Many investigations have attempted to determine whether the binaural squelch effects originally described by Koenig (1950) are available to hearing-impaired individuals wearing hearing aids. Essentially, the issue centers on whether binaural head-worn hearing aids facilitate speech understanding in a noisy background to a greater extent than a monaural head-worn instrument when the test is arranged so that head shadow is not a factor. The typical finding in studies of this issue is that although group results indicate that the binaural speech intelligibility score in noise is modestly but significantly superior to the monaural score, the results for individuals may range from a large binaural advantage to a binaural disadvantage (Causey & Bender, 1980; Cox, DeChianctus, & Wark, 1981; Dermody & Byrne, 1975; Sebkova & Bamford, 1981a). These data seem to indicate that some bilaterally impaired individuals are better candidates for binaural amplification than others.

In recommending appropriate amplification, it would be very useful to be able to identify the individuals who can expect to benefit from binaural squelch if fitted with two hearing aids. The identification procedure with the highest face validity would be a direct measure of binaurally aided speech understanding in noise compared with monaurally aided speech understanding under the same conditions. This procedure has been tried repeatedly with many variations in test protocols, but no clinically useable protocol with adequate reliability has been developed (see Konkle & Schwartz, 1981; and Ross, 1977, for reviews).

It seems that the difficulties associated with clinical quantification of binaural advantage for speech understanding in noise may be insurmountable. As a result, several attempts have been made to develop an alternative procedure which could be used to predict whether an individual could benefit from an aided binaural squelch effect. Potential predictors that have been investigated include: monosyllabic word tests under earphones (Dermody & Byrne, 1975), localization in noise (Sebkova & Bamford, 1981a), performance-intensity functions and central deficit (Mueller, Grimes, & Jerome, 1981). None of these measures has been found to predict accurately which individuals will demonstrate a binaural squelch effect on the criterion measure chosen by the investigators of aided speech understanding in noise.

The study described herein was undertaken to explore the usefulness of another predictor of binaural squelch abilities. The binaural unmasking that comprises the binaural squelch effect has conventionally been attributed to the utilization (within the central auditory nervous system) of the interaural differences in intensity and phase which are found in a true binaural signal-in-noise. It was hypothesized, therefore, that persons who demonstrated a binaural squelch effect on a criterion measure of speech understanding in noise would be able to distinguish a true binaural speech signal from a pseudobinaural speech signal on the basis of the improved intelligibility afforded by the interaural differences in the true binaural stimulus.

Both monosyllabic and sentence stimuli were used as criterion measures to explore a hypothesis that the binaural squelch effect might be greater with the sentences because (a) the longer stimulus provides more time for the auditory system to "focus" (Heffler & Schultz, 1964), and/or (b) interaural time differences in the binaural stimuli may be more readily utilized in the sentences because of their...
relatively greater dependence on low frequencies (Dirks & Wilson, 1969b; Speaks, 1967).

The primary research questions were:

1. Will hearing-impaired subjects be able to detect an intelligibility difference between a true binaural hearing-aid-processed speech-in-noise signal and a pseudobinaural hearing-aid-processed speech-in-noise signal? The observations of Koenig (1950) indicated that this difference is unmistakable for a normally hearing person and in favor of the true binaural system.

2. If there is an ability to detect greater intelligibility in the true binaural stimulus, will it be correlated with, and therefore a predictor of, the binaural squelch effect demonstrated on a criterion test of speech intelligibility in noise?

Secondary research questions included the following:

1. If there is an ability to detect greater intelligibility in the true binaural stimulus, will it be affected by the low-frequency cutoff of the hearing aids through which the signal is processed?

2. Will the binaural squelch demonstrated on the criterion measure be dependent on the type of speech material used in the test?

**METHOD**

**Subjects**

Subjects were 6 men and 6 women, aged 22 to 77 with a mean age of 52 years. All had bilateral, symmetrical, sensorineural hearing impairment. Their three-frequency pure-tone averages were between 40 and 80 dB HL. Word discrimination scores were similar bilaterally. Flat or gently sloping audiometric configurations (sloping 0 to 10 dB per octave) characterized 9 individuals; 3 persons had audiometric configurations that sloped 11 to 25 dB per octave.

All subjects were required to have a binaural-aided score in quiet of at least 30% on both criterion speech tests. (This was necessary to employ the adaptive test procedure as described below.) Binaural hearing aids were worn more than 4 hr per day by 1 subject, 7 persons wore a monaural hearing aid more than 4 hr per day, 1 subject wore a monaural hearing aid for less than 4 hr per day, and 3 subjects had no experience wearing hearing aids.

In addition to the 12 hearing-impaired subjects, 10 normally hearing subjects were used to provide normative data on the predictive measure only.

**Hearing Aids**

Each hearing-impaired subject was individually fitted with one pair of binaural hearing aids. Gain and SSPL90 specifications for each subject were derived using the method described in Cox (1983). In each fitting, the final choice from among several possibly appropriate pairs was made on the basis of speech intelligibility judgments as described by Cox and McDaniel (1983). A pool of six pairs of commercial postauricular hearing aids was available for this fitting. All were functioning within manufacturer's specifications. Each instrument incorporated both SSPL90 and tone controls and an omnidirectional microphone. Control settings were chosen individually for each subject. Volume control settings were lowered 5 dB during binaural listening to accommodate binaural summation of loudness effects (Burdo & Bassi, 1979/1980; Christen, 1980).

After the pair of hearing aids for a particular subject had been selected and adjusted, the in situ frequency response with the chosen settings was estimated in the following way: (a) The hearing aids were placed on a KEMAR manikin located at the subject's position in the audiometric test room (described below); (b) white noise (100–7000 Hz) was presented from the signal loudspeaker at a level of 65 dB SPL (the loudspeaker's response was equalized to present a flat spectrum ±5 dB at the subject's position in the sound field); (c) the output curve of the hearing aid at the manikin's eardrum position was recorded using a spectrum analyzer (Spectral Dynamics, Model 330A); (d) from these curves, the upper and lower frequency cutoff for each hearing aid was calculated using the procedure described in ANSI Standard S3.22-1976. Low-frequency cutoffs ranged from 120 Hz to 580 Hz. High-frequency cutoffs ranged from 3200 Hz to 6400 Hz. Hearing aid bandwidths ranged from 2810 Hz to 5820 Hz.

**Criterion Measures**

**Test stimuli.** Two types of speech stimuli were used as criterion measures of speech understanding: the Northwestern University Auditory Test #6 (NU-6), a monosyllabic word test recorded by Sommerville (1967), and the high-predictability sentences from the revised SPIN test (Nuetzel, Bilger, & Rzeczowski, 1980). A previous investigation utilizing the NU-6 recording had revealed a mean binaural squelch of 19% for subjects similar to those used in this study (Cox et al., 1981).

**Test environment.** The subject was seated in a sound-treated audiometric test room (2.13 m × 2.74 m, 0.91 m from the signal loudspeaker which was mounted at a 0° azimuth in the center of a 2.74-m wall. Uncorrelated competing speech babble was presented from two horizontal arrays of loudspeakers. Each array consisted of five loudspeakers within a single wall-mounted enclosure, 1.3 m in length, centered at + and − 90° azimuths to the subject. Acoustic foam having very nearly the same absorption characteristics as the sound room walls was secured across the glass window on the wall to the right of the subject. This foam was used to reduce any slight acoustic asymmetry in the test room due to the reflective properties of the glass. Both acoustic and psychoacoustic measurements were made to ensure that the long term average signal-to-babble ratios at the subject's two ears were essentially identical.

**Instrumentation.** The instrumentation used to present the criterion test stimuli was located in a control room.
adjacent to the test room. The prerecorded NU-6 and SPIN lists were replayed on a Revox tape recorder (Model A77) and directed to a Grason-Stadler audiometer (Model 1701), a Macintosh power amplifier, and to the signal loudspeaker. Two channels of prerecorded, uncorrelated, speech babble were replayed on a second, identical, Revox tape recorder and directed to a pair of programmable attenuators, a Mitsubishi power amplifier, and to the side loudspeaker arrays. The level of the competition was determined by the setting of the programmable attenuators. These were controlled by a logic system (Grason-Stadler 1200 series modular programming system) according to the adaptive protocols described in Levitt (1978).

Procedures. Data were collected in three sessions, one session devoted to the administration of the SPIN sentences and two sessions to the collection of NU-6 test data. Since several investigators have suggested that experience with aided binaural listening may be an important factor in studies of binaural advantage, each subject was provided with 15 min of binaural listening practice at the beginning of each session (Hedgecock & Sheets, 1958; Nabelek & Pickett, 1974; Sebkova & Bamber, 1981b). During this period, a subject wore the pair of hearing aids selected for use in the study and listened to both music and continuous discourse presented in the test environment.

For each criterion test, the binaural squelch was determined as the difference between the binaural and monaural signal-to-babble ratios at which the subject achieved a target score. A simple or transposed up-down adaptive procedure was used to derive the signal-to-babble ratios necessary to achieve the target score in the binaural and monaural conditions (Levitt, 1978). To derive the appropriate target score for binaural squelch measurements, the subject’s aided binaural score in quiet was measured for the NU-6 test using 150 test items and for the SPIN test using two 25-sentence lists (a total of 50 sentences). For each test, the target score was determined by reference to Table 1. These target scores result from specific sequences of yes/no responses in the adaptive test procedure (Levitt, 1978). Only the target scores shown in Table 1 were available. For each subject, the target score chosen was approximately half the subject’s aided binaural score in quiet for that test. As an example of how Table 1 was used, consider a subject who achieved an aided binaural score in quiet for the NU-6 test of 76%. This subject’s target score on this test would be 29.3%. The purpose of using this procedure was to ensure that the monaural/binaural differences would be maximized by measuring them on the ascending portion of each subject’s performance/intensity function.

To measure binaural squelch, the test stimuli were presented at a constant level of 65 dB SPL in the sound field, and the level of the competing babble was varied—in 2-dB steps—either up or down depending on the subject’s response to the previous test item (or several items). Using this procedure, the level of the competing babble converges on the level necessary for the subject to achieve the target score (Levitt, 1978). Following the test, this level was computed using the mean of the mid-run estimates of the odd runs beginning with the third run.

For the SPIN test, the signal-to-babble (S/B) ratio that produced the target score was determined with right ear aided, left ear aided, and both ears aided. Each determination was based on 50 SPIN sentences. Test sentences were never repeated.

For the NU-6 test, the S/B ratio that produced the target score was also determined with right ear aided, left ear aided, and both ears aided. Each determination was based on 50 monosyllabic words. In addition, all three measures were repeated on a different day: Data from the two sessions were combined to minimize variability.

In monaural listening conditions, the unaided ear was plugged and muffled. All experimental variables were counterbalanced or randomized to minimize order effects.

Predictive Measure

The predictive measure of binaural squelch utilized a paired comparison paradigm in which the subjects compared a true binaural stimulus with a pseudobinaural stimulus and selected the more intelligible stimulus. Studebaker, Bisset, Van Ort, and Hoffnung (1982) reported data on the sensitivity of this procedure that indicated that an intelligibility difference equivalent to 12% for NU-6 monosyllables would be detected 90% of the time by hearing-impaired subjects listening at +7 dB S/B ratio.

Test stimuli. The test stimuli were binaural recordings of hearing-aid-processed continuous discourse in a speech babble background. The continuous discourse was a 1-min passage spoken by a male talker and originally recorded in an anechoic environment. The speech babble background was the same stimulus as used in the criterion tests of speech understanding. The hearing-aid-processed recordings were made in the same audiometric test room used for the criterion tests with the hearing aids worn by a KEMAR manikin. To achieve a pseudobinaural stimulus during playback, a recording taken from one of the manikin’s ears was directed to both of the subject’s ears. Both right and left ear recordings were used as monaural stimuli.

Recordings were made through every subject’s pair of hearing aids at each of three S/B ratios: 0 dB, +4 dB, and +8 dB. In making the hearing-aid-processed recordings, and in their subsequent playback to subjects, the proce-
dures described by Cox and Studebaker (1980) were followed. These procedures ensure that the recorded stimulus received by the subject is essentially identical to the one that would have been received if the subject had actually worn the hearing aids.

Test environment. The paired comparison data were collected in a quiet but not sound-treated setting.

Instrumentation. The instrumentation for the portion of this investigation utilizing paired-comparison testing has been described in detail elsewhere (Studebaker et al., 1982). Briefly, the two stimuli (binaural and pseudobinaural) were replayed on separate tape recorders (Revox A77) which were started simultaneously. The tape recorder outputs were amplified and directed to a subject control panel that incorporated a switch allowing the subject to listen, at will, to either the binaural or the pseudobinaural stimulus. This panel also incorporated controls for adjusting the stimulus levels. The stimuli were transduced by a pair of hearing aid receivers (Knowles BP-1712). The receiver output was coupled to the subject's ear canal by a section of damped #13 standard polyvinyl tubing inserted into a standard earmold. The upper cutoff of the playback system exceeded 6 kHz. It was therefore adequate to reproduce faithfully all of the hearing aid responses used in the investigation.

Procedures 1: normal hearers. All data were collected in a single session. Each subject listened to continuous discourse recorded through two pairs of hearing aids with each pair of hearing aids presented twice—resulting in a total of four judgments. The two pairs of hearing aids were chosen to be dissimilar. The placement of hearing aids into similar or dissimilar categories was based entirely on their low-frequency cutoff, which was determined from the in situ measurements described earlier. Cutoff frequencies less than one-third octave apart were considered similar. Hearing aids that differed in low-frequency cutoff by more than one-third octave were considered dissimilar. The hearing aid conditions presented to each subject were chosen from the hearing-aid-processed recordings prepared for the hearing-impaired subjects. All of the hearing-aid-processed recordings used with the hearing-impaired subjects were used at least once with the normal hearers.

For each pair of hearing aids, the subject compared a binaural recording with a pseudobinaural recording. The two recordings were identified simply as A and B. The level of each recording was adjusted by the subject to be “as intelligible as possible but not so high as to be uncomfortable.” In addition, the levels in the two ears were adjusted to achieve equal loudness. Subjects were given sufficient practice to master these level adjustments before actual data collection. All normally hearing subjects listened at a 0-dB S/B ratio.

Instructions: For each binaural/pseudobinaural comparison, the subject followed these instructions:

Listen to the speech while switching the selector switch back and forth between A and B. Listen carefully to the speech heard in each position and decide which you believe is more intelligible. That is, in which position can the speech be more clearly understood.

After the subject decided whether A or B was more intelligible, he or she was asked to provide a rating reflecting confidence in the decision. These confidence ratings were made on a 5-point scale with the following values: 5 = very clear difference, 4 = distinct difference, 3 = small difference, 2 = barely detectable difference, 1 = no difference (“I made the best choice I could, but I could detect no real difference in intelligibility”).

To determine which of the two listening conditions (binaural or pseudobinaural) was judged as more intelligible in a paired comparison, a best-two-out-of-three strategy was used. In other words, the outcome of a judgment between a particular binaural/pseudobinaural pair was determined on the basis of two or three consecutive trials with that particular pair of conditions. The condition chosen in two of the trials was considered the “winner” of that comparison.

Procedures 2: hearing-impaired listeners. Data were collected in two sessions with the second session being a complete replication of the first. Each hearing-impaired subject listened to continuous discourse recorded through three pairs of hearing aids: (a) the pair of hearing aids chosen in the hearing aid selection described earlier for use by that particular subject, (b) a similar pair of hearing aids, and (c) a dissimilar pair of hearing aids. In the dissimilar condition, half of the subjects listened to instruments with a low-frequency cutoff lower than that of the instrument pair originally selected for their use, and half listened to instruments with a low-frequency cutoff higher than that of the pair originally selected for them. Each of the three pairs of hearing aids was presented twice, resulting in six judgments per session.

The levels at which the stimuli were presented were adjusted by each subject for maximum intelligibility consistent with comfort and for equal loudness at the two ears as described for the normal hearers. The S/B ratio was selected individually for each subject from the three available options: 0 dB, +4 dB, and +8 dB. The S/B was chosen to provide a listening condition in which the subject estimated, after some practice, that >50% but <100% of hearing-aid-processed continuous discourse could be understood.

Instructions: The instructions to the hearing-impaired subjects were identical to those presented to the normally hearing subjects.

In each paired-comparison judgment, subjects chose the more intelligible stimulus of the binaural/pseudobinaural pair and then supplied a confidence rating for that decision. As in the study with normal hearers, a best-two-out-of-three strategy was used to derive the ultimate winner in each comparison.

All experimental variables were counterbalanced or randomized to minimize order effects.

RESULTS

Criterion Measure

Table 2 shows the binaural squelch measured for the NU-6 monosyllabic words with data combined across the
TABLE 2. Binaural squelch (dB) measured with NU-6 monosyllabic words expressed in terms of the difference in S/B ratio required to achieve the target score during monaural and binaural listening. Results are given for two calculation methods.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Mean monaural minus binaural</th>
<th>Better monaural minus binaural</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.0</td>
<td>1.3</td>
</tr>
<tr>
<td>2</td>
<td>1.4</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>2.4</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>3.0</td>
<td>2.8</td>
</tr>
<tr>
<td>5</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>6</td>
<td>2.5</td>
<td>1.3</td>
</tr>
<tr>
<td>7</td>
<td>4.6</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>2.0</td>
<td>1.7</td>
</tr>
<tr>
<td>9</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>10</td>
<td>4.5</td>
<td>4.0</td>
</tr>
<tr>
<td>11</td>
<td>0.9</td>
<td>-1.2</td>
</tr>
<tr>
<td>12</td>
<td>7.8</td>
<td>7.4</td>
</tr>
</tbody>
</table>

\[ \bar{x} = 3.4 \quad \bar{x} = 2.1 \]

two testing sessions. Two methods of calculating binaural squelch are shown: (a) the difference between the mean monaural S/B ratio and the binaural S/B ratio and (b) the difference between the better monaural S/B ratio and the binaural S/B ratio. Both methods have been used in previous research and are presented here for comparison. Individual binaural squelch effects calculated by the first method ranged from 0.9 dB to 7.8 dB with a mean of 3.4 dB. When the second method was used, the range was -1.2 dB to 7.4 dB with a mean of 2.1 dB. All statistical analyses of the binaural squelch effects utilized data calculated by the second, more conservative, method.

Table 3 shows the binaural squelch measured for the revised SPIN high-predictability sentences. Only 9 of the 12 subjects were able to achieve the prerequisite 30% aided score in quiet on the SPIN sentences. Therefore, only these 9 subjects were used in this part of the study. Again, the two methods were used to calculate binaural squelch. The range of scores for the first method was 0.5 dB to 6.1 dB with a mean of 4.0 dB. The second method produced a range of -2.5 dB to 4.6 dB with a mean of 2.0 dB. Statistical analyses utilized data derived by the second method.

For each test, Pearson product-moment correlations were computed to evaluate the relationship between measured binaural squelch and (a) low-frequency cutoff, (b) high-frequency cutoff, and (c) bandwidth of the hearing aids used by the subjects. None of the six correlation coefficients was significant at the .05 level.

A one-way analysis of variance was performed on the data from the NU-6 and revised SPIN tests for the 9 subjects who participated in both tests. Results indicated that there was no significant difference in the binaural squelch obtained with the different types of stimuli.

Predictive Measure

Normal hearers. Figures 1 and 2 show the outcome of the paired-comparison predictive measure for the normally hearing subjects. Figure 1 shows the result of the four binaural/pseudobinaural intelligibility judgments made by each subject. As the figure indicates, 8 subjects picked the binaural stimulus as more intelligible all four times. The remaining 2 subjects chose the binaural stimulus three of the four times. Figure 2 shows the distribution of confidence ratings associated with the judgments depicted in Figure 1. Most of the ratings were either "4—distinct difference" or "3—small difference."

Hearing-impaired subjects. Each subject listened with three hearing aids and on two occasions. The McNemar test for the significance of changes (Siegel, 1956) was used to evaluate whether the proportion of binaural selections was different for any session or hearing aid condition. No significant differences were found. Hence,
data for all three hearing aid pairs and both test sessions were combined for analysis. Figures 3 and 4 show the outcome of the paired-comparison predictive measure for the hearing-impaired subjects. Figure 3 shows the result of the 12 binaural/pseudobinaural intelligibility judgments made by each subject. In order to reach statistical significance at the 8% level (Chi-Square test), it was necessary for an individual to choose the same stimulus, either binaural or pseudobinaural, in 9 of the 12 judgments. If an individual chose the same stimulus in 10 of the 12 judgments, the probability that this was a chance occurrence was reduced to 2%. As the figure shows, none of the subjects chose the binaural over the pseudobinaural stimulus frequently enough to reach statistical significance at the 8% level. In fact, only 4 of the subjects chose the binaural stimulus more often than half the time. On the other hand, 4 of the subjects selected the pseudobinaural stimulus in either 9 or 10 of the 12 intelligibility judgments. Figure 4 shows the distribution of confidence ratings associated with the judgments depicted in Figure 3. Confidence ratings associated with judgments in which the binaural stimulus was chosen are represented by shaded bars. Ratings associated with judgments in which the pseudobinaural stimulus was chosen are represented by unshaded bars. Subjects selected ratings of “1—no difference,” “2—barely detectable difference,” “3—small difference” about equally often, and together these ratings accounted for 75% of all binaural/pseudobinaural comparisons.

**Relationship Between Criterion and Predictive Measures**

This investigation was undertaken to determine whether the outcome of binaural/pseudobinaural intelligibility judgments would be predictive of results obtained with measures of aided binaural squelch employing monosyllabic and/or sentence stimuli. To consider this question, it was decided that the 4 subjects who selected the binaural stimulus in a majority of the binaural/pseudobinaural comparisons (seven or more times) would be deemed to have chosen the binaural stimulus overall. The other 8 subjects were treated as not having selected the binaural stimulus.

Point-biserial correlations were computed to estimate the relationship between the outcome of the binaural/pseudobinaural judgments and the measured binaural squelch effects (Glass & Stanley, 1970). To achieve a high correlation, it would be necessary for the subjects choosing the binaural stimulus to have yielded among the largest measured binaural squelch effects. The results for the NU-6 monosyllabic words are shown in Table 4. This table shows the individual binaural squelch effects ordered from greatest to least. The subjects marked with asterisks are those who selected the binaural stimulus in the paired-comparison judgments. The point-biserial correlation between these two sets of data is \( r_{pb} = .09 \).

Table 5 shows the analogous data for the revised SPIN high-predictability sentences (of the 9 subjects who participated in this test, 3 chose the binaural stimulus). The point-biserial correlation between these two sets of data is \( r_{pb} = .57 \). Neither correlation is statistically significant at the .05 level.

Additional point-biserial correlations were derived to determine whether particular subgroupings of subjects might register a higher correlation between the two methods of measuring binaural advantage. Subjects were grouped on the basis of age, sex, audiogram configuration, age of onset of hearing loss, symmetry of ear performance at the target level, and experience with amplification. None of these correlations reached the .05 level of significance.

**Discussion**

**Criterion Measure**

The binaural squelch effects shown in Tables 2 and 3 are essentially identical to those reported in the several comparable investigations that have employed hearing-impaired subjects listening to hearing-aid-processed speech (Dirks & Wilson, 1969a; Markides, 1977; Nabelek & Pickett, 1974; Olsen & Carhart, 1967; Sekkova & Bamford, 1981a; Wright & Carhart, 1960; Zelnick, 1970).

As mentioned earlier, both monosyllabic and sentence stimuli were used as criterion measures to explore a hypothesis that the binaural squelch would be greater with the sentences. The data did not support this hypothesis: The two stimuli yielded essentially the same amount of binaural squelch.

**Predictive Measure**

A comparison of Figures 1 and 2 with Figures 3 and 4 reveals that the normally hearing subjects performed very
differently from the hearing-impaired subjects in the paired-comparison task. Normal hearers made 40 binaural/pseudobinaural judgments (10 subjects x 4 judgments). The binaural stimulus was chosen 38 times. Furthermore, the confidence ratings (Figure 2) reveal that these subjects were usually fairly certain about their judgments; they seldom used the ratings that reflected a difficult or arbitrary decision (categories 1 and 2).

On the other hand, in the 144 binaural/pseudobinaural judgments made by hearing-impaired listeners, the binaural stimulus was chosen only 61 times. Furthermore, subjects did not choose the binaural stimulus more often when they were listening to the pair of hearing aids that had been individually selected and adjusted for them, and they did not show a preference for the binaural stimulus when listening to the pair of instruments which had the lowest low-frequency cutoff. Also, as Figure 4 shows, these subjects tended to be rather uncertain about their judgments, no matter which stimulus they were choosing. About half of all the choices were paired with a rating of 1 or 2—indicative of either an arbitrary decision or a barely detectable difference in intelligibility.

These results strongly suggest that the cues that were utilized by the normally hearing subjects to differentiate between the binaural and pseudobinaural stimuli were either unavailable to the hearing-impaired listeners or available to a reduced extent. Since the only difference between the two stimuli was the presence of interaural time and intensity differences in the binaural condition, it must be concluded that the hearing-impaired subjects were less capable than the normally hearing subjects of utilizing these cues to improve the intelligibility of speech in a background of noise.

This was an unexpected observation. One of the major reasons cited in support of binaural amplification has been the resultant ability of the hearing-impaired individual (expected on theoretical grounds) to profit from interaural differences in time and intensity to improve the effective signal-to-noise ratio. It is implied that once the stereophonic signal is made available, the person with hearing impairment can operate on it in much the same way as a normal hearer. In support of this position, several studies of binaural interaction abilities (localization, MLD) in persons with symmetrical cochlear or presbycusis hearing losses have suggested that their performance is essentially equal to that of normal hearers.

Table 4. Individual binaural squelch effects measured for NU-6 monosyllabic words ordered from greatest to least.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Binaural squelch (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12*</td>
<td>7.4</td>
</tr>
<tr>
<td>10</td>
<td>4.0</td>
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<tr>
<td>4</td>
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<tr>
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<td>7</td>
<td>0.5</td>
</tr>
<tr>
<td>11*</td>
<td>-1.2</td>
</tr>
</tbody>
</table>

* = Subjects who selected the binaural stimulus in the binaural/pseudobinaural judgments.

Table 5. Individual binaural squelch effects measured for revised SPIN high-predictability sentences, ordered from greatest to least.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Binaural squelch (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12*</td>
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<td>-1.4</td>
</tr>
<tr>
<td>9</td>
<td>-2.5</td>
</tr>
</tbody>
</table>

* = Subjects who selected the binaural stimulus in the binaural/pseudobinaural judgments.

Figure 3. Results of binaural/pseudobinaural intelligibility judgments by hearing-impaired subjects. Each subject made 12 judgments. The figure shows how often subjects chose the binaural stimulus as more intelligible.

Figure 4. Distribution of confidence ratings associated with binaural/pseudobinaural judgments made by hearing-impaired subjects. Shaded bars depict the confidence ratings associated with choice of the binaural stimulus as more intelligible. Unshaded bars depict the confidence ratings associated with choice of the pseudobinaural stimulus as more intelligible. Rating categories varied from 1 = no difference in intelligibility, to 5 = very clear difference in intelligibility.
(e.g., Melnick & Bilger, 1965; Tonning, 1973). On the other hand, another group of studies suggests that binaural interaction, at least in the form quantified by the MLD, may be decreased in these individuals (e.g., Olsen, Noffsinger, & Carhart, 1976; Quaranta, Cassano, & Cervellera, 1976).

In spite of their inability to detect an intelligibility difference between the binaural and pseudobinaural stimuli, it is apparent from a consideration of the binaural squelch effects (Tables 2 and 3) that most of these hearing-impaired subjects did realize some improvement in intelligibility when binaural listening was compared with monaural. If this improvement in intelligibility was not based primarily on an essentially normal utilization of interaural cues, why did it happen? The most obvious suggestion is that it was due to a redundancy effect similar to that suggested by Harris (1965). A redundancy hypothesis would suggest that the presentation of additional information to the second ear is primarily responsible for the improved intelligibility and that the interaural differences per se are relatively unimportant. According to this hypothesis, the improvement noted in the change from monaural to diotic (no interaural differences) listening would be almost as large as the improvement from monaural to binaural (normal interaural differences) listening. In addition, there would be little or no difference between diotic and binaural listening.

It is clear that this hypothesis is not substantiated for normally hearing persons. Several investigators have shown with normal hearers that, although there is a small improvement in intelligibility (equivalent to 2 dB or less improvement in S/B ratio) when monaural listening is compared to diotic listening, there is a considerable additional improvement noted under binaural listening conditions (Cox, Dechicchi, & Wark, 1981; Dirks & Wilson, 1969a, 1969b; MacKeith & Coles, 1971; Nordlund & Fritzell, 1963).

The situation is much more ambiguous when the data for hearing-impaired listeners are consulted. Harris (1965) tested 36 subjects with asymmetrical hearing loss of unspecified type. In addition to monaural and binaural listening conditions, he had two diotic (as defined here) conditions: a Y-cord condition (one channel fed to both ears) and a double-V-cord condition (two channels, both fed to both ears). The Y-cord condition provided negligible advantage over monaural listening. However, the binaural and double-V-cord conditions both resulted in much better intelligibility, with the double-V-cord being the better of the two. Zelnic (1970) tested 50 subjects with symmetrical, cochlear hearing loss. Like Harris, he compared monaural results with double-V-cord and binaural conditions. Both comparisons revealed significant improvement in intelligibility with two-ear listeners: The double-V-cord condition was minimally inferior to the binaural condition. Finally, Markides (1977), in a study of 13 subjects with symmetrical sensorineural hearing impairment, reported an advantage equivalent to 3 dB when diotic-aided listening (speech and competition both presented from a single loudspeaker at a 0° azimuth) was compared to monaural-aided listening, whereas an advantage of 1.8 dB was observed in the comparison of binaural- and monaural-aided listening. All of these studies provide support for the above-stated hypothesis for hearing-impaired persons.

On the other hand, Dirks and Wilson (1969a), in a study of 3 elderly subjects with sensorineural hearing impairment, found a small improvement accruing to the transition from monaural to diotic listening and a greater improvement in the transition from monaural to binaural listening. This outcome resembles those reported for normal hearers. Other investigators have reported a significant improvement in intelligibility for elderly hearing-impaired subjects when diotic listening is compared with monaural listening (Antonelli, 1978; Kaplan & Pickett, 1981). However, these studies did not include a comparison with binaural listening.

Most of these studies, and the one reported in this paper, are consistent with the suggestion that the intelligibility advantage experienced by many individuals wearing binaural amplification may not be primarily based on normal utilization of interaural time and intensity cues. It is possible that the improvement is achieved largely because of increased redundancy in the stimulus with minimal binaural interaction.

Relationship Between Criterion and Predictive Measures

The analysis of the relationship between the binaural/pseudobinaural judgments and the binaural squelch measured for NU-6 monosyllables, shown in Table 4, indicated that these two measures were quite independent. The comparison for the SPIN sentences, shown in Table 5, gave similar results in the sense that a nonsignificant correlation was obtained. It is noteworthy that the 3 subjects who chose the binaural stimulus most often in the paired-comparison judgments also achieved the largest binaural squelch on the SPIN sentences. However, there were also several subjects who achieved relatively large binaural squelch on the SPIN sentences and did not choose the binaural stimulus in the paired-comparison judgments.

CONCLUSION

This investigation attempted to establish a predictive relationship between binaural squelch measured using a conventional paradigm and binaural squelch inferred from the ability to select a binaural over a pseudobinaural (diotic) stimulus, presumably utilizing interaural time and intensity cues. Such a relationship could not be established because the hearing-impaired subjects were, on the whole, unable to detect an intelligibility difference between binaural and pseudobinaural continuous discourse.

It was not anticipated that none of the hearing-impaired subjects would be able to distinguish clearly between the binaural and pseudobinaural stimuli. As noted earlier,
previous investigations had established that the mean binaural squelch effect measured for the NU-6 monosyllables (Cox et al., 1981) was greater than the just detectable intelligibility difference measured in paired comparisons of continuous discourse (Studebaker et al., 1982). It should be noted, however, that in the study by Studebaker et al. the intelligibility judgments were based on comparisons of different amplifying systems: Interaural judgments of continuous discourse were termed the predictive measures. In view of the outcome of the investigation reported here, the role of conventional measures of binaural squelch in amplification decisions should be reexamined. It has usually been assumed that these measures quantify the ability of the listener to profit from interaural differences in phase and intensity (e.g., Konkle & Schwartz, 1981). The results of this investigation do not support this assumption.

Finally, the results of this investigation should not be construed as negating the overall desirability of binaural amplification. Binaural listening has several important advantages, such as summation of loudness and elimination of head shadow effects, which are not dependent on the listener’s ability to utilize interaural time and intensity cues.

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Requests for reprints should be sent to Robyn M. Cox, Ph.D., Memphis Speech and Hearing Center, 807 Jefferson Avenue, Memphis, TN 38105.