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THE EFFECT OF REVERBERATION TIME ON THE SPEECH DISCRIMINATION PERFORMANCE OF HEARING IMPAIRED INDIVIDUALS UNDER MONAURAL AND BINAURAL AMPLIFICATION

by

STANLEY A. GELFAND

A dissertation submitted to the Graduate
Faculty in Speech and Hearing Sciences in
partial fulfillment of the requirements
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1973

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May 1, 1973
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Abstract

THE EFFECT OF REVERBERATION TIME ON THE SPEECH DISCRIMINATION PERFORMANCE OF HEARING IMPAIRED INDIVIDUALS UNDER MONAURAL AND BINAURAL AMPLIFICATION

by

Stanley A. Gelfand

Advisor: Professor Irving Hochberg

This study investigated the effects of reverberation time upon the monaural and binaural speech discrimination of normal hearing persons and those with bilateral sensorineural hearing loss of cochlear origin. The Modified Rhyme Test was administered at reverberation times of 0, 1, 2 and 3 seconds to 30 normal and 30 hearing impaired subjects, monaurally and binaurally. Ten of the normals received monaural tests at sensation levels of 25, 30, 35 and 40 dB, and each of the hearing impaired subjects received an additional monaural test at 5 dB above the monaural administration level of the main experiment, to determine the effects of loudness increases upon the scores.

The following results were obtained: (a) For all conditions, the normal subjects performed significantly better than the impaired group, although a similar trend in the monaural vs. binaural results of both groups was evident. (b) Binaural discrimination scores were significantly higher at each reverberation time, for both groups. (c) For both groups, discrimination scores decreased with increasing reverberation time, both monaurally and binaurally. (d) Monaural scores were degraded at a faster rate than binaural scores with increasing reverberation time. This effect was more marked for the normal group. (e) Increasing the loudness of the monaural stimuli, to simulate the binaural loudness gain, did not result in significantly higher scores for either group.

It was concluded that binaural speech discrimination is superior to monaural under reverberation for both normal and hearing impaired persons. This is due, at least in part, to the ability of the binaural system, in and of itself, to squelch the effects of reverberation. Increasing reverberation results in decreased discrimination for both normals and those with impaired hearing. This degradation of discrimination ability as a function of reverberation time is more rapid monaurally than binaurally, reflecting the ability of the binaural system to squelch the effects of reverberation.

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Stanley A. Gelfand

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CHAPTER I

INTRODUCTION

A rather extensive body of literature attests to the advantages obtained when a normal hearing individual listens with both ears as opposed to just one. These benefits have been found to apply not only to artificial stimuli such as pure tones, but also to the perception of speech.

A similarly large amount of research has been carried out with the hearing impaired population under binaural and monaural amplification. Whereas virtually conclusive binaural advantages may be cited for the normal hearer, and while clinical reports in and out of the literature seem to indicate binaural advantages under amplification, the experimental reports attempting confirmation of such binaural benefits for the hearing impaired have generated equivocal results.

Many of the studies attempting to differentiate the performance of hearing impaired subjects under binaural and monaural amplification have employed noise in their testing procedures as a factor which frequently characterizes difficult listening situations. It is possible that the benefits reported by binaural hearing aid wearers, but which have not been conclusively corroborated in the laboratory, may at least partially be related to the resistance to reverberation offered by the use of two hearing aids instead of one.

It has been demonstrated that binaural hearing provides normal hearing individuals with resistance to the deleterious effects of reverberation. Further, while the overall level of speech discrimination performance decreases under prosthetic amplification (as would be expected due to the relatively low fidelity of such instruments), it has been shown that normal individuals demonstrate a similar reduction in speech discrimination when listening through hearing aids as for unaided listening, under reverberation.

It appears contradictory that such binaural effects, which are attributable to the auditory neural system, should be absent in an individual with deterioration of presumably peripheral functioning. It appears that investigation is warranted concerning the ability of persons with sensorineural hearing loss (of presumably cochlear origin) to perceive speech monaurally and binaurally under reverberant conditions. The results of such investigation should increase the understanding of the problems associated with the use of binaural hearing aids. In addition, the data are also expected to shed further light upon the theoretical aspects abnormal auditory functioning, and may have implications for the use of reverberant stimuli in both diagnostic and rehabilitative audiological programs.

The fundamental problem may be stated in the form of the following question: Is it possible that the superior performance in various listening situations reported by binaural hearing aid wearers is related to resistance to reverberation offered to them when the signal is amplified to within the usable range of both ears? Specifically, will speech discrimination scores under conditions of reverberation be superior binaurally or monaurally? Subproblems are as follows:

(1) Will speech discrimination ability among subjects with symmetrical sensorineural hearing loss be inferior relative to that of normal hearing subjects under different reverberation times, when the signals are presented monaurally and binaurally?

(2) Will speech discrimination ability among hearing impaired individuals be superior monaurally or binaurally for various reverberation times?

(3) Under the monaural condition, will the speech discrimination ability of the hearing impaired subjects be correspondingly degraded with increases in reverberation time?

(4) Under the binaural condition, will the speech discrimination ability of the hearing impaired subjects be

correspondingly degraded with increases in reverberation time?

(5) Will the speech discrimination ability of the hearing impaired subjects be degraded at a slower rate as reverberation time increases under the binaural condition than under the monaural condition?

Hypotheses

(1) There will be no significant differences in speech discrimination performance of subjects with bilateral symmetrical sensorineural hearing loss and of normal hearing subjects under conditions of monaural and binaural presentation, for various reverberation times.

(2) There will be no significant differences between the speech discrimination scores obtained monaurally and binaurally at each reverberation time for both normal and hearing impaired subjects.

(3) There will be no significant differences between the speech discrimination scores obtained binaurally at the various reverberation times for both normal and hearing impaired subjects.

(4) There will be no significant differences between the speech discrimination scores obtained monaurally at the various reverberation times for both normal and hearing impaired subjects.

(5) There will be no significant differences between the rates at which discrimination performance decreases as a function of reverberation time for monaural and binaural conditions among normal and hearing impaired subjects.

Definitions

Binaural: Binaural hearing refers to hearing with two ears.

Binaural Squelch: The binaural squelch effect refers to the ability of the individual to overcome the deleterious effects of reverberation and background noise, and to attend to a desired message, when listening with two ears (Koenig, 1950).

Dichotic: Dichotic refers to the presentation of a signal to both ears when some aspect of the signal differs at one ear relative to the other (Sonn, 1969).

Diotic: Diotic refers to the identical presentation of a signal to both ears (Sonn, 1969).

Head Shadow: The head shadow effect refers to the acoustic shadow cast by the head when it lies between a sound source and the ear receiving the sound.

Monaural: Monaural hearing refers to hearing with one ear.

Monotic: Monotic refers to the presentation of a signal to one ear (Sonn, 1969).

Pseudobinaural: Pseudobinaural, with reference to hearing aid use, refers to the use of one hearing aid whose output is directed to both ears. This is a diotic condition.

Reverberation: Reverberation refers to "the persistence of a sound in an enclosed space, as a result of multiple reflections after the sound source has been stopped" (Peterson and Gross, 1967, p. 223).

Reverberation Time: Reverberation time is the time required for the root-mean-square (rms) sound pressure level of a reverberant signal to decay by 60 dB after the sound source has been stopped (Peterson and Gross, 1967).

Signal-to-Noise (S/N) Ratio: Unless otherwise specified, the signal-to-noise ratio refers to "the ratio of the signal to the corresponding noise, where the signal and noise may be electric energy, electric power, voltage, current . . . , sound energy, sound pressure and sound partical velocity . . . ." (Sonn, 1969, p. 46).

Y-Cord: Y-cord refers to the diotic use of a hearing aid; i.e., the equivalent of "pseudobinaural." The term specifically refers to the shape of the wire leading from a hearing aid to the two ears, with the base of the "Y" arising from the output of the hearing aid, and the two upper parts of the "Y" being the bifurcation of the former single wire to lead to each ear.

CHAPTER II

REVIEW OF THE LITERATURE

BINAURAL HEARING

The advantages of binaural over monaural hearing have been delineated by numerous investigators. In the areas of localization, masking, loudness, and intelligibility, the cited advantages have led to the concept that "two ears are better than one." In addition, listening in reverber-and enclosures has been shown to be improved binaurally, reflecting an improved discriminating effect, and it has been shown that binaural hearing permits one to overcome (squelch) the effects of reverberation and noise.

The following review of literature is presented in relation to each of the factors cited above, and where appropriate, discussion is related to hearing impaired individuals under amplification.

LOCALIZATION

Sounds heard by an individual in a sound field are perceived to be *localized* extracranially in the environment; whereas sound heard through headphones are perceived to arise intracranially with the image *lateralized* along a plane between the two ears (Littler, 1965; Bocca, Teatini and Antonelli, 1967).

It is generally accepted that differences in interaural intensity and phase (time delay) account for localization of sounds (Konig, 1964). There is, however, some evidence to suggest that quality differences provide the individual with some localizing ability monaurally (Mouzon, 1955; Mathes,1955).

The early work of Rayleigh (1907) was cited by Littler (1965) as the first to establish the relation between time differences at the two ears and localization. Rayleigh calculated that the head shadow effect was negligible at low frequencies, and concluded that localization depends on interaural time differences for low tones. He further concluded that while azimuth positions of pure tones can be accurately perceived, the same cannot be said for front vs. rear discriminations. He asserted that in the case of complex waves like speech, such front-rear discriminations are based on quality differences due to diffraction effects of the skull and outer ears.

In 1936, Stevens and Newman concluded that since front-rear discriminations are more difficult for lower frequencies (for which phase differences determine localization to a major extent), than for high frequencies (for which localization is a function of interaural intensity differences, the high tone front-rear localizations must be due to intensity differences caused by the pinna. Since high frequencies are attenuated more readily than low tones, complex signals like speech coming from behind are better localized than pure tones, because the former signals are modified in quality and intensity (Stevens and Davis, 1938).

Sandel, Teas, Federson and Jeffress (1955) reported on a series of experiments on binaural localization, employing loudspeakers at three azimuths (0^{o}, 40^{o} and 320^{o}). They found that interaural time differences accounted for localizations of tones below about 1500 Hz, but that the only available cue for localizing above this frequency was in interaural intensity differences. That interaural time differences do not account for localization at higher frequencies was corroborated by Klumpp and Eady (1956) for headphone listening. They found that while interaural time delays lead to a difference in the perceived location of a variable tone burst compared to a standard one (at midline) for test frequencies up to 1300 Hz, no such effect was found at higher frequencies tested. In addition, the interaural time difference thresholds varied with the type of signal and with frequency. It was found to be 10 microseconds for broad band noise, 28 microseconds for a single one microsecond click, from 75 microseconds for a 90 Hz tone to 11 microseconds for a 1000 Hz tone, and 24 microseconds for a 1300 Hz tone.

Zwislocki and Feldman (1956) found that the just noticable difference (JND) for interaural phase through headphones is smallest (most acute) at medium sensation levels (SLs), and increases as intensity is raised or lowered. Sensitivity is most acute (approximately two degrees) for 250 Hz at 70 dB. The JND for interaural phase increased with positive acceleration as frequency increased, and became asymptotic about 1300 Hz. This is consistent with the findings of the preceding investigations.

In 1957, Federson, Sandel, Teas and Jeffress reported that the relation between localization and interaural time differences decreases with increasing frequency, and that localization depends on intensity differences at high frequencies. Here, it should be noted that while phase and time may be treated as essentially the same for pure tone stimulation, this relation breaks down with more complex stimuli, so that with the latter stimuli time of arrival becomes a more salient factor. Wallach, Newman and Rosenzweig (1949) found, in this respect, that an interaural time lag in the onset of a tone burst presented through headphones will determine the direction in which a sound is heard. The apparent image of the click was heard in the direction of the leading ear. This phenomenon has been generally referred to as the Precedence Effect.

The importance of spectral and head diffraction effects has been pointed out in the literature (Stevens and

Newman, 1936; Stevens and Davis, 1938; Wiener and Ross, 1946: Wiener, 1947; Sayers and Cherry, 1957; Bergman, 1957; Carhart, 1958; Nordlund, 1963). Cherry and Sayers (1956) suggested the possibility that an individual's experiences with how people sound in various situations (in doorways, corners of rooms, etc.) contributes to localization. However, Bergman (1957) took issue with this suggestion based upon his clinical experience with patients who could localize well immediately after amplification provided them with usable hearing, in spite of the fact that they had no apparent experience in localization upon which they could draw. It should be noted that Cherry (1961) later withdrew from his former position that experience with the speech signal is important to localization (p. 106):

> . . . experiments soon showed the effects to exist equally strongly, with sources other than speech (such as combinations of sine waves of different frequency, and many others), of which we humans have far less prior knowledge.

Hochberg (1966) found that subjects with bilateral hearing within normal limits tended to localize a test sentence more accurately for the front than for the rear quadrant. Individuals tended to make either front or rear quadrant confusions, rather than both. The subjects who were better localizers generally made fewer front-rear confusions. Subjects whose hearing was within normal limits clinically, but who had some degree of hearing loss were similarly tested (Hochberg, 1963). It was found that persons with presumably normal hearing but with interaural differences of 21 dB or more, demonstrated impaired localization ability. The correlation between interaural sensitivity and acuity of localization was nonsignificant for subjects with sensitivity differences between the ears of up to 20 dB; but there was a significant negative correlation for subjects with differences of 21 dB or more between the ears, who demonstrated a mean localization error of 33.19°.

ABSOLUTE THRESHOLD

While Sivian and White (1933) found no significant differences between the Minimal Audible Field (MAF) for the better ear and the binaural MAF, several investigators have demonstrated that the signal level required to reach absolute threshold is lower when two ears are used instead of one. Hirsh (1948a) referred to this phenomenon as "binaural summation at threshold." It was found by Keys (1947) and by Shaw, Newman and Hirsh (1947) that when one corrects for the difference in monaural thresholds of the two ears, thus equating them in terms of sensation level, the binaural absolute threshold is approximately three decibels lower than the monaural thresholds. Hirsh (1948a, 1950a, 1952) cited reports by Caussé and Chavasse who in 1941 obtained similar results using comparable methodology. Hirsh (1948a,

Figure 1, p. 203) demonstrated the strong correspondence in the data of these several studies. This phenomenon has also been found to occur for white noise (Pollack, 1948), and for speech (Keys, 1947; Shaw, Newman and Hirsh, 1947).

DIFFERENTIAL THRESHOLD

The findings of Shower and Biddulph (1931) demonstrated that differential sensitivity for frequency is greater for binaural listening than for monaural. Similarly, the differential threshold for intensity is more acute binaurally than monaurally (Churcher, King and Davies, 1934). It is interesting to note that Pikler and Harris (1955) reported no such binaural advantage for frequency DL when their stimuli were presented to the ears at matched sensation levels. They explained the difference between their findings and those of Shower and Biddulph on the basis of loudness differences between monaural and binaural hearing.

MASKING

Hirsh (1948a) was the first to describe the phenomenon of binaural release from masking, although he referred to it by the somewhat misleading term, "interaural inhibition." He found that the three decibel difference between monaural and binaural thresholds (which he referred to as binaural summation) decreased as the level of a masking noise increased, and that the relationship eventually reversed, so that the monaural masked threshold was lower than the binaural masked threshold. In other words, under the masked condition, the monaural threshold had actually become better than the binaural. This occurred at 250 Hz, 1000 Hz, and for speech, but not at 4000 Hz. Hirsh (1948a) related this phenomenon to interaural phase differences. When the tone and noise at the two headphones were both in phase, so that both signal and noise were perceived "to be in the same place in the head" (Hirsh, 1952, p. 238), the monaural threshold was lower than the binaural threshold (interaural inhibition, or release from masking). When the phase angles of the noise and tone were 180° out of phase (so that the noise and signal were perceived as spatially separate in the head), the binaural threshold was lower (binaural summation). These effects have been widely referred to as (binaural) masking level differences (MLDs), binaural unmasking, and binaural release from masking.

A similar effect has also been observed for speech stimuli (Licklider, 1948). The binaural unmasking of speech has been associated with the MLDs of the pure tones making up the spectral range critical for speech perception (Carhart, Tillman and Johnson, 1967; Levitt and Rabiner, 1967; Carhart, Tillman and Dallos, 1968).

LOUDNESS

Based upon loudness level measurements at given sound pressure levels, Fletcher and Munson (1933) concluded that a sound heard binaurally will sound twice as loud as the same stimulus heard monaurally. Hirsh (1952), too, stated that a sound heard by both ears is perceived to be twice as loud as the same sound heard monaurally. Hirsh (1948a, 1950a) referred to an investigation by Caussé and Chavasse in 1942, in which they matched the loudness of binaurally and monaurally presented tones. In order to produce equal loudness to a monaurally presented tone, a binaural tone had to be three decibels lower in intensity at threshold. The difference rose to six decibels at 35 dB SL, and remained constant up to 60 dB SL. This was corroborated by Hirsh and Pollack in 1948, who found that interaural phase had no effect on the loudness of a binaurally delivered tone until background noise rose to a level which produced masking. At this point, the loudness was affected by the interaural phase relationship of the signal and noise in a way similar to the masked threshold effects discussed above.

That loudness summates at the two ears was questioned by Raynolds and Stevens (1960). They found that while a sound is louder binaurally than it is monaurally, the difference is not one of summation, but of a "ratio that increases as a power function of the stimulus level (p. 1343). The exponent of the power function was not found to be precise across their several experimental techniques, but Raynolds and Stevens concluded that "if the binaural exponent is taken to be 0.6 the monaural exponent turns out to be 0.54" (p. 1343). They attributed the value of the binaural exponent, at least in part, to central processes.

INTELLIGIBILITY

Improved binaural intelligibility under difficult listening conditions has been related to interaural phase differences (Licklider, 1948; Heffler and Schultz, 1963); spacial separation of signal and noise (Hirsh, 1950a, 1950b, 1952; Pollack and Pickett, 1958; Chappell, et. al., 1963); and interaural time differences and azimuth (Schubert, 1956; Nordlund, 1963; Dirks and Wilson, 1969a).

Licklider (1948) was the first to find that speech intelligibility is improved under noise when it is antiphasic at the two ears, and that the effect of interaural phase differences increases as the listening situation deteriorates (i.e., at lower S/N ratios). This phenomenon, of course, is a case of binaural release from masking, discussed in a former section. Similarly, Heffler and Schultz (1963) found that binaural speech intelligibility was improved when the speech signals reaching the two ears were antiphasic.

Hirsh (1950a, 1950b, 1952) related the superiority of binaural over monaural intelligibility to spatial separation of noise and speech resulting when the head is permitted to move yielded superior intelligibility compared to the intelligibility obtained with the use of an immobile artificial head.

Pollack and Pickett (1958) found that the speech intelligibility of normal subjects during a competing "voice babble" (simultaneous speech by several speakers) was superior for the stereophonic condition than for the monaural. Similarly, Chappell, Kavanagh and Zerlin (1963) found that binaural intelligibility exceeded monaural by about 20% for normal subjects listening to phonetically balanced (PB) word lists read by several speakers in rotation, in a background of group conversation.

Schubert (1956) suggested that improved speech discrimination in competition may relate to time of arrival differences at the two ears, and that the findings of Hirsh may be explanable on the basis that spatial separation of his sound sources resulted in such time differences. Dirks and Wilson (1969a) demonstrated improved binaural over monaural speech discrimination when the signal and noise sources were separated by as little as ten degrees, and that the increased discrimination ability was more notable for spondee than PB words. Similarly, Nordlund (1963) found that binaural speech intelligibility in noise was superior to monaural intelligibility at all azimuths, though greatest at 60° and only six to seven percent at zero degrees and 180°. One might note that the latter azimuths correspond to the points directly in front of and behind the subject, where time differences between the ears are minimal, and also corresponding to the areas of least effective localization ability (see section on Localization).

It would appear that the underlying phenomenon is one of separation, either in time, phase or space, each of which relate to localization. Hirsh (1971), however, pointed out that localization and speech perception are not necessarily aspects of the same process. Instead, he emphasized that "localization of separate sources permitted the speech perception process to operate at lower S/N ratios than otherwise" (pp. 110-111).

EFFECTS OF REVERBERATION

Knudsen (1929) found that speech discrimination is reduced as reverberation time is increased. This finding has been corroborated by others such as Steinberg (1929), Bolt and MacDonald (1949), and Thompson, Webster and Gales (1961); and has been found to be greater for consonants than for vowels (John, 1957).

In addition to the amount by which reverberation will interfer with speech discrimination with increasing reverberation time, Knudsen (1929) also investigated its effects in terms of the volume of an enclosure. He found that as room size increases, the reverberation time for optimum intelligibility also increases, and that as speech intensity increases, so does intelligibility for a given reverberation time. The former finding may be taken to imply that as the direct energy of a speech signal is dissipated in a large enclosure, the reflected signal has the advantageous effect of adding energy to the dissipating direct one; as well as implying that in the larger enclosure, it takes longer for the direct signal to reach the ear of the listener, and it must also take longer for the reflected signals to reach his ear (i.e., a longer reverberation time) for these signals to be integrated by him. The second finding implies an increase in the direct sound resulting in a more favorable signal-to-noise ratio.

The deleterious effect of reverberation on speech intelligibility has been shown to increase with age. Bergman (1971) found that "reverberation time affects the relative intelligibility of speech for older persons" (p. 168) more than for younger individuals. He related this to difficulties experienced by the aging auditory system with temporal phenomena.

The Haas Phenomenon

Reverberation may have such an effect upon speech discrimination at least partly because of the Haas Phenomenon (Ross, 1972). Hass (1951) found that when a reflected sound arrived at a subject's ear within approximately 50 milliseconds after the direct sound, it was effectively masked by the direct sound. Thus, the ear integrates the direct and reflected sounds in a period of about 50 milliseconds. However, when the reflected signal arrived more than 50 milliseconds following the direct sound's arrival, the two were not integrated, and the reflected sound was perceived as an echo. The latter situation would result in the interference of the perception of the direct sound by the reflected sounds.

Binaural vs. Monaural Discrimination Under Reverberation

Moncur and Dirks (1967) referred to Koenig's (1950) finding that binaural hearing allows a listener to overcome (i.e., squelch) the deleterious effects of reverberation. They pointed out that Koenig did not state the degree of binaural advantage, and that he did not examine for differences between the monaural ear near to, and the one far from, the sound source. They emphasized this point, referring to Nordlund (1963), who found that intelligibility was markedly improved for the monaural near to the sound source over the other ear. Moncur and Dirks felt that the effect of the near vs. far ears is important because, as they explained in an earlier paper (Dirks and Moncur, 1965), when a monaural listener must attend to a sound source in a reverberant room, the level of the direct sound is reduced at the far ear (the one not facing the sound source), while the build-up of energy of the reflected sound due to reverberation is similar at the two ears, so that the ratio of direct to indirect sound at the far ear is reduced. The resulting situation is one which would be unfavorable to speech perception. Moncur and Dirks (1967) therefore undertook the study of "binaural versus monaural near-ear and far-ear speech intelligibility at various rates of reverberation" (p. 187).

Moncur and Dirks (1967) used recordings of the PB-50 word lists to test 48 normal subjects. The tests were carried out at four reverberation times, including 0.0 seconds (anechoic), 0.9 seconds, 1.75 seconds and 2.6 seconds, in quiet and under competition (a prose passage). Their test lists were recorded through an artificial head, with microphones at each ear, placed in an anechoic room or a reverberant room, depending upon the test condition. The lists were presented through one or the other of two speakers placed 45° from midline. The competing message was presented through a third speaker placed directly in front of the artificial head (i.e., at midline). The signal-to-noise ratio of the primary and competing signals was zero decibels at the near ear of the artificial head.

Twenty-four of their subjects were tested in the quiet condition (reverberation without a competing message), and 24 were tested in the competing condition (reverberation plus a competing message). The test tapes were presented through headphones at a sound pressure level of 70 dB.

Moncur and Dirks found that for all conditions, speech discrimination decreased as reverberation time increased. The binaural scores were superior under all conditions except the nonreverberant test in quiet. In addition, in the quiet condition, the monaural near ear scores were better than those for the far ear, and the difference increased with reverberation time. An even greater difference was found in the competing message conditions, in which the mean PB score at the 0.9 second reverberation time condition was only 3.8%, and no words were given correctly by the subjects at higher reverberation times. Moncur and Dirks used t-tests to test the differences between the means at each reverberation time. All of the differences were significant except for the anechoic-quiet condition.

In order to test the probability that their results were due to duplication of the signals at the two ears or to a small intensity increase binaurally, Moncur and Dirks tested five sophistocated subjects using the near-ear-anechoic-competing message tapes delivered to one ear and to both ears. They found a mean increase of only two percent between these two procedures, and concluded that little was added by the simple duplication of the monaural signal at both ears, and that the "interaural time differences were of key importance in contributing to binaural superiority" (p. 194) in their study.

Nabelek and Pickett (1972a) investigated the free-field monaural and binaural speech discrimination ability of five normal hearing subjects under reverberation and noise, using a form of the Modified Rhyme Test (MRT). They found that discrimination suffered in a reverberant room with noise, and that the advantage of binaural over monaural hearing decreased in reverberation. For the same subjects wearing Zenith Coronation hearing aids set to a maximum gain of ten decibels, they found an overall reduction in the discrimination scores (Nabelek and Pickett, 1972b). The reduction in discrimination under reverberation in the latter study approximated that of the unaided condition. Their investigation, however, was limited by the narrow range of short reverberation times used (0.3 and 0.6 sec.) (Nabelek and Pickett, 1972b).

No studies have as yet been reported in the literature investigating the performance of hearing impaired persons under controlled conditions of reverberation.

AMPLIFIED BINAURAL HEARING

Emphasizing that the ability to perceive speech in the presence of a background noise depends upon the spacial separation of speech and noise, Hirsh (1950a, 1950) suggested the use of binaural hearing aids for the hearing impaired. Carhart (1958, p. 46) asserted that the benefits of binaural hearing aids are demonstrated "(1) through increased ability to cope with noisy situations; (2) through greater effective gain when the reception of faint speech is critical; and (3) through a marked improvement in the precision of auditory orientation when the environment is complex."

DeCroix and Dehaussy (1964. p. 115) stated that monaural amplification "transforms such a hypocusic into an 'aural cyclops' because it does not restore acoustic perspective" or auditory figure-ground perspective. Similarly, binaural hearing aids have been suggested for aged individuals with mild presbycusis on the assertion that monaural amplification impedes the interaural balance of acoustic cues which these people need to maintain auditory figure-ground perception (Carhart, 1958); and for the pediatric population on the assertion that an acoustic advantage should be provided to whichever ear faces a sound source at any moment (Harris and Miller, 1966). The importance of the latter assertion has been emphasized by Olsen and Carhart (1967), who pointed out that a major problem of the monaural listener (as would be a hypocusic with only one hearing aid) is that of monaural indirect hearing, i.e., hearing with the monaural far ear. They asserted that the monaural hearer finds himself in this situation about half of the time, and that intelligibility is quite reduced in such circumstances.

In spite of the general acceptance of binaural superiority for the normal hearing population, Ling (1970, 1971) has pointed out that a controversy still exists regarding the relative advantages and disadvantages claimed for binaural over monaural hearing aids; and the need for further research in this area has been repeatedly emphasized (Newby, 1964; Ling, 1970, 1971; Miller, 1972).

EVIDENCE FOR BINAURAL AMPLIFICATION

Clinical and Qualitative Reports

Many reports of a clinical or qualitative nature have indicated better performance with binaural than monaural amplification. Carhart (1958) reported that a patient with a sensorineural hearing loss was able to obtain improved discrimination and to deal better with noisy situations when wearing two hearing aids as opposed to one. Haskins and Hardy (1960) reported that their patients profited enough from binaural amplification to choose this method; and Bentzen, Greisen and Jordan (1965) similarly stated that over four-fifths of their patients adopted binaural hearing aid use in some form. DeCroix and Dehaussy (1964) found that two patients with bilateral conductive hearing loss were able to obtain better speech thresholds with a minimum amount of gain, and experienced improved discrimination in noise, under binaural amplification.

Zelnick (1971) reported that while monaural hearing aid users complained about noisy environments, "when dichotic modes of amplification were used in the same reverberant environment the background noises faded in intensity and ambient noise became much more tolerable" (p. 5).

Surveys of Hearing Aid Users

Kodman (1961) polled fifty "successful" binaural hearing aid wearers to determine how they reacted toward binaural amplification. Successful use was defined as wearing the aids at least three hours per day for a minimum of one year. He found that binaural hearing aid users reported subjective advantages "reflecting better sound balance and ease of listening" (p. 304). Forty-two percent of the binaural aid users polled by Kodman reported no criticisms of their hearing aids, whereas in a former survey (Kodman and Fein, 1959) with monaural hearing aid wearers, only thirty percent offered no criticisms. In addition, it is noteworthy that the disadvantages cited by the binaural aid wearers related mainly to price, and complaints about extraneous noises and problems with earmolds.

Bentzen, Frost and Skaftason (undated) used a questionaire to poll 250 presbycusics who were managed with binaural hearing aids. The questionaire was distributed to patients after three months or more of binaural hearing aid use. They found that 37.2% of their patients reported using the aids full time (at least six hours per day), and that an additional 18% used them at least three hours per day. The authors emphasized the importance of "supplementary support from a hearing-therapist" (pp. 8-9), and suggested that binaural amplification be considered a standard treatment in binaural hearing loss due to presbycusis.

Quantitative Reports

Bergman (1957) found that subjects with one ear significantly poorer than the other demonstrated enhanced localization ability when spondee words were amplified above the detection threshold of the poorer ear. He reported the case of a blind, profoundly hard-of-hearing patient whose localization performance was considerably improved when binaural hearing aids were used instead of monaural amplification. Bergman suggested that binaural hearing aids be provided for patients who have improved hearing in one ear due to surgical intervention or monaural amplification. Improved localization was also found under binaural amplification by Larr and Webb (1956).

Watson (1942) reported that he obtained superior speech discrimination scores binaurally than monaurally for a subject with a severe, mainly conductive, hearing loss. Similarly, Markle and Aber (1958) reported that their subjects with conductive hearing loss performed better under binaural than monaural amplification.

Belzile and Markle (1959) found that the speech discrimination of their subjects with conductive and sensorineural hearing losses was improved with binaural hearing aids compared to a monaural hearing aid. Their study, however, has been the subject of controversy (see Jerger and Dirks (1961), below).

Nordlund and Fritzell (1963) investigated monaural (near and far ear) and binaural speech intelligibility at various azimuths. They found that intelligibility was significantly superior binaurally than for either monaural condition. The binaural superiority was over ten percent compared to the near ear, and greater compared to the far ear.

A major investigation of binaural versus monaural hearing was undertaken by Harris (1965). He used normal and hearing impaired subjects under nine conditions, including four that were monotic (one channel directed to the better ear, one to the worse ear, two channels to the better ear, and two to the worse ear); four that were dichotic (one channel to one ear and the second channel to the other ear, two channels to the better ear and one to the worse ear, two to the worse ear and one to the better ear, and two channels to each of the ears); and one diotic mode (in which one channel was directed to both ears simultaneously). The stimuli were presented through headphones.

Harris (1965, pp. 445-446) summarized his findings in the form of four principles, including:

> a. The Principle of Binaural S/N Gain: on a truly appropriate test, the improvement in intelligibility of dichotic over monotic modes is in the order of 25-33 percent (about +4 to +5 db S/N ratio).
>
> b. The Principle of Redundancy: a significant gain of 8-30 percent is achieved by adding a second channel to the monotic ear.*
>
> c. A possible though minor Principle of Blurring: there is a slight indication that adding a second channel from a noncongruent point in space may somewhat blur intelligibility; but this tendency would usually be overcome by the stronger Principle of Redundancy.
>
> d. The Principle of Degradation: the contribution of the defective ear in the Stereo Mode decreases binaural intelligibility as compared with leading two channels to the better ear.

While Harris did find some evidence for the binaural mode resulting in poorer performance, it must be pointed out that he emphasized that this was overcome by the much stronger effects favoring binaural conditions. It must be further pointed out that while Harris did note that

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* This was true whether the second ear was normal or abnormal.

his study employed subjects with asymmetric losses, he did not clearly specify the type and extent of these hearing losses, nor the degree of differences between the ears of the subjects with asymmetric losses. Harris' findings will be discussed further relative to other investigations below.

Dirks and Wilson (1969) found that patients with sensorineural hearing loss demonstrated a binaural advantage for spondees in noise and for Synthetic Sentence Lists (Jerger, Speaks and Trammell, 1968) in noise and competition similar to that found for normals. They emphasized the importance of azimuth in creating interaural time differences for at least one of the two signals, since the binaural advantage was absent in their study when the noise and signal came from the same loudspeaker to both ears simultaneously. In this case, of course, the signal and noise would be perceived as not spatially separated, in terms of Hirsh's position. Dirks and Wilson also found that differences were twice as large between the scores for the monaural near ear and monaural far ear than between the monaural near ear and the binaural scores. It is noteworthy that this last finding might indicate that the monaural near ear score was so high that a binaural advantage could not be demonstrated with the test being used.

Zelnick (1969, 1970) compared monaural, pseudobinaural and binaural amplification using a high fidelity system and commercial hearing aids. His test materials were recorded through microphones or hearing aids placed on a mannequin head, and the thus recorded materials were presented to his subjects with bilateral symmetrical hearing losses through headphones. The binaural mode resulted in higher discrimination scores than monotic administrations. He suggested that previous studies using competing noise which did not reveal differences between monaural and binaural aided intelligibility may have used signal-to-noise ratios resulting in monaural scores so high that a binaural score could not show any advantage.

EVIDENCE AGAINST BINAURAL AMPLIFICATION

Clinical and Qualitative Reports

DiCarlo and Brown (1960) reported that their patients with sensorineural hearing loss experienced a great deal of difficulty in adjusting to binaural hearing aids; and that all groups in their investigation, regardless of type of hearing loss, preferred monaural hearing aids over binaural.

Surveys of Hearing Aid Users

Dirks and Carhart (1962) circulated a three-part questionaire to users of monaural and binaural hearing aids, and to a control group of normal hearing individuals. The questionaire included 26 everyday listening circumstances and 15 true-false statements about hearing aid use and the subjects' opinions concerning amplification. The listening situations were rated according to the listening success each presented to the subject. As expected, normal hearers reported the best performance in each situation, suggesting that binaural amplification does not restore wearers, as a group, to normal hearing efficiency. There were no large differences between the two hearing aid groups. Binaural users did report better efficiency in "relatively exacting tasks in quiet environments" (p. 319), although not in noisy, difficult listening situations. Interestingly, most binaural hearing aid wearers said that the statement, "Scientific studies show that you can understand better with two hearing aids than with one," was true; while less than half of the monaural wearers agreed. The authors suggested that emotional conviction on the part of the binaural hearing aid wearers may have accounted for their performance. Dirks and Carhart concluded that the average hearing aid wearer who has experienced both monaural and binaural hearing aids "does not experience a clear and identifyable advantage with a binaural instrument" p. 320).

Quantitative Reports

Hedgecock and Sheets (1958) and Wright (1959) found that monaural and binaural hearing aids did not result in significantly different performance for subjects with sensorineural hearing loss.

While DiCarlo and Brown (1959) found improved localization in noise, and slightly lower speech reception thresholds, for binaural amplification compared to monaural or pseudobinaural, speech discrimination scores and signal-to-noise ratios (the level of noise in which spondee words presented at 70 dB SPL were just understandable) were no better for the binaural condition than for others.

Jerger and Dirks (1961), who closely replicated the Belzile and Markle (1959) study, failed to find superior results under binaural amplification. Jerger and Dirks cited a personal communication from Hirsh, which stated the the difference in results between the two studies may have been due to the placement of the aid during the monaural condition. Belzile and Markle placed it on the body, whereas Jerger and Dirks placed it on the head. Thus, according to Hirsh, Belzile and Markel's results were not due so much to the presence of two hearing aids as opposed to one, but instead to the placement of at least one aid (in the binaural condition) on the head, which could move and thereby pick up additional cues.

Jerger, Carhart and Dirks (1961) compared monaural aids on the body, monaural aids on the head, and binaural aids, using Northwestern University (N.U.) Auditory Test No. 2 (phonetically balanced words from one loudspeaker and competing sentences from a second speaker) and N.U. Auditory Test No. 3 (sentences and competing discourse randomly switched between the speakers between test items). They concluded that their "results fail to demonstrate the marked superiority of binaural amplification one has been led to expect from clinical reports" (p. 147).

Olsen and Carhart (1967) compared conductive, young sensorineural and presbycusic patients in quiet, and under conditions of monaural direct (near ear), monaural indirect (far ear), and binaural listening, using N.U. Auditory Tests Nos. 20S and 20N. Inspection of their data (Table 5, p. 39) revealed that the highest scores were obtained in quiet. For all groups, scores were systematically related to the quality of reproduction of the sound, with the high fidelity system yielding the highest scores and the poorest hearing aid the lowest. Monaural indirect scores were the lowest, but binaural scores were "only equal to or slightly better than their monaural direct counterparts, thereby indicating little binaural superiority when the monaural direct scores are already on the plateaus of discrimination ability of the listener" (p. 42).

EVALUATION OF THE CONTROVERSY

Inter-Study Differences

Differences in subjects, relative positions of speech and noise sources, test materials, etc., may account, at least in part, for the disparities between the results of the studies comparing monaural and binaural amplification for the hearing impaired.

That the results of Harris (1965) were different from those of Jerger, Carhart and Dirks (1961) and Olsen and Carhart (1967) may reflect differences in methodology. While the two latter studies employed commercial hearing aids worn by the subjects with the stimuli presented in sound field, Harris presented his stimuli through headphones. Thus, differences relating to head movements and other factors of the subject's person, as well as quality of stimulus reproduction, were possible causes for the disparities in the results. Subject and test material differences, too, may have been factors.

Similarly, Zelnick (1970) pointed out that differences between his own and other studies may have been due to the possibility that "where competing noise has been used in prior studies, the S/N ratio employed in comparing monaural to binaural discrimination scores resulted in such high intelligibility scores for the monaural mode that a binaural improvement could not be domonstrated" (p. 95). This, too, may have been a factor active in the conflicting data of the several studies.

According to Ling (1970, 1971), the work of Harris (1965) brought much of the controversy about binaural hearing aids into perspective. Harris asserted (as did Hirsh in 1950 and Carhart in 1958, in their suggestions for the evaluation of hearing aids) that the researchers who failed to find improvement under binaural amplification had neglected to take account of such variables as the effects of head and body shadows, or the relative effects of speech and noise sources, or that they had employed tests lacking sufficient sensitivity to demonstrate monaural-binaural differences.

The State of the Binaural-Monaural Controversy

Although Ling (1971) has pointed out that "Most workers would now agree with the position taken by Hirsh that patients should, if possible, not only use head level aids so that the microphone can move with the head but be equipped binaurally" (p. 37), the Federal Trade Commission (FTC) (1969) has taken the position that two hearing aids do not provide sufficient advantage over one to warrant the added expenditure. That such a disparity exists attests to the fact that the issue of monaural vs. binaural amplification remains a major controversy in the aural rehabilitation of the hearing impaired individual.

SUMMARY AND CONCLUSIONS

It is apparent that the auditory functioning of the normal individual is enhanced when binaural hearing is permitted. The many areas in which binaural hearing is superior to monaural hearing suggest that this enhancement of functioning depends upon both internal and external factors, and to a large extent the interaction of these. It appears from analysis of the literature that the normal auditory nervous system can perform at lower signal-to-noise ratios and with greater acuity when information is obtained from both ears instead of just one. In addition, it appears that when externally produced modifications are present in the signal at one ear relative to its counterpart at the other (for example, interaural intensity or time differences), the amount of information available to the auditory system is increased, and so the differences between binaural and monaural functioning become more obvious.

Similarly, qualitative evidence shows that the binaural auditory system of the normal hearing person provides him with the ability to squelch the effects of reverberation and to maintain a considerable degree of auditory figure-ground discrimination. The ability of the normal listener to overcome the effects of reverberation binaurally and monaurally has received very little attention, with only two investigations in this area (Moncur and Dirks, 1967; Nabelek and Pickett 1972a) to the writer's knowledge.

The rationale for binaural amplification for the hearing impaired lies within the wealth of knowledge that has been accumulated about binaural hearing among normals. However, examination of the literature in the area reveals that the evidence of the advantages of binaural over monaural amplification is still equivocal. Clearly, further research in this area is needed (Ling, 1971; Miller, 1972).

While the effects of reverberation upon monaural versus binaural hearing has received little attention with reference to the normal hearing population, it has been virtually ignored with the hearing impaired. Investigation of the effects of binaural and monaural amplification for hearing impaired individuals under conditions of controlled reverberation should provide insight into the use of prosthetic aids for this population. It is also expected that research in this area will bear some light upon the incomplete knowledge existing of the functioning of the auditory system. It is paradoxical that lesions of the peripheral auditory system which are not so severe that they preclude prosthetic amplification, do at the same time prohibit enhancement of intelligibility, which is obviously a function of more than just the peripheral hearing mechanism. Study of the effects of reverberation upon the monaural and binaural speech discrimination of hearing impaired individuals is clearly indicated.

CHAPTER III

METHODOLOGY

SUBJECTS

The subjects included 30 normal hearing individuals and 30 persons with relatively symmetrical sensorineural hearing loss. The normal subjects included 11 males and 19 females, and ranged in age from 19 years 7 months to 35 years 3 months, with a mean age of 23 years 8 months. There were 18 males and 12 females in the hearing impaired group. They ranged in age from 23 years 2 months to 54 years 11 months, with a mean age of 40 years 11 months.

Normal hearing was established by a pure tone air-conduction screening test at 15 dB (ANSI-1970 Standard) and a negative otologic history. Persons with upper resiratory infections or allergies were not included.

For inclusion in the study, hearing impaired individuals had to exhibit (a) bilateral sensorineural hearing losses in excess of 30 dB (ANSI-1970 Standard) for the average of the thresholds at 500, 1000 and 2000 Hz; (b) speech reception thresholds (SRTs) of at least 30 dB; (c) symmetrical pure tone losses in which the differences in threshold did not exceed 15 dB between the ears between

250 and 4000 Hz; (d) hearing losses audiologically consistent with a cochlear locus, as determined by tone decay (Carhart, 1957) of 15 dB or less, and Short Increment Sensitivity Index (SISI) scores (Jerger, Shedd and Harford, 1959) greater than 75%, measured at 1000 and 4000 Hz in each ear; and (e) age not to exceed 55 years old. The maximum age was chosen to be 55 years based upon Bergman's data (1971), which indicated an accelerated effect of reverberation on speech discrimination performance for age groups over the 50 to 59 year age decade. A similar deterioration of speech discrimination under reverberation was shown by Schubert (1958). In this way, an attempt was made to limit the effects of aging upon the results.

PREPARATION OF TEST LISTS

The original test lists were recorded by the experimenter in a double-walled Industrial Acoustics Company audiometric booth (Series 1600), located in the Communication Sciences Laboratory of the City University of New York. This booth was used because an anechoic chamber was not available at the time the recording was being made, and the booth proved to be quite adequate for the needs of the investigation. Such a booth has an average Noise Reduction Coefficient of 0.95 for the frequencies from 125 to

4000 Hz (Table 1)*. Reverberation in this room is thus negligible relative to the reverberation conditions which were employed in this study. The ambient noise level within the room did not exceed 30 dBA.

Recording Instrumentation and Procedure

The Modified Rhyme Test (MRT), developed by House, Williams, Hecker and Kryter (1965), was recorded by the investigator on Scotch Brand Type 131 Low Print Tape. The recording was made at a recording and playback speed of 7½ inches per second (ips) on a Tandberg tape recorder (Model 11). Each of the 300 original test words was preceded by the carrier phrase, "Cross out the word . . . ," such that the last word of the carrier ("word") was recorded at a level of 0 VU. The test word was then said with equal emphasis as the last word of the sentence. Approximately seven seconds elapsed between test items.

After the test was recorded, a 1000 Hz calibration tone produced by a Hewlitt Packard low frequency oscillator (Model 202C) was added to the tape.

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* The Noise Reduction Coefficient (NRC) is a measure of sound absorbtion within Industrial Acoustics Company (IAC) audiometric booths, and is based upon measurements of IAC in booths with four inch thick walls (Bulletin 5.0601.0 (16-ACT), Industrial Acoustics Company, 1971).

TABLE 1

SOUND ABSORBTION COEFFICIENTS (SACs) OF INDUSTRIAL ACOUSTICS COMPANY SERIES 1600 BOOTHS*

Freq. (Hz)	125	250	500	1000	2000	4000	NRC**
SAC	.70	.99	.99	.99	.94	.83	.95

* Based upon measurements of the Industrial Acoustics Company for their Series 1600 audiometric booths with four inch thick walls (Industrial Acoustics Company, Bulletin 5.0601.0 (16 ACT), 1971).

** Noise Reduction Coefficient; an average of the several Sound Absorbtion Coefficients.

The signal-to-noise ratio was measured with a Tektronix oscilloscope (Type 561B), and was found to be approximately 46 dB.

The master tape recording was played for three speech pathologists certified by the American Speech and Hearing Association, who judged the recording to be representative of Eastern American speech and free of articulatory defects.

Four of the six MRT lists were arbitrarily chosen for inclusion in the study. Since a word was found to be missing from the recording of MRT List A, it was decided that Lists B, C, D and E would comprise the experimental test lists. These lists and a 1000 Hz calibration tone were dubbed from the original recording to make up the master test recording using two Ampex tape recorders (Model AG500).

The master test recording was then re-recorded through the following circuitry to produce the reverberant conditions (Figure 1).

The master tape was played on a Sony tape recorder (Model TC-352D). The line output of the tape recorder was directed to the main input of a Kay Auto-Vox, which was set to its reverberation mode. The output of the Kay Auto-Vox was connected to an Allison variable filter (Model AL-2ABR), which passed the band from 400 to 4000 Hz. The output of the filter was terminated at the input of a

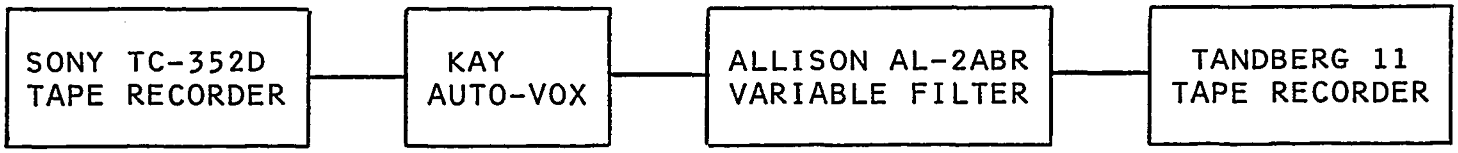

Figure 1.-- Instrumentation to produce reverberant conditions.

Tandberg tape recorder (Model 11), on which the reverberant lists were recorded.

A Kay Auto-Vox is a device which uses a revolving disk and movable recording and playback heads to produce a variable delay onto an input signal. In addition, its circuitry includes a reverberation mode which creates a continuous loop from its output to its input. The period of the delay is controlled by an internal attenuator and adding circuit. The heads are manipulated by sliding them along a track, thus changing their relative positions on the recording disk. The intensity of the signal fed back to the system is controlled by the reverberation dial on the face of the Auto-Vox console.

The frequency regions below 400 Hz and above 4000 Hz were filtered out for two reasons. First, such a frequency response more closely approximates that of most commercial hearing aids, thus making the results of this study more applicable to the limited response capabilities of prosthetic amplifiers. In addition, this filtering markedly reduced residual and ambient machine noise that was on the recording, while maintaining all necessary aspects of the speech signal.

The reverberation control was adjusted so that each successive delay of a signal was six decibels less than the preceding one. Thus, if a tone burst of x milliseconds was put through the system, the output would occur at whatever delay the machine was set to, with the first "reflection" of the tone burst (delayed tone burst) being six decibels less than the first, the second "reflection" 12 dB less than the first, etc.

The 6 dB attenuation step was calibrated using a Tektronix storage oscilloscope (Type 564B). A photograph demonstrating the 6 dB attenuation step is shown in Figure 2*. The stimulus was a 1000 Hz tone burst produced by a Hewlitt Packard low frequency oscillator (Model 202C).

Each of the three reverberant conditions was recorded in the above manner. For the one second reverberation time (RT) condition, the delay was set to 100 msec. Thus, the signal decreased 60 dB in one second, corresponding to a 1 sec. RT. For the 2 sec. RT, the delay was set to 200 msec., and for the 3 sec. RT, the delay was set at 300 msec. Therefore, the signals for these conditions decreased by 60 dB in two and three seconds, respectively.

The delay times were calibrated using the storage oscilloscope, and by manipulating the position of the heads on the Auto-Vox until the desired delays were obtained. Figures 3, 4 and 5 show the delay times for each of the reverberant conditions, using a 1000 Hz tone burst as

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* Examination of Figures 2 through 5 will reveal some variation in the form and duration of the input signal. This was due to hand switching of the tone.

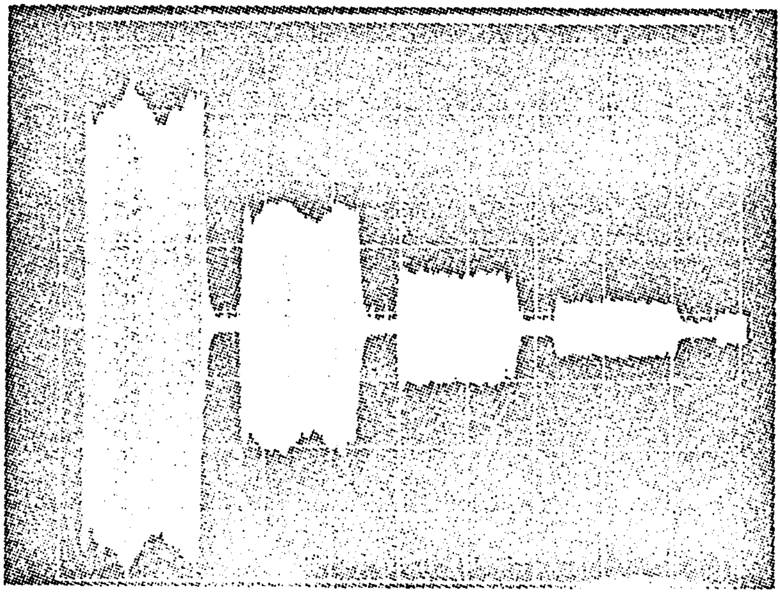

Figure 2.-- Photograph demonstrating the 6 dB decrease with each successive "reflection" of the input signal. The stimulus is a 1000 Hz tone burst. The horizontal scale is divided into arbitrary units of time, and the vertical scale into arbitrary units of voltage.

Figure 3.-- Photograph demonstrating the calibration of the Kay Auto-Vox to produce 100 msec. delays for the 1 sec. RT condition. The lower tone burst shows the input signal, while the upper series shows the successive "reflections" at 100 msec intervals. The horizontal scale is divided into 100 msec. intervals, and the vertical scale is divided into arbitrary units of voltage. The input signal is a 1000 Hz tone burst.

Figure 4.-- Photograph demonstrating the calibration of the Kay Auto-Vox to produce 200 msec. delays for the 2 sec. RT condition. The lower tone burst shows the input signal, while the upper series shows the successive "reflections" at 200 msec. intervals. The horizontal scale is divided into 100 msec. intervals, and the vertical scale is divided into arbitrary units of voltage. The input signal is a 1000 Hz tone burst.

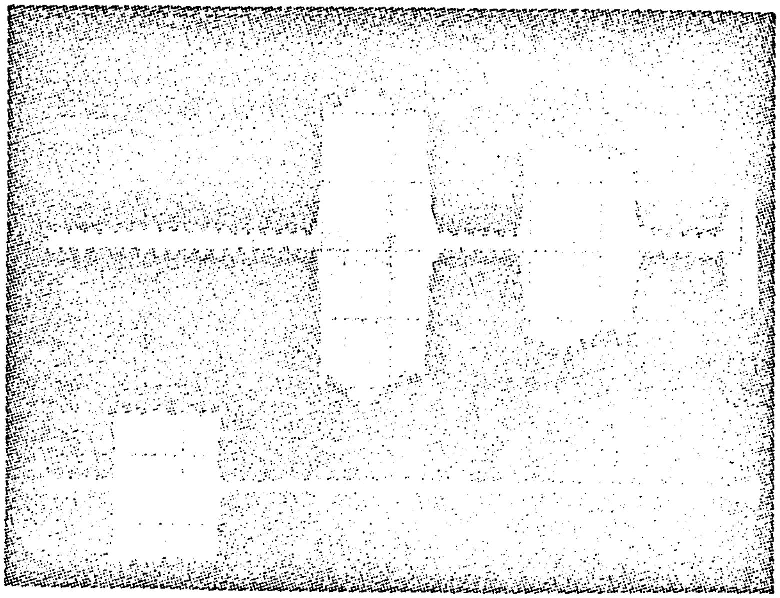

Figure 5.-- Photograph demonstrating the calibration of the Kay Auto-Vox to produce 300 msec. delays for the 3 sec. RT condition. The lower tone burst shows the input signal, while the upper series shows the successive "reflections" at 300 msec. intervals. The horizontal scale is divided into 100 msec. intervals, and the vertical scale is divided into arbitrary units of voltage. The input signal is a 1000 Hz tone burst.

the calibration signal. Before each reverberation time condition was recorded, the Auto-Vox was calibrated in this manner for the desired delay.

The nonreverberant condition (0 sec. RT) was recorded in a similar manner, except that the Auto-Vox was set to the direct mode, thus not recording reverberation onto the tape.

Randomization of Test Tapes

The four tapes of Lists B, C, D and E of the original MRT, one at each of the RT conditions (0, 1, 2 and 3 sec. reverberation times), resulting from the above procedure were cut into half-lists of 25 words each, and spliced into four test lists. Each test list was made up of eight 25 word lists, two at each reverberation time. The 25 word lists were labeled according to (a) the original MRT List from which thay came ("B," "C," "D," or "E"); (b) whether they were from the first half ("F") or the second half ("S") of the original list; and (c) the reverberation time in seconds ("0," "1," "2," or "3"). Therefore, the 25 word list which originated from the first 25 words of MRT List C, and which contained words with a reverberation time of 2 seconds, was labeled "CF2"; while a list originating from the second half of MRT List B, with a reverberation time of 1 second, was labeled "BS1." The Test

Lists were called Lists 1, 2, 3 and 4. Table 2 shows the individual 25 word lists which made up each of the four Test Lists. As Table 2 shows, the 32 combinations of 25 word lists were arranged such that any one appeared only once among the four lists.

A subject heard one of the two 25 word lists at each RT monaurally, and the other at that RT binaurally. The next subject to hear the same Test List heard the 25 word lists in the opposite manner; i.e., those which the former subject heard monaurally, the latter heard binaurally, and vice versa.

The order of the eight 25 word lists in each Test List was determined according to a table of random numbers; and once a list so randomized was heard by two subjects (as described in the preceding paragraph), that list was re-randomized. Order effects were controlled for in this way.

The subjects were tested in audiological testing suites located in the following audiological facilities: Veterans Administration Regional Office, New York City, N.Y.; New York League for the Hard of Hearing, New York City, N.Y.; Kingsbrook Jewish Medical Center, Brooklyn, N.Y.; Brooklyn College of the City University of New York, Brooklyn, N.Y.

Table 3 shows the audiometer and tape recorder makes and models used at each testing location. The calibration

TABLE 2

TWENTY-FIVE WORD LISTS COMPRISING THE FOUR EXPERIMENTAL TEST LISTS*

List 1	List 2	List 3	List 4
BS0	DF0	CF0	BF0
EF0	ES0	DS0	CS0
CS1	BS1	BF1	DS1
DF1	CF1	ES1	EF1
CF2	BF2	BS2	DF2
DS2	CS2	EF2	ES2
BF3	DS3	CS3	BS3
ES3	EF3	DF3	CF3

* The first ("B," "C," "D," or "E") letter denotes the orginal MRT List from which the 25 word list was taken. The second letter tells whether that list is from the first ("F") or second ("S") 25 words of the original MRT List. The number represents the reverberation time condition at which that 25 word list was recorded.

TABLE 3

INSTRUMENTS USED AT EACH TESTING LOCATION

Location	Audiometer	Tape-Recorder
Brooklyn College	Grason-Stadler 1701	Viking 87
Kingsbrook Jewish Medical Center	Beltone 15 C	Viking 87
New York League for the Hard of Hearing	Maico MA-24	Viking 88
New York Veterans Administration Outpatient Clinic	Grason-Stadler 1701	Sony TC-366

of the test equipment was carried out by the experimenter using a Bruel and Kjaer Sound Level Meter (Type 2203) and Octave Filter Set (Type 1612).

Preliminary Evaluation of Normal Subjects

Before taking part in the experimental tests, the normal subjects were given pure tone air-conduction screening tests, and case histories were obtained. The screening test was accomplished at 15 dB for the frequencies from 250 to 8000 Hz in octave steps, for both ears. Failure to respond at any frequency in either ear resulted in that subject being eliminated from the sample. Potential subjects with any history of significant otologic involvement, or past or current hearing difficulty of any kind, were similarly excluded from participation in the study. The normal subjects were not screened for speech discrimination ability, since such evaluation would have been needlessly redundant in light of the fact that the nonreverberant conditions of the experimental tests provided such a measure.

Subjects who demonstrated any evidence of upper respiratory infections or allergies, or who were taking medications of any kind, were not included in this study.

Preliminary Evaluation of Hearing Impaired Subjects

Following a carefully obtained case history, the hearing impaired subjects were given audiological evaluations consisting of the following measures: (a) pure tone air- and bone-conduction audiometry in octave steps from 250 to 8000 Hz (4000 Hz for bone-conduction); (b) speech reception thresholds; (c) speech discrimination scores obtained for each ear and binaurally at 30, 35 and 40 dB Sensation Level (SL); (d) Carhart Tone Decay Test (Carhart, 1957) at 1000 and 4000 Hz for each ear; and (e) Short Increment Sensitivity Index (Jerger, Shedd and Harford, 1959) at 1000 and 4000 Hz for each ear.

Speech discrimination scores for phonetically balanced words were obtained at three sensation levels in order to insure that the experimental Test Lists were administered at PB Max. The ear with the higher discrimination score was the one chosen for the monaural condition, while a similarly obtained binaural PB Max level was used as the test level for the binaural conditions of the study. A binaurally obtained PB Max was used in order to avoid difficulties that might have arisen due to trying to predict binaural PB Max from the two monaural PB Max scores. The ear evidencing the higher speech discrimination score was used for the monaural conditions of the study since use of the ear with the lower discrimination score (as might occur if one were to alternate the monaural ear from subject to subject) would result in biasing the data unrealistically in favor of the binaural condition. This reasoning is consistent with the decision one must make when deciding whether or not to prescribe two hearing aids for a patient.

The speech discrimination scores were obtained by using half-lists of the Central Institute for the Deaf W-22 Word Lists, which were recorded by the experimenter using the same instruments used to record the Modified Rhyme Test lists.

Administration of the Experimental Test Lists

Following the preliminary evaluation, subjects were given a short rest to avoid fatigue, and then were given instructions for taking the experimental tests. The following instructions were given to all subjects:

> You are going to hear a tape recording which will test your ability to hear words with various amounts of distortion. The speaker on the tape will ask you to cross out one word from a choice of six rhyming words on these sheets of paper. Sometimes the words will be very clear, and other times they will be very difficult to understand, but for each word you must cross out one of the six choices. If you are not sure of which word you have heard, it is very important that you guess. You must cross out one word on every line. After every twenty-fifth word, I will stop the tape to give you time to rest. Are there any questions?

> Remember, cross out one word on every line. If you are not sure of a word, it is very important that you guess.

The subjects were asked to read along to themselves from a written transcript of the instructions while the experimenter read them aloud.

The test tape recording was administered, directed either monaurally or binaurally according to the randomization schedule, at the levels determined during the preliminary evaluations for the hearing impaired subjects, and at 30 dB SL for the normal subjects.

Since binaural hearing results in increased loudness corresponding to a three-to-six decibel increment, the first ten normal subjects heard the monaural test tapes at 25, 35 and 40 dB SL in addition to the standard level of 30 dB SL. This was done to determine whether or not such loudness increments could account for improved performance in the binaural mode.

In view of the difficulty encountered in finding hearing impaired subjects to volunteer for the study, as well taking into account the burden placed upon the subject with such a procedure, the hearing impaired subjects were not asked to take the monaural tests at several sensation levels. Instead, as a compromise, each hearing impaired subject was asked to listen to one extra test list monaurally, at a level 5 dB above the experimental test level. Thus, subject one took an extra monaural test (at 5 dB above experimental test level) at the 0 sec. RT condition, subject two at the 1 sec. RT condition, etc. This resulted in eight scores at the 0 and 1 sec. RT conditions, and seven at the 2 and 3 sec. RT conditions.

CHAPTER IV

RESULTS

This study investigated the effects of reverberation time upon the speech discrimination of normal and hearing impaired individuals. The speech discrimination of each subject was tested at reverberation times (RTs) of 0, 1, 2 and 3 seconds, monaurally and binaurally.

The discrimination scores of each subject are listed in Appendices A and B. The means, standard deviations, and ranges of the scores appear in Table 4, and the means and standard deviations are shown graphically in Figure 6. A four factor analysis of variance was used to analyse the data. Since the data are in the form of proportions, an arcsine transformation was used to stabolize the variance (Brownlee, 1960, pp. 113-116 and 556-557; Winer, 1962, pp. 221 and 650). Table 5 summarizes the results of this analysis.

Since the analysis of variance used did not result in an individual error term, the interaction of the effects of reverberation time (R), monaural vs. binaural (E), subjects (S), and normal vs. hearing impaired (H), was used as mean square error for all F scores, except

TABLE 4

MEANS, STANDARD DEVIATIONS AND RANGES*

	Normals			Hearing Impaired		
Condition	Mean	S.D.	Range	Mean	S.D.	Range
M0	24.7	0.62	23-25	18.1	2.48	12-22
M1	18.8	2.06	14-22	13.7	2.04	10-17
M2	13.7	1.79	9-16	10.7	2.47	7-17
M3	13.1	0.87	11-17	9.2	2.77	3-14
B0	24.9	0.31	24-25	19.3	1.84	15-23
B1	22.5	1.66	20-25	15.9	1.92	13-20
B2	20.2	1.86	16-25	13.9	2.35	10-17
B3	15.9	2.20	13-21	12.0	2.20	7-16

*In terms of number of words correct.

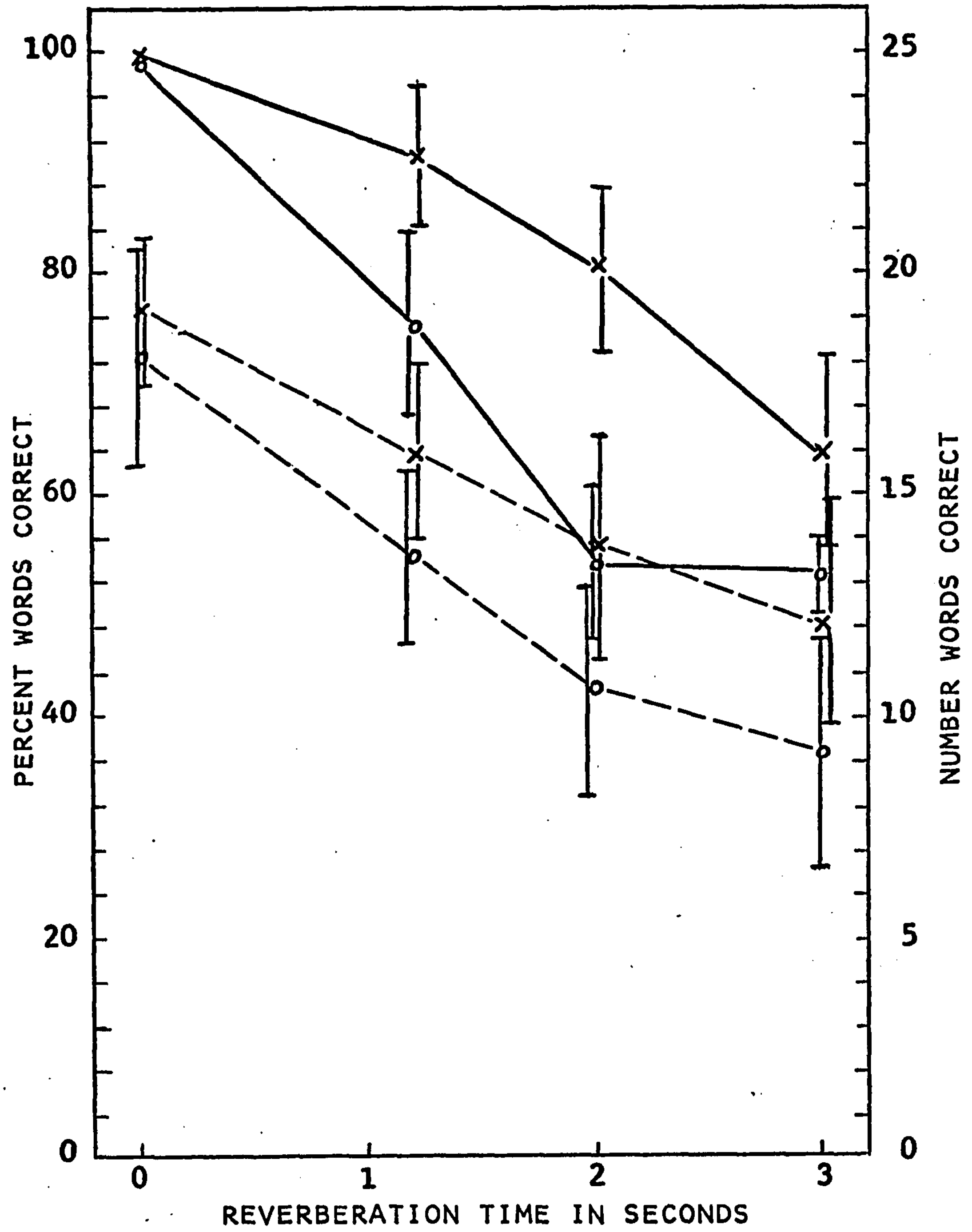

Figure 6.-- Means and standard deviations for all conditions. Binaural data points are indicated by crosses; monaural data points are indicated by circles. Solid lines connect the data points of the normal subjects, and dashed lines connect the data points of the hearing impaired subjects. Vertical lines above and below each data point indicate one standard deviation above and below the mean.

TABLE 5

ANALYSIS OF VARIANCE*

Source	SS	df	MS	F	p
R **	69.6	3	23.2	1262.0	.001
E	8.5	1	8.5	460.6	.001
S	4.0	29	0.1	1.0	
H	38.2	1	38.2	280.9	.001
RxE	1.7	3	0.6	31.1	.001
RxS	1.7	87	0.02	0.2	
ExS	1.0	29	0.03	0.1	
RxH	7.2	3	2.4	17.8	.001
ExH	0.5	1	0.5	3.9	
SxH	3.9	29	0.1	7.4	.01
RxExS	1.4	87	0.01	0.1	
RxExH	0.7	3	0.2	1.8	
RxSxH	2.1	87	0.02	0.02	
ExSxH	1.2	29	0.04	0.3	
RxExSxH	1.6	87	0.02		
Total	143.3	479			

*Key:	SS	Sum of Squares
	df	Degrees of freedom
	MS	Mean Square
	F	F score
	p	Significance level

**Variable Key:	R	Reverberation
	E	Monaural vs. Binaural
	S	Subjects
	H	Normal vs. Hearing Impaired

except those involving factors or interactions between subjects, for which the interaction of subjects and normal vs. hearing impaired was used as mean square error.

Three of the main effects, reverberation time, monaural vs. binaural, and normal vs. hearing impaired, were significant beyond the .001 level.

The interactions of reverberation time and monaural vs. binaural, and reverberation time and normal vs. hearing impaired, were significant beyond the .001 level, and the interaction of subjects and normal vs. hearing impaired was significant beyond the .01 level. However, the interactions of reverberation time and subjects, monaural vs. binaural and subjects, and monaural vs. binaural and normal vs. hearing impaired, failed to reach statistical significance. The three factor interactions of reverberation time, monaural vs. binaural and subjects; reverberation time, monaural vs. binaural and normal vs. hearing impaired; reverberation time, subjects and normal vs. hearing impaired; and monaural vs. binaural, subjects and normal vs. hearing impaired, were similarly nonsignificant.

Hypothesis I

Inspection of Figure 6 revealed that the normal subjects performed at a consistently higher level than the hearing impaired subjects, at each reverberation time. In no case did the normals' mean discrimination scores for the monaural condition fall below those of the impaired subjects, as was similarly true for the binaural scores. Further, in only one case did a mean score of the normals fall below any mean score (at the same reverberation time) of the hearing impaired group; which was the case of the normals' *monaural* score falling below the hearing impaired subjects' *binaural* score at the 2 sec. RT condition. The difference, however, was not statistically significant.

The differences between the scores of the normal subjects and those of the hearing impaired subjects was significant beyong the .001 level (F = 280.9). Similarly, the interactions of reverberation time and normal vs. hearing impaired (F = 17.8, $p < .001$) and of subjects and normal vs. hearing impaired (F = 7.4, $p < .01$), were also statistically significant. The first hypothesis, that there would be no differences between the normal and hearing impaired subjects for the various conditions, is therefore rejected, indicating that the normal subjects obtained significantly better discrimination scores overall that did the hearing impaired subjects.

Hypothesis II

Observation of the graph in Figure 6 revealed that, for both normal and impaired groups, the mean binaural scores were consistently better than their respective monaural scores, at each reverberation time. The differences between monaural and binaural scores (F = 460.6), and the interaction of reverberation time and monaural vs. binaural (F = 31.1), were significant beyond the .001 level. Therefore, the second hypothesis, that there would be no significant differences between monaural and binaural scores at the various reverberation times, for both groups of subjects, is rejected, indicating that the binaural scores were significantly better than the monaural.

Hypotheses III and IV

Except for the normals' scores at the 2 sec. RT and 3 sec. RT conditions, inspection of Figure 6 revealed that for both groups, the monaural and binaural scores decreased with increasing reverberation time. The differences between the reverberation times (F = 1262.0), reverberation time and monaural vs. binaural (F = 31.1), and reverberation time and normal vs. hearing impaired (F = 17.2), were all significant beyond the .001 level. The third and forth hypotheses, that there would be no significant differences between the scores at the various reverberation times, are thus rejected; indicating that, for both groups, increasing reverberation time results in decreased speech discrimination performance.

Hypothesis V

In order to test the hypothesis that there are no significant differences in the rates of decline of the speech discrimination scores monaurally and binaurally with reverberation time, the data in Figure 6 were standardized in terms of the nonreverberant discrimination scores. This was accomplished by assigning a value of zero to each nonreverberant score (M0 and B0 for both groups), and then assigning values to the other scores equal to the differences between each original mean score and the 0 sec. RT score. Thus, for example, if the 0 sec. RT score was 25 and the 1 sec. RT score was 22, the 0 sec. RT score would be assigned a value of "0," and the 1 sec. RT score a value of "-3." This transformation of the data is shown in Figure 7.

It is evident from Figure 7 that for both groups, the monaural scores decreased more rapidly with increasing reverberation time than did the binaural scores. A striking observation is that the normals' monaural scores fell so rapidly with reverberation time. Taking into consideration that the differences between monaural and binaural scores, and the interaction of reverberation time and monaural vs. binaural, were significant, the fifth hypothesis, that the monaural and binaural scores would

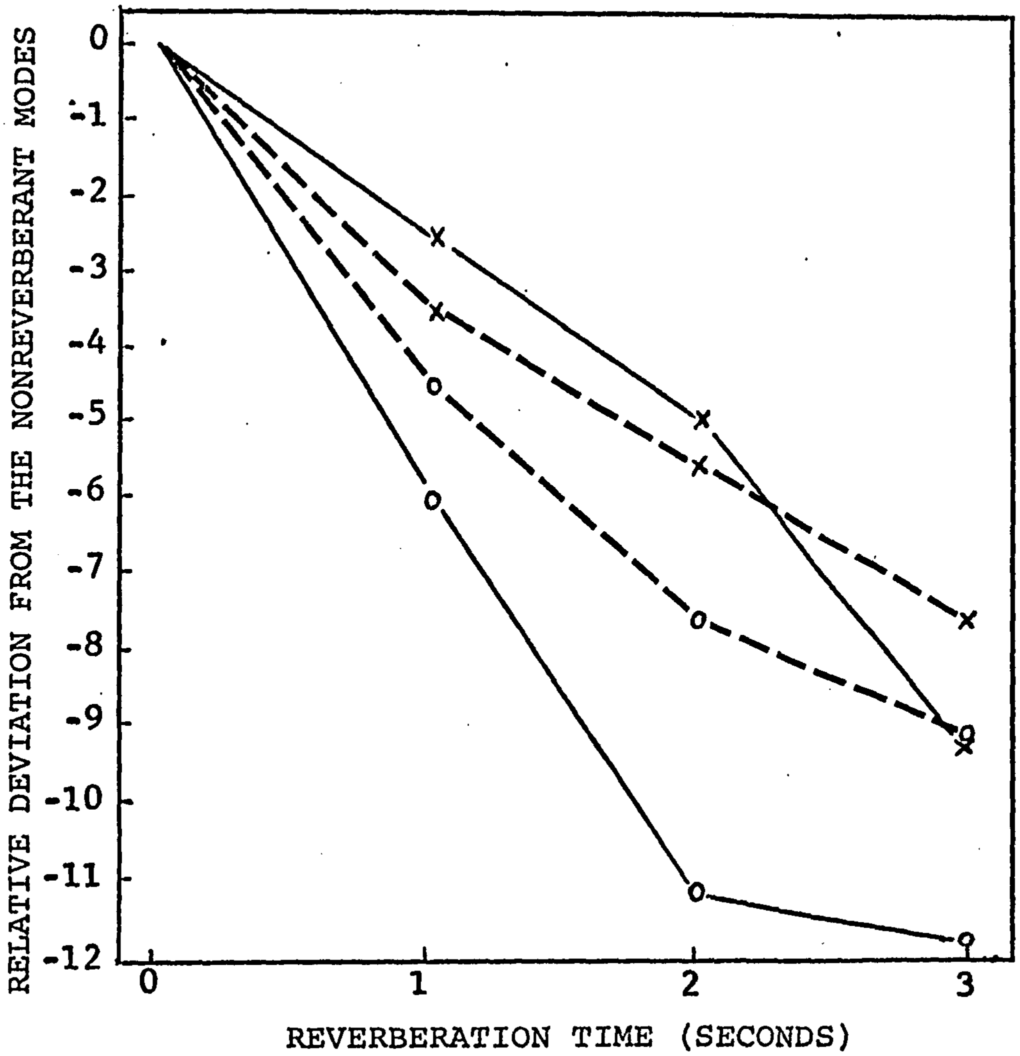

Figure 7.-- Mean scores for all conditions equated in terms of the nonreverberant conditions, and expressed as relative deviations from the nonreverberant conditions. Crosses denote binaural data points, and circles denote monaural data points. The data points of the normal subjects are connected with solid lines, and the data points of the hard-of-hearing subjects are connected with dashed lines.

decrease at the same rate with increasing reverberation time, is rejected; thus indicating that the monaural scores declined at a faster rate than the respective binaural scores, for both groups.

It is interesting to note that except for the comparably low mean scores obtained by the normals at the monaural 2 sec. RT condition, the curves in Figure 7 are remarkably similar. In fact, if this graph is replotted in terms of the differences between binaural and monaural scores for each group (Figure 8), it becomes clearer that a similar trend was operative for both groups; while, of course, the differences were greater for the normal subjects.

Effect of Loudness

The possibility that the loudness advantage, equivalent to about 3 to 6 dB, of binaural over monaural hearing may have accounted for differences between the one-ear and two-ear scores, was investigated for both groups. In addition to receiving the tests at sensation levels used for all normal subjects, the first ten normals were also tested at 25, 35 and 40 dB SL. In addition, each hearing impaired subject received one additional test monaurally at a level 5 dB above the monaural test level used for the subject. The reverberation time of the additional test was alternated between subjects, so that eight re-

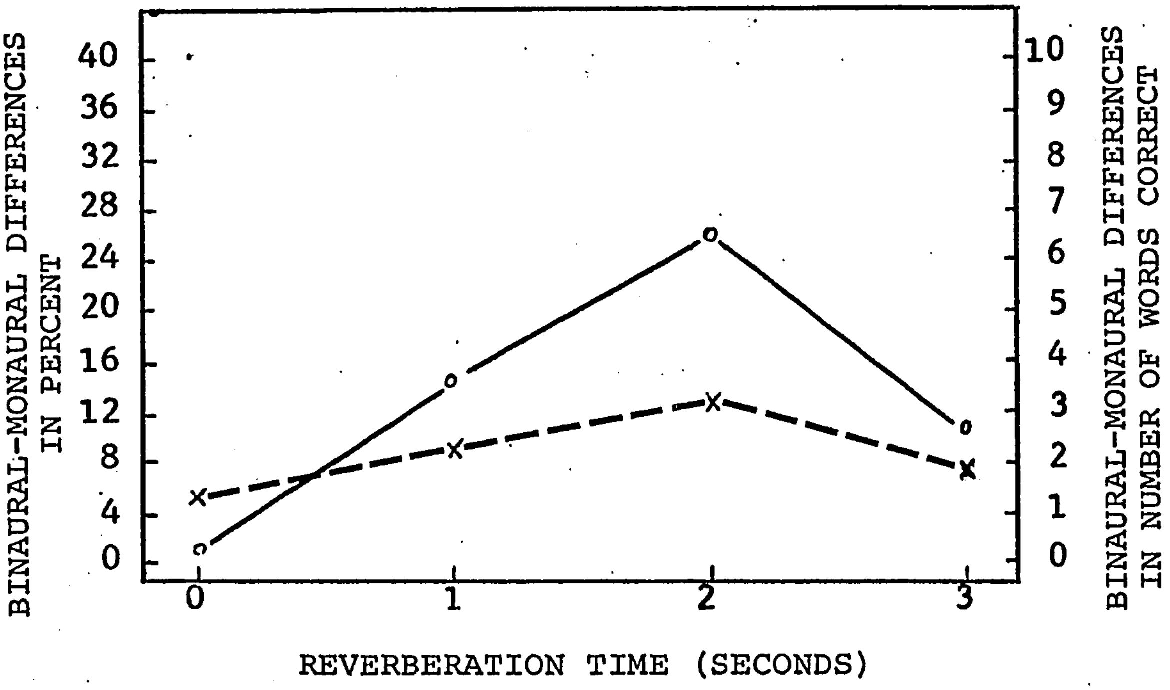

Figure 8.-- Differences between the binaural and monaural scores of each group as a function of reverberation time. Circles denote the data points of the normal subjects, and crosses indicate the data points of the hard-of-hearing subjects.

ceived an extra M0 list, eight an M1 list, seven an M2 list, and seven an M3 list.

The raw scores of the normal subjects at each SL are listed in Appendix C. The means for each SL are listed in Table 6, and are plotted in Figure 9. The scores at each reverberation time were treated independently with analyses of variance (Winer, 1962, pp. 105-124), the results of which are summarized in Tables 7, 8, 9 and 10. There were no significant differences between the scores at each SL for the M0 condition (F = 1.1). However, the F scores for the analyses at the M1 (F = 11.5), M2 (F = 7.2) and M3 (F = 7.7) conditions were all significant beyond the .01 level. Therefore, Tukey Tests of a posteriori pair-wise comparisons (Winer, 1962, pp. 87-89) were performed for the signigicant analyses. The results of these tests appear in Appendices D, E, and F. In each case, only the scores at the 25 dB sensation levels were found to be significantly different from any of the other scores.

The scores for the hearing impaired subjects at the monaural test levels compared to the scores obtained monaurally at levels five decibels above, are listed in Appendix G. The differences between the monaural scores obtained at the test levels and at the 5 dB increments are also listed in Appendix G. (positive differences indicate that the plus-five decibel level yielded a higher

TABLE 6

MEAN SCORES FOR TEN NORMAL SUBJECTS AT FOUR SENSATION LEVELS (NUMBER CORRECT)

	Sensation Level			
Condition	25 dB	30 dB	35 dB	40 dB
M0	24.6	24.7	24.9	24.9
M1	17.3	18.8	19.1	19.0
M2	12.8	14.1	14.4	14.2
M3	12.0	13.4	13.2	13.1

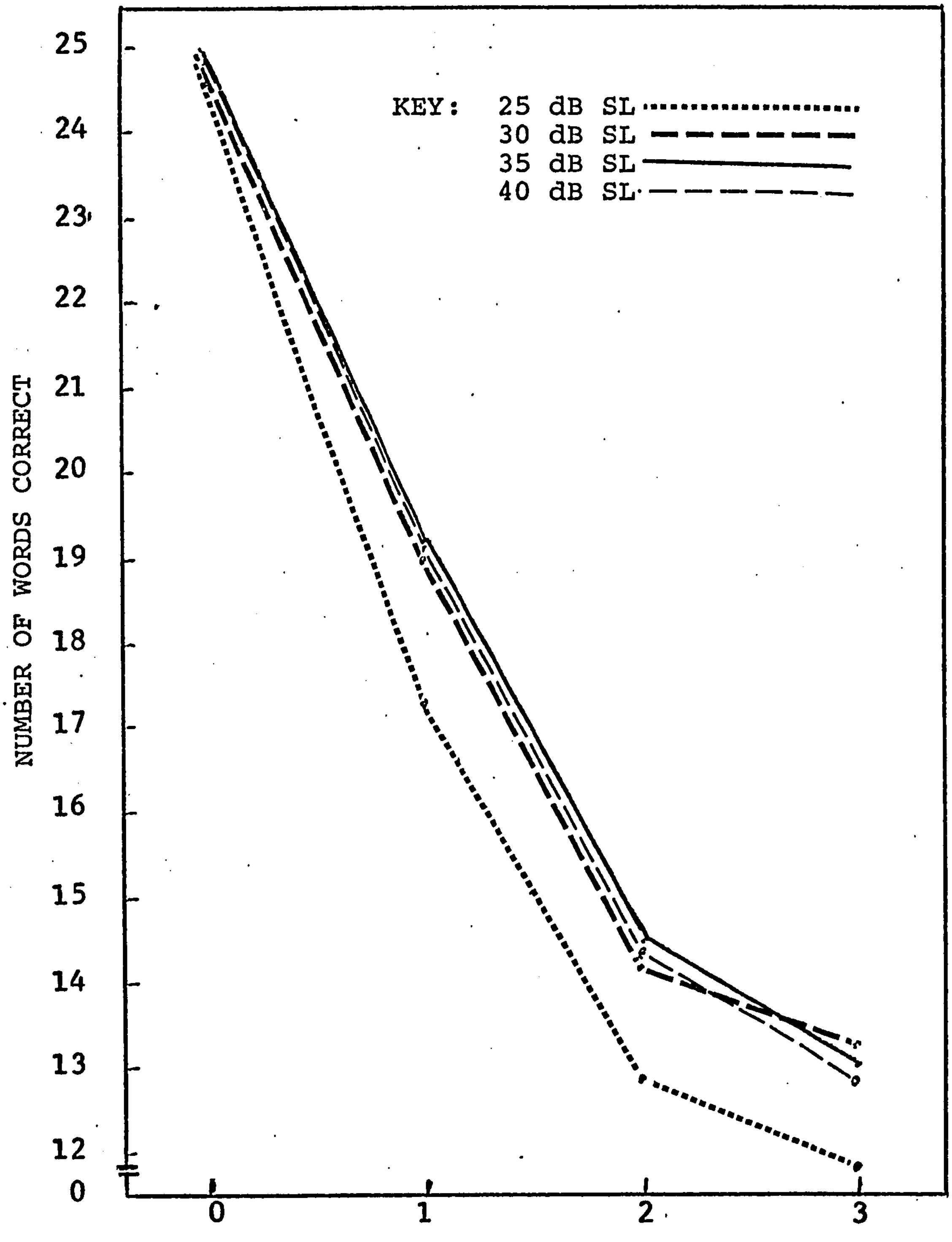

Figure 9.-- Mean scores at 25, 30, 35 and 40 dB sensation level for the first ten normal subjects.

TABLE 7

ANALYSIS OF VARIANCE FOR THE MONAURAL DATA OF TEN NORMALS AT FOUR SENSATION LEVELS (0 SEC. RT)

Source	SS	df	MS	F	p
Between Subjects	2.725	9			
Within Subjects	6.25	30			
Sensation Level	0.675	3	0.225	1.0897	n.s.
Residual	0.575	27	0.2065		
Total	8.975	39			

TABLE 8

ANALYSIS OF VARIANCE FOR THE MONAURAL DATA OF TEN NORMALS AT FOUR SENSATION LEVELS (1 SEC. RT)

Source	SS	df	MS	F	p
Between Subjects	225.9	9			
Within Subjects	38.0	30			
Sensation Level	21.3	3	7.1	11.4793	.01
Residual	16.7	27	0.6185		
Total	263.9	39			

TABLE 9

ANALYSIS OF VARIANCE FOR THE MONAURAL DATA OF TEN NORMALS AT FOUR SENSATION LEVELS (2 SEC. RT)

Source	SS	df	MS	F	p
Between Subjects	40.675	9			
Within Subjects	35.75	30			
Sensation Level	15.875	3	5.2916	7.1885	.01
Residual	19.875	27			
Total	76.375	39			

TABLE 10

ANALYSIS OF VARIANCE FOR THE MONAURAL DATA OF TEN NORMALS AT FOUR SENSATION LEVELS (3 SEC. RT)

Source	SS	df	MS	F	p
Between Subjects	155.025	9			
Within Subjects	25.75	30			
Sensation Level	11.875	3	3.9583	7.7039	.01
Residual	33.875	27	0.5138		
Total	180.775	39			

score). The differences for each of the conditions are quite small and are very similar. Therefore, the data were treated as a whole. The significance of the differences was tested with the Wilcoxon Matched-Pairs Signed Ranks Test (Siegel, 1956, pp. 75-83). The results of the test revealed that the differences between scores at the two levels were not significant (T = 117.5); indicating that there were no significant differences between the monaural scores of the hearing impaired subjects at the experimental test levels and at a five decibel increment, for the various reverberation time conditions.

Effect of Age

The effect of age upon the results was tested for each group of subjects with the Spearman Rank Correlation (Siegel, 1956, pp. 202-213). For each group, the subjects were rank ordered by age and by the overall proportion of the total number of items they responded to correctly on the experimental tests. The data are shown in Figure 10. The Spearman Rank Correlations were found to be .19 and .16, for the normal and hearing impaired subjects, respectively; indicating no significant relation between age and scores for either group.

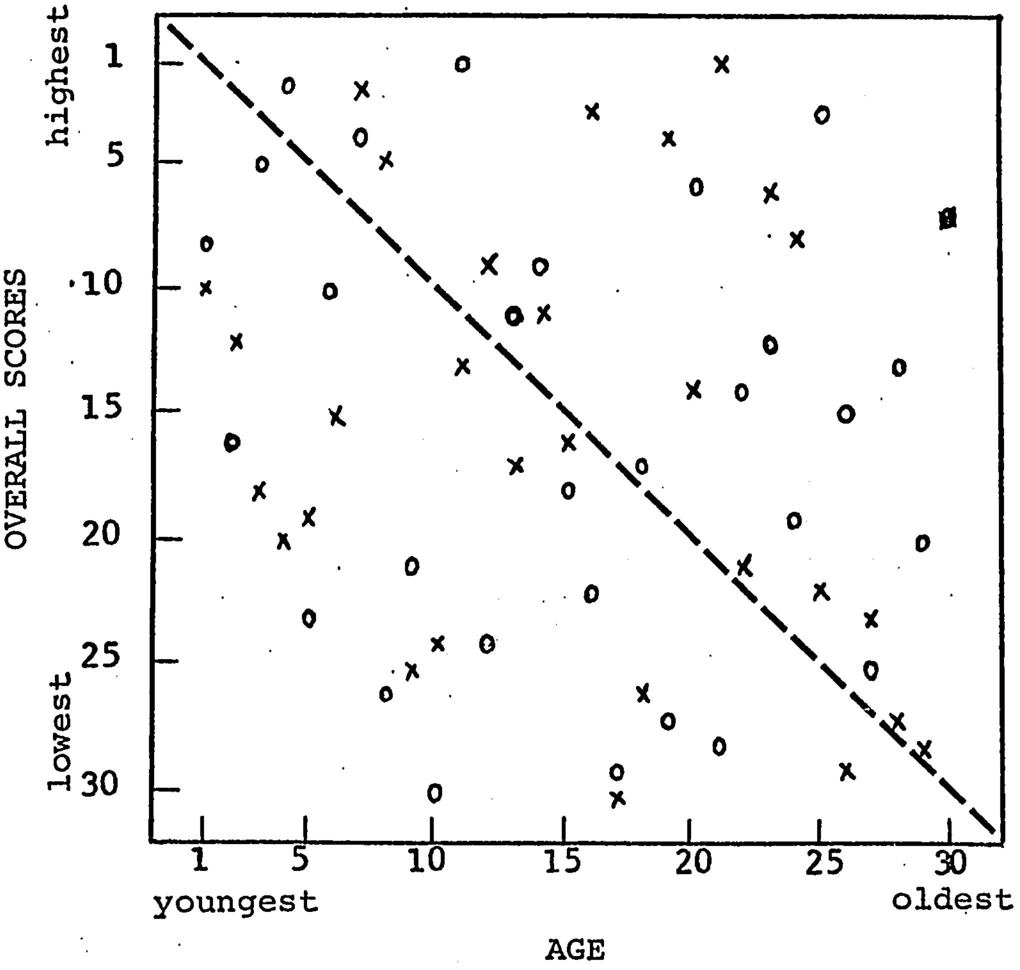

Figure 10.-- Relationship of age and overall scores for both groups of subjects, in terms of rank-ordering of the data. The crosses refer to the normal subjects and the circles to the hearing impaired subjects. The diagonal line indicates the theoretical correlation of 1.0 between aging and decreasing speech discrimination performance on the tests.

CHAPTER V

DISCUSSION

The major finding of this study was that binaural hearing resulted in superior speech discrimination under reverberation for both normal and hearing impaired subjects, compared to monaural hearing. As reverberation time increased, the monaural scores of both groups dropped substantially compared to the binaural scores, and this was most striking for the normal subjects.

If one were to rank order the relative monaural and binaural scores, the binaural discrimination score of either group is superior to the monaural score of either group (except for the 3 sec. RT condition, for which the normal-monaural and hearing impaired-binaural points are quite similar). This result is important in that it shows that the presence of sensorineural hearing loss of presumably peripheral (cochlear) origin, does not impede the ability of the individual to overcome reverberation binaurally, in spite of the general reduction of auditory functioning associated with the hearing loss. This leads one to the conclusion that while a bilateral peripheral lesion does reduce overall auditory functioning, certain higher order activities may remain in tact. The relative binaural advantage, however, is smaller than that for the normal hearing.

It is noteworthy that while the relative binaural scores of the normals, as a function of reverberation time, are essentially parallel to those of the hearing impaired, the normals' monaural results show a strikingly sharp decrement in the monaural speech discrimination scores with reverberation time. This dramatic decrease for the normals may provide a cue as to how the binaural system deals with reverberation.

Whereas evidence of binaural resistance to reverberation was observed qualitatively by Koenig (1950), there has been little quantitative research on this phenomenon (Moncur and Dirks, 1967; Nabelek and Pickett, 1972a, 1972b), and there are no published data on this effect with the hearing impaired to the writer's knowledge. This is in contrast to the large amount of research on binaural release from masking for speech since the effect was first reported by Licklider (1948) at about the same time. Part of the reason for the difference in emphasis may be due to the difficulty of specifying exactly appropriate or typical reverberant conditions. For example, reverberation time is defined empirically and is no more than a gross measure of the time aspect of reverberation, since many different types of reverberation may have the same reverberation time. This study, being the first of its type, used an extreme case of reverberation that is easily replicated in the laboratory. Also, the subjects were denied interaural cues. In spite of this, the binaural improvements observed are quite large, and are comparable to the improvements in intelligibility obtained by Licklider (1948) and others (Levitt and Rabiner, 1967) for binaural release from masking for speech. This represents a substantial binaural effect in improving percent articulation scores*.

In real life there are obvious differences in the location of speech and noise sources, which in turn result in interaural differences between speech and noise, leading to improved intelligibility. Much of the early research on binaural release from masking was geared toward determining the link between interaural differences and improvements in intelligibility of signals in noise. The improvements obtained with such heterophasic effects provided the original basis for investigating the possible values of binaural amplification (Hirsh, 1950a).

The effects of reverberation in real life are quite important, although not readily apparant. To appreciate the deleterious effects of reverberation, on has only to

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* The large differences obtained also lend themselves to the testing of theoretical points relative to the binaural processing of speech.

place a tape recorder in a room with moderate reverberation (for example, a classroom), and then to listen to the recording of the speech in that room. Listening to such a recording with one ear is quite difficult, but when two ears are used, one is better able to deal with the interference caused by the reverberation, as Koenig has pointed out. The degradation of speech intelligibility in typical rooms has only recently been appreciated with the development of conference telephony (in which a loudspeaker and microphone are used in place of the conventional handset) (Levitt, 1973).

One may view reverberant speech as almost the equivalent of speech in noise; and therefore as a homophasic phenomenon, since both the direct and reflected signals are present in similar form at each ear. As such, reverberation represents a form of noise capable of interfering with speech perception.

The question is raised, now, as to the effects of such reverberant environments upon the hearing impaired individual. Under such circumstances, will a person with a bilateral peripheral hearing impairment be able to enjoy the benefits of binaural hearing to overcome the effects of reverberation? The results of this study suggest that binaural processing does provide such an advantage to the hearing impaired individual, just as it does for the normal hearing person. Because interaural differences denied to the listener in this study due to the manner of stimulus presentation, it is suggested that the binaural auditory neural system, in and of itself, is capable of squelching the effects of reverberation to a measurable extent without external cues, and that this occurs whether the peripheral organ is normal or impaired (within the range of impairments studied in this investigation).

It may be argued that the improvements obtained were due to binaural summation. However, it was found that if intensity is increased by an amount comparable to the effective increase due to binaural summation, there is a negligibly small increase in intelligibility. Is was found that binaural summation was a significant factor only at lower sensation levels, when a more substantial portion of the speech power is only minimally audible, if heard at all. This is shown in Figure 9, in which the higher level speech stimuli resulted in virtually superimposed results, and only the data for the 25 dB SL condition are noticably deviant. Thus, even if binaural summation is a factor in enhancing speech intelligibility in this study, its contribution was found to be relatively small compared to the large binaural-monaural differences observed.

The results of the current study are in agreement with the findings reviewed by Bocca and Calearo (1963) that the addition of a second ear increased speech intelligibility. The results are also consistent with Harris' (1964) Redundancy Principle, in that the redundancy afforded by the added information to the second ear was able to increase the discrimination scores. However, it is not identical to the Principle of Redundancy, since Harris found this effect to occur when a second channel was added to one ear.

Comparison of the results of this investigation with those of Nabelek and Pickett (1972a, 1972b) is extremely difficult because of the very short reverberation times used in their studies (0.3 and 0.6 sec.). However, their data do show a decrease in intelligibility with increased reverberation time, so that a similarity of trend is seen in the current study and those of Nabelek and Pickett.

The results of Moncur and Dirks (1967)* and those for the normal subjects in this study are compared in Figure 11. As is quite clear in the graph, a similar trend is observed for both the monaural and binaural results of both studies. In this light, the two studies are considered corroborative. However, it is notable that a sizable difference exists between the binaural data of the two studies, with the binaural improvement of the cur-

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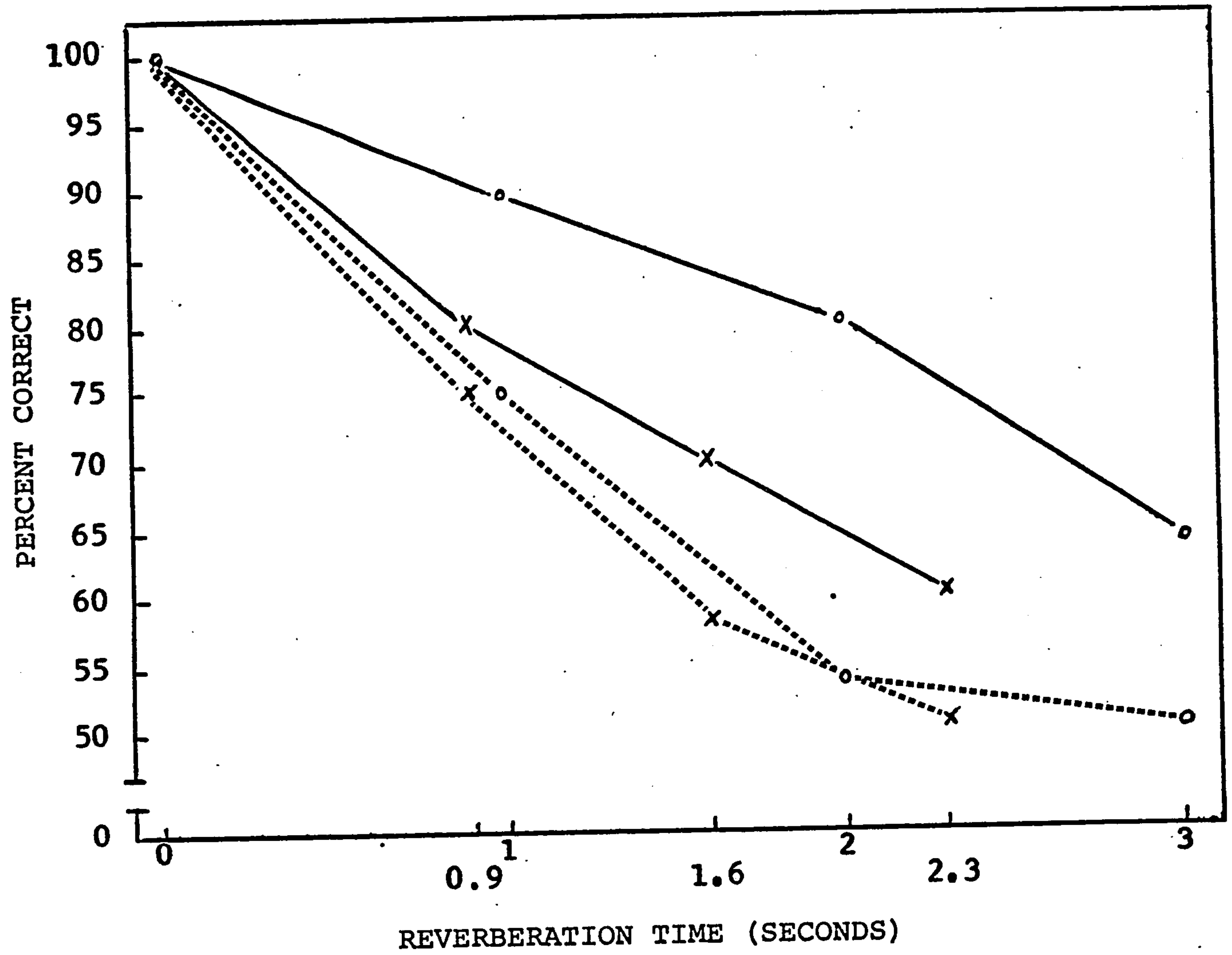
* Moncur and Dirks' monaural near-ear data are used since these more realistically reflect the better ear results in their study.

Figure 11.-- Results of the current study for normal subjects compared to the data of Moncur and Dirks (1967) for their binaural and monaural near-ear conditions. Circles refer the the data of the current investigation, and crosses refer to the data of Moncur and Dirks. Binaural data points are connected by solid lines, and monaural data points are connected by dashed lines.



100
95
90
85
80
75
70
65
60
55
50
0
PERCENT CORRECT
0
1
0.9
1.6
2
2.3
3
REVERBERATION TIME (SECONDS)

rent investigation being greater than that found by Moncur and Dirks.

The differences in the experimental data of the two studies presumably reflect the differences in methodology. While Moncur and Dirks employed naturally produced reverberation, an open-set test (PB-50 lists), and administration of the stimuli preserving interaural differences; the current study used artificial reverberation, a closed-set test (MRT lists), and headphone administration without interaural differences. It is recalled that Moncur and Dirks recorded their tapes through an artificial head with a loudspeaker at 45° azimuth. Therefore, in spite of their use of headphones to test their subjects, the effects of the head shadow, and of interaural time, phase and intensity differences, were still present. It is believed that the binaural scores were greater in the current study because thestimuli were presented at equal levels to both ears, whereas the binaural data of Moncur and Dirks reflected level differences at each ear (due to the head shadow effect), so that their binaural results are mainly due to the contribution of the near ear instead of the equal contribution of both. Moncur and Dirks asserted that the prime factor causing the binaural advantages in their study was related to interaural time differences. Such interaural time differences were not operative in the current study.

The striking decrease in monaural scores with increasing reverberation time observed for the normal subjects may reflect an increased masking effect. As noted in Chapter III, the reverberant signals decayed in ten 6 dB steps, spaced at intervals of 100, 200 or 300 msec., depending upon the reverberation time desired. The delayed signals lasted longer at each successive reverberation time before being attenuated an additional six decibels*. It is possible that the added sound existed at a higher sensation level for the normals than it did for the abnormal subjects, which may have accounted for additional masking, and therefore, the lower scores in the normal data.

A possible model to explain how the reverberation in this study might have been squelched binaurally is as follows. Although the mode of stimulus presentation used here was homophasic, it is noteworthy that multiple reflections are inherent in reverberation. If one were to view the direct sound as occurring at time *0*, and the reflected sounds arriving at delays of *x* msec. as occurring at time *t*, then a possible framework may be constructed in which the binaural system cross-correlates the information at

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* It is noted that the effect upon the S/N ratio was less and less with each additional echo at -6 dB, since each added 1/4 the power. Thus the total noise caused by the reflections was 1/4 + 1/16 + 1/64 + ... , for a total of about 1/3, or 1.3 dB. The corresponding S/N ratio is 3 for the direct to reflected sound, or 4.8 dB.

the two ears to extract added cues, as though the stimuli were heterophasic. This could be accomplished through a cross-correlation of the direct sound at time *0* in one ear with the relfected counterpart of that signal at time *t* in the other ear.

Such a model is similar to that proposed by Cherry and Sayers (1956) and Sayers and Cherry (1957), and could serve as a theoretical explanation for the binaural advantages seen in this study which is consistent with the available data on heterophasic effects. Further, such a model would be consistent with similar performance by the normal and hearing impaired subjects, since all that would be required by the binaural cross-correlator would be similar peripheral coding of the input signals at the two ears. The presence of peripheral impairements would just cause a general reduction of performance rather than preclude central processing altogether. This, of course, assumes that the peripheral impairment is not so severe thatthe input signals are distorted beyond usefulness; and it also assumes some degree of similarity of functioning at the two ears, as with a symmetrical hearing loss.

One further aspect of the data deserves attention. This is the apparant notch in the normals' monaural data at the 2 sec. reverberation time. This is clearly deviant from the general trend of the data under all conditions for either group, as shown in Figure 7. Analysis of the raw data revealed that this unexpectedly low data point probably reflects the deviant scores of a few individual subjects (subjects 4, 14, 18, 19, 20 and 29 in Appendix A) whose monaural 2 sec. RT scores were lower than their respective 3 sec. RT scores. In 20 cases, the 2 sec. RT scores were higher than the 3 sec. RT scores, and in four cases they were equal. It is therefore suggested that the apparant notch in the normals' mean monaural score at the two second reverberation time is probably the result of experimental error.

Implications for the Hearing Impaired

The current study lends support to the use of binaural hearing aids for the hearing impaired. In agreement with Zelnick (1970), it is asserted that many previous studies did not use tasks sufficiently difficult to yield a measurable binaural advantage. It is expected that the use of two hearing aids will allow the individual with bilateral sensorineural hearing loss of cochlear origin to better overcome the effects of reverberation to a greater extent than with monaural amplification. The use of reverberant speech discrimination tests may be used to demonstrate such an advantage. The results of this study may also be taken to suggest that Y-cord fittings would also provide the individual with more resistance to reverberation than monaural amplification; but this would not be expected to be of the magnitude of binaural aids, which also allow for interaural cues to be obtained. It is further expected that real world situations will result in greater binaural advantages than obtained in this study, since interaural cues which are available to the hearing impaired individual in daily life were not availed to the subjects in this study.

The possibility exists that the relatively low fidelity of commercial hearing aids may reduce the binaural advantage to some extent. An attempt was made in this investigation to limit the frequency range of the stimuli to that of most commercial aids (400 to 4000 Hz); however, high fidelity instruments were used, and one cannot legitimately equate the flat response with smooth roll-off characteristics of high fidelity instruments with the characteristics of hearing aids merely on the basis of a similar bandwidth.

Just as noise is an example of communicative interference used in clinical hearing aid evaluations, reverberation should also be used in such evaluations, as a further characteristic of difficult listening situations. The use of reverberant speech discrimination test results should provide insight into the ability of the patient to make justifiable use of two hearing aids as opposed to one.

A further implication of this investigation is that since reverberation does result in decreased speech discrimination, hearing impaired persons should be exposed to reverberant conditions in auditory training programs.

Suggestions for Further Research

Since the current study was done with headphones to the exclusion of environmental and concomitant head movement effects, duplication in sound field is suggested to determine whether or not interaural effects will result in larger binaural advantages than obtained here. This should be done with both normal and hearing impaired subjects. Further duplication in a similar manner with commercial hearing aids should also be attempted, so that the effects of such low fidelity instruments may be ascertained. The latter suggestion is important because if binaural advantages as found here are limited to high quality sound systems, the application of these results to general clinical use would be markedly reduced.

The use of reverberant stimuli in auditory training should also be investigated, since its use may prove benificial in the habilitation and rehabilitation of the hearing impaired.

It would be desirable to replicate this study with a variety of subjects and discrimination tests, and with naturally as well as artificailly produced reverberation, in order to confirm the current results as well as to determine the generality of their application.

Subsequent studies should attempt to investigate the effects of reverberation on speech discrimination at reverberation times other than those used here, including those at shorter intervals (perhaps 0.3 or 0.5 second reverberation times). Such study should provide insight into the effects of small changes in reverberation, as well as into any deviations in the trends found in this investigation.

Researchers should also investigate the possibility of employing reverberant speech discrimination tests, monaurally and binaurally, for diagnostic purposes on at least two levels: (a) for differentiating peripheral from central dysfunctions; and (b) for prognosticating the binaural advantages patients may expect to accrue with binaural amplification in difficult listening situations.

CHAPTER VI

SUMMARY AND CONCLUSIONS

This investigation sought to determine the effects of reverberation time upon the speech discrimination performance of normal and hearing impaired subjects. Thirty normal hearing persons, and thirty individuals with bilateral symmetrical sensorineural hearing loss with audiological evidence of cochlear locus, were administered the Modified Rhyme Test, monaurally and binaurally, at four reverberation times (0, 1, 2 and 3 seconds). The stimuli were administered through headphones for both conditions. In addition, ten of the normal subjects were tested monaurally at four sensation levels (25, 30, 35 and 40 dB), in order to determine the effects of increased loudness upon the results. Similarly, each of the hearing impaired subjects listened to one extra test list, monaurally, at a sensation level five decibels above the monaural administration level used for that subject for the main experiment.

The significance of the differences obtained were tested with an analysis of variance with an arcsine transformation. The following results were obtained:

(1) Normal hearing subjects obtained significantly higher scores than did the hearing impaired persons for all conditions. However, when the nonreverberant speech discrimination scores of both groups were equated, and the reverberant scores were analyzed as deviations from their respective nonreverberant scores, the groups performed in a similar manner.

(2) For both groups of subjects, the speech discrimination scores for each reverberation time condition were significantly higher binaurally than they were monaurally.

(3) The speech discrimination scores of both groups of subjects decreased significantly as reverberation time increased, for both the monaural and binaural conditions.

(4) With increasing reverberation time, the monaural speech discrimination scores decreased at a faster rate than did the binaural scores, although this effect was more marked for the normal subjects.

(5) Increasing the loudness of the monaural stimuli, to simulate the binaural loudness gain, did not result in significantly higher speech discrimination scores, for both groups of subjects.

CONCLUSIONS

Speech intelligibility under reverberation is superior binaurally than monaurally, for both normal hearing individuals and those with bilateral sensorineural hearing loss of cochlear origin; although the magnitude of this binaural enhancement is greater for normals than for the hearing impaired. This is due, at least partially, to the ability of the binaural auditory neural system, in and of itself, to squelch the effects of reverberation.

As reverberation time increases, both normal and hearing impaired persons experience decreased speech discrimination ability, monaurally and binaurally. This degradation of speech discrimination ability as a function of reverberation time is more rapid monaurally than binaurally, reflecting the ability of the binaural system to squelch the deleterious effects of reverberation.

APPENDIX A

NORMAL SUBJECTS' RAW SCORES FOR ALL CONDITIONS (NUMBER CORRECT)

Subj.	M0	M1	M2	M3	B0	B1	B2	B3
1	25	21	14	13	25	22	18	15
2	25	19	14	12	25	24	21	16
3	24	22	16	16	25	22	22	21
4	25	17	14	17	25	20	16	13
5	25	16	12	11	25	24	23	19
6	25	18	13	11	25	23	21	18
7	24	14	15	15	25	23	25	13
8	24	20	15	13	25	22	20	17
9	25	22	14	13	25	23	20	20
10	25	19	14	13	25	24	21	14
11	25	18	16	15	25	23	20	17
12	25	18	13	12	24	22	19	13
13	25	18	12	11	25	21	18	15
14	25	18	10	11	25	24	22	16
15	25	17	13	13	25	20	18	15
16	25	21	15	13	25	22	20	15
17	25	19	12	11	25	21	19	15
18	23	15	11	13	24	20	18	15
19	25	16	12	14	25	25	21	16
20	25	16	14	15	25	21	17	14
21	25	20	15	14	25	23	21	17
22	25	21	16	14	25	24	22	18
23	25	19	15	14	25	22	19	17
24	25	22	16	14	25	24	22	16
25	25	22	15	12	25	24	23	20
26	24	18	14	12	25	23	20	13
27	24	18	12	12	25	21	19	17
28	25	20	15	14	24	21	19	13
29	23	18	9	11	25	24	20	13
30	24	22	14	13	25	24	21	16

APPENDIX B

HEARING IMPAIRED SUBJECTS' RAW SCORES FOR ALL CONDITIONS (NUMBER CORRECT)

Subj.	M0	M1	M2	M3	B0	B1	B2	B3
1	19	16	10	11	19	16	14	13
2	16	14	11	8	17	16	12	11
3	22	13	13	12	23	19	18	13
4	15	10	7	6	15	13	10	7
5	18	14	10	7	18	15	14	16
6	21	17	14	14	22	20	16	13
7	17	13	11	8	17	15	12	12
8	20	12	10	9	21	17	15	12
9	19	11	8	8	20	16	14	12
10	16	13	12	9	18	16	16	9
11	14	12	10	9	20	13	11	10
12	16	15	9	11	22	20	16	14
13	18	12	7	7	18	15	10	11
14	20	14	10	11	20	17	17	15
15	20	15	10	8	20	17	15	14
16	19	14	11	9	20	14	13	10
17	21	16	17	14	20	17	17	11
18	19	12	10	6	20	14	11	9
19	17	12	9	9	19	15	10	12
20	12	11	7	8	19	13	13	11
21	18	15	12	9	18	15	13	13
22	22	16	14	11	22	18	15	13
23	19	16	12	6	20	16	16	11
24	20	17	12	12	20	17	16	15
25	15	11	7	4	17	14	10	10
26	19	15	12	11	19	16	15	13
27	17	14	14	12	19	16	14	14
28	19	14	11	10	21	18	15	14
29	20	16	13	14	19	16	16	15
30	14	10	7	3	16	13	12	8

APPENDIX C

NORMAL SUBJECTS' RESPONSES AT FOUR SENSATION LEVELS (NUMBER CORRECT)

Subject	Condition	SL: 25 dB	30 dB	35 dB	40 dB
1	M0	25	25	25	25
	M1	20	21	21	20
	M2	14	14	13	14
	M3	10	13	12	13
2	M0	24	25	25	25
	M1	19	19	20	19
	M2	12	14	14	13
	M3	11	12	12	12
3	M0	24	24	25	24
	M1	20	22	21	21
	M2	15	16	16	15
	M3	14	16	15	16
4	M0	25	25	25	25
	M1	16	17	17	18
	M2	12	14	16	15
	M3	17	17	18	16
5	M0	23	25	25	25
	M1	14	16	17	17
	M2	10	12	13	13
	M3	9	11	11	11
6	M0	25	25	25	25
	M1	17	18	18	18
	M2	13	13	13	12
	M3	10	11	11	12
7	M0	25	24	24	25
	M1	10	14	15	15
	M2	13	15	15	16
	M3	14	15	15	15

APPENDIX C--*Continued*

Subject.	Condition	SL: 25 dB	30 dB	35 dB	40 dB
8	M0	25	24	25	25
	M1	20	20	21	21
	M2	15	15	15	15
	M3	13	13	13	11
9	M0	25	25	25	25
	M1	20	22	21	22
	M2	13	14	15	15
	M3	12	13	13	13
10	M0	25	25	25	15
	M1	17	19	20	19
	M2	11	14	15	14
	M3	10	13	12	12

APPENDIX D

TUKEY TEST FOR THE SIGNIFICANCE OF PAIR-WISE COMPARISONS AT FOUR SENSATION LEVELS (1 SEC. RT)

	a (173)	b (188)	d (190)	c (191)	CV
a (173)	-	15**	27**	18**	11.8
b (188)		-	2	3	11.8
d (190)			-	1	11.8
c				-	

**Significant beyond the .01 level.

APPENDIX E

TUKEY TEST FOR THE SIGNIFICANCE OF PAIR-WISE COMPARISONS AT FOUR SENSATION LEVELS (2 SEC. RT)

	a (128)	b (141)	d (142)	c (144)	CV
a (128)	-	13**	14**	16**	12.7
b (141)		-	1	3	12.7
d (142)			-	2	12.7
c (144)				-	12.7

**Significant beyond the .01 level.

APPENDIX F

TUKEY TEST FOR THE SIGNIFICANCE OF PAIR-WISE COMPARISONS AT FOUR SENSATION LEVELS (3 SEC. RT)

	a (120)	d (131)	c (132)	b (134)	CV
a (120)	-	11**	12**	14**	10.7
d (131)		-	1	3	10.7
c (132)			-	2	10.7
b (134)				-	10.7

**Significant beyond the .01 level.

APPENDIX G

DIFFERENCES BETWEEN SCORES AT MONAURAL TEST LEVEL AND FIVE DECIBELS ABOVE FOR IMPAIRED SUBJECTS (NUMBER CORRECT)

		Scores		
Condition	Subject	Test Level	Five dB Above	Difference
M0	1	19	20	+1
	5	18	19	+1
	9	19	21	+2
	13	18	18	0
	17	21	19	-2
	21	18	19	+1
	25	15	14	-1
	29	20	18	-2
				$\bar{X}$ = 0
M1	2	14	15	+1
	6	17	19	+2
	10	13	13	0
	14	14	15	+1
	18	12	13	+1
	22	16	16	0
	26	15	15	0
	30	10	7	-3
				$\bar{X}$= +.25
M2	3	13	13	0
	7	11	9	-2
	11	10	10	0
	15	10	12	+2
	19	9	8	-1
	23	12	12	0
	27	14	14	0
				$\bar{X}$= -.14
M3	4	6	8	+2
	8	9	8	-1
	12	11	9	-2
	16	9	10	+1
	20	8	10	+2
	24	12	9	-3
	28	10	10	0
				$\bar{X}$= -.14

APPENDIX H

PURE TONE THRESHOLDS* OF HEARING IMPAIRED SUBJECTS

Subj.	Ear	Mode	Freq: 250	500	1000	2000	4000	8000
1	Rt.	Air	20	30	35	40	50	75
	Lt.	Air	30	35	30	45	55	65
	Rt.	Bone	20	30	30	40	50	--
	Lt.	Bone	25	30	30	45	50	--
2	Rt.	Air	35	35	40	50	50	60
	Lt.	Air	30	40	45	45	50	55
	Rt.	Bone	30	30	35	40	35	--
	Lt.	Bone	25	30	35	40	40	--
3	Rt.	Air	20	35	50	45	55	65
	Lt.	Air	15	40	50	50	55	65
	Rt.	Bone	25	35	50	50	50	--
	Lt.	Bone	25	35	50	50	50	--
4	Rt.	Air	40	50	60	55	65	50
	Lt.	Air	50	45	65	55	65	60
	Rt.	Bone	45	50	60	50	60	--
	Lt.	Bone	45	50	60	55	60	--
5	Rt.	Air	30	35	35	40	35	25
	Lt.	Air	25	30	35	40	40	25
	Rt.	Bone	30	30	35	40	35	--
	Lt.	Bone	25	30	35	40	40	--
6	Rt.	Air	50	40	35	40	45	45
	Lt.	Air	45	35	30	45	50	40
	Rt.	Bone	50	40	30	35	45	--
	Lt.	Bone	45	35	35	40	45	--
7	Rt.	Air	25	20	30	50	60	60
	Lt.	Air	25	20	35	45	60	55
	Rt.	Bone	25	25	30	50	55	--
	Lt.	Bone	25	25	30	45	60	--
8	Rt.	Air	30	40	45	50	75	80
	Lt.	Air	35	40	45	55	70	80
	Rt.	Bone	30	40	45	50	65	--
	Lt.	Bone	30	45	45	55	65	--

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* In decibels re: ANSI 1970 Standards (American National Standards Institute, Inc., 1970).

APPENDIX H--*Continued*

Subj.	Ear	Mode	Freq:	250	500	1000	2000	4000	8000
9	Rt.	Air		20	20	30	65	75	85
	Lt.	Air		20	30	30	60	75	85
	Rt.	Bone		20	30	30	60	65	--
	Lt.	Bone		20	30	30	60	65	--
10	Rt.	Air		30	40	50	55	60	70
	Lt.	Air		35	40	50	55	60	75
	Rt.	Bone		35	40	45	55	65	--
	Lt.	Bone		35	40	45	50	60	--
11	Rt.	Air		40	45	40	40	65	80
	Lt.	Air		40	45	35	45	70	80
	Rt.	Bone		35	45	35	40	65	--
	Lt.	Bone		35	45	35	45	65	--
12	Rt.	Air		35	35	65	75	70	70
	Lt.	Air		35	30	65	75	70	75
	Rt.	Bone		35	30	65	65	65	--
	Lt.	Bone		35	35	65	65	65	--
13	Rt.	Air		25	25	35	60	50	55
	Lt.	Air		25	30	35	55	55	55
	Rt.	Bone		25	30	40	55	55	--
	Lt.	Bone		25	30	35	55	50	--
14	Rt.	Air		35	50	50	60	65	50
	Lt.	Air		30	55	60	60	70	50
	Rt.	Bone		30	50	50	60	60	--
	Lt.	Bone		30	50	55	55	65	--
15	Rt.	Air		20	30	30	40	60	NR
	Lt.	Air		15	35	30	40	60	85
	Rt.	Bone		20	30	30	40	65	--
	Lt.	Bone		15	30	30	40	60	--
16	Rt.	Air		40	55	50	35	45	65
	Lt.	Air		50	60	45	45	50	70
	Rt.	Bone		40	55	50	35	45	--
	Lt.	Bone		40	55	45	40	50	--
17	Rt.	Air		40	35	25	40	65	80
	Lt.	Air		30	30	30	50	60	80
	Rt.	Bone		30	30	25	45	60	--
	Lt.	Bone		35	30	25	45	60	--

APPENDIX H--Continued

Subj.	Ear	Mode	Freq: 250	500	1000	2000	4000	8000
18	Rt.	Air	15	30	40	50	50	35
	Lt.	Air	20	25	35	50	55	35
	Rt.	Bone	15	25	40	45	55	--
	Lt.	Bone	15	25	40	45	50	--
19	Rt.	Air	15	35	50	55	70	70
	Lt.	Air	15	30	40	45	70	75
	Rt.	Bone	20	40	50	50	65	--
	Lt.	Bone	20	40	40	50	65	--
20	Rt.	Air	45	40	45	50	70	80
	Lt.	Air	45	45	50	55	70	80
	Rt.	Bone	NR	40	50	50	65	--
	Lt.	Bone	NR	45	50	55	65	--
21	Rt.	Air	20	35	70	65	70	80
	Lt.	Air	20	35	60	65	75	80
	Rt.	Bone	25	30	65	65	NR	--
	Lt.	Bone	25	30	65	65	NR	--
22	Rt.	Air	25	35	35	40	45	65
	Lt.	Air	20	30	30	40	45	70
	Rt.	Bone	20	35	35	40	40	--
	Lt.	Bone	20	30	30	40	45	--
23	Rt.	Air	50	40	35	30	35	35
	Lt.	Air	40	45	40	35	45	45
	Rt.	Bone	40	35	40	30	40	--
	Lt.	Bone	40	40	40	30	40	--
24	Rt.	Air	15	40	60	60	55	70
	Lt.	Air	15	35	55	60	55	60
	Rt.	Bone	15	35	55	60	55	--
	Lt.	Bone	15	35	55	60	55	--
25	Rt.	Air	50	60	55	55	65	75
	Lt.	Air	50	65	60	55	65	85
	Rt.	Bone	NR	60	55	55	65	--
	Lt.	Bone	NR	65	60	55	65	--
26	Rt.	Air	20	30	35	50	40	40
	Lt.	Air	15	35	35	50	45	40
	Rt.	Bone	15	35	50	40	40	--
	Lt.	Bone	15	35	50	40	40	--

APPENDIX H--Continued

Subj.	Ear	Mode	Freq:	250	500	1000	2000	4000	8000
27	Rt.	Air		25	35	50	50	50	50
	Lt.	Air		20	30	50	50	50	45
	Rt.	Bone		20	30	45	50	50	--
	Lt.	Bone		20	30	45	50	50	--
28	Rt.	Air		25	30	35	40	60	80
	Lt.	Air		35	35	30	40	55	85
	Rt.	Bone		30	30	30	40	60	--
	Lt.	Bone		30	35	30	40	55	--
29	Rt.	Air		20	30	35	35	40	30
	Lt.	Air		25	30	40	40	35	30
	Rt.	Bone		20	30	30	35	40	--
	Lt.	Bone		20	30	35	40	40	--
30	Rt.	Air		55	50	60	55	75	75
	Lt.	Air		50	55	55	55	70	70
	Rt.	Bone		NR	55	60	55	65	--
	Lt.	Bone		NR	50	60	55	60	--

APPENDIX I

SPEECH RECEPTION THRESHOLDS* FOR HEARING IMPAIRED SUBJECTS

Subj.	Right	Left	Binaural	Subj.	Right	Left	Binaural
1	35	35	35	16	50	50	45
2	45	45	40	17	35	35	35
3	40	40	35	18	40	35	40
4	50	50	50	19	45	40	35
5	40	35	35	20	50	50	50
6	40	40	35	21	45	40	40
7	35	35	35	22	40	35	35
8	40	45	40	23	35	30	35
9	40	40	45	24	45	40	40
10	50	50	55	25	55	60	55
11	35	35	35	26	40	40	35
12	35	40	35	27	45	45	45
13	35	35	35	28	35	35	40
14	55	60	55	29	40	35	35
15	35	35	35	30	45	45	40

* In decibels re: ANSI 1970 Standards (American National Standards Institute, Inc., 1970).

APPENDIX J

SPEECH DISCRIMINATION SCORES (PERCENT) FOR HEARING IMPAIRED SUBJECTS

		Right			Left			Binaural		
Subj.	S.L.:	30 dB	35 dB	40 dB	30 dB	35 dB	40 dB	30 dB	35 dB	40 dB
1		80	80	80	80	76	76	80	84	80
2		72	72	68	72	64	64	76	80	72
3		84	80	84	80	80	76	84	84	80
4		68	64	64	60	64	60	76	76	72
5		80	80	72	76	84	84	84	88	84
6		84	88	84	76	68	72	80	80	80
7		80	68	76	76	72	72	84	84	88
8		92	88	88	80	84	80	92	96	88
9		84	80	80	80	80	80	88	84	88
10		84	80	72	72	72	68	68	72	72
11		88	88	88	84	88	88	88	92	84
12		68	72	72	80	80	76	88	84	84
13		84	80	80	88	92	84	92	88	88
14		80	84	88	80	88	88	80	80	84
15		84	80	84	84	88	88	80	80	88
16		52	60	48	76	76	80	76	80	80
17		84	80	80	76	80	72	80	84	80
18		88	88	88	88	84	84	84	88	80
19		68	64	72	60	52	56	68	68	64
20		60	60	64	76	72	76	76	72	68

APPENDIX J--<u>Continued</u>

		Right			Left			Binaural		
Subj.	S.L.:	30 dB	35 dB	40 dB	30 dB	35 dB	40 dB	30 dB	35 dB	40 dB
21		68	60	52	64	64	60	68	60	60
22		88	84	84	84	80	84	88	88	80
23		80	80	76	80	84	88	84	84	84
24		88	84	84	88	88	92	92	88	92
25		64	56	60	72	64	72	80	80	84
26		88	92	88	88	84	80	92	88	88
27		84	84	80	84	80	80	88	88	84
28		76	76	72	76	72	72	80	72	80
29		88	88	80	84	80	88	88	88	92
30		60	64	64	72	68	72	64	76	68

APPENDIX K

SHORT INCREMENT SENSITIVITY INDEX RESULTS FOR HEARING IMPAIRED SUBJECTS

	Right Ear		Left Ear	
Subj.	1000 Hz	4000 Hz	1000 Hz	4000 Hz
1	95%	95%	100%	95%
2	90%	100%	100%	95%
3	85%	85%	85%	90%
4	100%	100%	100%	100%
5	95%	100%	90%	100%
6	90%	100%	100%	95%
7	100%	100%	100%	100%
8	100%	100%	90%	100%
9	100%	100%	90%	100%
10	90%	100%	100%	100%
11	90%	100%	95%	100%
12	100%	100%	100%	100%
13	90%	100%	95%	100%
14	95%	100%	100%	100%
15	90%	100%	90%	95%
16	100%	100%	100%	90%
17	95%	100%	100%	100%
18	100%	95%	100%	100%
19	100%	100%	100%	100%
20	100%	100%	100%	100%
21	100%	100%	100%	100%
22	100%	100%	100%	100%
23	95%	100%	100%	90%
24	100%	100%	100%	100%
25	85%	100%	100%	100%
26	90%	90%	95%	100%
27	100%	100%	100%	100%
28	100%	100%	100%	100%
29	95%	100%	100%	100%
30	100%	100%	100%	100%

APPENDIX L

TONE DECAY TEST RESULTS FOR HEARING IMPAIRED SUBJECTS

	Right Ear		Left Ear	
Subj.	1000 Hz	4000 Hz	1000 Hz	4000 Hz
1	5 dB	5 dB	5 dB	5 dB
2	5 dB	10 dB	10 dB	10 dB
3	10 dB	10 dB	5 dB	10 dB
4	10 dB	15 dB	10 dB	15 dB
5	5 dB	10 dB	10 dB	10 dB
6	5 dB	10 dB	5 dB	10 dB
7	10 dB	10 dB	10 dB	10 dB
8	10 dB	10 dB	10 dB	15 dB
9	15 dB	10 dB	10 dB	5 dB
10	10 dB	15 dB	5 dB	10 dB
11	5 dB	5 dB	10 dB	5 dB
12	10 dB	15 dB	10 dB	15 dB
13	10 dB	10 dB	5 dB	15 dB
14	10 dB	10 dB	10 dB	10 dB
15	5 dB	10 dB	5 dB	5 dB
16	15 dB	15 dB	10 dB	10 dB
17	5 dB	10 dB	10 dB	10 dB
18	5 dB	10 dB	10 dB	5 dB
19	10 dB	15 dB	15 dB	15 dB
20	10 dB	15 dB	10 dB	10 dB
21	15 dB	15 dB	10 dB	10 dB
22	5 dB	5 dB	5 dB	5 dB
23	10 dB	10 dB	15 dB	10 dB
24	15 dB	10 dB	10 dB	10 dB
25	10 dB	15 dB	10 dB	15 dB
26	5 dB	5 dB	5 dB	5 dB
27	10 dB	10 dB	15 dB	10 dB
28	10 dB	10 dB	10 dB	15 dB
29	10 dB	10 dB	5 dB	10 dB
30	10 dB	15 dB	15 dB	15 dB

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