaller than that with the **4T/.5F** signal, and RMS error with the **.5T/4R** signal is significantly smaller than that with the **4T/.5R** signal.

With the data from the various interferer locations collapsed, the question raised earlier concerning differences among subjects may now be addressed. To answer that question, within-group analyses were performed. In the first ANOVA, the three conditions in which the .5 kHz NBN was the target (.5 kHz, .5T/4F and .5T/4R) were compared. In the second ANOVA, the three conditions in which the 4 kHz NBN was the target (4 kHz, 4T/.5F and 4T/.5R) were compared.

The ANOVAs (signal condition X subject, blocked on subject) for the NH listeners indicate no significant differences in localization errors based on interference condition or subject. For the IH group, the ANOVA for the .5 kHz signal conditions reveals a non-significant difference for interference condition and a significant difference based on subject ($F=13.51$, $df=5,10$, $p<.05$). The ANOVA for the 4 kHz signal conditions in the IH group reveals significant differences for both subject ($F=4.71$, $df=5,10$, $p<.05$) and interference condition ($F=5.69$, $df=2,10$, $p<.05$).

A *post-hoc* Duncan's analysis of the IH subjects with the .5 kHz target indicates IH S3 localizes more accurately than each of the other five IH subjects, and those five perform similarly to each other ($p<.05$):

3	1	2	5	4	6
────	═══════	═══════	═══════	═══════	═══════

With a 4 kHz target, the Duncan's test indicates that the IH subjects split into two overlapping groups ($p<.05$):

```
  2       3       4       5       1       6
 _________________________________________
                                 ===========
```

IH S1 and IH S6 perform similarly, and IH subjects 1-5 perform similarly. IH S6's performance is poorer than IH subjects 2, 3, 4, and 5. Note, too, that the order of the subjects' mean performance is different with the 4 kHz target signals compared to the .5 kHz target signals. The Duncan's test run on signal condition for the ANOVA with a 4 kHz target reveals no significant differences among the three signal conditions.

<u>Individual Data</u>

As with Experiment I, the NH data is presented as average group data (solid squares) in each panel of Figure 14 for comparison. Figure 14 also contains individual data for each of the IH subjects (open circles) for the localization task. The three signal conditions with .5 kHz as the target are located on the left-hand side of each panel and the three signal conditions with 4 kHz as the target are on the right-hand side.

The individual localization results are summarized in Figure 14 and Table 6. Table 6 contains the percent correct and the percent of answers to the left and right of the actual stimulus location for each IH subject and the NH

Figure 14. RMS error for each IH subject in each collapsed signal condition. The ordinate represents the RMS error in degrees and the abscissa the signal conditions. The open circles represent the means for each IH subject and the solid squares the means for the NH group.

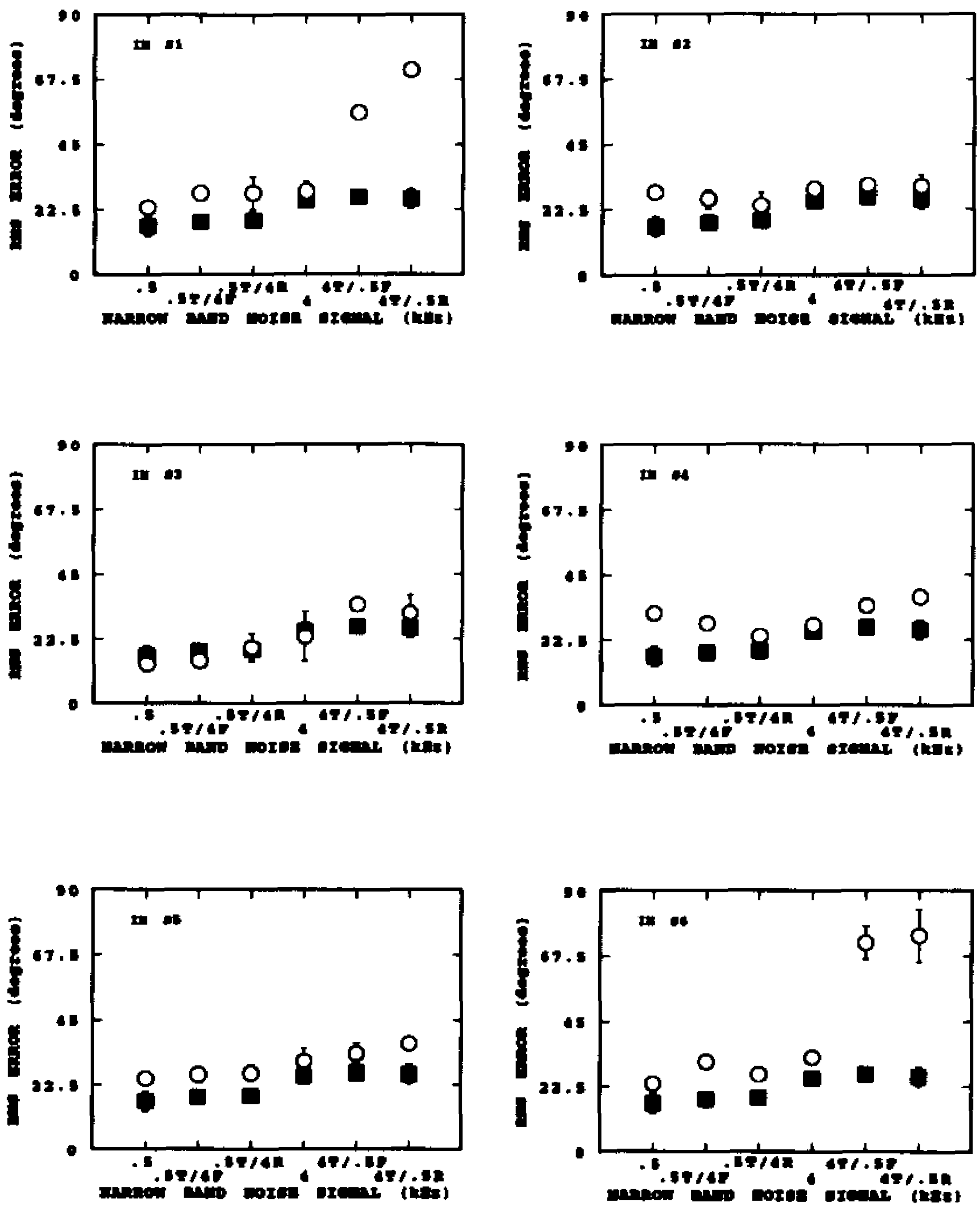


Table 6. Percent of Localization Responses Which Were to the Left, to the Right, and Correct for Each Impaired-Hearing Subject and Mean of the Normal-Hearing Subjects.

All values given in percent.

Subject	Signal Condition Targ/Int	Interfer. Location	Left	Right	Correct
NH	4T/.5F	1	33.6	25.9	40.4
		5	27.5	28.7	43.8
		9	30.9	30.2	38.9
	4T/.5R	1	26.8	31.5	41.7
		5	34.3	25.0	40.7
		9	28.7	31.5	39.8
	.5T/4F	1	17.0	23.4	59.6
		5	17.0	22.8	60.2
		9	17.6	25.6	56.8
	.5T/4R	1	15.7	27.8	56.5
		5	16.7	29.6	53.7
		9	13.0	24.0	63.0
IH S1	4T/.5F	1	71.3	12.0	16.7
		5	48.1	29.6	22.2
		9	17.6	63.0	19.4
	4T/.5R	1	72.2	13.9	13.9
		5	47.2	55.6	16.7
		9	5.6	86.1	8.3
	.5T/4F	1	54.6	8.3	37.0
		5	32.4	30.6	37.0
		9	27.8	33.3	38.9
	.5T/4R	1	50.0	11.1	38.9
		5	30.5	30.6	38.9
		9	25.0	44.4	30.6
IH S2	4T/.5F	1	35.2	29.6	35.2
		5	38.9	28.7	32.4
		9	34.2	30.6	35.2
	4T/.5R	1	44.4	27.8	27.8
		5	36.1	36.1	27.8
		9	33.3	27.8	38.9
	.5T/4F	1	38.0	18.5	43.5
		5	34.3	21.3	44.4
		9	32.4	24.1	43.5
	.5T/4R	1	50.0	13.9	36.1
		5	41.7	22.2	36.1
		9	33.3	22.2	44.4

(table con'd.)

Subject	Targ/Int	Int. Loc.	Left	Right	Correct
IH S3	4T/.5F	1	36.1	29.6	34.3
		5	41.7	29.6	28.7
		9	36.1	32.4	31.5
	4T/.5R	1	47.2	25.0	27.8
		5	38.9	22.2	38.9
		9	36.1	25.0	38.9
	.5T/4F	1	18.5	6.5	75.0
		5	21.3	13.0	65.7
		9	23.1	15.7	61.1
	.5T/4R	1	22.2	11.1	66.7
		5	22.2	16.7	61.1
		9	27.8	19.4	52.8
IH S4	4T/.5F	1	38.0	23.1	38.9
		5	28.7	37.0	34.3
		9	9.3	63.0	27.8
	4T/.5R	1	30.6	38.9	30.6
		5	16.7	41.7	41.7
		9	19.4	55.6	25.0
	.5T/4F	1	24.1	32.4	43.5
		5	28.7	26.0	45.4
		9	25.9	25.9	48.1
	.5T/4R	1	19.4	36.1	44.4
		5	13.9	33.3	52.8
		9	22.2	41.7	36.1
IH S5	4T/.5F	1	55.6	15.7	28.7
		5	19.4	49.1	31.5
		9	21.3	48.1	30.6
	4T/.5R	1	41.7	22.2	36.1
		5	25.0	52.8	22.2
		9	16.7	69.4	13.9
	.5T/4F	1	42.6	23.1	34.3
		5	27.8	30.6	41.7
		9	7.4	51.9	40.7
	.5T/4R	1	44.4	27.8	27.8
		5	22.2	33.3	44.4
		9	19.4	38.9	41.7
IH S6	4T/.5F	1	38.9	38.9	22.2
		5	29.6	52.9	18.5
		9	1.9	88.0	10.2
	4T/.5R	1	61.1	30.6	8.3
		5	38.9	47.2	13.9
		9	5.5	80.6	13.9
	.5T/4F	1	34.3	31.5	34.3
		5	35.2	26.9	38.0
		9	13.9	54.6	31.5
	.5T/4R	1	25.0	33.3	41.7
		5	30.6	13.9	55.5
		9	22.2	38.9	38.9

group. The percentage of answers to the left of the actual stimulus location was calculated by summing the number of responses in each matrix below the diagonal divided by the total number of responses. Similarly, the percentage of answers to the right of the actual stimulus location was calculated by summing the number of responses in each matrix above the diagonal divided by the total number of responses. While the RMS error provides a convenient way to summarize the overall error of each subject in each condition, Table 6 allows a closer inspection of the pattern of errors, or bias of responses, for each IH subject. As a group, the NHlisteners exhibit no striking bias patterns with the 4 kHz target; however, with the .5 kHz target, the NH listeners tended to respond consistently to the right of the actual stimulus location.

The RMS localization errors for IH S1 are similar on all tasks except the two with a 4 kHz target with an interferer. IH S1 localizes more accurately with a fixed than a random interferer, but her performance is much worse in these two conditions than all the other conditions. Table 6 indicates that the responses of IH S1 are affected by interferer location in the conditions with 4 kHz as the target. With a .5 kHz target, her responses reflect choice of a source location closer to the interferer location in the random interferer case, and with a fixed interferer at location 1. However, with a fixed interferer at locations 5 and 9 she

does not respond with a choice that is close to the interferer location.

IH S2, whose performance is only slightly poorer than the NH subjects, has similar localization errors across all signal conditions. He is the only subject in either group who demonstrates little difference between the two target frequencies. As can be seen in Table 6, IH S2 split his responses almost evenly in every condition except .5T/4R1, in which he tended to respond toward the left, or toward the interferer location.

IH S3 performs comparably to the NH subjects with a .5 kHz NBN target and with a 4 kHz NBN in isolation. In the 4T/.5F and 4T/.5R conditions, however, his RMS error is larger than that of the NH listeners. Table 6 shows that in no condition do his responses to the right or left suggest he is responding to interferer location. However, overall he exhibits a trend across target and interferer location conditions to respond more often to the left than to the right of the correct stimulus location.

IH S4 presents an RMS error pattern different from the other subjects. He has the most difficulty with the .5 kHz and 4T/.5R conditions, and the least trouble with the .5T/4R and 4 kHz conditions. He exhibits a larger RMS error whenever the 4 kHz target has an interferer, but little difference is noted for the fixed or random interference conditions, as shown in Figure 14. He demonstrates a

tendency to indicate source location to the right of the correct one in several signal conditions, primarily when the interferer is at the right ear.

IH S5 performs similarly to the NH group, but exhibits more difficulty with the **4T/.5F** and **4T/.5R** conditions than any of the other signal conditions (Figure 14). This subject displays a tendency to respond to the location of the interferer rather than the target in all 4 target+interferer conditions, whether .5 or 4 kHz is the target. Additionally, with a 4 kHz target, she tends to answer more often to the right of the correct stimulus when the interferer is at location 5.

IH S6 exhibits the most localization difficulty of any subject, as can readily be seen in Figure 14. Recall that he stated some of the sounds appeared to emanate from behind his head. Nonetheless, his RMS errors for the .5 kHz targets and 4 kHz target in isolation are quite good, though somewhat larger than the NH group. Variability in his performance is quite low; however, when an interfering sound is introduced with the 4 kHz target, his performance is degraded and the variability increases. RMS localization error for this subject for the 4 kHz target with an interferer is large (about 3.5 locations, or 78.75°), but little difference is noted for the fixed or random interference conditions. Table 6 shows that his responses are pulled to the location of the interfering sound, rather than the target signal, in the

4T/.5R condition. With a 4 kHz target and the .5 kHz interferer random at location 1, IH S6 has 61.1% responses to the left of the actual stimulus location and 30.6% to the right; with the interferer in location 5, his responses are almost equally divided left and right at 38.9% and 47.2%, respectively; with the interferer in location 9, his responses are 5.5% to the left and 80.6% to the right. Also, his responses are to the right of the correct location with an interferer at location 9 in the 4T/.5F condition (1.9% to the left and 88.0% to the right of the actual stimulus location). With a .5 kHz target, his errors are fairly evenly distributed.

Summary of Localization Results

The NH listeners demonstrate significantly more accurate localization of a low frequency signal than a high frequency one. When an interfering sound is added to the task, NH listeners show no significant change in their ability to localize the target signal, whether the interfering sound is at a fixed location or occurs at random locations.

Overall, the IH listeners are less accurate than the NH listeners at indicating source location. They, too, demonstrate significantly poorer performance with the high frequency signal than the low frequency one (see Appendix J). Also like the NH subjects, when an interfering sound is added to the low frequency target, the IH listeners show no change in their ability to indicate source location. Unlike the NH

listeners, however, when an interfering sound is introduced with a 4 kHz target, the RMS error increases in most cases, and the signal with a random interferer yields slightly higher (but not significantly higher) RMS errors than with a fixed interferer.

Relationship Between Interaural Discrimination and Localization

Based on theoretical and experimental evidence, it is expected that localization ability is related to interaural discrimination. Therefore, scatterplots of performance on these two tasks are examined. The localization RMS error values are used rather than the measures of bias because the RMS error provides an overall measure of localization performance. Figures 15 and 16 contain scatterplots of localization accuracy versus interaural discrimination JNDs for the normal-hearing and impaired-hearing groups, respectively.

The discrimination variables chosen reflect theoretical principles of the availability of interaural time and intensity cues for localization. That is, because localization of low frequency signals is mediated primarily by timing information (in the fine structure, i.e., cycle-by-cycle, of the signal), the .5 kHz time JND data are compared to the **.5 kHz** and **.5T/4I** (.5 kHz target signal with a 4 kHz interfering signal) localization signal conditions. Interaural intensity information is used primarily in

Figure 15. Scatterplots of localization performance versus discrimination performance for the NH subjects. (a) .5 kHz localization RMS versus .5 kHz interaural time JND; (b) 4 kHz localization RMS versus 4 kHz interaural intensity JND; (c) .5T/4I localization RMS versus .5 kHz interaural time JND; (d) 4T/.5I localization RMS versus 4 kHz interaural intensity JND; (e) .5T/4I localization RMS versus 5hd interaural time JND; (f) 4T/.5I localization RMS versus 4kd interaural intensity JND.

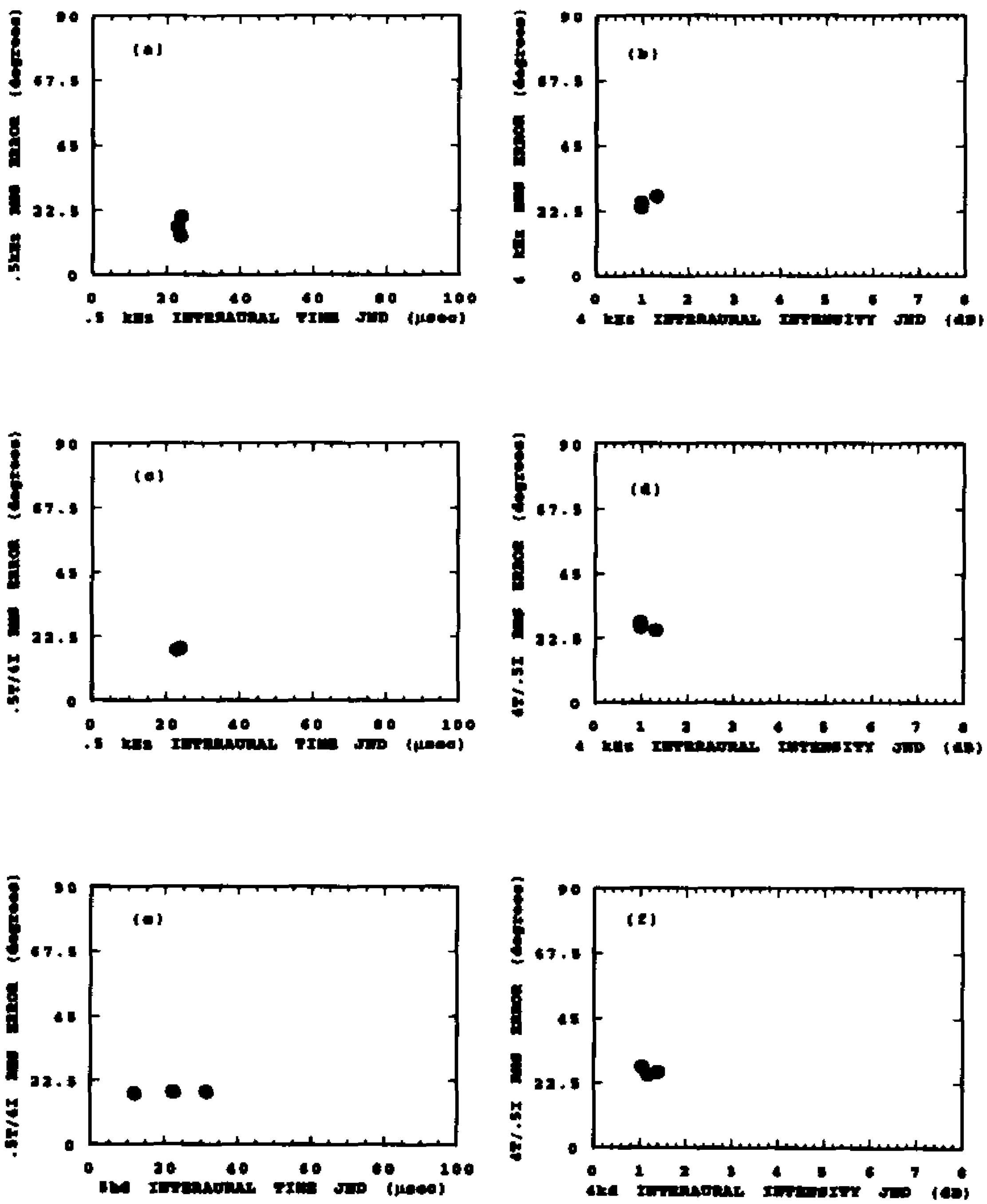
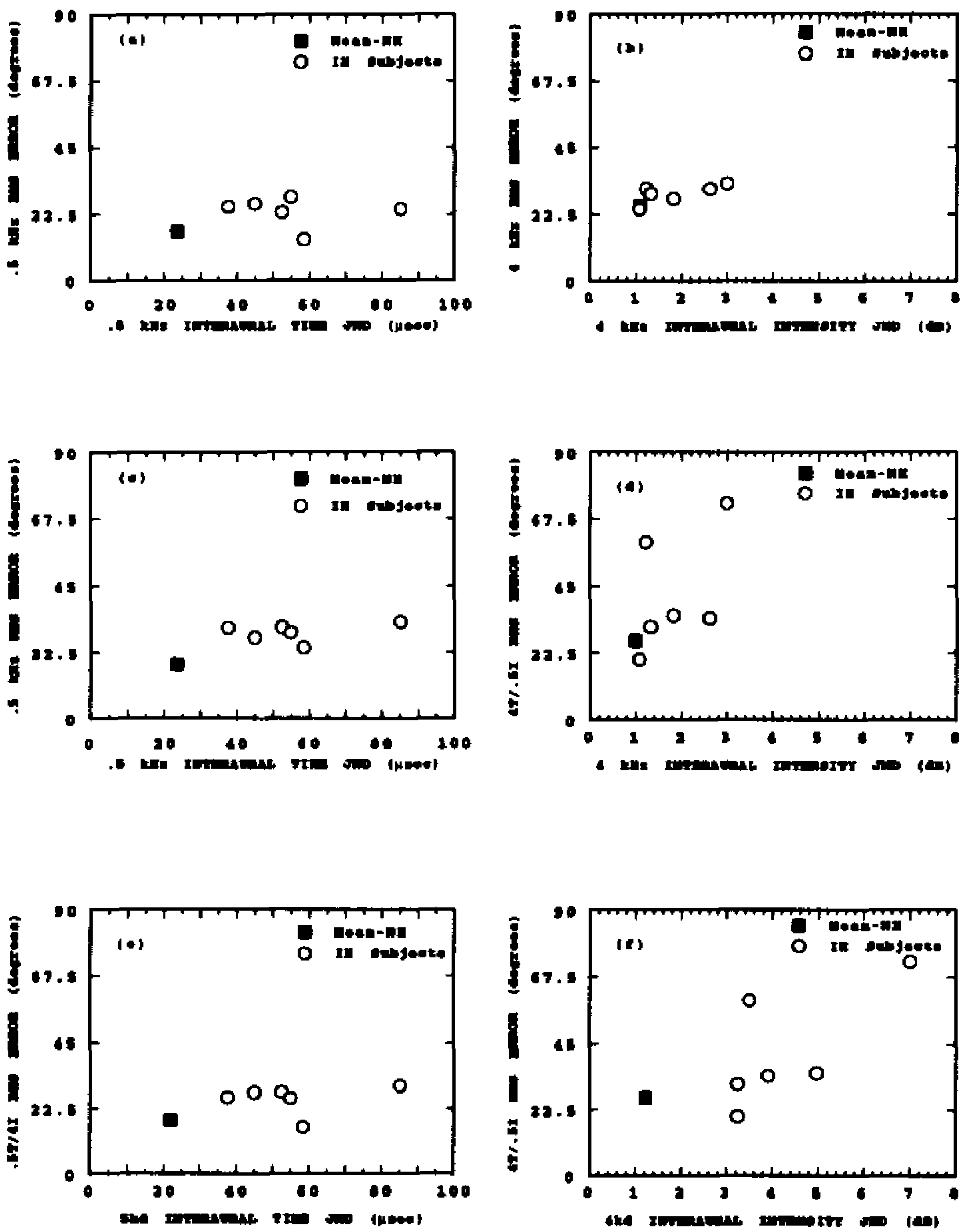

(a)
(b)
(c)
(d)
(e)
(f)
90
67.5
45
22.5
0
0 20 40 60 80 100
0 1 2 3 4 5 6 7 8

Figure 16. Scatterplots of localization performance versus discrimination performance for the IH subjects. (a) .5 kHz localization RMS versus .5 kHz interaural time JND; (b) 4 kHz localization RMS versus 4 kHz interaural intensity JND; (c) .5T/4I localization RMS versus .5 kHz interaural time JND; (d) 4T/.5I localization RMS versus 4 kHz interaural intensity JND; (e) .5T/4I localization RMS versus 5hd interaural time JND; (f) 4T/.5I localization RMS versus 4kd interaural intensity JND.


(a)
(b)
(c)
(d)
(e)
(f)
Mean-NH
IH Subjects
.5 kHz INTERAURAL TIME JND (µsec)
4 kHz INTERAURAL INTENSITY JND (dB)
(degrees)
0
22.5
45
67.5
90
20
40
60
80
100

localizing high frequency signals; accordingly, the 4 kHz signal localization data (**4 kHz** and **4T/.5I**) are compared to the 4 kHz interaural intensity JND data. The incongruent double-band stimuli in the discrimination experiment are plotted on the abscissa in the scatterplots against the appropriate target+interferer localization conditions (e.g., **5hd** time versus **.5T/4I**).

The data for the normal-hearing listeners in the scatterplots of Figure 15 are clustered in the lower left-hand part of each panel. Such clustering indicates good performance by all subjects on both the interaural discrimination and localization tasks.

Figure 16 shows the scatterplots for the IH subjects. Clearly, performance varies widely across these subjects in contrast to the NH subjects. Looking at the panels in the left column (a, c, e), which compare localization to interaural time JNDs, subjects' time JNDs vary between 30 and 90 μsec, yet localization RMS errors are fairly tightly grouped around 22.5°. In panel 16b the intensity JNDs ranged between 1 and 3 dB and localization RMS errors again are grouped in a small area just greater than 22.5°. In panels 16d and 16f there is much more variability among the IH subjects for the RMS error measures compared to the other panels. Notice that the subjects' interaural intensity JNDs for the **4 kHz** signal in isolation range from 1 to 3 dB (16d), while the interaural intensity JNDs for the **4kd** signal range

from 3 to 7 dB (16f) but the RMS error in each varies between 22.5° and about 75°. A slightly stronger relationship between interaural intensity discrimination and localization than between interaural time discrimination and localization is suggested by visual inspection of the right-hand and left-hand panels of Figure 16, respectively. For example, in the left-hand panels, a horizontal line with little to no slope would adequately fit the data, while in the right-hand panels a line with some positive slope is needed to fit the data.

To further explore these relationships, rank order correlations using Spearman's rho (r) were run on all the data for the IH subjects. Results of the rank order correlation analysis are shown in Table 7. Notice that the interaural intensity performance correlates more highly with localization performance than does the interaural time performance.

The implications derived from the above correlation results are considered preliminary, given the small number of data points in the present study and the fact that localization ability varies less across subjects than discrimination in almost all conditions.

Table 7. Rank Order Correlation Results for the Localization Signal Conditions of the Impaired-Hearing Listeners.

Localization Signal Condition	Discrimination Signal Condition	Rank Order Correlation
.5 kHz	.5 kHz-Time	-0.3714
4 kHz	4 kHz-Int	0.6000
.5T/4I	1. .5 kHz-Time	0.0857
	2. 5hd-Time	0.3142
4T/.5I	1. 4 kHz-Int	0.6000
	2. 4kd-Int	0.8142

* indicates significance at the (p<.05) level

DISCUSSION

Interaural Discrimination

Target Signals in Isolation

The results of the interaural time discrimination experiment obtained for the normal-hearing (NH) listeners are comparable to those obtained by other researchers (e.g., Klumpp and Eady, 1956; McFadden and Pasanen, 1976; Hawkins and Wightman, 1980; Smoski and Trahiotis, 1986; Koehnke et *al*., 1986; Heller, 1992; Koehnke *et al*., 1995), with the .5 kHz narrow band noise (NBN) just noticeable difference (JND) smaller than the 4 kHz NBN JND, by 40 μsec. Likewise, the JNDs of the listeners with impaired hearing (IH) are similar to those of listeners with high-frequency sensorineural hearing loss reported in other studies (e.g., Hawkins and Wightman, 1980; Smoski and Trahiotis, 1986; Koehnke et *al*., 1995); the .5 kHz NBN JND is smaller than the JND for the 4 kHz NBN by a factor of 4.8. The JNDs for the **.5 kHz**, **cong**, and **5hd** signals are not significantly different between the NH and IH groups. Again, statistical comparison is not possible with the **4k** and **4kd** signals; however, the average JND for the IH group is 4 times larger than the NH group for the **4 kHz** NBN in isolation, and the IH subjects cannot discriminate interaural time differences as large as 1000 μsec with the **4kd** signal (except IH S2). See Figure 6 for the interaural time JNDs of both groups. The inability of some of the IH listeners to perform the interaural time

discrimination task with the 4 kHz NBN in isolation is consistent with the data of some of Koehnke *et al.*'s (1995) and Gabriel *et al.*'s (1992) subjects. On the other hand, at least one IH subject in the present study (IH S2 with a mild high frequency loss) has interaural time JNDs within the normal range for the 4 kHz NBN target. Such large intersubject variability is common in psychophysical experiments, especially among IH subjects (e.g., Hawkins and Wightman, 1980; Koehnke *et al.*, 1995; Häusler *et al.*, 1983).

Results of the interaural intensity discrimination experiment (see Figure 7) obtained in this study agree with those studies which have examined intensity discrimination in normal-hearing and/or impaired-hearing listeners. The NH subjects' intensity JNDs of about 1 dB for NBNs in isolation are equivalent across frequency and are similar to those reported by Heller (1992) and Koehnke *et al.* (1986). The IH listeners' JNDs of 3-7 dB are comparable to those reported by Gabriel *et al.* (1992) and Koehnke *et al.* (1995). The IH subjects' JNDs for the high frequency NBN in isolation are slightly smaller than the JNDs for the low frequency NBN. This indicates that all the IH subjects, regardless of the degree of hearing loss at 4000 Hz, are able to process interaural intensity information. This finding is important because an interaural intensity difference (due to the head-shadow effect) is the primary binaural cue available in high frequency signals in free field listening situations.

Because the IH subjects' are able to discriminate interaural intensity differences, it is expected that the subjects will be able to localize high frequency signals.

Overall, the results for interaural time and intensity discrimination of NBNs in isolation are consistent with those reported in the literature. The IH group has larger JNDs than the NH group in almost every signal condition for both interaural time and interaural intensity discrimination.

Target Signals with an Interferer

When a second band with different spectral content and congruent interaural information is added in the interaural discrimination experiment, neither group demonstrates significantly smaller JNDs for interaural time discrimination. The JNDs in the **cong** (.5 kHz + 4 kHz signal with the same interaural information in each) and **.5 kHz** (the .5 kHz signal in isolation) signal conditions are comparable, which suggests that interaural time discrimination of the congruent signals is dominated by the .5 kHz NBN. The NH listeners display results for interaural intensity discrimination similar to their results for interaural time discrimination--no improvement with the addition of congruent interaural information across frequency. This is probably due to a ceiling effect obtained for the NH group with the isolated NBN signals (i.e., there was little room for improvement). However, the IH subjects, as a group, exhibit significantly improved interaural intensity discrimination

when the interaural information is congruent across frequency versus the 4 kHz NBN in isolation. This result is encouraging because it indicates that IH listeners can benefit from congruent interaural cross-frequency intensity information in a discrimination task. However, in free-field listening situations the interaural intensity difference is negligible for signals below about 1000 Hz so there is little useable low frequency interaural intensity information. Therefore, when localization of high frequency signals is measured, it may not be as good as expected from the interaural intensity discrimination results, because there is no congruent interaural intensity information available in the low frequencies.

When a second signal of differing spectral composition and _incongruent_ interaural information is added in the discrimination experiments, the listener must use the interaural information in the target signal and ignore the incongruent information in the interfering signal in order to accurately discriminate interaural time or intensity differences. If listeners can ignore the interfering signal, their JNDs should be similar to those obtained with the NBNs in isolation. Alternatively, if they cannot ignore the second NBN, their JNDs should be larger than those obtained with the NBNs in isolation.

There were three conditions in which timing information was present in the low frequency signal (.5k, cong, 5hd). In

all three conditions JNDs within each subject group are almost identical. In the two conditions with timing information in only the high frequency signal (**4k**, **4kd**) there are also similar results within each group. When the target signal in isolation is high frequency (**4k**), discrimination is poorer than with the .5 kHz target. Interaural time discrimination is degraded even more when a low frequency interfering signal (**4kd**) is added. Again, only one of six IH subjects could discriminate interaural time information in the **4kd** condition.

The NH group performs similarly in all conditions of interaural intensity discrimination (JNDs of between 1-1.5 dB) except the **5hd** condition, which was larger (1.97 dB) (See Figure 7). These results are consistent with those of Gabriel *et al.* (1992) and Koehnke *et al.* (1995). The larger JND for the **5hd** condition may be an anomaly, however, due to poor performance by one of the three NH listeners. If that larger JND is removed, the mean for the other two subjects is 1.54 dB, a JND much closer to that for the other four signal conditions. Because the NH subjects' JNDs are similar in the **5hd** and **4kd** signal conditions, these results suggest that NH listeners can ignore irrelevant interaural information in a remote spectral region in an interaural intensity discrimination task.

The IH group demonstrates a different pattern of performance than that of the NH group for interaural

intensity discrimination (See Figure 7). The IH group has significantly smaller JNDs in the congruent condition than in the **4 kHz** condition. This result suggests that when additional interaural intensity information is available in the low frequency region, IH listeners can detect smaller interaural differences than when the interaural intensity information is available in the high frequency region alone. With incongruent interaural information across frequency, IH listeners have JNDs in the **5hd** and **4kd** conditions that are not significantly different from the **.5 kHz** and **4 kHz** NBN signals in isolation, respectively. However, the IH listeners have JNDs with the **4kd** signal that are, on the average, 2 dB larger than with the **4 kHz** signal alone. Although not statistically significant, it is clear that at least some of the IH listeners have greater difficulty detecting interaural intensity differences in a high frequency signal in the presence of a low frequency interferer than interaural differences in a high frequency signal in isolation. Figure 9 shows that IH subjects 1, 2, and 3 have JNDs of about 1 dB for the **4 kHz** signal; IH S4 about 1.75 dB for the **4 kHz** signal and IH S5 and IH S6 have larger JNDs of about 2.5 dB and 3.75 dB, respectively. JNDs for the **4kd** signal condition (Figure 9) indicate that those subjects who perform best with the **4 kHz** signal have about a 2 dB increase in JND with the **4kd** signal. JNDs of IH

subjects 4 and 6 increase about 3 dB while IH S5's JND increases only about 1.5 dB in **4kd** versus 4 kHz.

Results with incongruent interaural information across frequency (**5hd**, **4kd**) suggest that IH listeners can ignore irrelevant interaural intensity information when the target is low frequency with a high frequency interferer (**5hd**), but not in the reverse case (**4kd**). In terms of free-field listening then, it would be expected that localization of a 4 kHz signal might be degraded when there is a low frequency interfering signal.

It is interesting that the IH subjects have similar performances in interaural time and intensity discrimination in the **4kd** condition; i.e., in both cases the JND for **4kd** increases over **4k** alone. Unlike interaural time discrimination, however, in which 5 of 6 IH listeners could not discriminate a 1 msec interaural time difference, 3 of 6 IH subjects could discriminate interaural intensity differences with the **4kd** signal, and two other IH subjects may or may not have used interaural intensity information. It is probable that the sixth IH subject used monaural intensity cues in the **4kd** condition (JND = 7 dB). That more IH listeners appear able to perform interaural intensity discrimination using signals with which they are unable to perform interaural time discrimination is consistent with reports by other researchers (Hawkins and Wightman, 1980; Gabriel *et al.*, 1992; Koehnke *et al.*, 1995). However, as

pointed out by several authors, the relationship between interaural time and intensity discrimination is not straightforward (e.g., Hawkins and Wightman, 1980; Gabriel *et al.*, 1992). That is, a subject with impaired hearing may not be able to discriminate interaural time differences, but that does not necessarily mean s/he cannot discriminate interaural intensity differences with the same signal, or vice versa.

One important issue which may account for some of the results obtained in this study is gating of the target and interfering signals. Trahiotis and Bernstein (1990) described interesting results concerning gating effects in an interaural time discrimination experiment in normal-hearing listeners. Trahiotis and Bernstein used independently constructed target and flanking bands of noise. The target bands were 40% of the target frequencies (.5, 1, 2, 3, and 4 kHz) and were generated by passing Gaussian noise through the appropriate bandpass filter. The flanking bands of noise (interferers) were generated by using band-reject filters with cutoff points which coincided with the lower and upper cutoffs, respectively, used to produce the target bands. The interaural time delays were imposed on only the target bands. The interfering bands were interaurally correlated (diotic) in some conditions and interaurally uncorrelated in other conditions. When the interferer was interaurally correlated, the same source of noise was led to each band-reject filter; when uncorrelated, separate noise sources were employed.

To determine whether simultaneous gating of the target and interfering signals had an effect on their results for interaural time discrimination, they employed two interfering signal conditions: (1) interfering signal gated coincidentally with the targets, and (2) interfering signal presented continuously. The duration of both the target and interferer, with coincidental gating, was 100 msec. In the other cases, the interferer was continuously present with the 100 msec target band presented during the appropriate intervals. They reported larger JNDs for their interference condition compared to the 4 kHz NBN in isolation when the two noises were gated simultaneously, and little or no difference in JNDs when the interferer was continuous. In the condition with a high frequency target and diotic interferer which was gated simultaneously with the target, Trahiotis and Bernstein found that the JND increased from about 100 μsec for the 4 kHz NBN in isolation to about 620 μsec for their condition with a 4 kHz target and a low frequency interfering signal. In the current study, the NH subjects' JNDs increased from about 70 μsec for the 4 kHz NBN to about 180 μsec in 4kd. The absolute values are less important than the fact that the JND increases so dramatically in the 4kd condition with a simultaneously-gated interferer compared to the 4 kHz NBN in isolation. In the current study, all signals were gated simultaneously. This may account for at least some of the binaural interference displayed by the NH subjects. For the

IH subjects, however, it seems unlikely that the gating can account for the interference because most of the subjects are unable to perform the interaural time discrimination task in the 4kd signal condition.

The methodology used by Trahiotis and Bernstein (1990) and in the present study was similar in that both studies employed a two-cue, two-interval adaptive paradigm. However, because the band-reject interferer of Trahiotis and Bernstein had cutoffs that coincided with those of the target signal, the flanking noise may have interfered with discrimination to a greater extent than a spectrally remote masker. This difference could account for the differences in absolute values of the interaural time JNDs.

There are a number of possible explanations for the IH listeners' inability to discriminate interaural time differences in the 4kd condition. First, it is likely among listeners with sensorineural hearing loss of cochlear origin that there is decreased frequency selectivity and a subsequent decrease in neural synchrony in the basal region of the cochleae as a result of cochlear damage (Evans and Harrison, 1975; Liberman and Dodds, 1984). In both of these studies the researchers induced cochlear damage in animals and measured neural tuning curves. A neural tuning curve is produced by presenting a probe tone and plotting the intensity at a specific stimulus frequency necessary to yield

a constant, criterion number of action potentials per second in response to that probe tone.

Evans and Harrison (1975) introduced kanamycin, an aminoglycoside known to have ototoxic effects, into guinea pig cochleae. They subsequently measured neural tuning curves and found that the curves, which have a sharp peak and a low threshold when measured in healthy cochleae, are broadened in shape and raised in threshold after introduction of the ototoxic drug. Interestingly, high frequency fibers were affected to a greater degree than low frequency fibers. Liberman and Dodds (1984) reported similar findings, also from single nerve recordings, in acoustically damaged cochleae of cats.

In humans, psychophysical tuning curves are believed to be a correlate of the neural tuning curves measured in animals. Psychophysical tuning curves are produced by plotting the locus of frequency and intensity necessary to just mask a constant low level tone. Florentine *et al.* (1980) measured psychophysical tuning curves in adult listeners with normal hearing and listeners with impaired hearing. They reported results comparable to those of the Evans and Harrison (1975) and Liberman and Dodds (1984) animal studies. That is, in the normal-hearing listeners the psychophysical tuning curves were sharply tuned with a low threshold while in the impaired-hearing listeners the psychophysical tuning curves were broadened with a raised

threshold. However, measurements of psychophysical tuning curves were made at different SPLs in the normal-hearing and hearing-impaired listeners, which might explain the differences obtained in the tuning curves. That is, with a higher level masker the tuning curve may lose its sharp peak. To explore this possibility, Florentine *et al.* (1980) measured psychophysical tuning curves in NH listeners as a function of level. They then compared the tuning curves from each group at equal SPL levels and showed that the tuning curves of the normal-hearing listeners were still more sharply tuned than those of the impaired-hearing listeners.

The results of these studies show a broadening of neural tuning curve peaks in animals subjected to ototoxic drugs and acoustic trauma as well as broadening of psychophysical tuning curve peaks in humans with cochlear damage. It is reasonable to think that neural synchrony in humans will be adversely affected by the cochlear damage. Such a statement is supported by results of studies which have measured the auditory brainstem response (ABR) in listeners with hearing loss of cochlear origin (e.g., Coats and Martin, 1977). An ABR test is a test of neural synchrony, primarily in the 1-4 kHz region, which records a waveform with five peaks (called Waves I-V) from various sites in the auditory system. Generally speaking, persons with hearing loss of cochlear origin have an indistinct or absent Wave I, and the latency of later waves may be prolonged compared to persons with

normal hearing (Hall, 1992). Thus, it is likely the IH subjects in the present study have broadened tuning curves, accompanied by decreased neural synchrony.

Additionally, listeners with hearing loss of cochlear origin may experience increased upward spread of masking compared to NH listeners (e.g., Gagne, 1988). Upward spread of masking refers to the phenomenon where a masking sound is sufficiently intense to produce more masking at frequencies above the frequency of the masker than at frequencies below the masker (e.g., Wegel and Lane, 1924). Several studies of upward spread of masking have been performed with IH subjects. In most of these studies, investigators (e.g., Gagne, 1988; Florentine *et al.*, 1980) report that listeners with sensorineural hearing losses exhibit a greater amount of upward spread of masking than listeners with normal hearing. Reduced neural synchrony and upward spread of masking explanations for the data of the present study are peripheral and monaural; i.e., cochlear dysfunction is the underlying mechanism operating during these detection experiments.

A second way to explain the results of the IH subjects' interaural discrimination with the **4kd** signal is to consider the interference to be a central phenomenon. Heller (1992), Heller and Trahiotis (1994), and Trahiotis and Bernstein (1990) examined the origin of binaural interference in normal-hearing listeners. Heller (1992) demonstrated that interaural time and intensity discrimination tasks were

differentially affected by the relative spectral characteristics of the signal and interferer, as is seen in the current study for the NH listeners. Heller (1992) examined the possibility of accounting for binaural interference with a peripheral masking explanation. She reasoned that if peripheral masking were the origin of binaural interference, interaural time and intensity discrimination would show the same pattern of spectral interference between the target and interferer (low/high and high/low, respectively). However, for interaural time discrimination an interfering signal lower in frequency than the target caused poorer discrimination than an interfering signal higher in frequency than the target (Heller, 1992). McFadden and Pasanen (1976) and Buell and Trahiotis (1993) reported results similar to Heller's in interaural time discrimination with a high frequency target signal and low frequency interfering signal. For interaural intensity discrimination an interfering signal lower or higher in frequency than the target caused interaural intensity discrimination of the target to be poorer (Heller, 1992). Heller argues that these data do not support a peripheral masking explanation. In the current study a result similar to Heller's was obtained for the NH listeners, but a different result was seen for the IH listeners: in interaural intensity discrimination, there was little change in performance with a high frequency interferer, but the JND

increased with a low frequency interferer, mirroring their performance in the interaural time discrimination task. Because the JNDs for the 4kd signals in interaural time and interaural intensity discrimination of the IH listeners increased with a high frequency target and low frequency interferer, upward spread of masking may explain some of the results obtained for the impaired hearing listeners in the present study.

Trahiotis and Bernstein (1990) also tried to determine whether the interference observed with high and low frequency signal/interferer, respectively, in an interaural time discrimination paradigm could be attributed to a peripheral, monaural phenomenon or a central, binaural one. They postulated that if interference is peripheral, then the interaural correlation of the interfering signal would have no effect on performance. To test this hypothesis they used diotic and uncorrelated interferers. They found that the JND for a diotic, continuous interferer was essentially the same as that for the 4 kHz NBN in isolation, but the JND for an interaurally uncorrelated, continuous interferer was almost double that of the 4 kHz NBN in isolation. Based on these results, the authors argue that a peripheral, monaural explanation is precluded.

While these arguments can explain the results obtained for the NH listeners in this study, they may not be sufficient to explain the results of the IH listeners. It is

clear from the current results that NH and IH listeners do not perform comparably in similar listening conditions. That is, with the 4kd signal the NH listeners show no interference effects in interaural intensity discrimination but do exhibit interference effects in interaural time discrimination, while the IH listeners' performance in the 4kd signal condition demonstrate interference effects in both interaural time and intensity discrimination. Given these performance differences between subject groups, it may be that a peripheral, monaural explanation is a necessary component to completely explain the phenomenon of "binaural interference" in IH listeners. This question could be answered with more research regarding the effects of interaural correlation of masking signals on the performance of interaural discrimination tasks in IH listeners.

Another factor that may have affected the present results concerns the possible effects of level on the performance of the IH listeners. When the IH subjects listened to the double-band stimuli, the .5 kHz NBN was at a higher sensation level than the 4 kHz NBN. To determine whether the IH listeners' results for the conditions when only the 4 kHz NBN signal was dichotic were due to a level effect, a second level condition should be used. In this condition each NBN would be presented at 25 dB SL, referenced to the binaural threshold for that individual with that signal. For example, for a NH listener with thresholds of 10

dB SPL at .5 kHz and 8 dB SPL at 4 kHz, the .5 kHz NBN would be presented at 35 dB SPL and the 4 kHz NBN at 33 dB SPL while for an IH subject with thresholds of 20 dB SPL at .5 kHz and 60 dB SPL at 4 kHz, the .5 kHz NBN would be presented at 45 dB SPL and the 4 kHz NBN at 85 dB SPL. JNDs for each task with each band at equal sensation level would then be measured, and an answer to the question of an effect of level could be obtained. There is evidence (Hawkins and Wightman, 1980; Smoski and Trahiotis, 1986) that when NH and IH listeners are tested with signals of equal sensation level performance of the two groups is much more similar to one another than when tested at equal SPL (due to larger JNDs for the NH group rather than smaller JNDs for the IH group). It is not clear what effect a level manipulation might have on interaural discrimination of signals in the presence of interference. But, it is reasonable to think, based on the results of Hawkins and Wightman (1980) and Smoski and Trahiotis (1986), that NH listeners' performance would be degraded because the overall level of the sounds is reduced. IH listeners with a high frequency loss may demonstrate improved performance in a **4kd** condition with signals at equal sensation level because the low frequency (interfering) signal would be less intense than the high frequency (target) signal. In fact, equal sensation level of the high frequency target and low frequency interfering signals may be sufficient to overcome any peripheral upward spread of

masking effects in IH listeners. The possible effects of level are important to consider in understanding how IH listeners' auditory systems function in binaural processing.

Localisation

Target Signals in Isolation

In Experiment II the distance between source locations was 22.5°. Therefore, the root mean square (RMS) error in degrees indicates the average difference between the perceived source location and the actual source location, without taking direction into account. With the .5 kHz NBN the NH listeners were accurate to about 17°, slightly less than the distance between adjacent source locations and similar to the accuracy of NH listeners reported by Nordlund (1964), Tonning (1975), Noble *et al.* (1994) and Besing and Koehnke (1995). The NH group had more trouble localizing the 4 kHz NBN, with an accuracy of about 25.5°, or slightly greater than the distance between two adjacent source locations. With an RMS value of about 24°, the IH group was significantly less accurate than the NH group for the .5 kHz NBN signal. The IH group RMS error of 29° for the 4 kHz NBN was not significantly different from that of the NH group. Quantitative comparisons between results of the current study and those of previous research is difficult due to differences in the stimuli and methods of data presentation; however, in all previous studies the IH listeners performed less accurately than the NH listeners (Tonning, 1975; Noble

et al., 1994; and Besing and Koehnke, 1995). As shown in Figure 13 the difference in RMS error between the .5 kHz and 4 kHz signal conditions is smaller for the IH listeners than for the NH listeners. Just as with interaural time discrimination, the IH listeners have greater difficulty localizing the .5 kHz NBN than the NH listeners; at 4 kHz the differences in RMS error between groups are still present but are smaller.

There was not a significant difference in RMS localization error between the groups for the 4 kHz NBN in isolation but there was a significant difference between groups for the .5 kHz NBN in isolation. More systematic differences between NH and IH groups might be observed if testing were carried out under different conditions, e.g., more locations in the horizontal plane, vertical and horizontal localization, localization in three dimensions. Noble, Byrne and LePage (1994) measured localization accuracy in the horizontal and vertical planes for listeners with different etiologies, configurations and degree of hearing loss. The stimuli were bursts of pink noise presented through loud speakers placed 18° apart on two hemicircumferential arcs. Listeners with normal hearing achieved 98% correct with an "average error score" (equivalent to the RMS error of the current study) of 1 location, or about 18°, which agrees very well with the 17° RMS error of the NH group for the .5 kHz NBN in the present

study. The Noble *et al.* subjects with sensorineural hearing loss attained 77% correct responses with an average error score of 1.4, or 25.2°. In the present study the IH listeners had an overall RMS error of about 23° for the .5 kHz NBN. The NH and IH listeners in the Noble *et al.* (1994) and the subjects in the current study exhibit similar magnitudes of error.

<u>Target Signals with an Interferer</u>

When an interferer is added in the localization task, some of the IH listeners exhibit a tendency to shift the perceived source location toward the position of the interferer, more so with the high frequency target signal/low frequency interfering signal condition than the reverse (Table 6). Heller (1992) reported her NH subjects tended to shift their identification of source location in the direction of the interfering signal in her lateralization task; however, the NH subjects in the present study did not demonstrate a change in localization performance as a function of the location of the interfering signal. This result in the NH listeners is found for both spectral configurations, high frequency target signal with low frequency interfering signal and vice versa, although localization was more accurate in the low-frequency target signal/high-frequency interfering signal conditions.

The results of this localization experiment raise some interesting questions. First, why doesn't the random

interferer affect localization differently than the fixed interferer for either group? It is expected that as signal uncertainty increases (i.e., the interferer is random), subjects will have more difficulty and localization accuracy will decrease. Such an expectation arises from reports of decrease in performance with signal uncertainty for detection of tones (Wright and Dai, 1994), comodulation masking release (Grose and Hall, 1990), and intensity discrimination (Spiegel *et al.*, 1981). Perhaps because there were only three possible locations for the interferer, most of the listeners learned, then ignored, the interferers at those locations. This seems true of the NH listeners, as they show no tendency to shift their responses toward the location of the interfering signal (Table 6). However, among the IH group there was a tendency to shift responses toward an interfering signal, although overall accuracy was not significantly affected; perhaps if there had been more source locations, it would have been possible to demonstrate a greater effect of interference type on localization accuracy. A more difficult localization task with the interferer randomly presented from any of the nine source locations would likely have a greater effect on localization ability. The results of such a study may provide more insight into the effect of interference on localization.

A second question regarding these results is why did the addition of an interfering noise band not significantly

affect localization accuracy? An explanation may be found in studies which have investigated the dominance of the low frequency portion of a broadband signal in localization (Yost, Wightman and Green, 1971; Wightman and Kistler, 1992). Researchers have reported that with a broadband or multiple component signal which emanates from the same source location (i.e., all interaural information is congruent across frequency), listeners rely on interaural information in the low frequency portion of that signal (Yost, Wightman, and Green, 1971). More recently, evidence has been presented which suggests that listeners rely exclusively on interaural time information which is present in the low frequency portion (Wightman and Kistler, 1992) of a broadband signal, as opposed to interaural intensity and/or monaural spectral information contained in the high frequency portion.

The Wightman and Kistler (1992) study is important to consider because it demonstrates that for localization, NH listeners appear to rely solely on interaural timing information for low frequency signals and interaural intensity information for high frequency signals. For example, they found that with a wideband signal listeners localize a sound source based on the interaural timing information contained in the low frequency portion, even if the interaural intensity and monaural spectral information indicate a source location on the opposite side of the head. With a broadband signal restricted to the high frequencies

(>2.5 kHz), they found the interaural timing information contained in the envelope of the signal is effectively ignored in favor of the interaural intensity and spectral information (Wightman and Kistler, 1992).

If listeners rely solely on interaural timing information to localize the .5 kHz NBN and interaural intensity information to localize the 4 kHz NBN, then the spectral differences between the two bands may not contribute much to interference in localization because the listener is using two separate cues to localize those signals. But if the primary localization cue in the interfering source is the same as the primary cue in the target source, a much greater effect on localization would be expected. If the same cue is being used to localize two signals of different frequency, the signals must both be either <1000 Hz or >1500 Hz. One would then have to be concerned about whether the two might fall into the same "critical band" and be treated as one signal by the ear rather than two signals. Assuming interaural time and intensity cues could be chosen that were close in frequency but not so close together that the ear would process them as one wideband signal, the "same cue" hypothesis could be tested by having subjects localize targets similar to those in the current study but with different interfering sounds. The three conditions would be (1) a target signal with a spectrally remote NBN interfering signal, as in the current experiment (control condition); (2)

the wideband interfering band is spectrally distinct from the target; and (3) the wideband interfering noise encompasses the target band. Using these three conditions the effects of competing interaural information in the target band and no competing interaural information in the target band could be examined. The best localization accuracy would be expected with the two spectrally distinct NBNs (as in the present experiment); poorer localization accuracy would be expected when the interfering sound was a wideband signal but did not encompass the target NBN and the interaural information did not conflict in the same spectral region; and even poorer localization accuracy would be expected when the interfering sound was a wideband signal and encompassed the target NBN and the interaural information conflicted within the target band of noise. The expected bias, or the tendency to shift one's responses toward an interfering signal, would be expected to be greatest when the interaural information is conflicting within the same band of noise and smallest when the interferer is a spectrally remote NBN, with the bias in the third condition falling between those two.

Two of the IH subjects (IH S1 and IH S6) experienced difficulty in localizing the 4 kHz NBN with a .5 kHz NBN interferer. For these subjects, it seems reasonable that the results are due to a level effect. That is, the interfering signal at .5 kHz had a much higher sensation level than the target at 4 kHz so the interaural information in the 4 kHz

NBN target was not detectable, although the 4 kHz NBN was intense enough to be heard by each subject. Smoski and Trahiotis (1986) used equal sound pressure level (80 dB SPL) and equal sensation level (25 dB SL) in an interaural time discrimination task. In the equal SL condition, the intensity levels for the NH listeners ranged between 35 and 65 dB SPL, and the intensity levels for the IH listeners ranged between 35 and 95 dB SPL. These researchers reported all listeners' JNDs got larger in the equal sensation level condition compared to the equal sound pressure level condition.

For IH S6, recall that in the localization experiment he reported sounds apparently emanating from behind his head; something in the stimulus was apparently producing a different perception for him than for all other subjects. The stimuli in the localization experiment were constructed by convolving the impulse responses (called the head-related transfer functions, or HRTFs) measured in KEMAR's ears for each of the nine source locations with the narrow band noise signals. Perhaps IH S6's head-related transfer functions are substantially different from KEMAR's; evidence suggests that listeners' perception of "out of head" signals under headphones decreases when constructed with HRTFs which are different from their own (Kistler and Wightman, 1992). If the HRTFs of KEMAR and IH S6 are sufficiently different, the convolved signals used in the localization task would be

different from the subject's own experience with externalized signals. IH S3 has a hearing loss very similar to that of IH S6 (Figure 2), yet he performed comparably to the NH group in almost every localization condition. The data from IH S3 and IH S6 provide a good example of the vast differences in binaural abilities exhibited by IH listeners with similar audiograms that have been reported by other investigators for various binaural tasks (e.g., Koehnke and Besing, 1995; Koehnke *et al.*, 1995; Tonning, 1975).

Relationship Between Interaural Discrimination and Localization

Zurek (1993) extended the Levitt and Rabiner (1967) model to account for improved speech intelligibility in noise when using two ears compared to one. Two underlying factors for the model were proposed by Zurek: binaural interaction (or capitalizing on the interaural differences in a sound source) and the head-shadow effect. The argument was made that similar measures in the current study, i.e., interaural intensity discrimination and interaural time discrimination, might be used to predict localization accuracy of listeners.

To examine these relationships, data obtained in the present study were first displayed in scatterplots. The scatterplots for the NH listeners (Figure 15) indicate good performance for both interaural time and intensity discrimination and localization of all signals. Due to such good performance on all tasks and the small number of

subjects, further testing or attempts to correlate performance on the two tasks was not warranted. These data do not provide an answer to the question of predicting localization accuracy with interaural time and intensity discrimination measures in NH listeners. Further research on the idea of predicting localization error based on interaural discrimination measures is needed.

Scatterplots for the IH listeners (Figure 16) demonstrate greater variability among the IH subjects than among the NH subjects, with greater variability in the interaural discrimination tasks than the localization task. Following is a comparison of the performances among the IH listeners on the discrimination tasks. Results expected on the localization task based on those discrimination performances are also included.

IH subjects 1, 3, and 5 have performances on interaural time discrimination which are quite similar to one another. That is, their interaural time JNDs for the signal conditions .5 kHz, cong, and 5hd are slightly larger than the JNDs for the NH group but are all <100 μsec. Performance with the 4 kHz and 4kd signals are also similar to one another; all three subjects could discriminate interaural time differences with the 4 kHz signal (with JNDs larger than that of the NH group) but could not discriminate interaural time differences in the 4kd signal.

On the interaural intensity discrimination task IH subjects 1, 3, and 5 have JNDs that are comparable to the NH group's JNDs for the cong and 5hd signal conditions. All three also have interaural intensity JNDs which are substantially larger than those of the NH group in the 4kd condition. The performances of these three subjects vary slightly on interaural intensity discrimination of the NBNs in isolation; subjects 1 and 3 have JNDs comparable to the NH group for the 4 kHz signal and greater than the NH group's JND for the .5 kHz signal while subject 5 has a JND comparable to the NH group for the .5 kHz signal and a larger JND than the NH group for the 4 kHz signal.

Similar performances among these subjects on the localization task would be expected based on the similarity of performances for interaural discrimination. Figure 14 shows that their RMS localization errors are quite similar to one another and to the NH group for the two NBNs in isolation and for the .5T/4F and .5T/4R signal conditions. Because interaural intensity JNDs for these subjects are similar in the 4kd condition and larger than that for the NH group, similar performance among these subjects would be expected on the conditions with a 4 kHz target signal and a .5 kHz interfering signal (4T/.5R and 4T/.5F). While similar RMS localization errors are shown in Figure 14 for IH subjects 3 and 5, which are comparable to the NH group, IH S1 has RMS

localization errors much larger than those of the NH group and IH subjects 3 and 5.

IH S2 has interaural discrimination JNDs which are only slightly larger than those of the NH group in every signal condition for time and intensity discrimination except the **4kd** signal condition for intensity (Figure 8 and 9). His interaural intensity JND for **4kd** is about 2 dB larger than the NH group and the variability in his performance is large. Based on these data it is expected that IH S2 would have RMS localization errors similar to the NH group on all signal conditions except 4T/.5R and 4T/.5F. Instead, his RMS localization errors (Figure 14) are comparable to the NH group on all signal conditions in Experiment II.

IH S4 has JNDs slightly larger than the NH group for interaural time discrimination for **.5 kHz**, **cong**, and **5hd** signal conditions. He cannot discriminate interaural time differences when the relevant information is at 4 kHz (**4 kHz**, **4kd**) (Figure 8). IH S4 can also discriminate interaural intensity differences as well as the NH group with every signal except **4kd** (Figure 9). His RMS localization errors shown in Figure 14 indicate performance comparable to the NH group with the **4 kHz** and **.5T/4R** signals, with performance in the other four signal conditions only slightly worse than the NH group.

IH S6 had the overall worst performance of any of the IH subjects. He is able to discriminate interaural time

differences on .5 kHz, cong, and 5hd, although his JNDs are larger than the NH group and larger than most of the other IH subjects' JNDs. Like IH S4 he is unable to discriminate interaural time differences in the 4 kHz and 4kd signals (Figure 8). Figure 9 shows that his JNDs for interaural intensity discrimination are much larger than the NH group in every signal condition except 5hd, and the variability in his performance is quite large. Given these interaural discrimination performances, which are so much worse than the NH group, it is expected that his RMS localization errors would also be quite large compared to the NH group. That result was not obtained, as shown in Figure 14. IH S6 has RMS localization errors similar to or only slightly worse than the NH listeners for all three signal conditions with a .5 kHz target and for 4 kHz. He exhibits large RMS errors with only the 4T/.5R and 4T/.5F signal conditions, similar to IH S1 who had an interaural intensity JND in the 4kd condition which was about one-half that of IH S6.

Given the variability among the subjects' performances on the interaural discrimination and localization tasks, there does not appear to be a clear, consistent effect of high frequency sensorineural hearing loss on binaural performance. Accordingly, Zurek's model apparently cannot predict results for these impaired-hearing subjects on localization based on interaural time and interaural intensity discrimination.

Summary and Conclusions

Results of the interaural discrimination experiment suggest the following:

(1) both NH and IH groups can ignore a high frequency interfering signal but not a low frequency interfering signal in interaural time discrimination;

(2) NH listeners can ignore the .5 kHz NBN interfering signal in interaural intensity discrimination but cannot ignore the 4 kHz NBN interferer. Because only one of the three NH subjects had trouble with the **5hd** condition, it is likely that most NH listeners are able to ignore a low frequency interfering signal in an intensity discrimination task.;

(3) the IH group can ignore the 4 kHz NBN interfering signal but not the .5 kHz NBN interfering signal in interaural intensity discrimination.

Results of the localization experiment suggest the following:

(1) both NH and IH listeners can ignore a high frequency interferer with a low frequency target signal;

(2) some IH listeners have great difficulty localizing a high frequency target signal in the presence of a low frequency interfering signal (this may be explained as a level effect);

(3) IH listeners have a greater tendency than NH listeners to shift responses toward an interfering signal, though this tendency does not appear to inflate the RMS error.

The results of this study do not show a clear or strong relationship between interaural discrimination and localization performance. Localization and interaural discrimination of the NH subjects is good on all tasks. Changes in the parameters of the study of localization in NH listeners may provide data which could be subjected to analyses to define a relationship between interaural discrimination and localization. For the IH subjects, prediction of expected localization from discrimination results do not hold. Because sensorineural hearing loss does not appear to cause consistent differences in performance for IH listeners compared to NH listeners, extending Zurek's model to predict localization in IH listeners would probably not successfully predict results for IH subjects on localization based on interaural discrimination.

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APPENDIX A

Consent Form

Informed-Consent Document for Listeners with Normal and Impaired Hearing

Localization and Interaural Discrimination of Complex Signals in Normal-Hearing & Hearing-Impaired Listeners

Principal Investigators: Laura Smith, Dr. Janet Koehnke

Department of Communication Sciences and Disorders

Louisiana State University, Baton Rouge, LA 70803

The purpose of this research project is to investigate the ability of normal-hearing and hearing-impaired listeners to discriminate between sounds and locate sounds in various listening situations. The primary goal is to see how the performance of listeners with hearing impairment compares to that of listeners with no hearing impairment in those listening situations. The subjects participating in these experiments are usually obtained from the student body and staff at Louisiana State University, or from the surrounding community.

The procedures used in these experiments are not intended to be therapeutic or rehabilitative in any way. You should realize that the practical benefits of these studies are likely to lie far in the future and do not apply to you directly. If you are a subject with a hearing loss, you will not experience any improvement in your hearing as a consequence of your participation in these experiments. If you are a university student or staff member, your status will not be affected by your participation, and you will receive no special benefits. There will be no monetary compensation for your participation.

During the experiments you will be seated in a quiet, sound-treated room and presented with auditory stimuli through headphones. You will be asked to make judgements concerning certain characteristics of the stimuli that consist of noise, and to record your judgements by pressing a key on a response terminal. Typically, these experiments will involve a number of sessions spaced over a period of weeks or months. Each session generally lasts 2 to 3 hours, interrupted by frequent rest periods.

If at any time during the experiment you wish to take an additional "break", you may do so. Further, your participation is completely voluntary and you may withdraw

your consent to participate at any time without penalty and request that your data not be used in the study. Likewise, the Principal Investigators may terminate the participation of a subject at any time and without advance notice. For example, a subject may be terminated if they cannot complete a task in a way which provides useable data.

The sounds that the subjects listen to in these experiments are not at a level that is loud enough to be harmful under normal conditions and will never exceed 110 decibels sound pressure level. The level of the stimuli typically used will be comparable to that of speech at normal conversation levels of about 70 decibels sound pressure level. Also, you are encouraged to describe to the Principal Investigators or their associates how the stimuli sound to you, and to report to them immediately if any of the sounds are uncomfortable or if you notice any decrease in hearing or experience ringing in your ears. If the situation is uncomfortable in any way, the experimental procedure will be revised. In order to closely monitor the hearing of all subjects, hearing tests will be performed routinely prior to beginning any experiment and at the conclusion of the experiments.

The information and results of these experiments are confidential and will be available only to laboratory personnel. It is expected that the findings from the studies will be published in scientific journals or books, but complete anonymity will be maintained for all subjects in reporting the results. Data will be stored in the laboratory in the Music and Dramatic Arts building.

If at any time you have questions or comments regarding these procedures, or would like further information about the experiments, you are encouraged to ask. You will be provided with a copy of the "Informed consent" form. If the Principal Investigators or their associates ask you any questions during the time you are participating as a subject, you may refuse to answer them.

I have read and understood this description of the procedures and agree to participate in the project. My questions have been answered to my satisfaction and I understand that if I have any questions in the future they will be answered by the Principal Investigators or their associates.

Smith, L. and Koehnke, J., Localization and Interaural Discrimination

It is not the policy of Louisiana State University to compensate subjects in the event that a research procedure results in physical injury. The University will, however, make its most advantageous recommendation upon request.

Subject Name: ______________________________

Date: ______________________________

Signature: ______________________________

Experimenter: ______________________________

Date: ______________________________

Signature: ______________________________

APPENDIX B

Acoustical measurement of each NBN used in Experiment I

Filename	SPL Out Right	SPL Out Left
NB5H1.LKS	109.5	110.0
NB5H2.LKS	110.0	110.5
NB5H3.LKS	111.0	111.5
NB5H4.LKS	110.0	110.0
NB5H5.LKS	110.5	111.0
NB5H6.LKS	109.5	110.0
NB5H7.LKS	110.0	110.5
NB5H8.LKS	109.0	109.5
NB5H9.LKS	110.5	111.0
NB5H10.LKS	112.0	112.0
NB5H11.LKS	109.5	110.0
NB5H12.LKS	110.0	110.0
NB5H13.LKS	112.0	112.0
NB5H14.LKS	111.0	111.5
NB5H15.LKS	110.0	110.5
NB5H16.LKS	112.0	112.0
NB5H17.LKS	109.0	109.5
NB5H18.LKS	111.0	111.5
NB5H19.LKS	111.0	111.5
NB5H20.LKS	111.0	111.5
NB4K1.LKS	108.5	108.5
NB4K2.LKS	109.0	109.0
NB4K3.LKS	107.5	107.5
NB4K4.LKS	109.0	109.0
NB4K5.LKS	109.0	109.0
NB4K6.LKS	110.0	110.0
NB4K7.LKS	108.5	108.5
NB4K8.LKS	107.0	107.0
NB4K9.LKS	107.5	108.0
NB4K10.LKS	109.0	109.0
NB4K11.LKS	109.5	109.5
NB4K12.LKS	109.0	109.0
NB4K13.LKS	107.5	107.5
NB4K14.LKS	108.5	108.5
NB4K15.LKS	109.5	110.0
NB4K16.LKS	109.0	109.0
NB4K17.LKS	108.0	108.0
NB4K18.LKS	109.0	109.5
NB4K19.LKS	109.5	110.0
NB4K20.LKS	109.5	109.5

APPENDIX C

RMS amplitude for each convolved signal used in Experiment II

	LOCATION								
FILENAME	NINE	EIGHT	SEVEN	SIX	FIVE	FOUR	THREE	TWO	ONE
4KC_1.RE	3223.23	3410.16	2912.05	3227.51	2621.16	1375.80	1151.08	896.01	1129.33
4KC_1.LE	2419.41	1929.34	1756.21	2189.07	3339.96	3209.37	3404.45	3545.74	2950.46
4KC_2.RE	3376.66	3093.38	2943.92	2792.01	2368.32	2260.35	1107.21	794.04	993.80
4KC_2.LE	2675.32	1795.28	1838.15	1795.09	2930.06	3299.80	3214.53	2730.97	2743.08
4KC_3.RE	3133.72	3036.37	2932.00	3474.70	2685.37	1344.28	1064.69	865.05	1041.14
4KC_3.LE	2378.93	1754.17	1852.83	2241.07	3482.12	3153.36	3302.00	3084.73	2753.59
4KC_4.RE	3452.43	3253.14	2984.11	3458.74	2377.81	1450.34	1217.24	908.09	1166.91
4KC_4.LE	2718.19	1905.21	1817.51	2326.50	2848.26	3328.92	3475.31	3236.41	2937.63
4KC_5.RE	3279.85	3439.96	2477.19	3209.05	2549.21	1276.12	920.96	1083.20	1263.37
4KC_5.LE	2601.30	2028.32	1503.75	1987.79	3183.57	2996.54	2852.72	3691.30	3264.68
4KC_6.RE	3497.58	3382.21	3180.92	3421.61	2717.49	1490.69	1272.00	1001.09	1164.20
4KC_6.LE	2851.66	2093.56	1962.99	2265.14	3393.60	3539.30	3765.18	3333.32	2962.92
4KC_7.RE	3316.28	3112.29	2625.82	3005.79	2463.41	1482.73	819.06	680.28	1290.29
4KC_7.LE	2556.47	1860.28	1615.85	2020.86	3099.17	3376.04	2474.95	2339.09	3363.79
4KC_8.RE	3223.23	3410.16	2329.83	3227.51	2621.15	1375.80	1151.08	986.01	1129.33
4KC_8.LE	2419.41	1929.34	1405.17	2189.07	3339.96	3209.37	3404.45	3545.74	2950.46
4KC_9.RE	2891.53	3271.29	3636.38	3593.78	2958.90	1379.52	1095.12	925.31	1218.67
4KC_9.LE	2256.00	1898.81	2219.57	2367.31	3596.49	3200.88	3336.72	3185.74	3239.40
4KC_10.RE	3277.63	3161.82	3363.21	3718.84	2685.21	1196.22	1067.46	953.66	1067.18
4KC_10.LE	2660.76	1891.52	2115.01	2315.61	3287.23	2911.05	3176.85	3381.73	2819.01

				LOCATION					
FILENAME	NINE	EIGHT	SEVEN	SIX	FIVE	FOUR	THREE	TWO	ONE
4KC_11.RE	3410.17	3386.92	3329.86	3295.28	2740.00	1463.45	1152.27	1025.74	1052.18
4KC_11.LE	2632.91	2102.30	2058.61	2095.86	3347.44	3293.46	3305.92	3368.99	2796.64
4KC_12.RE	3347.34	3168.72	3157.39	3487.34	2801.66	1385.02	1114.25	815.30	1067.37
4KC_12.LE	2632.81	2012.03	1849.70	2207.31	3354.26	3313.01	3301.49	2906.75	2978.19
4KC_13.RE	3447.26	2678.96	3366.95	3298.26	2515.58	1622.46	1016.81	916.72	1035.99
4KC_13.LE	2755.67	1624.23	2090.84	2173.48	3137.08	3845.82	3183.87	3227.97	2818.42
4KC_14.RE	3003.18	2946.28	3354.34	3226.20	2593.04	1455.10	1082.68	895.71	1244.97
4KC_14.LE	2362.71	1752.85	2050.20	2130.71	3073.98	3250.85	3130.48	3191.20	3389.35
4KC_15.RE	3110.34	3575.44	3084.66	3426.67	2225.63	1427.79	1125.87	760.61	1384.88
4KC_15.LE	2417.34	2094.58	1960.07	2288.17	2809.29	3312.29	3322.70	2536.96	3539.40
4KC_16.RE	2706.94	2008.81	2602.41	2788.11	2512.12	2809.29	3312.29	860.77	1106.73
4KC_16.LE	2095.25	1159.61	1654.30	1901.73	3129.29	1427.80	2307.49	2912.97	2817.95
4KC_17.RE	2895.85	3086.75	3286.97	3239.17	2562.69	1549.21	1138.23	905.34	1177.57
4KC_17.LE	2197.69	1858.40	2054.96	2222.17	3107.25	3514.08	3335.89	3118.39	3143.05
4KC_18.RE	3094.70	3377.12	2906.57	3082.44	2508.73	1403.45	1014.33	917.01	1099.17
4KC_18.LE	2435.69	2109.00	1785.16	2049.00	3161.75	3282.22	3109.94	3302.01	2786.10
4KC_19.RE	3385.60	2873.42	3336.45	3676.48	2950.25	1285.64	937.19	816.61	1365.06
4KC_19.LE	2620.09	1779.36	1975.64	2379.01	3655.02	3086.32	2786.19	2882.09	3540.04
4KC_20.RE	3181.41	3157.43	3476.36	3266.76	2588.58	1182.98	947.60	825.15	1107.44
4KC_20.LE	2523.07	1930.18	2180.47	2133.40	3210.67	2853.55	2820.98	2837.31	2935.75
AVERAGE	2861.64	2508.47	2475.86	2729.86	2913.32	2340.51	2167.99	2004.78	2095.89

				LOCATION					
FILENAME	NINE	EIGHT	SEVEN	SIX	FIVE	FOUR	THREE	TWO	ONE
5HC_1.RE	3525.38	3108.68	3179.93	3516.71	2834.38	2407.85	2728.45	2454.43	2238.13
5HC_1.LE	2199.36	2396.61	2795.57	2323.18	2294.35	2662.71	3636.13	3433.30	3569.75
5HC_2.RE	2902.62	2504.28	2743.98	2956.29	2314.07	2179.58	2333.00	2186.93	1935.75
5HC_2.LE	1737.58	2029.93	2126.93	2178.30	2045.32	2398.88	3075.09	2740.52	3281.88
5HC_3.RE	3454.50	2926.55	3154.10	3517.91	2958.33	2418.43	3047.71	2375.44	2059.04
5HC_3.LE	2241.16	2362.84	2701.29	2530.78	2461.14	2913.70	3590.99	3105.86	3335.96
5HC_4.RE	3400.11	4060.16	3195.24	3688.13	3816.80	3066.98	2714.58	3337.63	2386.15
5HC_4.LE	2128.52	2865.66	2671.05	2592.53	3289.65	3518.30	3779.60	4278.82	3811.30
5HC_5.RE	3697.64	3645.92	3824.83	3518.17	3498.92	3281.00	2681.50	3193.99	2378.88
5HC_5.LE	2076.13	2793.84	3249.17	2547.37	2926.59	3730.40	3478.62	3993.36	3778.66
5HC_6.RE	3864.94	4208.11	3868.34	3487.03	3202.75	3160.25	3109.38	3022.22	2771.09
5HC_6.LE	2747.05	2798.34	2869.55	2296.13	3150.92	3780.51	3772.50	3882.93	3841.51
5HC_7.RE	3366.23	3208.88	3145.47	2771.66	2983.34	2890.91	2614.80	2626.63	1786.19
5HC_7.LE	2163.21	2529.76	2604.11	1880.92	2575.49	3193.62	3453.40	3390.54	2889.42
5HC_8.RE	4729.65	4207.87	3867.92	3505.49	4057.47	3471.71	3538.72	3229.72	2235.72
5HC_8.LE	3131.20	3167.63	3126.22	2504.34	3390.04	3920.14	4385.60	3945.58	3392.95
5HC_9.RE	3500.18	3523.25	3505.99	3760.81	3560.16	3802.58	3668.50	2449.29	2381.21
5HC_9.LE	2078.02	2637.26	2893.74	2717.95	3024.39	4221.18	2449.29	3406.04	3758.86
5HC_10.RE	2850.78	3590.18	3578.78	4198.38	3838.82	3211.89	2592.79	2683.54	1942.73
5HC_10.LE	1797.45	2710.06	2901.92	3029.36	3427.11	3587.01	3461.97	3620.62	3121.81

				LOCATION					
FILENAME	**NINE**	**EIGHT**	**SEVEN**	**SIX**	**FIVE**	**FOUR**	**THREE**	**TWO**	**ONE**
5HC_11.RE	3757.13	3624.00	3701.43	3824.32	3546.92	3356.23	2672.95	2203.32	2562.20
5HC_11.LE	2345.65	2887.67	3254.43	2423.29	2987.31	3629.88	3252.14	3245.49	4047.80
5HC_12.RE	3616.35	3624.99	3300.09	3331.16	3493.66	3280.86	3123.97	3158.43	2136.53
5HC_12.LE	2207.51	2648.16	2715.96	2500.13	3132.90	3675.47	3854.38	4133.22	3433.98
5HC_13.RE	3078.51	3737.89	3590.69	3391.19	3555.96	3275.83	2878.20	2191.41	1788.86
5HC_13.LE	1791.42	2943.83	2717.93	2336.29	3121.60	3802.37	3479.51	2979.77	2945.08
5HC_14.RE	3869.82	3443.07	3317.12	3082.66	3714.47	2872.00	3414.24	2503.92	1892.13
5HC_14.LE	2465.91	2965.93	2754.97	2109.91	3128.97	3079.68	3967.86	3501.93	3208.44
5HC_15.RE	3943.11	3169.69	3553.05	3323.82	3608.80	3295.34	2851.32	2526.50	2451.28
5HC_15.LE	2666.96	2647.43	2917.52	2303.34	2910.55	3906.82	3756.09	3361.11	3797.71
5HC_16.RE	4015.09	3574.35	3699.45	3907.40	3688.32	2982.07	2880.29	2817.56	2451.57
5HC_16.LE	2222.74	2685.38	3282.28	2860.71	2999.40	3178.65	3569.15	3500.37	3837.19
5HC_17.RE	3850.68	4166.76	3025.22	3826.17	3648.57	3197.16	3034.06	2567.92	2024.49
5HC_17.LE	2242.44	3050.75	2581.81	2702.50	3049.97	3728.74	4020.99	3358.88	3485.73
5HC_18.RE	4064.16	3934.91	3922.00	3222.85	2750.27	2617.79	2900.53	2788.67	2507.97
5HC_18.LE	2297.61	2787.92	3563.92	2298.41	2223.38	3064.44	3593.90	3554.62	3930.76
5HC_19.RE	3811.32	3874.35	4006.71	3690.29	3572.94	3156.62	2603.65	2931.22	2064.04
5HC_19.LE	2324.61	3119.83	3292.15	2624.18	3038.50	3718.70	3258.34	3861.24	3409.22
5HC_20.RE	3822.60	3542.26	3392.48	3677.03	3529.99	3340.89	2726.79	2589.12	2024.87
5HC_20.LE	2387.03	2610.19	2757.51	2569.94	2924.27	3908.22	3221.91	3448.54	3258.06
AVERAGE	**2964.41**	**3179.21**	**3194.09**	**2991.77**	**3188.11**	**3310.92**	**3231.80**	**3123.50**	**2851.24**

APPENDIX D

dB SPL values referenced to 108 dB SPL (1 volt) for all samples of .5k and 4 kHz NBNs at location 5 in Experiment II

4 kHz NBN Smpl/R Ear	dB re:108dB SPL (1V RMS)	4 kHz NBN Smpl/L Ear	dB re:108dB SPL (1V RMS)
1	106.06	1	108.17
2	105.18	2	107.03
3	106.27	3	108.53
4	105.22	4	106.78
5	105.82	5	107.75
6	106.38	6	108.31
7	105.52	7	107.52
8	106.06	8	108.17
9	107.12	9	108.81
10	106.27	10	108.03
11	106.45	11	108.19
12	106.64	12	108.21
13	105.71	13	107.62
14	105.97	14	107.45
15	104.64	15	106.67
16	105.69	16	107.60
17	105.87	17	107.54
18	105.68	18	107.69
19	107.09	19	108.95
20	105.95	20	107.83
AVERAGE	**105.98**		**107.84**

.5 kHz NBN Sub/R Ear	dB re:108dB SPL (1V RMS)	.5 kHz NBN Sub/L Ear	dB re:108dB SPL (1V RMS)
1	106.74	1	104.91
2	104.98	2	103.91
3	107.11	3	105.52
4	109.33	4	108.04
5	108.57	5	107.02
6	107.80	6	107.66
7	107.19	7	105.91
8	109.86	8	108.30
9	108.72	9	107.31
10	109.38	10	108.39
11	108.69	11	107.20
12	108.56	12	107.61
13	108.71	13	107.58
14	109.09	14	107.60
15	108.84	15	106.97
16	109.03	16	107.23
17	108.94	17	107.38
18	106.48	18	104.63
19	108.75	19	107.35
20	108.65	20	107.01
AVERAGE	108.27		106.88

APPENDIX E

Acoustical measurement of the location 5 NBNs used in Experiment II

Filename	SPL-R	Filename	SPL-L
5HC51.RE	107.5	5HC51.LE	106.5
5HC52.RE	106.0	5HC52.LE	105.0
5HC53.RE	108.0	5HC53.LE	107.0
5HC54.RE	109.5	5HC54.LE	109.0
5HC55.RE	109.5	5HC55.LE	108.5
5HC56.RE	108.5	5HC56.LE	109.5
5HC57.RE	108.0	5HC57.LE	107.5
5HC58.RE	110.5	5HC58.LE	109.5
5HC59.RE	108.5	5HC59.LE	108.0
5HC510.RE	109.5	5HC510.LE	109.0
5HC511.RE	109.5	5HC511.LE	109.0
5HC512.RE	109.5	5HC512.LE	109.5
5HC513.RE	109.5	5HC513.LE	109.0
5HC514.RE	110.0	5HC514.LE	109.0
5HC515.RE	110.0	5HC515.LE	109.0
5HC516.RE	108.5	5HC516.LE	107.5
5HC517.RE	109.5	5HC517.LE	108.5
5HC518.RE	107.5	5HC518.LE	106.0
5HC519.RE	109.5	5HC519.LE	109.5
5HC520.RE	109.5	5HC520.LE	108.5
4KC51.RE	105.5	4KC51.LE	108.5
4KC52.RE	104.5	4KC52.LE	107.0
4KC53.RE	105.5	4KC53.LE	108.5
4KC54.RE	104.5	4KC54.LE	107.0
4KC55.RE	105.0	4KC55.LE	108.0
4KC56.RE	106.0	4KC56.LE	108.5
4KC57.RE	105.0	4KC57.LE	108.5
4KC58.RE	105.5	4KC58.LE	108.5
4KC59.RE	106.5	4KC59.LE	109.0
4KC510.RE	105.5	4KC510.LE	108.5
4KC511.RE	106.0	4KC511.LE	108.5
4KC512.RE	106.0	4KC512.LE	108.5
4KC513.RE	105.0	4KC513.LE	108.0
4KC514.RE	105.5	4KC514.LE	108.0
4KC515.RE	104.0	4KC515.LE	107.0
4KC516.RE	105.0	4KC516.LE	107.5
4KC517.RE	105.0	4KC517.LE	107.5
4KC518.RE	105.5	4KC518.LE	108.0
4KC519.RE	106.5	4KC519.LE	109.5
4KC520.RE	105.0	4KC520.LE	108.0

APPENDIX F

Raw data for each subject from Experiment I

			IH #1		
TIME JNDS (in μsec)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	37.72	92.96	29.91	35.43	3207.11
	28.29	60.04	46.20	36.10	957.11
	35.43	150.89	25.06	18.86	728.55
	100.22	131.47	21.15	18.86	2000.00
	60.21	266.74	35.43	80.02	1353.55
Mean	52.37	140.42	31.55	37.85	1649.26
Std Dev	29.29	78.84	9.78	25.04	995.51
INTENSITY JNDS (in dB)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	1.75	1.40	1.75	2.40	4.50
	3.50	1.15	1.95	2.40	2.55
	3.00	1.15	0.95	0.80	3.15
	0.85	1.20	1.05	1.00	4.00
	6.50	1.20	1.70	2.75	3.30
Mean	3.12	1.22	1.48	1.87	3.50
Std Dev	2.16	0.10	0.45	0.90	0.76

			IH #2		
TIME JNDS (in μsec)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	75.44	90.12	56.68	30.34	371.86
	56.58	130.69	32.67	40.01	275.89
	32.67	45.53	37.72	30.58	182.14
	75.44	84.30	53.35	25.06	150.89
	33.82	104.01	23.24	40.01	160.04
Mean	54.79	90.93	40.73	33.20	228.16
Std Dev	21.13	31.06	14.09	6.60	94.41
INTENSITY JNDS (in dB)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	1.35	3.25	0.80	1.15	1.05
	1.60	0.40	1.15	1.55	4.00
	0.75	0.60	1.15	2.75	6.25
	3.05	1.75	0.90	1.70	2.20
	1.55	0.60	0.90	3.25	2.70
Mean	1.66	1.32	0.98	2.08	3.24
Std Dev	0.85	1.20	0.16	0.88	1.99

			IE #3		
TIME JNDS (in μsec)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	50.11	390.17	61.16	50.11	1944.54
	53.35	239.28	95.65	52.01	3207.11
	53.35	356.69	34.49	37.72	3414.21
	59.82	382.58	106.69	56.58	2750.00
	75.44	320.08	25.06	47.82	2000.00
Mean	58.41	337.76	64.61	48.85	2663.17
Std Dev	10.15	61.49	36.12	7.00	675.22
INTENSITY JNDS (in dB)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	1.80	0.80	1.70	2.05	1.45
	1.70	1.30	1.55	3.00	3.50
	1.80	1.30	1.50	1.90	2.50
	2.40	1.15	1.40	2.75	4.00
	3.75	0.80	1.35	3.00	4.75
Mean	2.29	1.07	1.50	2.54	3.24
Std Dev	0.86	0.25	0.14	0.53	1.29

			IE #4		
TIME JNDS (in μsec)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	14.95	4000.00	28.29	18.86	4000.00
	43.25	4000.00	63.45	40.01	3414.21
	53.35	3207.11	42.30	26.67	4000.00
	66.29	2457.11	26.67	53.35	2707.11
	46.48	4000.00	37.72	47.82	2853.55
Mean	44.86	3532.84	39.69	37.34	3394.97
Std Dev	18.92	692.46	14.79	14.39	612.12
INTENSITY JNDS (in dB)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	1.55	1.15	1.20	1.15	7.25
	1.30	2.05	1.00	1.20	1.30
	0.80	2.55	1.15	0.95	4.00
	0.90	1.55	1.30	1.90	6.50
	1.15	1.80	1.40	1.20	5.75
Mean	1.14	1.82	1.21	1.28	4.96
Std Dev	0.30	0.53	0.15	0.36	2.37

			IH #5		
TIME JNDS (in µsec)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	59.82	566.94	25.06	64.40	957.11
	24.39	301.78	68.97	75.44	478.55
	26.67	640.17	15.19	22.77	3414.21
	50.11	676.78	70.87	70.87	3414.21
	26.67	390.17	21.15	22.29	603.55
Mean	37.53	515.17	40.25	51.15	1773.53
Std Dev	16.31	162.47	27.32	26.42	1507.98
INTENSITY JNDS (in dB)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	1.30	1.95	1.45	1.45	3.00
	0.85	3.75	0.70	1.80	4.00
	1.55	1.90	1.15	1.15	2.80
	1.55	3.50	0.95	0.60	3.00
	1.70	1.95	1.35	1.90	6.75
Mean	1.39	2.61	1.12	1.38	3.91
Std Dev	0.33	0.93	0.30	0.53	1.66
			IH #6		
TIME JNDS (in µsec)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	56.58	2707.11	92.96	53.35	1707.11
	63.06	2560.66	56.58	75.44	4000.00
	167.30	3414.21	42.30	53.35	1603.55
	18.86	1478.55	122.32	45.53	4000.00
	119.64	2957.11	108.03	42.30	4000.00
Mean	85.09	2623.53	84.44	53.99	3062.13
Std Dev	58.39	717.35	33.97	12.93	1284.75
INTENSITY JNDS (in dB)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	1.55	3.50	0.60	2.75	4.50
	2.75	4.00	3.00	1.45	5.50
	3.00	4.00	2.50	3.25	8.00
	3.75	2.00	1.20	2.50	8.00
	5.25	1.45	4.75	3.25	9.00
Mean	3.26	2.99	2.41	2.64	7.00
Std Dev	1.36	1.19	1.63	0.74	1.90

			MM #1		
TIME JNDS (in µsec)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	14.15	70.87	32.20	18.86	226.33
	25.06	92.96	5.98	33.82	187.50
	20.01	86.49	46.48	9.43	97.54
	25.06	122.32	28.29	13.34	163.87
	35.43	115.85	28.29	36.10	226.33
Mean	23.94	97.70	28.25	22.31	180.31
Std Dev	7.84	21.23	14.52	12.05	53.41
INTENSITY JNDS (in dB)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	1.10	1.00	0.80	2.75	1.30
	0.45	1.05	1.00	1.80	1.40
	0.85	1.15	0.80	1.30	0.90
	1.10	0.80	1.00	0.85	1.30
	1.15	0.90	0.80	0.80	2.05
Mean	0.93	0.98	0.88	1.50	1.39
Std Dev	0.29	0.14	0.11	0.81	0.42
			MM #2		
TIME JNDS (in µsec)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	13.57	48.49	17.72	20.01	75.44
	29.91	53.35	13.34	8.86	75.44
	28.29	30.58	5.86	9.55	59.82
	29.91	26.67	8.05	7.48	53.35
	13.34	47.82	14.15	13.00	87.44
Mean	23.00	41.38	11.82	11.78	70.30
Std Dev	8.74	11.92	4.80	5.03	13.64
INTENSITY JNDS (in dB)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	1.30	1.00	1.40	1.45	1.00
	1.55	0.90	1.15	0.90	0.90
	0.80	1.00	1.00	2.00	1.15
	2.50	0.80	1.15	2.00	1.00
	1.30	1.15	0.90	1.55	1.15
Mean	1.49	0.97	1.12	1.58	1.04
Std Dev	0.63	0.13	0.19	0.46	0.11

			ME #3		
TIME JNDS (in µsec)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	16.91	37.72	30.18	21.26	253.49
	14.15	91.07	38.26	44.59	113.17
	26.67	37.72	18.86	33.82	434.36
	34.49	59.82	20.02	24.39	218.57
	26.67	91.07	29.91	32.77	302.77
Mean	23.78	63.48	27.45	31.37	264.47
Std Dev	8.24	26.75	8.05	9.13	117.74
INTENSITY JNDS (in dB)					
NBN(kHz)	.5 k	4 k	.5+4 k	.5di+4	.5+4di
	1.80	1.30	0.90	3.50	0.60
	1.30	1.30	1.35	3.00	1.50
	0.60	1.40	0.80	0.70	1.30
	1.40	1.55	1.20	3.50	1.15
	1.80	1.00	0.80	3.50	1.30
Mean	1.38	1.31	1.01	2.84	1.17
Std Dev	0.49	0.20	0.25	1.22	0.34

APPENDIX G

Raw data for each subject from Experiment II

See pambinder for diskette

APPENDIX H

Analysis of variance tables

All F-ratios are based on the residual mean square error.

Analysis of Variance for Time JNDs

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
MAIN EFFECTS					
A:group	28880.242	1	28880.242	24.340	0.0000
B:sig	3258.922	2	1629.461	1.373	0.2578
C:rep	1564.996	4	391.249	0.330	0.8574
INTERACTIONS					
AB	2424.3772	2	1212.1886	1.022	0.3636
AC	1553.6614	4	388.4153	0.327	0.8591
BC	5431.1092	8	678.8887	0.572	0.7986
ABC	2621.9699	8	327.7462	0.276	0.9724
RESIDUAL	124587.02	105	1186.5431		
TOTAL	177780.60	134			

Analysis of Variance for Intensity JNDs

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
MAIN EFFECTS					
A:group	55.230050	1	55.230050	36.379	0.0000
B:sig	54.089300	4	13.522325	8.907	0.0000
C:rep	3.431189	4	0.857797	0.565	0.6884
INTERACTIONS					
AB	57.985256	4	14.496314	9.549	0.0000
AC	3.131589	4	0.782897	0.516	0.7243
BC	7.379533	16	0.461221	0.304	0.9958
ABC	8.088244	16	0.505515	0.333	0.9930
RESIDUAL	265.68042	175	1.5181738		
TOTAL	508.46500	224			

Analysis of Variance for Localization RMS, 14 tasks

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
MAIN EFFECTS					
A:group	15.003016	1	15.003016	51.735	0.0000
B:sig	19.651188	13	1.511630	5.213	0.0000
C:rep	0.126635	1	0.126635	0.437	0.5166
INTERACTIONS					
AB	5.5028290	13	0.4232945	1.460	0.1356
AC	0.1739400	1	0.1739400	0.600	0.4479
BC	0.4964376	13	0.0381875	0.132	0.9999
ABC	0.2705725	13	0.0208133	0.072	1.0000
RESIDUAL	56.839059	196	0.2899952		
TOTAL	107.61683	251			

Analysis of Variance for Localization RMS, 6 tasks

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
MAIN EFFECTS					
A:group	5.2201354	1	5.2201354	31.160	0.0000
B:sig	7.9409881	5	1.5881976	9.480	0.0000
INTERACTIONS					
AB	1.9120706	5	0.3824141	2.283	0.0524
RESIDUAL	16.082337	96	0.1675243		
TOTAL	34.862447	107			

Analysis of Variance for Time JNDs

Randomized Block, Blocked on Subject

.5 vs cong vs 5hd in Normal-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	1187.842271	2	593.9211356	3.7536	>.05
Signal	23.490058	2	11.7450289	0.0742	>.05
Exp Er	632.902915	4	158.2257289		
Samp Er	3034.185320	36	84.2829256		
TOTAL	4878.426941	44			

Analysis of Variance for Time JNDs

.5 vs cong vs 5hd in Impaired-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	13941.416860	5	2788.283373	5.9216	<.01
Signal	2087.887247	2	1043.943623	2.2171	>.05
Exp Er	4708.604500	10	470.860450		
Samp Er	43800.965000	72	608.346736		
TOTAL	64538.87361	89			

Analysis of Variance for Intensity JNDs

.5 vs cong vs 5hd in Normal-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	3.07911111	2	1.53955556	1.7240	>.05
Signal	7.54811111	2	3.77405556	4.1994	>.05
Exp Er	3.59488889	4	0.89872222		
Samp Er	12.67600000	36	0.35211111		
TOTAL	26.8981111	44			

Analysis of Variance for Intensity JNDs

.5 vs cong vs 5hd in Impaired-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	27.00480556	5	5.5009611	6.9176	<.001
Signal	7.77738889	2	3.8886944	4.9806	<.025
Exp Er	7.80761111	10	0.7807611		
Samp Er	56.03200000	72	0.7782222		
TOTAL	98.62180556	89			

Analysis of Variance for Time JNDs

4 vs cong vs 4kd in Normal-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	49771.73656	2	24885.86828	1.845	>.05
Signal	175679.3982	2	87839.69908	6.5123	>.05
Exp Er	53952.85401	4	13488.21350		
Samp Er	74031.21136	36	2056.42254		
TOTAL	353435.2001	44			

Analysis of Variance for Intensity JNDs

4 vs cong vs 4kd in Normal-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	0.112	2	0.056	0.3113	>.05
Signal	0.29233333	2	0.14616667	0.8124	>.05
Exp Er	0.71966667	4	0.17991667		
Samp Er	1.953	36	0.05425		
TOTAL	3.07699997	44			

Analysis of Variance for Intensity JNDs

4 vs cong vs 4kd in Impaired-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	54.33555556	5	10.8671111	4.9698	<.025
Signal	144.2177222	2	72.1088611	32.9772	<.005
Exp Er	21.86627778	10	2.1866278		
Samp Er	101.157	72	1.4049583		
TOTAL	321.5765555	89			

Analysis of Variance for Localization RMS, Loc 1 vs 5 vs 9
.5 Target with 4k Fixed, Normal-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	0.01415544	2	0.00707772	0.9064	>.05
Signal	0.00179244	2	0.00089622	0.1148	>.05
Exp Er	0.03123356	4	0.00780839		
Samp Er	0.116421	9	0.01293567		
TOTAL	0.16360244	17			

Analysis of Variance for Localization RMS, Loc 1 vs 5 vs 9
.5 Target with 4k Fixed, Impaired-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	1.91805333	5	0.38361067	16.2119	<.005
Signal	0.08368517	2	0.04184258	1.7683	>.05
Exp Er	0.2366235	10	0.02366235		
Samp Er	0.327387	18	0.01818817		
TOTAL	2.565749	35			

Analysis of Variance for Localization RMS, Loc 1 vs 5 vs 9
.5 Target with 4k Random, Normal-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	0.01059244	2	0.00529622	0.2103	>.05
Signal	0.04278678	2	0.02139338	0.8496	>.05
Exp Er	0.10072489	4	0.02518122		
Samp Er	0.173989	9	0.01933211		
TOTAL	0.71317413	17			

Analysis of Variance for Localization RMS, Loc 1 vs 5 vs 9
.5 Target with 4k Random, Impaired-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	0.582478472	5	0.11649569	1.7728	>.05
Signal	0.198843056	2	0.09942153	1.5130	>.05
Exp Er	0.657120944	10	0.06571209		
Samp Er	0.8589525	18	0.04771958		
TOTAL	2.297394972	35			

Analysis of Variance for Localization RMS, Loc 1 vs 5 vs 9
4 Target with .5 Fixed, Normal-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	0.02838411	2	0.01419206	0.3362	>.05
Signal	0.06648078	2	0.03324039	1.1664	>.05
Exp Er	0.16887722	4	0.04221931		
Samp Er	0.2564755	9	0.02849728		
TOTAL	0.52021761	17			

Analysis of Variance for Localization RMS, Loc 1 vs 5 vs 9
4 Target with .5 Fixed, Impaired-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	13.46877314	5	2.69375463	3.0459	>.05
Signal	0.48885756	2	0.24442878	0.2764	>.05
Exp Er	8.84394144	10	0.88439414		
Samp Er	0.7277615	18	0.04043119		
TOTAL	23.52933364	35			

Analysis of Variance for Localization RMS, Loc 1 vs 5 vs 9
4 Target with .5 Random, Normal-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	0.18736044	2	0.09368022	3.7202	>.05
Signal	0.22036744	2	0.11018372	4.3756	>.05
Exp Er	0.10072489	4	0.02518122		
Samp Er	0.173989	9	0.01933211		
TOTAL	0.68244177	17			

Analysis of Variance for Localization RMS, Loc 1 vs 5 vs 9
4 Target with .5 Random, Impaired-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	21.16319492	5	4.23263898	10.4123	<.005
Signal	1.87446317	2	0.93723158	2.3056	>.05
Exp Er	4.06502017	10	0.40650202		
Samp Er	1.4919745	18	0.08288747		
TOTAL	28.59465276	35			

Analysis of Variance for Localization RMS, .5 kHz vs .5T/4F vs .5T/4R (runs collapsed across the fixed and random conditions), Normal-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	0.038791	2	0.0193955	1.3699	>.05
Signal	0.01875833	2	0.00937917	0.6625	>.05
Exp Er	0.05663267	4	0.01415817		
Samp Er	0.089936	9	0.00999289		
TOTAL	0.204118	17			

Analysis of Variance for Localization RMS, .5 kHz NBN vs .5T/4F vs .5T/4R (runs collapsed across the fixed and random conditions), Impaired-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	1.21675558	5	0.24335112	13.5061	<.005
Signal	0.12285817	2	0.06142908	3.4093	>.05
Exp Er	0.1801785	10	0.01801785		
Samp Er	0.2681025	18	0.01489458		
TOTAL	1.78789475	35			

Analysis of Variance for Localization RMS, 4 kHz NBN vs 4T/.5F vs 4T/.5R (runs collapsed across the fixed and random conditions), Normal-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	0.01546211	2	0.00773106	0.3220	>.05
Signal	0.01130144	2	0.00565072	0.2353	>.05
Exp Er	0.09605122	4	0.02401281		
Samp Er	0.199165	9	0.02212944		
TOTAL	0.32197977	17			

Analysis of Variance for Localization RMS, 4 kHz NBN vs 4T/.5F vs 4T/.5R (runs collapsed across the fixed and random conditions), Impaired-hearing listeners

Source	Sum of Squares	Df	Mean Square	F-ratio	Signif Level
Subj	9.44429814	5	1.88885963	4.7069	<.025
Signal	4.47860822	2	2.23930411	5.6869	<.025
Exp Er	3.93766177	10	0.39376618		
Samp Er	0.6023855	18	0.03346586		
TOTAL	18.46295363	35			

APPENDIX I

Duncan's multiple range tests

Multiple range analysis for group on time discrimination task. Normal-hearing and impaired-hearing groups.

Method: 95 Percent Duncan

Level	Count	LS Mean	Homogeneous Groups
1 (NH)	75	61.42267	X
2 (IH)	150	301.44513	X

contrast	difference
1 - 2	-240.022 *

* denotes a statistically significant difference at the p<.05 significance level on all tests which follow.

Multiple range analysis for signal condition on time discrimination. Normal-hearing and impaired-hearing groups.

Level	Count	LS Mean	Homogeneous Groups
4 (5hd)	45	32.84883	X
3 (cong)	45	36.35800	X
1 (.5 kHz)	45	45.23233	X
2 (4 kHz)	45	292.45483	X
5 (4kd)	45	500.27550	X

contrast	difference
1 - 2	-247.222 *
1 - 3	8.87433
1 - 4	12.3835
1 - 5	-455.043 *
2 - 3	256.097 *
2 - 4	259.606 *
2 - 5	-207.821 *
3 - 4	3.50917
3 - 5	-463.918 *
4 - 5	-467.427 *

Multiple range analysis for subject on time discrimination task: .5 kHz vs cong vs 5hd. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups
4	15	39.63	X
1	15	40.59	X
2	15	42.91	X
5	15	42.98	X
3	15	57.29	XX
6	15	74.51	X

contrast	difference
1 - 2	- 2.32
1 - 3	-16.70
1 - 4	0.96
1 - 5	- 2.39
1 - 6	-33.92*
2 - 3	-14.38
2 - 4	3.28
2 - 5	- 0.07
2 - 6	-31.60*
3 - 4	17.66
3 - 5	14.31
3 - 6	-17.22
4 - 5	- 3.35
4 - 6	-34.88*
5 - 6	-31.53*

Multiple range analysis for signal condition on time discrimination task: 4 kHz vs cong vs 4kd. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups
2 (cong)	30	44.95	X
1 (4 kHz)	30	455.26	X
3 (4kd)	30	871.36	X

contrast	difference
1 - 2	410.31
1 - 3	-416.10
2 - 3	-826.41*

Multiple range analysis for group on intensity discrimination task. Normal-hearing and impaired-hearing groups.

Level	Count	LS Mean	Homogeneous Groups
1 (NH)	75	1.3060000	X
2 (IH)	150	2.3570000	X

-contrast	difference
1 - 2	-1.05100 *

Multiple range analysis for intensity discrimination of group and signal condition interaction for the normal-hearing and impaired-hearing groups.

Level	Count	LS Mean	Homogeneous Groups
3 (cong-NH)	45	1.00	X
2 (4 kHz-NH)	45	1.09	X
5 (4kd)	45	1.20	X
1 (.5 kHz-NH)	45	1.27	X
8 (cong-IH)	45	1.45	X
7 (4 kHz-IH)	45	1.84	X
4 (5hd-NH)	45	1.97	X
9 (5hd-IH)	45	1.97	X
6 (.5 kHz-IH)	45	2.14	X
10 (4kd-IH)	45	4.31	X

contrast	difference
1 - 2	0.20
1 - 3	0.27
1 - 4	-0.70
1 - 5	0.07
1 - 6	-0.87
1 - 7	-0.57
1 - 8	-0.18
1 - 9	-0.70
1 - 10	-3.04*
2 - 3	0.07
2 - 4	-0.90
2 - 5	-0.13
2 - 6	-1.07
2 - 7	-0.77
2 - 8	-0.38
2 - 9	-0.90
2 - 10	-3.24*

3 - 4	-0.97
3 - 5	-0.20
3 - 6	-1.14
3 - 7	-0.84
3 - 8	-0.45
3 - 9	-0.97
3 - 10	-3.31
4 - 5	0.77
4 - 6	-0.17
4 - 7	0.13
4 - 8	0.52
4 - 9	0.00
4 - 10	-2.34*
5 - 6	-0.94
5 - 7	-0.64
5 - 8	-0.25
5 - 9	-0.77
5 - 10	-3.11*
6 - 7	0.30
6 - 8	0.69
6 - 9	0.17
6 - 10	-2.17*
7 - 8	0.39
7 - 9	-0.13
7 - 10	-2.47*
8 - 9	-0.52
8 - 10	-2.86*
9 - 10	-2.34*

Multiple range analysis for signal condition on intensity discrimination task: .5 kHz vs cong vs 5hd. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups
2 (cong)	30	1.45	X
1 (5hd)	30	1.97	X
3 (.5 kHz)	30	2.14	X

contrast	difference
1 - 2	-0.52
1 - 3	-0.69
2 - 3	-0.17

Multiple range analysis for subject on intensity discrimination task: .5 kHz vs cong vs 5hd. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups
4	15	1.21	X
5	15	1.30	XX
2	15	1.57	XX
3	15	2.11	XX
1	15	2.16	XX
6	15	2.77	X

contrast	difference
1 - 2	0.59
1 - 3	0.05
1 - 4	0.95*
1 - 5	0.86
1 - 6	-0.61
2 - 3	-0.54
2 - 4	0.36
2 - 5	0.27
2 - 6	-1.20*
3 - 4	0.90*
3 - 5	0.81
3 - 6	-0.66
4 - 5	-0.09
4 - 6	-1.56*
5 - 6	-1.47*

Multiple range analysis for signal condition on intensity discrimination task: 4 kHz vs cong vs 4kd. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups
2 (cong)	30	1.45	X
1 (4kd)	30	1.84	X
3 (4 kHz)	30	4.31	X

contrast	difference
1 - 2	0.39
1 - 3	-2.47*
2 - 3	-2.86*

Multiple range analysis for subject on intensity discrimination task: 4 kHz vs cong vs 4kd. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups	
2	15	1.85	X	
3	15	1.94	X	
1	15	2.07	X	
5	15	2.55	X	
4	15	2.66	X	
6	15	4.13		X

contrast	difference
1 - 2	0.22
1 - 3	0.13
1 - 4	-0.59
1 - 5	-0.48
1 - 6	-2.06*
2 - 3	-0.09
2 - 4	-0.81
2 - 5	-0.70
2 - 6	-2.28*
3 - 4	-0.72
3 - 5	-0.61
3 - 6	-2.19*
4 - 5	-0.11
4 - 6	-1.47*
5 - 6	-1.75*

Multiple range analysis for group on localization task (14 signal conditions). Normal-hearing and impaired-hearing listeners.

Level	Count	LS Mean	Homogeneous Groups	
1 (NH)	84	0.9773095	X	
2 (IH)	168	1.4949107		X

contrast	difference
1 - 2	-0.51760 *

Multiple range analysis for signal condition (14 conditions) on localization task. Normal-hearing and impaired-hearing groups.

Level	Count	LS Mean	Homogeneous Groups
1 (.5 Khz)	18	0.8901667	X
3 (.5T4F5)	18	0.9366250	X
6 (.5T4R5)	18	0.9490833	X
2 (.5T4F1)	18	0.9715000	X
5 (.5T4R1)	18	0.9733750	X
7 (.5T4R9)	18	0.9856667	X
4 (.5T4F9)	18	1.0059583	X
8 (4 kHz)	18	1.2043750	XX
10 (4T.5F5)	18	1.4865417	XX
9 (4T.5F1)	18	1.5103333	XX
12 (4T.5R1)	18	1.5338333	XX
13 (4T.5R5)	18	1.5496667	XX
11 (4T.5F9)	18	1.5984583	XX
14 (4T.5R9)	18	1.7099583	X

contrast	difference	
1 - 2	-0.08133	
1 - 3	-0.04646	
1 - 4	-0.11579	
1 - 5	-0.08321	
1 - 6	-0.05892	
1 - 7	-0.09550	
1 - 8	-0.31421	
1 - 9	-0.62017	*
1 - 10	-0.59638	*
1 - 11	-0.70829	*
1 - 12	-0.64367	*
1 - 13	-0.65950	*
1 - 14	-0.81979	*
2 - 3	0.03488	
2 - 4	-0.03446	
2 - 5	-0.00188	
2 - 6	0.02242	
2 - 7	-0.01417	
2 - 8	-0.23288	
2 - 9	-0.53883	*
2 - 10	-0.51504	*
2 - 11	-0.62696	*
2 - 12	-0.56233	*
2 - 13	-0.57817	*
2 - 14	-0.73846	*
3 - 4	-0.06933	
3 - 5	-0.03675	
3 - 6	-0.01246	
3 - 7	-0.04904	
3 - 8	-0.26775	

3 - 9	-0.57371 *
3 - 10	-0.54992 *
3 - 11	-0.66183 *
3 - 12	-0.59721 *
3 - 13	-0.61304 *
3 - 14	-0.77333 *
4 - 5	0.03258
4 - 6	0.05687
4 - 7	0.02029
4 - 8	-0.19842
4 - 9	-0.50438 *
4 - 10	-0.48058 *
4 - 11	-0.59250 *
4 - 12	-0.52788 *
4 - 13	-0.54371 *
4 - 14	-0.70400 *
5 - 6	0.02429
5 - 7	-0.01229
5 - 8	-0.23100
5 - 9	-0.53696 *
5 - 10	-0.51317 *
5 - 11	-0.62508 *
5 - 12	-0.56046 *
5 - 13	-0.57629 *
5 - 14	-0.73658 *
6 - 7	-0.03658
6 - 8	-0.25529
6 - 9	-0.56125 *
6 - 10	-0.53746 *
6 - 11	-0.64938 *
6 - 12	-0.58475 *
6 - 13	-0.60058 *
6 - 14	-0.76088 *
7 - 8	-0.21871
7 - 9	-0.52467 *
7 - 10	-0.50088 *
7 - 11	-0.61279 *
7 - 12	-0.54817 *
7 - 13	-0.56400 *
7 - 14	-0.72429 *
8 - 9	-0.30596
8 - 10	-0.28217
8 - 11	-0.39408
8 - 12	-0.32946
8 - 13	-0.34529
8 - 14	-0.50558 *
9 - 10	0.02379
9 - 11	-0.08812
9 - 12	-0.02350
9 - 13	-0.03933
9 - 14	-0.19963
10 - 11	-0.11192

10 - 12	-0.04729
10 - 13	-0.06312
10 - 14	-0.22342
11 - 12	0.06463
11 - 13	0.04879
11 - 14	-0.11150
12 - 13	-0.01583
12 - 14	-0.17613
13 - 14	-0.16029

Multiple range analysis for group (6 signal conditions, collapsed across interferer location) on localization task. Normal-hearing and impaired-hearing groups.

Level	Count	LS Mean	Homogeneous Groups
1 (NH)	36	0.9731111	X
2 (IH)	72	1.4394861	X

contrast	difference
1 - 2	-0.46638 *

Multiple range analysis for signal condition (6 signal conditions, collapsed across interferer location) on localization task. Normal-hearing and impaired-hearing groups.

Level	Count	LS Mean	Homogeneous Groups
1 (.5 kHz)	18	0.8901667	X
4 (.5T/4R)	18	0.9787917	XX
3 (.5T/4F)	18	0.9850833	XX
2 (4 kHz)	18	1.2043750	X
5 (4T/.5F)	18	1.5605417	X
6 (4T/.5R)	18	1.6188333	X

contrast	difference
1 - 2	-0.31421 *
1 - 3	-0.09492
1 - 4	-0.08862
1 - 5	-0.67037 *
1 - 6	-0.72867 *

2 - 3	0.21929
2 - 4	0.22558
2 - 5	-0.35617 *
2 - 6	-0.41446 *
3 - 4	0.00629
3 - 5	-0.57546 *
3 - 6	-0.63375 *
4 - 5	-0.58175 *
4 - 6	-0.64004 *
5 - 6	-0.05829

Multiple range analysis for subject on localization task: .5 kHz vs .5T/4F vs .5T/4R signal conditions. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups
3	6	0.70	X
1	6	1.17	X
2	6	1.17	X
5	6	1.18	X
4	6	1.20	X
6	6	1.22	X

contrast	difference
1 - 2	0.00
1 - 3	0.47*
1 - 4	-0.03
1 - 5	-0.01
1 - 6	-0.05
2 - 3	0.47*
2 - 4	-0.03
2 - 5	-0.01
2 - 6	-0.05
3 - 4	-0.50*
3 - 5	-0.48*
3 - 6	-0.52*
4 - 5	0.02
4 - 6	-0.02
5 - 6	-0.04

Multiple range analysis for subject on localization task: 4 kHz vs 4T/.5F vs 4T/.5R signal conditions. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups
3	6	1.32	X
2	6	1.38	X
4	6	1.47	X
5	6	1.49	X
1	6	2.29	XX
6	6	2.65	X

contrast	difference
1 - 2	0.91
1 - 3	0.97
1 - 4	0.82
1 - 5	0.80
1 - 6	-0.36
2 - 3	0.06
2 - 4	-0.09
2 - 5	-0.11
2 - 6	-1.27*
3 - 4	-0.15
3 - 5	-0.17
3 - 6	-1.33*
4 - 5	0.02
4 - 6	-1.18*
5 - 6	-1.16*

Multiple range analysis for signal condition on localization task: 4 kHz vs 4T/.5F vs 4T/.5R. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups
1 (4 kHz)	12	1.278	X
2 (4T/.5F)	12	1.932	X
3 (4T/.5R)	12	2.094	X

contrast	difference
1 - 2	-0.654
1 - 3	-0.816
2 - 3	-0.162

Multiple range analysis for subject on the localization task: .5T/4F signal conditions. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups
3	6	0.65	X
2	6	1.15	X
5	6	1.15	X
4	6	1.25	X
1	6	1.25	X
6	6	1.38	X

contrast	difference
1 - 2	0.10
1 - 3	0.60*
1 - 4	0.00
1 - 5	0.10
1 - 6	-0.13
2 - 3	0.50*
2 - 4	-0.10
2 - 5	0.00
2 - 6	-0.23
3 - 4	-0.60*
3 - 5	-0.50*
3 - 6	-0.73*
4 - 5	0.10
4 - 6	-0.13
5 - 6	-0.23

Multiple range analysis for subject on localization task:
4T/.5R signal condition. Impaired-hearing group.

Level	Count	LS Mean	Homogeneous Groups
3	6	1.37	X
2	6	1.45	X
5	6	1.60	X
4	6	1.66	X
1	6	3.08	X
6	6	3.20	X

contrast	difference
1 - 2	1.63*
1 - 3	1.71*
1 - 4	1.42*
1 - 5	1.48*
1 - 6	-0.12
2 - 3	0.08
2 - 4	-0.21
2 - 5	-0.15
2 - 6	-1.75*
3 - 4	-0.29
3 - 5	-0.23
3 - 6	-1.83*
4 - 5	0.06
4 - 6	-1.54*
5 - 6	-1.60*

APPENDIX J

Paired *t*-Tests run on frequency in Experiment II

* denotes significance difference at $\alpha = 0.05$.

Normal-hearing group:

<u>.5 kHz vs 4 kHz</u>

Mean $d_i = 0.384666$ $\Sigma d_i^2 = 1.083706$

$s_d^2 = 0.039179066$ $s_d = 0.197939027$

$t = d_i / (s_d/\sqrt{n})$

$= 0.384666666/(0.197939027/\sqrt{3})$

$= 4.76$*

<u>.5T/4F vs 4T/.5F</u>

Mean $d_i = 0.382333$ $\Sigma d_i^2 = 1.010394$

$s_d^2 = 0.026664266$ $s_d = 0.163291967$

$t = d_i / (s_d/\sqrt{n})$

$= 0.382333/(0.163291967/\sqrt{3})$

$= 5.73$*

<u>.5T/4R vs 4T/.5R</u>

Mean $d_i = 0.323666$ $\Sigma d_i^2 = 0.77767$

$s_d^2 = 0.029821866$ $s_d = 0.172690088$

$t = d_i / (s_d/\sqrt{n})$

$= 0.323666/(0.172690088/\sqrt{3})$

$= 4.59$*

Impaired-hearing group:

.5 kHz vs 4 kHz

Mean d_i = 0.24375 $\Sigma\ d_i^2$ = 1.207217

s_d^2 = 0.044931659 s_d = 0.211970892

$t = d_i\ /\ (s_d/\sqrt{n})$

$= 0.24375/(0.211970892/\sqrt{6})$

$= 3.98$*

.5T/4F vs 4T/.5F

Mean d_i = 0.768666 $\Sigma\ d_i^2$ = 11.5+-85032

s_d^2 = 0.408622787 s_d = 0.639236097

$t = d_i\ /\ (s_d/\sqrt{n})$

$= 0.768666/(0.63923697/\sqrt{6})$

$= 4.17$*

.5T/4R vs 4T/.5R

Mean d_i = 0.987916 $\Sigma\ d_i^2$ = 18.803473

s_d^2 = 0.644701901 s_d = 0.80293331

$t = d_i\ /\ (s_d/\sqrt{n})$

$= 0.987916/(0.80293331/\sqrt{6})$

$= 4.59$*

VITA

Laura Smith received her Bachelor's degree in English, with a concentration in linguistics, from Louisiana State University in 1985. Ms. Smith was a Pre-doctoral Fellow in Audiology with the Veteran's Administration in 1992-1993. While working at the Veteran's Administration Medical Center in New Orleans, Louisiana, she obtained her Certificate of Clinical Competence in Audiology from the American Speech-Language-Hearing Association. She earned a Master's degree in Audiology from Louisiana State University in 1994, and is currently working as a clinical audiologist at The Ear, Nose, and Throat Center in Shreveport, Louisiana. Ms. Smith will begin teaching as an Assistant Professor at Southwest Missouri State University in the Fall semester, 1995.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Laura K Smith

Major Field: Communication Disorders

Title of Dissertation: Interaural Discrimination and Localization of Cross-Frequency Stimuli in Normal-Hearing and Impaired-Hearing Listeners

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Co-Chair

Date of Examination:

03/27/95