THE EFFECT OF SPATIALLY SEPARATED SOUND SOURCES ON SPEECH INTELLIGIBILITY

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A series of five experiments was conducted to investigate the effects of spatial separation of speakers on the intelligibility of spondaic and PB words in noise and the identification of synthetic sentences in noise and competing message. Conditions in which the spatial location of the speakers produced interaural time differences ranked highest in intelligibility. The rank order of other conditions was dependent on the S/N ratio at the monaural near ear. Separations of only 10° between the speech and noise sources resulted in measurable changes in intelligibility. The binaural intelligibility scores were enhanced substantially over the monaural near ear results during conditions where an interaural time difference was present. This result was observed more effectively when spondaic words or sentences were used rather than PB words. The implications of this result were related to the interaural time difference and the frequency range of the critical information in the primary message. Although the initial experiments were facilitated by recording through an artificial head, almost identical results were obtained in the final experiment when subjects were tested in the sound field.

Intelligibility of speech in noise for sound field listening conditions is dependent primarily on the signal-to-noise (S/N) ratio at the ears, the difference in the time of arrival of the signals at the two ears, the type of speech material, the physical characteristics of the chamber, and the capacity of the listener. In "real life" conditions, intensity and time parameters can be varied by the locations of the primary and competing message sources and by the movement of the head. Hirsh (1950) demonstrated that the threshold of intelligibility for spondaic words in noise was higher when the speech and noise sources were located in approximately the same place than when either one or the other of the signals was at different locations. The ability to separate the loudspeakers spatially was facilitated when two ears rather than one were used and when movement of the head was permitted.

In a later investigation, Schubert (1956) emphasized the role of a time difference at the two ears on the intelligibility of speech in competing messages. Although sound-field listening conditions were not included in the experiment, the possible application of the results to sound-field conditions was discussed. Schubert suggested that Hirsh's earlier results might also be explained on the

basis of the time differences at the ears as a consequence of the spatial arrangements of the loudspeakers. It might be anticipated that conditions where the speech or noise arrived earlier at the one ear would result in better intelligibility scores than conditions where the interaural delay for both signals was zero. To support this suggestion, it was noted that in the Hirsh investigation LF (speech on the left and noise in front), RB (speech on the right and noise in back), and RL (speech on the right and noise on the left) were consistently superior to conditions where no time differences were present at the ears.

In Hirsh's experiment loudspeakers, one for the speech and another for the noise, were set side by side for the FF (both signals in front), the BB (both signals in back), and the RR (both signals on the right) conditions. The loudspeakers were one meter from the center of the subject's head and there was a separation between the center of the loudspeaker cones of approximately 12″. Since the distance between the head and speaker was one meter, the signal from one or the other of the sound sources arrived at the nearer of the two ears approximately 200-300 μsec sooner than at the far ear. The results of Spieth, Curtis, and Webster (1954) suggested that a time interval of only 120 μsec or a separation of 10° between loudspeakers could be beneficial for intelligibility.

In discussing the comparative results from the FB and FF positions, Hirsh alludes to the question of whether the scores obtained during the FF, BB, and RR would be reduced or changed if the speech and noise signals had not been spatially separated. Such reductions in intelligibility could change the relative rank ordering of these conditions among other experimental conditions where the spatial arrangement of the loudspeakers permitted time and an S/N ratio difference at the ears.

Hirsh also compared binaural and monaural thresholds of intelligibility but did not precisely specify whether the monaural ear chosen was the ear nearest or farthest away from the primary loudspeaker. His measurements on the dummy head had indicated that substantial changes due to the effect of the head shadow were primarily found at frequencies above 2000 Hz. However, the graphic results from the left dummy microphone (Hirsh, 1950, Figure 3) showed that there was an estimated increase of approximately 5 dB in the lower frequency range from 200 to 1000 Hz when the speaker was positioned directly at the left ear rather than in the front or 0° azimuth position. During the RL condition the noise was coming directly into the left ear and the speech was delivered directly to the right ear. Considering even a small difference due to the head shadow effect in the lower and middle frequency range, the signal-to-noise ratio at the right or left monaural ears should be somewhat different. Thus the comparison between binaural and monaural thresholds might have been dependent on the position of the monaural ear in the listening situation.

The current experiments were designed to investigate the effects of the spatial separation of loudspeakers on the intelligibility of speech in further detail. Attempts were also made to isolate other factors which influence the relationship between intelligibility scores and loudspeaker location or azimuth. In particular the effects on intelligibility of the type of speech material and the

use of binaural as opposed to monaural listening conditions were systematically investigated.

The current investigations were in general carried out with a specially designed artificial head. An artificial head was employed since head movements are difficult to describe and control precisely during sound field experiments. Also, by merely eliminating one channel (one ear in the artificial head), it is possible to produce a more complete monaural condition than when an ear on a human head is plugged or occluded. However, in the last of the current experiments, measurements of binaural and monaural intelligibility were made in which subjects were tested in the sound field itself. These final measurements were included to substantiate the earlier results using the artificial head.

Development of Speech Materials

Two types of speech materials were employed in the current investigations: spondaic words and phonetically balanced monosyllabic words. The spondaic words had been previously recorded by an adult male. The master list consisted of 30 spondaic words recorded without a carrier phrase. Seven different randomizations of this list were recorded on magnetic tape.

An adult male recorded 13 PB-50 lists in an anechoic chamber on Channel I of an Ampex PR-10 tape recorder. The PB words were peaked on a VU meter at the level of a 1000 Hz calibration signal. Each list consisted of 50 monosyllabic words recorded in a random manner from the PB lists described by Egan (1948).

A competing message consisted of broad band random noise. The output of the noise generator was filtered above 7000 Hz and recorded on Channel II of an Ampex PR-10 tape recorder.

Preliminary experiments were then conducted to determine the adequacy of employing recordings of the master tapes via the artificial head for the current investigations. Comparisons of intelligibility scores were made among conditions where the master tapes were delivered directly (1) to earphones, (2) through a loudspeaker to subjects with heads fixed, and (3) from recordings produced via the artificial head and delivered through earphones to the subjects. Intelligibility scores were obtained for the three conditions at various S/N ratios on 12 young adults with normal hearing.

At each condition the primary speech signal (spondaic or PB words) was presented binaurally at an intensity level of 70 dB SPL. The recorded words were presented through TDH-39 earphones encased in MX41/AR cushions in the first condition. During the second condition, the words were delivered via a loudspeaker (Altec Lansing, Model 841B) at a distance of one meter from the subject's head at 0° azimuth. The heads of the subjects were fixed in place with a backrest and a clamping device which fit partially around the top of the head. For the third condition, the speech signal was presented via the same loudspeaker and recorded from the two microphones (Altec 21-D) situated at the entrance to the ear canals of the artificial head. The artificial head was

placed in a position identical to that of the live subjects. The resulting tapes were played back to subjects via earphones at a sound pressure level of 70 dB.

The construction of the artificial head has been described previously (Dirks and Moncur, 1967). Briefly, it was molded of fiberglass and plastic and filled with polyurethane foam plastic. The entire head and pinnas were coated with diluted silicone rubber. The two ⅝″ microphones were situated at the entrance to the ear canal and simulate approximately the frequency response found at the entrance of the external auditory meatus for normal adult heads as determined by Wiener (1947). The frequency characteristics of the two microphones in the artificial head as measured with pure tones from a loudspeaker one meter from the center of the head are shown in Figure 1, along with similar data collected by Wiener (1947) on human ears. The time difference across the

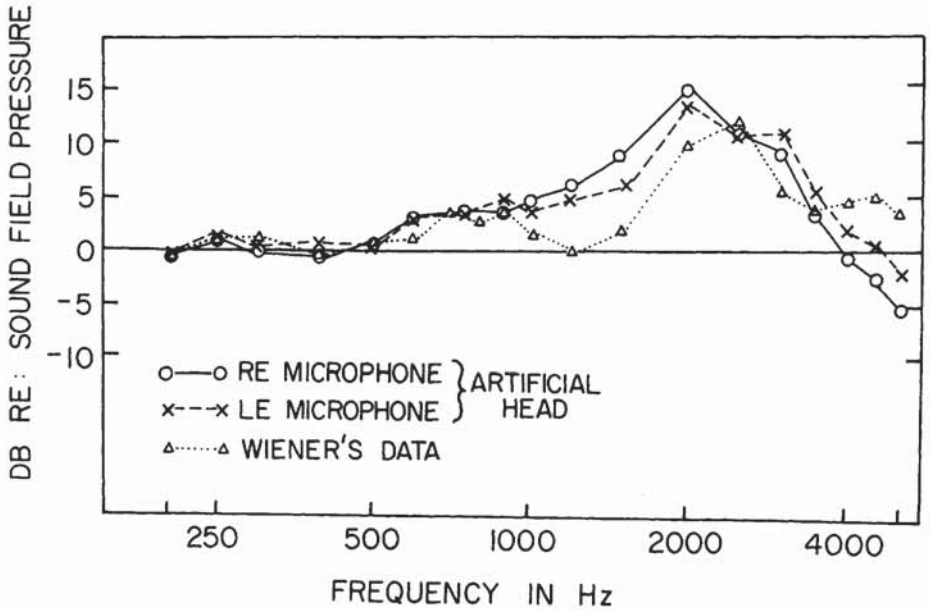

FIGURE 1. The ratio, in decibels, of the sound pressure at the artificial ear microphones to the free field pressure.

head is also comparable to that observed in a group of adult heads. The right and left ear microphones terminate in Channels I and II of an Ampex PR-10 respectively.

The average results for the twelve subjects at the three experimental conditions are shown in Figure 2. Notice that for both sets of speech material, subjects scored slightly better when the master tapes were delivered directly to the individuals via earphones. There are only small, insignificant differences between the intelligibility functions when fixed heads were used and when recordings were made through the artificial head and played back later via earphones. At least two possible explanations for the differences between the ear-

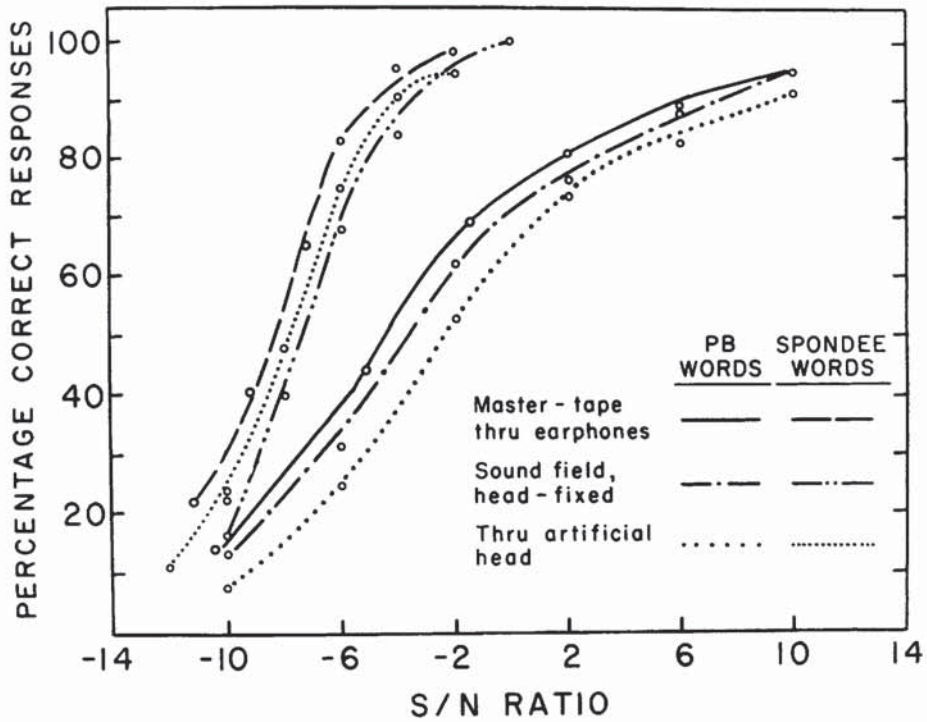

FIGURE 2. Intelligibility functions for spondaic and PB words under three preliminary experimental conditions.

phone conditions and the fixed and artificial head conditions can be suggested. In the former, the frequency response of the speech on the tapes was in no way altered by the characteristics of the live heads or by the microphones in the artificial head. In addition, during the condition in which the master tapes were delivered directly to the earphones, the characteristics of the loudspeaker could not influence the results.

The articulation gain functions were calculated from the linear portion of the intelligibility curves between points corresponding to the 20% and 80% scores. The results are recorded in Table 1 at each experimental condition for both spondaic and PB word lists. Observe that the gain functions rise at similar rates during each experimental condition. On the basis of the results of the preliminary investigations, it was concluded that the results of intelligibility scores

TABLE 1. Articulation gain functions in percent per dB for the two experimental speech materials in the three experimental conditions.

Conditions	*Spondaic Words*	*PB Words*
Earphones	10.09	4.32
Sound-Field with Head Fixed	11.29	4.49
Through Artificial Head via Earphones	10.94	4.38

collected via the artificial head were comparable to sound-field, fixed-head responses and thus were acceptable for the current series of investigations.

GENERAL METHOD

Apparatus and Procedures

Tape recordings of the speech stimuli at the various experimental azimuths were recorded through the artificial head and then played back to subjects via earphones at a later date. This procedure required two apparatus arrangements, one for recording the tapes via the artificial head and the second for playing back the recordings to the subjects.

A block diagram of the apparatus used in recording the tapes through the artificial head is shown in Figure 3. Either the experimental speech materials or a competing signal (white noise) was delivered to the microphones in the artificial head via a loudspeaker (Altex Lansing, Model 604E). The competing signal was a broad-band random noise filtered above 7000 Hz. This random noise seemed appropriate for comparison with results of earlier investigations. The frequency characteristics of the loudspeaker were measured in the anechoic chamber. The loudspeaker was found to have a reasonably flat response

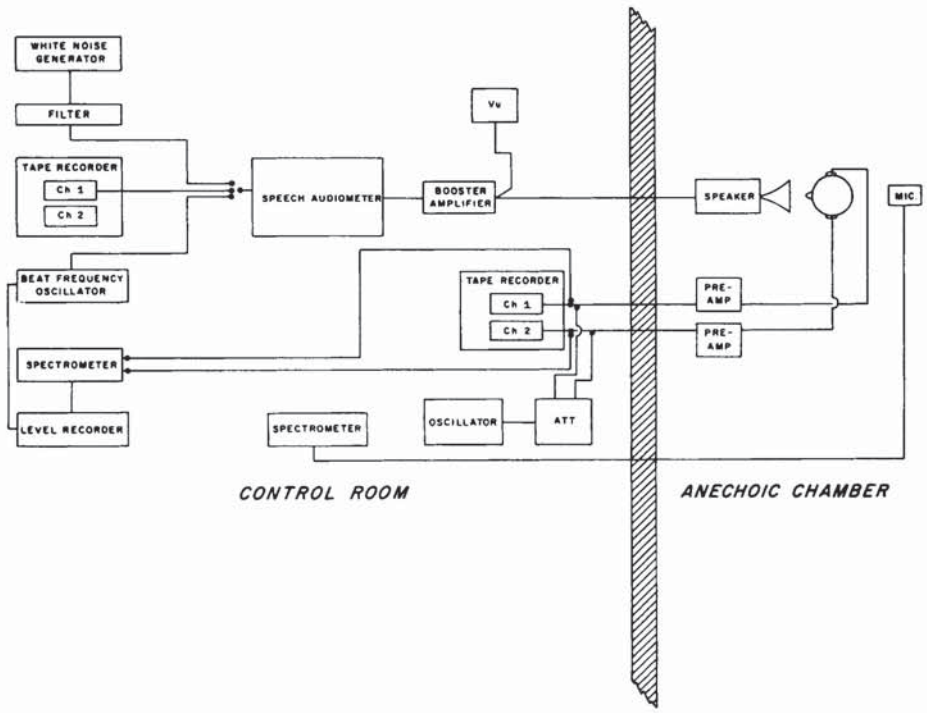

FIGURE 3. Block diagram of the equipment arrangement for producing recordings through the artificial head.

between 100 and 8000 Hz with only minor deviations as large as ± 3 dB. The loudspeaker was placed one meter from the center of the artificial head. Recordings were made at azimuth positions of 0°, 10°, 90°, 180°, 270°, and 350°. During the recording sessions the loudspeaker remained stationary at one of the experimental positions and the head was rotated on an axis to the desired azimuths.

The speech material was reproduced from an Ampex PR-10 tape recorder through a speech audiometer (Grason-Stadler, Model 162) and booster amplifier and then delivered to the loudspeaker. For the competing message signal, the output of a white-noise generator (Grason-Stadler, Model 901 B) was filtered and then delivered through the speech audiometer and booster amplifier to the same speaker as was the speech signal. The filter was set to pass a band extending from 100 to 7000 Hz.

The right microphone on the artificial head was fed to Channel I of an Ampex AG-350 tape recorder while the left microphone was fed to Channel II of the same recorder. Thus separate tapes were made at each experimental azimuth for the speech material at each ear and for the competing message at each ear.

The resultant tapes were utilized during the experimental test sessions of the current investigations. Figure 4 shows the equipment arrangement used in this

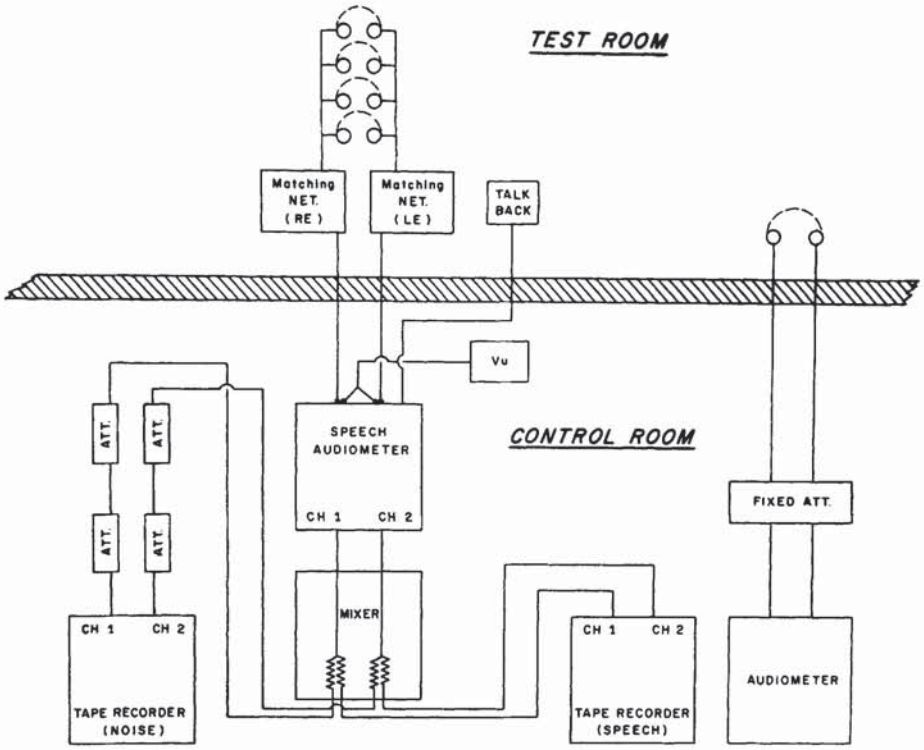

FIGURE 4. Block diagram of the equipment utilized in the experimental testing procedure.

portion of the experiments. The speech signals containing the right-ear material on Channel I and the left-ear material on Channel II were mixed with the attenuated competing message signal from a second tape recorder (Channel I containing the noise from the right ear and Channel II containing the noise from the left ear). The appropriately combined speech and noise signals were amplified and attenuated to obtain the desired S/N ratios. The subjects recorded the words on score sheets.

Finally, each signal was divided four times through an impedance matching network so that measurements could be made on four subjects simultaneously. The frequency response of a large group of TDH-39 earphones was obtained from acoustic measurements made using a Bruel and Kjaer calibration unit. Pairs of earphones that were chosen were virtually identical. The largest difference at any frequency between 200 and 7000 Hz was 1.5 dB. Between pairs of earphones, the largest difference permitted was 3 dB. When a difference as large as 3 dB occurred, it was found in the frequencies above 2000 Hz. Further steps were taken to insure that the pairs of matched phones were electrically in phase.

Experimental Conditions

In order to appreciate the physical experimental conditions, it is important to precisely define the terminology used to designate the various conditions. Two capital letters are used to explain each individual experimental condition: the first letter refers to the location of the speech source and the second letter refers to the location of the noise source, both in regard to the artificial head. The left portion of Figure 5 demonstrates the relation between the azimuth location and the letter designation used. The symbol F (front) was used for the 0° azimuth location, R (right) for 90°, B (back) for 180°, and L (left) for 270°. Note on the figure that there are two additional azimuth positions (10° and 350°). These two situations are referred to as the "FF" condition, as opposed to being the true FF condition which is taken from the 0° azimuth.

The right portion of Figure 5 schematically shows two of the experimental conditions (RB and LF). As can be seen in the figure, the RB condition involves the speech source at the 90° azimuth or the right ear of the artificial head and the noise source at the 180° azimuth or directly behind the head. Likewise, the LF condition has the speech source at the 270° azimuth or the left ear of the head and the noise source at the 0° azimuth or directly in front of the head.

Physical Measurements on the Artificial Head

Prior to recording at each azimuth position, a frequency response curve was obtained from each ear of the artificial head. Pure tones were delivered to the loudspeaker by impressing a constant one volt across the terminals of the loudspeaker. A random sine generator (Bruel and Kjaer, Type 1024) was employed

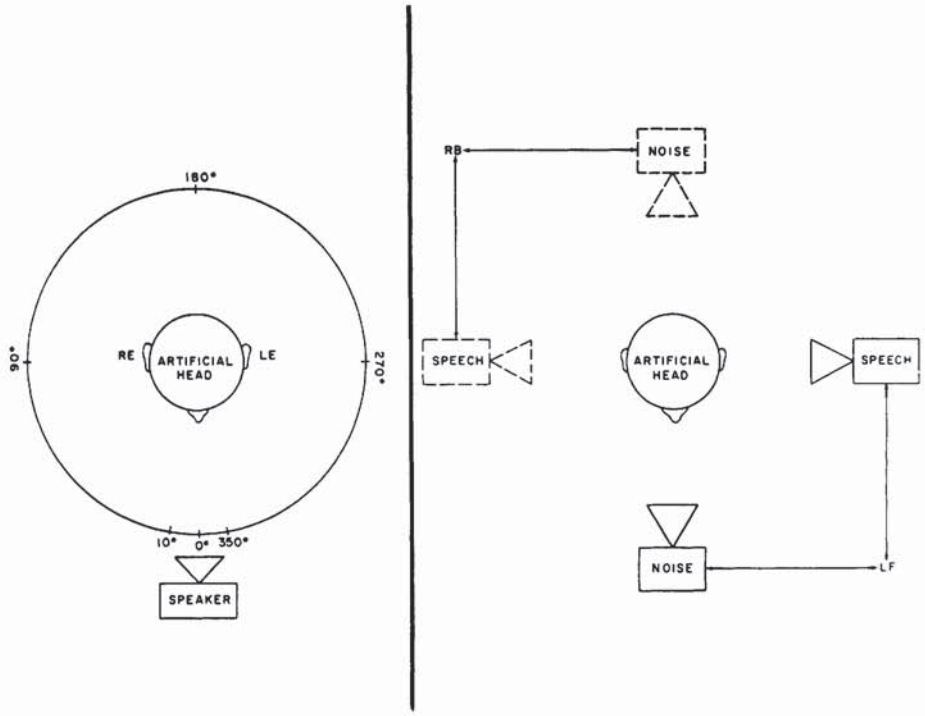

FIGURE 5. Schematic diagram indicating the various experimental azimuth locations (left side) and two examples showing the speech and noise loudspeakers positions with appropriate letter designations (right side).

for these measurements and swept across the frequency range from 100 to 7000 Hz. The results were recorded graphically by a level recorder (Bruel and Kjaer, Type 2305). A constant input level at the center of the head was maintained by a monitoring condensor microphone (Bruel and Kjaer 4132), microphone amplifier, and the compressor circuit of the random sine generator. The changes in frequency response as the artificial head turned to the major experimental azimuth positions are shown in Figure 6 for the right and left head microphones.

Three major changes in frequency response at the ears were observed as the head position was rotated. As the right or left ear became a "near ear" (the ear closer to the loudspeaker), the intensity at that ear became slightly greater than in the 0° azimuth position. Second, at the "far ear" (the ear farther from the loudspeaker) the shadow of the head introduced a significant reduction in intensity across the head, especially at the frequencies above 1000 Hz. Third, when the sound came from the back of the head (180° azimuth) a small reduction in intensity was observed in the high frequencies. This is probably the result of interference by the pinna.

Interaural time differences were also measured from the artificial head in the anechoic chamber at azimuths of 0°, 90°, 180°, and 270°. Pure tones at fre-

quencies of 1000, 2000, 3000, and 4000 Hz were delivered through the loudspeaker. The phase difference between the signals from the two head microphones were read simultaneously on a dual beam oscilloscope (Tektronix, Type 502). The phase difference was calculated from the oscilloscope by measuring the horizontal distance between two corresponding points in the sinusoidal curves. A similar method was described earlier by Nordlund (1962).

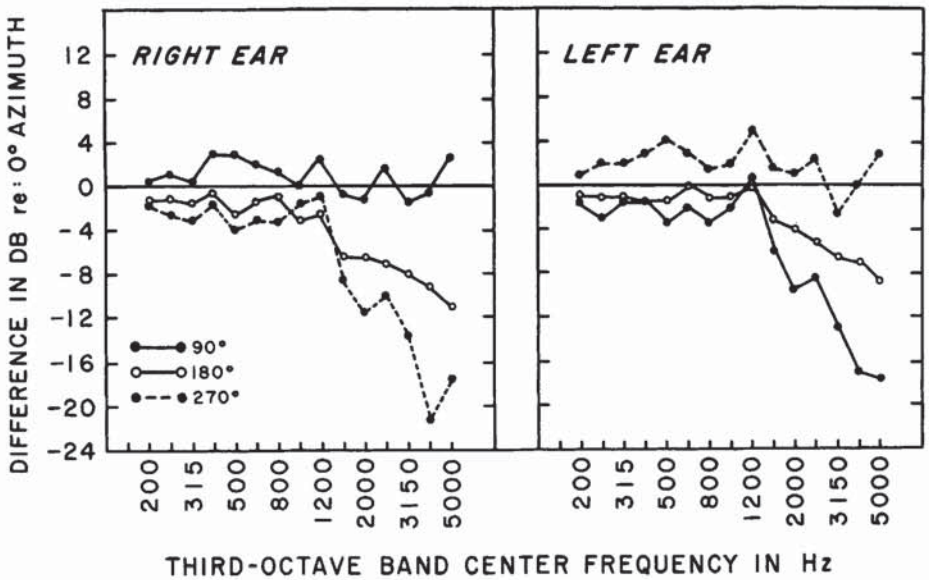

FIGURE 6. Changes in frequency response re 0° azimuth at each head microphone as the artificial head was placed in the various azimuths.

The results indicated that there were no measurable interaural time differences when the head was positioned at an azimuth of 0° and 180° from the loudspeaker. At 90° and 270° the time intervals between ears ranked from 0.76 to 0.81 msec on repeated measurements.

Following the recording sessions, the frequency response of the noise and a sample of the spondaic and PB words were analyzed in ⅓ octave bands over the range from 120 to 5000 Hz. Since this procedure was lengthy, 20 PB words and 10 spondaic words were chosen at random from the total lists for this analysis. The analysis was carried out for each experimental condition and at each ear. The results are shown graphically in Figure 7. The decision was made arbitrarily to use a S/N ratio of −14 dB during the FF condition as the reference. This particular S/N ratio permitted the most clear visualization of the various spectra for both speech and noise signals. The overall S/N ratios are displayed along the right side of each ear condition. The difference between the line for the noise and that of the speech would be the S/N ratio for that particular condition.

Several generalizations are applicable to the seven conditions shown in

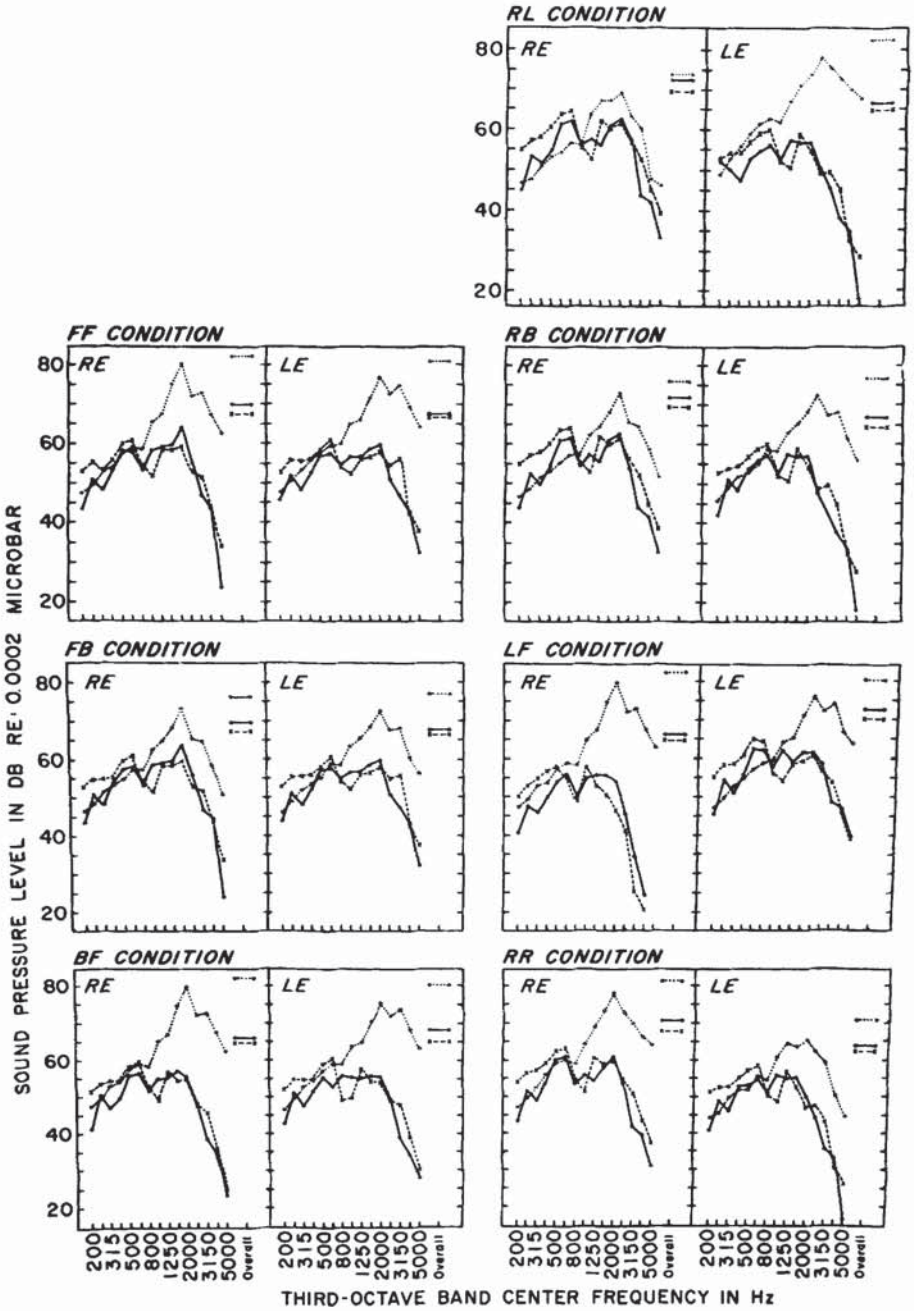

FIGURE 7. Third-octave band analysis of the white noise, PB words, spondee words for the right and left ears under the seven experimental conditions at one meter distance. o. . . . . .o white noise; • —— • PB words; and x – – x spondee words.

Figure 7. Notice that the various spectral configurations described in the figure are the result of characteristics of the microphones in the artificial head, the speech and noise spectra delivered via the loudspeaker, and the particular azimuth chosen. In order to determine the influence that azimuth imposed on the results, it is important to refer to the reference FF position, in which the azimuth was 0° for each experimental signal. The relatively high intensity observed in the area around 1500 and 2000 Hz is largely due to the resonance found at the entrance of the auditory canal as simulated by the position of the microphones in the canal. The rather abrupt drop in intensity at and above 5000 Hz is related to the poorer response of the microphones in the head together with the fact that the noise spectrum was filtered above 7000 Hz. Finally, as expected, the intensity levels in the lower and middle frequencies are always somewhat greater for spondaic words than for PB words under identical conditions.

Since there are no time differences between ears for three conditions (FF, FB, and BF), it would seem feasible to predict their rank order from highest to lowest in intelligibility from the data in Figure 7. On the basis of the overall S/N ratio, it would be expected that the FB condition would be the most favorable condition of the three since the speech is from the front, whereas the noise is from the back and is less effective in the high frequencies due to the pinna. In the BF condition, the opposite is the case and consequently more masking is available than in the FB condition. For intelligibility purposes, the S/N ratio for the FF condition would be more favorable than for the BF condition since the intensity of the speech is not attenuated by the pinna in the former.

Three of the four remaining conditions (RL, RB, and LF) are involved with time differences at the two ears in addition to differing S/N ratios. With time differences operating in these three conditions (RL, RB, and LF), it would be predicted that they would rank themselves higher than the first group of conditions (FF, FB, and BF). In comparing the RL, RB, and LF conditions, the first (RL) is the only condition where a time difference at the ears occurs for both messages. At the same time, the RL condition has the most favorable monaural (RE) S/N ratio of any of the conditions in this study. Therefore, it might be expected that the intelligibility function of the RL condition would be higher than either the RB or LF function.

Both the RB and LF conditions have the same time difference for the speech signal with no time difference for the noise signal. However, RB has a more favorable S/N ratio than LF because of the "pinna effect" and, therefore, one might expect RB to result in the higher intelligibility scores.

In the remaining condition (RR), there is a time of arrival difference for both of the signals at the two ears; however, the time difference is identical for both the speech and noise since both sources are in the same location. The "head-shadow effect" is also involved, but again it alters both the speech and noise. Thus for the RR condition, the overall S/N ratio at the far ear is similar to the S/N ratio at the near ear.

EXPERIMENT I. SPONDAIC WORDS

In the first experiment, the effect on binaural intelligibility of altering the spatial arrangements of the speech and noise sources was investigated. Intelligibility functions were obtained at various S/N ratios. Tape recordings produced in the anechoic chamber via the artificial head were employed. During the first experiment spondaic words were used as the speech stimulus and a broad-band white noise, as described previously, was the competing signal. The distance between the head and the loudspeaker was always one meter.

Subjects

Twelve young adults with normal hearing between the ages of 18 and 21 years served as subjects. Audiometric pure-tone tests were administered prior to inclusion in the study to determine the eligibility of the individuals. No subject was included in the experiments if the threshold was greater than 10 dB ISO at the test frequencies of 250, 500, 1000, 2000, or 4000 Hz. The subjects were paid for their services.

Procedure

Seven experimental conditions were investigated in the first experiment. They were as follows: FF (front, front), FB (front, back), RB (right, back), RR (right, right), LF (left, front), RL (right, left), and BF (back, front). The first letter refers to the location of the speech source and the second letter refers to the location of the noise source. The symbol F was used for the 0° azimuth location, R for the 90° azimuth location, B for the 180° azimuth location, and L for the 270° azimuth location.

In this experiment where spondaic words were used, seven randomizations of the basic 30-word list were available. These lists were administered during six test sessions of one hour duration each. The first one hour session was always a practice period. Thereafter, two lists of spondees were administered to each subject at every S/N ratio for all conditions. The first presentation was used for practice and the second constituted the experimental list. This procedure was employed to reduce practice effects to a minimum.

The spondaic word lists were administered to the subjects at an intensity level of 70 dB SPL re the FF condition. The intensity level of the white noise was varied to obtain S/N ratios of −20, −16, −12, −8, and −4 dB. The FF condition was always used as the reference location for the intensity level of the noise.

For both the speech and noise tapes, a 1000 Hz pure tone was employed as the reference signal. The peaks of the speech or the noise signals during the FF condition were monitored on a VU meter at the level of the reference tone. Before each experimental recording was produced, the intensity of the reference tone on the master tape or the noise generator output was measured

via a microphone placed directly above the artificial head. This procedure was employed to maintain the intensity of the speech or noise signals in the sound field at the same level for all recordings. As the head was changed to the desired azimuth, the speech or noise increased or decreased, depending on the physical arrangement of the head re the sound source. The reference tone, however, was always recorded at a level identical to the level of the reference tone during the FF condition. Thus, the tape recordings at each experimental condition realistically reflected the intensity and time modifications resulting from the particular arrangement of the head and loudspeaker.

Results

The intelligibility functions for the spondaic words in noise at each experimental condition are shown graphically in Figure 8. The S/N ratios refer to the levels in the sound field at the center of the head in the FF position. For convenience, the spatial arrangements were ordered from the highest to the lowest in terms of the S/N ratio needed to obtain a score of 50% on the intelligibility function. This rank ordering is also shown in Figure 8. One condition, the "FF" arrangement, is similar to that employed by Hirsch (1950). During that condition the speakers were separated slightly and thus it was not a true FF condition. The "FF" condition was included in Figure 8 for comparative purposes and will be discussed at length in Experiment III.

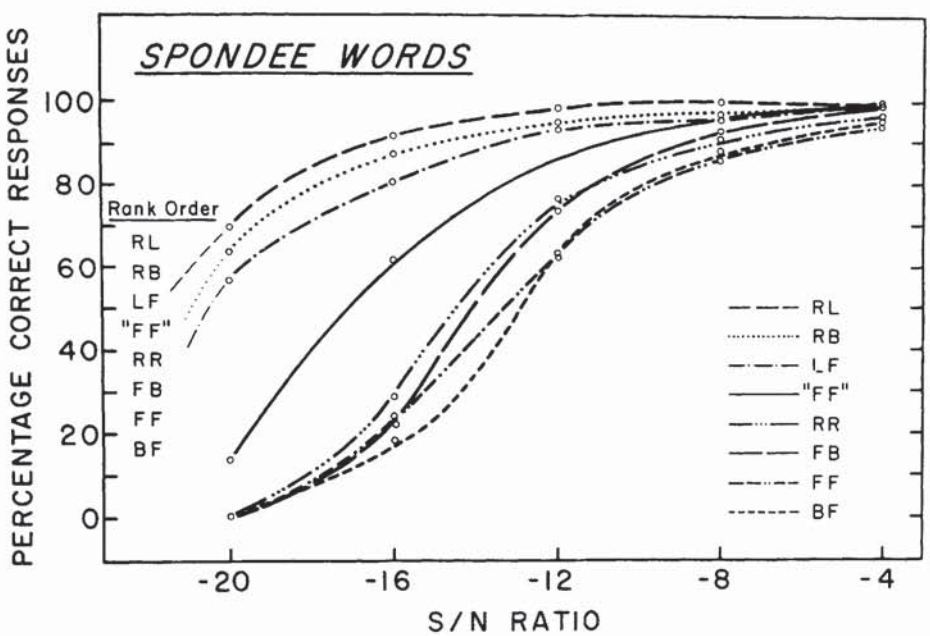

FIGURE 8. Intelligibility functions for spondaic words in noise at the various experimental conditions.

Essentially, the results divided the conditions into two groups. The three conditions with the highest intelligibility scores were RL, RB, and LF followed by the "FF" condition. The poorest conditions were FB, FF, and BF respectively. An obvious difference between the two sets of conditions is that an interaural time delay is present for either or both the speech or noise signals for the conditions in which scores were the highest. During the poorest conditions, no interaural time delay was present even though the speakers were separated maximally as in the FB and BF conditions. Although the interaural time delay on certain conditions offers an interesting explanation for this superiority, it should be recalled that larger S/N ratios were present at the near ear during the RL, RB, and LF conditions and probably also influenced the ordering among these three conditions. The rank order of the RR condition is somewhat difficult to explain since the time delay between ears for both sound sources is identical. Further, the S/N ratio created at the two ears remains similar since the head shadow effect reduces both signals at the far ear. The relative contribution of S/N ratios and time intervals between ears were investigated and will be discussed later in this paper.

EXPERIMENT II. PHONETICALLY BALANCED WORDS

Subjects and Procedure

A procedure similar to the one described for Experiment I was used in the second investigation except that PB words were the speech signal. Ten lists of PB-50 words were available for the experiment. Each subject was tested during the eight one-hour sessions. The first session was used as a practice period, and the final seven periods constituted the experimental sessions. Thus, for each condition at every S/N ratio a sample of 100 words was obtained from each subject. The speech signal was presented at 70 dB SPL for the FF condition, which was again used as the reference location, as in the experiment with spondaic words. The noise level was varied to obtain S/N ratios of +6, +2, −2, −6, and −10. In the preliminary study, these S/N ratios were found to be appropriate for demonstrating a wide range of the intelligibility function for the experimental material. The subjects for the second experiment were 12 young adults with normal hearing as determined by procedures used in the first investigation.

Results

The results from the second experiment are shown in Figure 9. In addition to the graphic representation of the intelligibility functions, the conditions were ranked from highest to lowest on the basis of the S/N ratios needed to obtain an intelligibility score of 50%.

The results of the second experiment were similar to those observed in the first investigation. The highest intelligibility scores were found during the RL,

RB, and LF conditions. The RR, FF, and BF arrangements resulted in the poorest intelligibility scores. One unusual result was the appearance of the FB condition in the upper half of the conditions. The S/N ratio at the ears during this condition was higher than during the FF, BF, and RR. On this basis, the

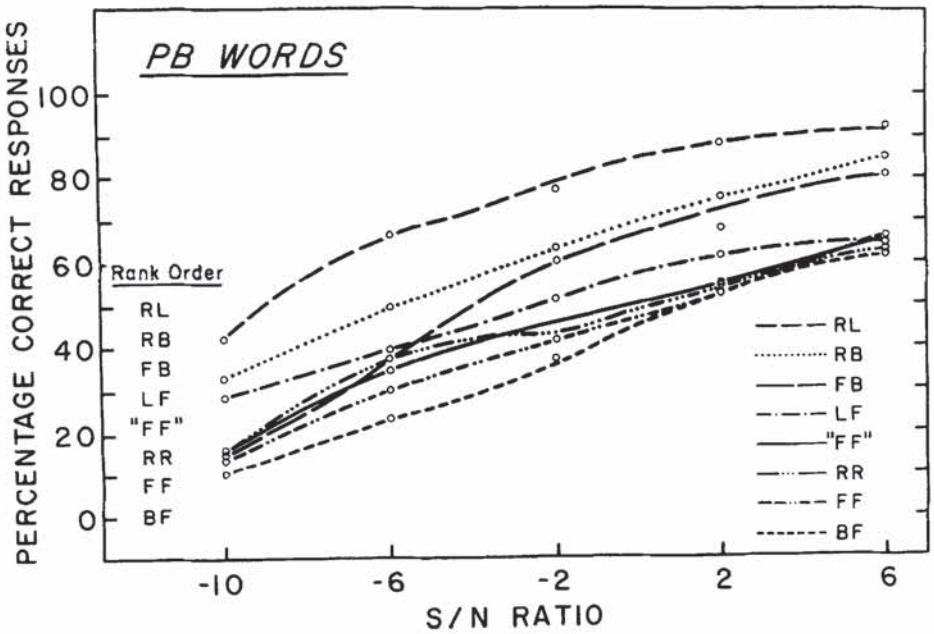

FIGURE 9. Intelligibility functions for PB words in noise at the various experimental conditions.

FB condition should be expected to rank somewhat higher than the aforementioned arrangements. However, it is more difficult to understand why the FB condition resulted in scores superior to the LF condition in which a time delay was present for the speech signal.

EXPERIMENT III. SUPPLEMENTAL INVESTIGATION

In the investigation by Hirsh (1950) the speech and noise signals were delivered separately from two loudspeakers during the FF condition. In this condition the two loudspeakers were placed side by side (about 12 inches from the center of one loudspeaker to the center of the other). This arrangement resulted in an estimated 10 to 20° separation of the two sound sources, i.e., 10° off the true 0° azimuth in each direction. A 10° change in the sound source will result in a change of the time of arrival of the stimuli at the two ears and thus a superior intelligibility score. Since the speakers in the Hirsh "FF" and "RR" conditions were separated, results from these conditions probably do not necessarily reflect results that would be obtained in FF or RR arrangements in which

both signals were from exactly the same source. In order to investigate the effects on intelligibility of 10° and 20° separations between loudspeakers, two investigations were conducted.

Subjects and Procedure

Two groups of 12 individuals with normal hearing were used as subjects in the two investigations. In the first of the two experiments spondaic words were used, and in the second PB words were employed as the speech signal.

During the initial experiment with spondaic words, the following conditions were compared: FF with both signals at 0°, "FF" with each signal moved 10° off center, a separation of 20° between loudspeakers; and "FF" with either the speech or the noise signal moved 10° off center, a separation between loudspeakers of 10°. In the second experiment with PB words, conditions in which both signals were from the same source were compared with conditions in which a 20° separation was permitted.

Tape recordings of the speech and noise signals had been reproduced through the artificial head, as described previously. The experimental apparatus was the same as diagrammed in Figure 4.

Practice sessions were employed as in the earlier experiments. During experimental sessions in which spondaic words were utilized, subjects received two lists of 30 words each at all conditions and S/N ratios. When PB words were used during the experimental sessions, every subject received 100 words at each S/N ratio and condition.

Results

The intelligibility functions for spondaic words were obtained for each experimental condition. The results are shown in Figure 10. Since the results were similar, regardless of whether the noise or speech was on one side or the other, they were averaged together in the figure. The results demonstrate clearly that changes which result in separations of only 20° between sources are beneficial to intelligibility in noise. In the conditions where only the speech or noise source was moved 10° from the center position, the intelligibility scores were slightly higher than the condition where both sources were from exactly the same position. However, when analysis of variance was applied to the data, the results were not statistically significant. The only place where a substantial difference was found was at a S/N ratio of −16 dB. Although there is a tendency for higher scores to be found during the 10° separation condition than in the FF condition, the superiority is somewhat small. Analysis of variance was also computed between the FF and 20° separation conditions; these were found to be statistically significant at $p = 0.001$.

Figure 11 includes the intelligibility functions obtained when PB words were the speech signal. Data were collected only in the conditions of no separation and a separation of 20° between speakers. It is evident that a separation of 20°

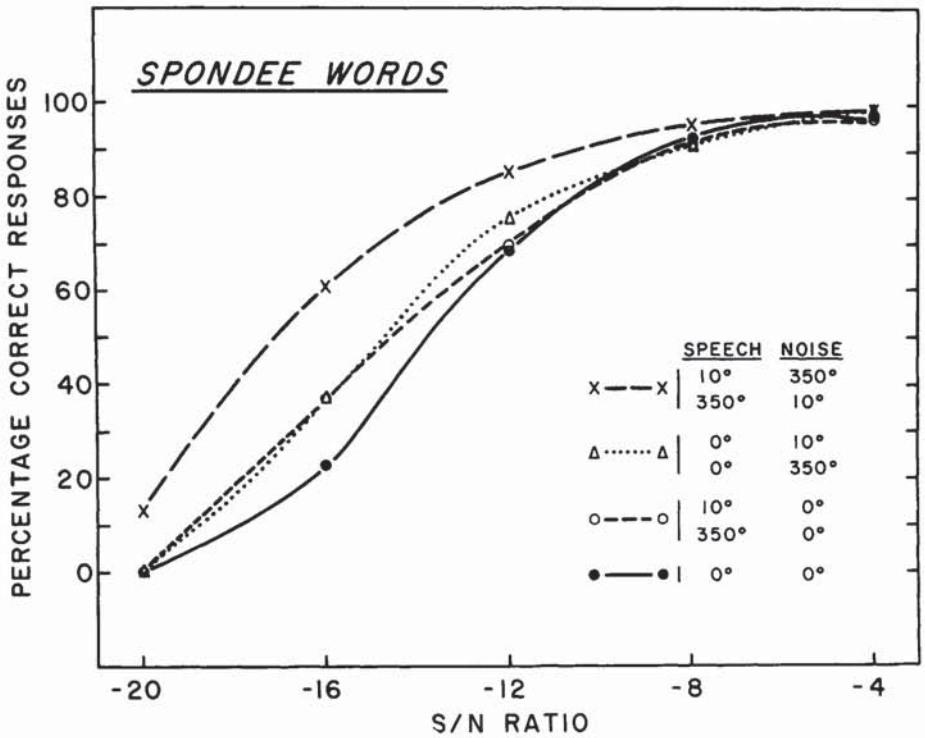

FIGURE 10. Intelligibility functions for spondaic words in noise at indicated changes in loudspeaker position.

between the speech and noise signals results in superior intelligibility scores than in the no separation condition. Analysis of variance calculated from the data also verified that the functions obtained with the separation of the speakers were statistically different from the function obtained with no separation at $p = 0.01$. In order to visually compare the rank order changes between the true FF and the "FF" (separation between speakers) conditions, the results in Figures 8 and 9 should be reexamined.

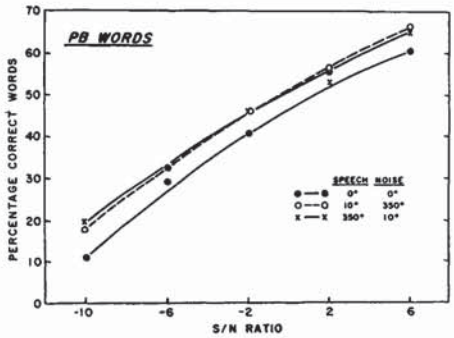

FIGURE 11. Intelligibility functions for PB words in noise at indicated changes in loudspeaker position.

EXPERIMENT IV.
BINAURAL AND MONAURAL INTELLIGIBILITY

The previous investigations were conducted under conditions of binaural listening. The results in each experiment lead us to the conclusion that interaural time differences may have played an important part in determining the rank order position of the various conditions. It is, of course, difficult from the previous results to determine precisely the magnitude of the contribution of the various time differences to intelligibility. The advantage of a time difference to the binaural listener is somewhat unclear in sound field experiments since any change in the time of signal arrival (from alteration in speaker azimuth) almost always results in a simultaneous change in the S/N ratios. Figure 7, depicting the physical changes in the speech and noise signals at each experimental condition, demonstrates this point vividly.

In order to describe further the effects of interaural time and intensity differences on binaural reception in a sound field, additional experiments were devised. It was reasoned that if time differences played a significant part in the rank ordering of the various binaural conditions, improvement in intelligibility should occur when the binaural listening conditions were compared to the monaural near-ear conditions. The monaural near-ear condition should be the critical comparative condition rather than the monaural far ear since the intensity of the speech signal in the former was not reduced by the head shadow effect and therefore presented the most favorable S/N ratio. However, the time difference for the speech or noise signal could not be appreciated in the monaural near ear as in the binaural condition. Thus, conditions such as RL, LF, and RB should result in a substantial improvement during the binaural situations as compared to the monaural near ear conditions. For conditions such as FB and BF, where spatial separation took place but no time delay was found, the intelligibility should be similar for both binaural and monaural listening situations. Likewise no change in intelligibility should be observed during the binaural and monaural conditions of the FF arrangement.

A final comparison was also made between monaural near- and far-ear conditions. This comparison indicated the magnitude of the change in intelligibility due to the diffraction characteristics of the head or head shadow effect introduced by the intervening head.

Subjects and Procedure

The S/N ratios obtained in the previous experiments, at which 50 to 70% binaural intelligibility scores were obtained, constituted the guidelines for the S/N ratios used in the following experiments. Again, the seven major experimental conditions (FF, FB, BF, RR, RL, LF, and RB) were utilized; however, there were three subconditions for each. The subconditions were: (1) binaural, (2) monaural (NE), and (3) monaural (FE). In conditions in which no time difference between ears existed, there was no NE or FE, only a monaural right or left ear, e.g., with the FF, FB, and BF conditions.

The intensity of the speech was again 70 dB SPL. The following are the S/N ratios at which the spondaic words were administered: RL (−20), RB (−20), LF (−20), RR (−14), and BF (−14). Similarly, the PB words were administered at the following S/N ratios: RL (−6), RB (−4), FB (−2), LF (+2), RR (+2), and BF (+2).

Both spondaic and PB words were administered to two groups of 12 young adults with normal hearing. The presentation order of the main experimental conditions and the presentation order of the subconditions was randomized. All test conditions were repeated twice for each subject.

The results based on the spondaic words are representative of 720 total words delivered at each subcondition; the same type of results with the PB material are based on 1200 total words at each condition.

Results (Spondaic Material)

The means and standard deviations of the intelligibility scores of each experimental conditions, but they are considerably smaller than for RL, RB, binaural, near ear, and far ear intelligibility for each condition are more easily visualized in Figure 12. If one compares the binaural and the near-ear results, the binaural superiority is very evident for the three conditions, RL, RB, and

TABLE 2. The means and standard deviations of the binaural and monaural intelligibility scores in per cent correct for spondaic and PB words at each of seven major test conditions.

Conditions		*Spondaic Words*		*PB Words*	
		Mean	*∂*	*Mean*	*∂*
	Bin.	81.7	9.54	57.6	9.14
RL	NE	41.5	13.26	49.7	13.72
	FE	0.9	2.75	4.6	3.61
	Bin.	84.5	7.79	48.8	7.19
RB	NE	18.4	12.23	41.7	7.99
	FE	1.0	2.12	15.8	7.22
	Bin.	66.8	10.81	62.2	7.52
LF	NE	6.1	7.52	58.7	8.91
	FE	1.3	16.80	43.1	8.02
	Bin.	72.1	8.54	54.8	12.75
RR	NE	59.3	10.53	49.7	7.40
	FE	45.8	16.64	49.9	9.03
	Bin.	61.7	11.71	39.9	5.97
FB	RE	54.3	12.25	35.5	7.54
	LE	43.7	15.52	38.4	11.69
	Bin.	62.3	10.03	55.4	8.10
FF	RE	44.5	12.84	56.5	5.90
	LE	47.7	14.08	55.8	11.17
	Bin.	50.0	14.40	47.8	5.81
BF	RE	35.8	10.12	48.8	6.64
	LE	34.6	14.18	47.1	9.06

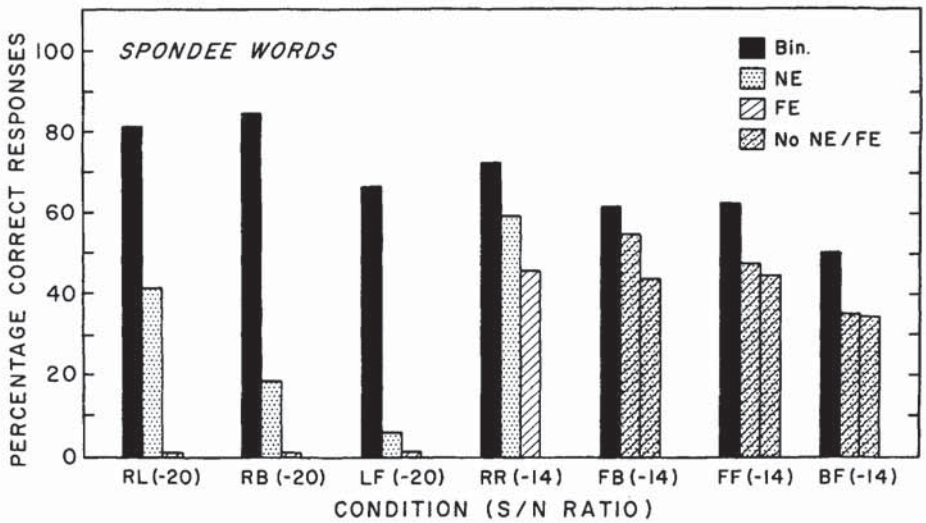

FIGURE 12. Histogram showing percentage correct responses for spondaic words in noise at various binaural and monaural experimental conditions.

LF, in which a time difference is present for either or both the speech and noise signals. Small binaural effects are also observed during the other experimental conditions, but they are considerably smaller than for RL, RB, and LF. Analysis of variance tests were computed between the results of the binaural and near-ear listening conditions. In the RL, RB, and LF conditions, the differences between binaural and monaural near-ear intelligibility were obviously statistically significant at $p = 0.01$. Using a similar level of confidence, the difference between the scores for RR and BF were also found to be statistically significant, but not for the differences in the FB and FF conditions. It is difficult to determine why the binaural scores in the latter four conditions were always slightly larger than the monaural scores. Possibly the small differences in the frequency response at each microphone permitted advantageous discrimination cues. Hirsh (1950) also reported a small binaural advantage during the FB and BF conditions.

The changes in intelligibility due to head shadow can be observed from the difference in the scores between the near ear and far ear conditions. During the FF, FB, and BF conditions only small differences were seen since both monaural ears were equidistant from the loudspeaker. The differences between the near and far ear are also small for the RR condition because both the masking noise and the primary signal are affected by the head shadow. The difference here of 13% was not statistically significant at $p = 0.01$.

For all practical purposes the intelligibility in the far ear is completely absent for the RL, RB, and LF conditions. These results show the detrimental effect that the shadow of the head may have on speech intelligibility. In spite of the almost complete absence of any intelligibility in the far ear during these

three conditions, the addition of the far ear in the presence of the near-ear signal still contributes heavily in producing a substantial binaural effect.

Percentage differences in intelligibility are somewhat deceptive unless consideration is given to the percent per decibel growth in the intelligibility function for the particular speech material employed. The results reported in Table 2 and Figure 12 were converted to differences in decibels and will be described later in this paper as a comparison with the results when PB words were used.

Results (PB Material)

The analysis for data collected with PB words was similar to that employed when spondaic words were used. The means and standard deviations for the intelligibility scores obtained under the various experimental conditions can be observed in Table 2 and graphically in Figure 13.

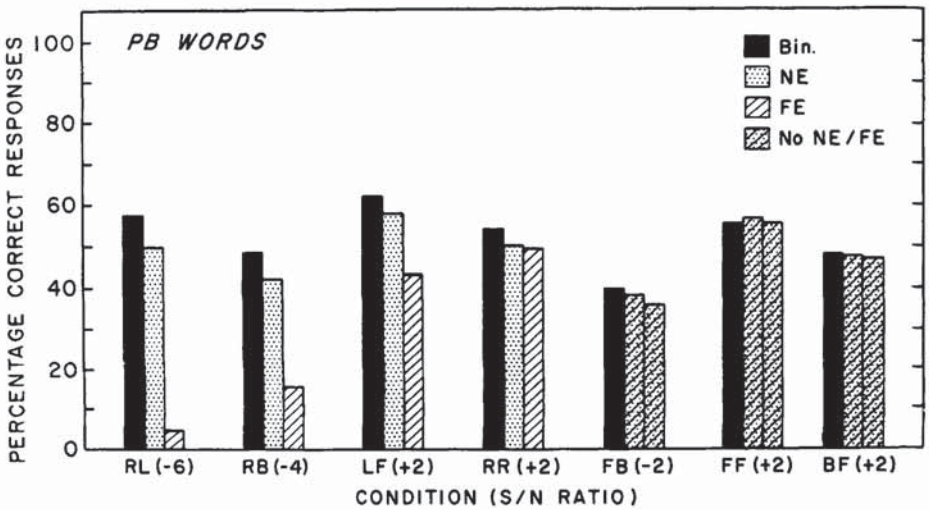

FIGURE 13. Histogram showing percentage correct responses for PB words in noise at various binaural and monaural experimental conditions.

Observe from Table 2 and Figure 13 that no changes in the intelligibility scores occur during FF, FB, and BF conditions when the items were presented binaurally or monaurally. For conditions RL, RB, LF, and RR, improvements of from six to eight percent were noted when the binaural presentation was compared to the monaural near ear condition. In each case results of statistical tests indicated that the differences were significant at $p = 0.01$. As with the spondee material, the conditions which showed a superior binaural score are those where a time difference was present for either or both the speech and noise signals. The improvement in binaural intelligibility during the RR condition may be a true result since no such improvement was noted during the

FF, FB, and BF conditions. Possibly a small binaural effect should be anticipated in the RR condition since the arrival time of both the speech and noise is delayed at the left ear even though both signals come from the same loudspeaker.

The effect of the head shadow on the intelligibility of the monaural far ear was again forcefully demonstrated in the RL, RB, and LF conditions. During the RR condition no reduction in intelligibility was observed when comparison was made between near and far ears. Recall from the earlier data on the physical measurements of the head that the shadow of the head affected both speech and noise signals in such a manner that the S/N ratios were similar at both ears for this condition.

To permit a more precise and meaningful comparison of the results of Experiment IV, the percentage differences in intelligibility were converted to differences in decibels. Conversion from percentage change to equivalent change in decibels was based on the calculated slope of the intelligibility functions (between the 20 and 80% points) observed during the binaural conditions in the previous experiments. Comparisons between the binaural scores and the monaural near ear scores can be seen in Figure 14 for both spondaic and PB material.

When comparative binaural versus monaural differences were considered in terms of decibel change, substantially greater binaural improvements were observed when spondaic words rather than PB words were utilized. The RL, RB, and LF conditions indicated this result dramatically. Only small and primarily statistically nonsignificant differences in binaural versus monaural near ear intelligibility were observed during the other experimental conditions.

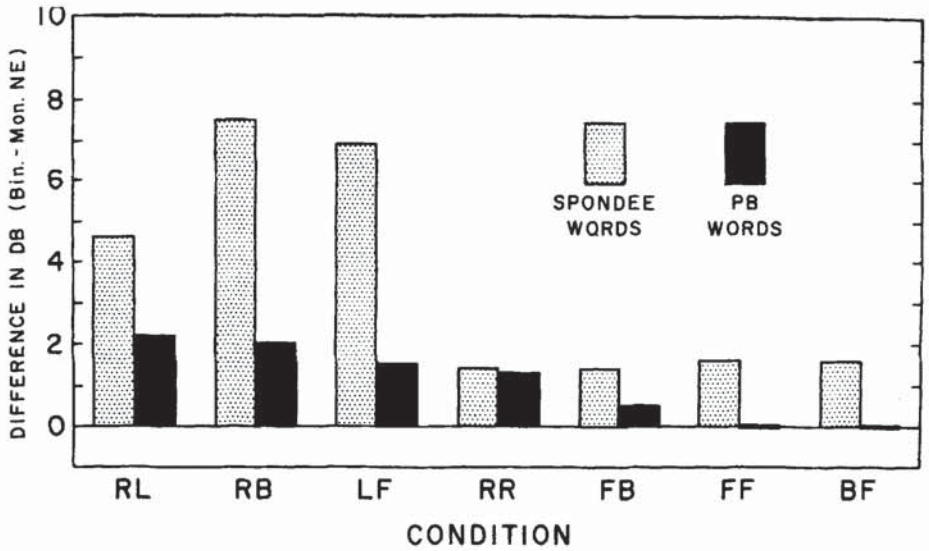

FIGURE 14. Comparison of differences in decibels (binaural-monaural near ear) for spondee and PB words in noise at various experimental conditions.

The following factors are suggested as responsible for these results. It has been established that time differences can be most advantageously appreciated in the frequency range below 1500 Hz. As would be anticipated, the results from the third-octave band analysis (Figure 7) showed that more energy was found in the lower frequency range for the spondees than for the PB material. It is probably more important to recall that the informational elements necessary for intelligibility for spondees are located in a frequency range lower than found for PB words. The current results demonstrate that greater binaural superiority was observed when spondaic words rather than PB words were employed during conditions where an interaural time difference was permitted. The present investigators suggest that speech stimuli in which the informational elements in the words are found in the middle or lower frequency end of the speech spectrum, such as spondees, will allow for greater improvements in binaural over monaural near ear intelligibility than for speech materials, such as PB words, where higher frequencies contribute substantially to the intelligibility score. This hypothesis assumes that the binaural superiority observed is primarily a result of the clues afforded by the interaural time difference for either the speech or noise signals.

Some supporting evidence for the above hypothesis is found in the experiment by Schubert and Schultz (1962). They demonstrated that binaural improvement was greatest when the speech signal was restricted to the frequency range from 200 to 1600 Hz as compared to middle and high frequency ranges. The primary signal in their investigation was running speech passages, and the interfering signal was broad-band random noise.

EXPERIMENT V. EXPERIMENTS IN SOUND FIELD

Schubert and Schultz (1962) have pointed out that the small differences between the binaural and monaural hearing systems for signal selection ability are often disappointing to the researcher in binaural hearing. They note that the differences between the two systems are often only a few decibels for some speech discrimination tasks. A good example is afforded by some of the earlier investigations (Hedgecock and Sheets, 1958; Belzile and Markle, 1959; Wright and Carhart, 1960; DiCarlo and Brown, 1960; Jerger, Carhart, and Dirks, 1961; and Jerger and Dirks, 1961) concerned with comparisons between binaural and monaural amplification systems. With a few exceptions, investigations seeking empirical demonstration of the efficiency of the binaural as contrasted to the monaural hearing aid failed to yield results for speech discrimination tasks conclusively favoring the binaural aid condition. In laboratory experiments time and intensity changes were electronically altered and the binaural and/or monaural signals were delivered via earphones (Schubert and Schultz, 1962; Feldmann, 1965). These results clearly demonstrated the effectiveness of the binaural system for intelligibility measurements.

A review of the aforementioned literature might suggest that it would be difficult to duplicate results similar to the ones collected with the dummy head

and earphones if the subjects themselves had been tested in the sound field environment. Thus it was decided to repeat portions of our initial experiments with the subjects located in the sound field of the anechoic chamber and compare these results with the data collected via the artificial head.

During the administration of the earlier experiments, the investigators became familiar with the interesting experiments conducted by Speaks and Jerger (1965) using synthetic sentence material as a primary message. It was decided that these synthetic sentences might be especially well suited for inclusion in the current studies. Our reasoning was that these sentence materials appeared to be considerably different from spondaic words in structure and method of measurement. The frequency area most important for identification of the sentences, however, was somewhat similar to that for spondaic words (Speaks, 1967). The sentence materials were constructed as approximations to "real" sentences on the basis of the sequential probabilities of word units. The test contains closed rather than open message sets and requires the listener to identify the appropriate sentence heard.

Speaks (1967) reported that the most important informational elements in the synthetic sentences were found in the frequency area around 725 Hz. One might anticipate substantial binaural superiority over monaural listening if these sentences were used under several of the conditions similar to those in our current series of experiments. Two assumptions were involved in our reasoning: (1) that binaural improvement in intelligibility was critically dependent on the presence of interaural time differences for either the primary or secondary messages; and (2) that the interaural time difference could be appreciated and translated into improved identification scores for material in which the most important informational elements were in frequency range lower than 1200 Hz, even though the task and material were different from spondee discrimination. The current investigations provided an excellent opportunity to gain information concerning comparative binaural and monaural identification of sentence type speech materials as well as for spondee words under conditions of sound field listening.

Subjects and Procedures

For the purposes of this experiment, three individuals who had served as subjects in the previous experiment were used as subjects. Each was seated in the anechoic chamber with his or her head resting on a backrest and affixed with a head band arrangement so that virtually no movement was allowed.

The three conditions chosen for this study were FF, LF, and RL. The latter two conditions are, of course, those in which substantial binaural superiority was obtained in the earlier studies while in the FF condition little, if any, binaural effect was observed. The loudspeakers were placed at a distance of one meter from the center of the subject's head.

For portions of the experiment, spondee words were employed as the primary message, and a wide-band white noise was used as the competing mes-

sage. Spondaic words were chosen rather than PB material since it was found in the earlier experiments that binaural superiority was more evident when spondee words were used.

When the synthetic sentences[1] were used as the primary message, the competing message consisted of either a wide band white noise or continuous discourse recorded by an adult male speaker. The latter competing message has been used and described by Speaks, Karmen, and Benitez (1967) in a previous experiment. When this competing message was employed the performance-intensity characteristics of the synthetic sentences were substantially altered as compared to the function when white noise was the competing message.

Performance-intensity functions were obtained for each of the conditions from every subject in the following manner: the primary message was delivered via loudspeaker at 40 dB SPL and the competing message intensity was varied, depending upon the desired S/N ratio.

In order to obtain an estimate of the intelligibility functions under binaural and monaural conditions, tests were performed at four S/N ratios for each experimental condition. Four complete lists of the sentence or spondee material were administered to each subject in a random manner. Since there were three subjects, each point on the function is the average of 12 complete lists from three subjects.

Results

The intelligibility functions of the spondaic words in white noise for each of the three experimental conditions (FF, LF, and RL) are shown in Figure 15. The figure contains the intelligibility functions obtained from binaural, monaural near-ear, and monaural far-ear conditions.

Consider first the results from the FF condition (Figure 15a). Essentially, the contour, slope, and position of the binaural and monaural (RE and LE) functions are identical. The difference between the binaural function and either monaural function is less than 1.0 dB at any given place on the function. Thus, no binaural advantage was demonstrated during the FF condition.

The results of the LF condition (Figure 15b) are quite different from those obtained in the FF condition. Remember that in this condition (LF) the head shadow effect and interaural time factors were operating whereas in the FF condition these factors were not present. It is obvious that in the monaural FE the respective intelligibility functions are displaced in S/N ratio from one another. At 50% intelligibility, the binaural advantage over the monaural NE is 5.5 dB and the monaural NE is 3.0 dB superior to the monaural FE.

The intelligibility functions for the RL conditions are presented in Figure 15c. The binaural advantage over the monaural NE is 4 dB at 50% intelligibility and the monaural FE is 7.5 dB poorer than the monaural NE.

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[1]The original authors were kind enough to loan us a copy of the synthetic sentences for use in the present experiment.

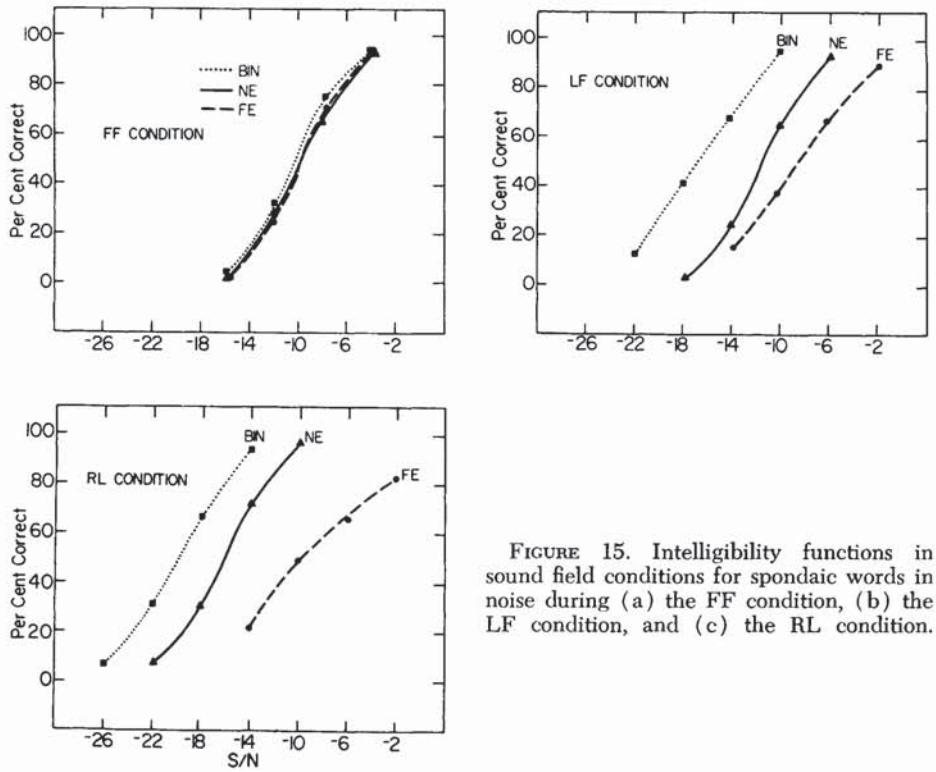

FIGURE 15. Intelligibility functions in sound field conditions for spondaic words in noise during (a) the FF condition, (b) the LF condition, and (c) the RL condition.

The results of the above conditions involving subjects in the sound field of an anechoic chamber clearly confirm the validity of the earlier results (Table 2) obtained via the artificial head. In the current experiment, no binaural advantage was observed in the FF condition; however, for the LF and RL conditions a binaural advantage over the monaural NE was effectively demonstrated.

The binaural advantages for the LF and RB conditions found in Experiment V are slightly smaller than those observed in Experiment IV; however, due to technical limitations the monaural conditions obtained with the artificial head could not be identically recreated in the sound field environment. For example, the muff utilized to produce the monaural situation in the sound field did not totally eliminate stimuli from the ear it covered. For the LF condition, the binaural advantage over the monaural NE was 5.5 dB in the current experiment and 7.0 dB in the earlier results. For the RL condition, the binaural advantage was 4.0 dB in this experiment and 4.5 dB when the artificial head was used. Some caution must be used in these comparisons since the results in Experiment IV were obtained at only one critical S/N ratio.

Figure 16 contains the performance-intensity functions for the three synthetic sentence conditions when white noise was the competing signal. Again, the FF condition demonstrates little if any binaural advantage over either of the two

monaural situations. In the performance area from 20 to 80%, the gain function of 12% per dB closely approximates that observed earlier by Speaks, Jerger, and Jerger (1966).

In the LF condition a substantial binaural advantage (7.5 dB) over the monaural NE was observed at 50% identification. The monaural NE function was about 2.5 dB superior to the monaural FE. A smaller but still distinctive binaural advantage (5 dB) over the monaural NE was present during the RL condition at the 50% point on the functions. In the RL condition the monaural FE was approximately 6 dB poorer than the monaural NE. Both LF and RL conditions had gain functions that ranged from 9 to 12% per dB and both conditions clearly demonstrated a binaural advantage over the monaural NE.

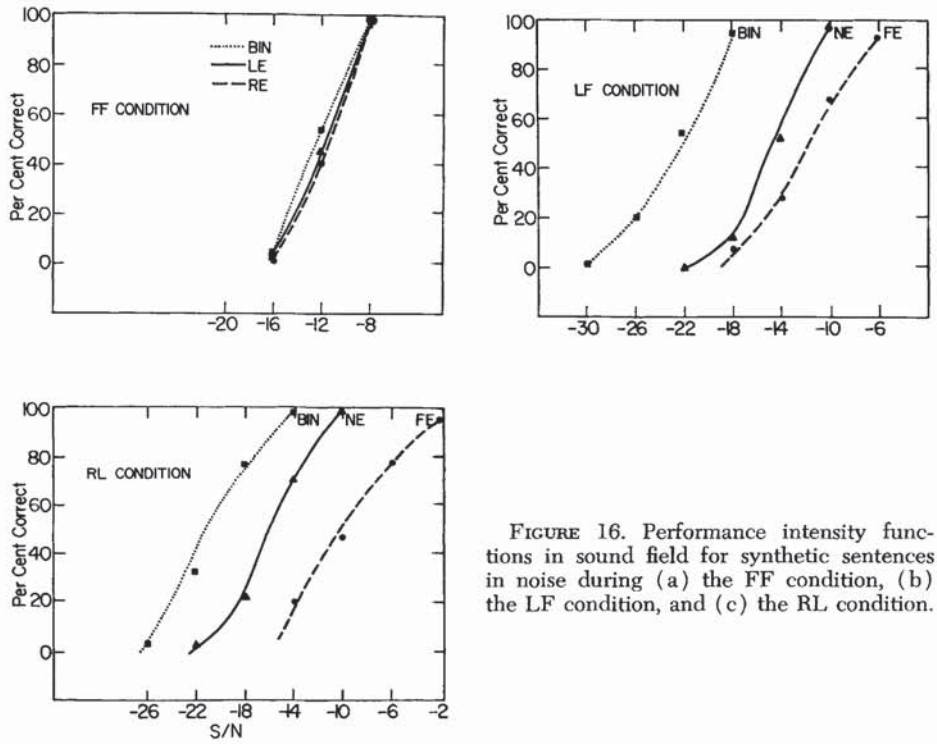

FIGURE 16. Performance intensity functions in sound field for synthetic sentences in noise during (a) the FF condition, (b) the LF condition, and (c) the RL condition.

Figure 17 shows the performance-intensity functions for the synthetic sentences when the competing message consisted of a speaker reading continuously. The same speaker who recorded the primary message also recorded the competing signal. Observe that during the FF condition there is a rather minor binaural advantage (1 dB) over either of the monaural conditions at the 50% point on the functions. However, the results of both binaural and monaural results are almost identical in the lower portions of the functions. The gain function for all three curves is approximately 4.3% per dB. The reduc-

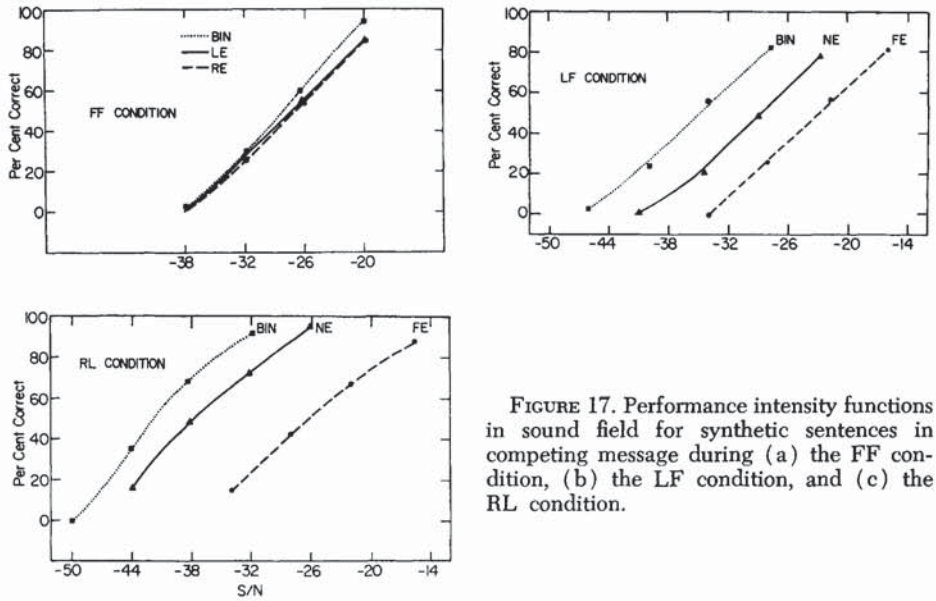

FIGURE 17. Performance intensity functions in sound field for synthetic sentences in competing message during (a) the FF condition, (b) the LF condition, and (c) the RL condition.

tion in the steepness of these functions in comparison to the earlier ones where white noise was the competing signal are in agreement with similar results reported by Speaks et al., 1967, under monaural earphone conditions.

The results from the LF condition show clearly the binaural superiority (6 dB) over the monaural NE at 50% identification; the monaural FE is 6 dB poorer than the monaural NE. Likewise, the binaural advantage over the monaural NE during the RL condition was evident (4.5 dB). However, for RL the monaural NE was considerably superior to the monaural FE (12 dB). The gain functions observed in both LF and RL ranged from 4.3 to 5.3% per dB.

There are a few relationships in this final experiment which are especially worthy of note. First, there are slightly larger binaural advantages over the monaural NE scores when the synthetic sentence test material is used as compared to spondaic words. For example, in the LF condition the binaural superiority over the monaural NE at 50% intelligibility is 5.5 dB for spondaic words in noise. For the same condition the binaural advantage was 7.5 dB and 6.0 dB when the sentences were embedded in noise and continuous discourse respectively. The difference between binaural and monaural NE intelligibility was not as large during the RL condition as in the LF conditions. A similar result was also observed in Experiment IV. For spondaic words in noise the results favored the binaural condition by 4.0 dB. When sentences were employed the binaural results showed a 5.0 dB (in noise) and 4.5 dB (in voice/competing message) advantage over the monaural NE. A slightly larger binaural over monaural NE advantage was found in both the LF and RL conditions when sentence material rather than spondaic words were the primary

message. The reason may be that for the synthetic sentence material the most critical informational elements are reportedly in the frequency area around 725 Hz while for the spondaic words this frequency area may be slightly higher. Recall that the antiphasic MLD is slightly larger (Durlach, 1963; Rabiner et al., 1966) at frequencies around 700 Hz as compared to slightly higher frequencies. Again we emphasize that the binaural advantage for speech intelligibility tasks must be dependent on the speech frequency range carrying the critical information so that the interaural time differences of certain conditions can be most effectively appreciated. A similar argument was used earlier in this paper to explain the larger binaural advantages found when spondaic rather than PB materials were employed.

DISCUSSION

The results of the present series of experiments partially reaffirm the earlier report by Hirsh (1950). The current data again suggested that for binaural sound-field listening conditions, the intelligibility for spondaic words in noise was greater when the sources of the speech and noise were separated and resulted in an interaural time difference for one or the other of the messages. The results of the current investigation permit us to extend this general conclusion to PB words in noise. However, the order of the experimental conditions ranked in terms of highest intelligibility differed in certain instances from the earlier investigation and these require some discussion.

The results of Experiment III are of interest since they demonstrated that the rank ordering of the conditions in terms of highest intelligibility may be altered if even a small separation is permitted between the speech and noise sources. In Experiment III the intelligibility for both spondaic and PB words was significantly improved by a 20° separation of the speech and noise sources and slightly improved by merely changing one of the loudspeakers by 10°. Figure 8 demonstrated the comparative change in rank order for the FF condition under the various conditions. As in the Hirsh investigation, the "FF" condition (where a small separation was permitted) ranked higher than the FB condition of the current series (Figure 8). These results seemed unlikely since the effect of the pinna reduced the measured masking level of the noise for the FB condition when compared to the true FF condition. When no separation of the sound sources was permitted, as in Experiment I, the FF condition did in fact rank lower than the FB condition. Thus it appears reasonable that the rank order position of "FF" in the Hirsh data may have been influenced by the small time difference in the arrival of the signals at the ears due to the loudspeaker separation.

The three conditions RL, RB, and LF always ranked highest among the various binaural experimental conditions. Hirsh (1950) observed that intelligibility was highest when speech came from the side and noise from the front or the back of the head. The only difference between the two experiments is that the RL condition always ranked highest in our results. We suggest that

the current result is reasonable for our data when the various factors are considered. First, the overall S/N ratio at the near ear was greater by measurement for the RL condition than for the other experimental combinations and thus must contribute substantially to the overall intelligibility score during the binaural condition. The more favorable S/N ratio during the RL condition is due partially to the fact that the sound pressure is greatest for the primary signal when the loudspeaker faces the ear microphone directly. At the same time there is a reduction in the intensity of the competing signal due to the effect of head shadow, thus permitting an extremely favorable S/N ratio at the near ear. Second, an interaural time difference is present for both signals because of the location of the sound sources.

From the results of Experiment IV, the binaural advantage over the monaural NE was 4.5 dB. It should be noted, however, that this binaural advantage is slightly smaller than that observed for RB and LF. The results of Experiment V also indicate that the binaural effect is smaller for RL than for LF. There appears to be no important advantage to the binaural system when both primary and competing signals are delayed over the condition where only one of the signals is delayed. It should be recalled that Carhart, Tillman, and Johnson (1967) reported that double or opposite delays yielded no greater release from masking for spondaic words than did a single delay.

The aforementioned considerations lead us to the conclusion that the high binaural rank order for the RL condition is a result primarily of the favorable S/N ratio at the near ear together with a secondary advantage due to the time delay. If the S/N ratio at the near ear had been identical for the RB, LF, and RL conditions, then the RB and LF conditions would have ranked higher than the RL condition because of the greater improvement in intelligibility associated with the time delay during the RB and LF conditions.

There are other isolated comparisons which need brief explanation. For example, note in Figures 8 and 9 that FB ranks higher than true FF, and BF ranks lowest of all conditions. Since very little if any "binaural effect" is produced in any of these conditions, the S/N ratio at the ears must be the determiner of the rank order positions. In the FB condition the pinna reduces the intensity, especially in the higher frequencies, for the noise signal but not for the primary message. The opposite occurs during the BF condition (Figure 7). Of the three conditions (FF, FB, and BF) the FB condition has the most favorable S/N ratio, while BF has the least favorable S/N ratio. Since the pinna does not play a similar role in the FF condition, it would seem appropriate that this condition fall between FB and BF in performance. The rank ordering for both spondaic and PB words support this explanation.

The RR condition poses an interesting problem. Although both speech and noise sources come from the same loudspeaker, the time of arrival of both signals is delayed at the left ear in reference to the right. It is difficult to determine whether an improvement in intelligibility should be expected. There is a delay in the time of arrival of the signals at the left ear; however, the delay is the same for both signals. The results of Experiment IV showed only small,

if any, improvement in the intelligibility for the RR condition during the binaural presentation as compared to the monaural near-ear condition. The results indicated that the S/N ratios at the ears were the principle determiners of the rank order position of the RR condition among the other experimental binaural conditions.

The results of Experiments IV and V demonstrated that the binaural scores were substantially larger than comparable monaural near-ear results during the RL, RB, and LF conditions. We attributed these results primarily to the interaural time differences produced during the RL, RB, and LF conditions. Even though the evidence strongly supports this conclusion, it must be remembered that interaural intensity differences were also present during these three conditions. Feldmann (1965) observed changes in intelligibility when interaural intensity was systematically varied. Thus the possible effect of the interaural intensity changes as a result of the head shadow effect must be considered in the current investigation.

Although the effect was not specifically studied in the present experiments some suggestion of possible results can be found in the literature. Feldmann found that the effect of an interaural time difference upon a speech signal in noise was stronger than that of an interaural intensity change. In results somewhat comparable to the current ones he found that the favorable effects of an interaural time difference of the speech signal in noise could not be improved by attenuating the signal on the trailing side. Just the opposite occurred; the results became worse until intelligibility reached a level corresponding to the monaural/binaural condition. If the leading ear was attenuated, the intelligibility was reduced to the level obtained with monaural speech and binaural noise. Zerlin (1966), using a 600 Hz low-pass transient as the primary signal, found that the effect of an intensity difference between ears was to diminish the MLD that results from a time difference alone. In attempting to relate these results to the sound field condition of RL, RB, and LF, it would be predicted that the effect of an interaural intensity difference in the presence of the time difference would reduce rather than improve the present experimental results.

The results of the Hirsh (1950) experiment implied that two hearing aids, electronically independent, and at ear level, might be more advantageous for the hearing aid used than one ear level aid. However, in some experiments (Belzile and Markle, 1959; DiCarlo and Brown, 1960; Hedgecock and Sheets, 1958; Jerger, Carhart, and Dirks, 1961; Jerger and Dirks, 1961) the degree of binaural aided improvement on speech intelligibility tests has been small and at times discouraging. When the binaural aided condition was compared to the monaural near ear aided condition, the average improvement was approximately 7 to 10%. It may have been important that the primary message used in these experiments was often PB material whereas in the earlier results by Hirsh (1950) spondaic words in noise were employed.

It is proposed by the current investigators that a result more favorable to the binaural aid might have resulted if the emphasis had been placed on mea-

surements of spondee words in noise rather than PB words. Our present results show that even in the more favorable conditions where a time difference operates (LF, RB, and RL) the average binaural improvement is only 8% or 2 dB, when PB words are used. However, in comparable conditions in which spondaic words are employed the binaural improvement may be as large as 6 dB. In the hearing aid experiments, the loudspeakers were often located at azimuths 45° to the right and left of the listener. Even though an interaural time difference was present, the advantage to the binaural hearing aid user may have been necessarily reduced because of the type of speech material. As suggested earlier in this paper, the critical information in PB material is in a frequency range higher than for spondee words and, therefore, the time difference may not be as effectively utilized by the binaural system for the former as for the latter.

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