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The spatial attributes of stimulus frequency and their role in monaural localization of sound in the horizontal plane

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Listeners, whose right ears were blocked, located low-intensity sounds originating from loudspeakers placed 15 deg apart along the horizontal plane on the side of the open, or functioning, ear. In Experiment 1, the stimuli consisted of noise bursts, 1.0 kHz wide and centered at 4.0 through 14.0 kHz in steps of .5 kHz. We found that the apparent location of the noise bursts was governed by their frequency composition. Specifically, as the center frequency was increased from 4.0 to about 8.0 kHz, the sound appeared to move away from the frontal sector and toward the side. This migration pattern of the apparent sound source was observed again when the center frequency was increased from 8.0 to about 12.0 kHz. Then, with center frequencies of 13.0 and 14.0 kHz, the sound appeared once more in front. We referred to this relation between frequency composition and apparent location in terms of spatial referent maps. In Experiment 2, we showed that localization was more proficient if the frequency content of the stimulus served to connect adjacent spatial referent maps rather than falling within a single map. By these means, we have further elucidated the spectral cues utilized in monaural localization of sound in the horizontal plane.

Throughout the past several decades, interest in localization of sound in space has centered on the role played by interaural difference cues. The consensus, based on a multitude of studies, is that interaural differences in stimulus arrival time are utilized for locating low-frequency tonal stimuli in the horizontal plane as well as high-frequency transients, and that interaural differences in stimulus intensity are utilized for locating high-frequency tonal stimuli. But, one can locate sound reasonably well when listening with only one ear (Fisher & Freedman, 1968; Gatehouse, 1976; Gatehouse & Cox, 1972). Certain conditions, however, must obtain: viz, the sound must be complex—sinusoids cannot be located at an accuracy exceeding chance expectation (Angell & Fite, 1901; Butler, 1971); the stimulus must contain the higher audio frequencies, as noise bands consisting only of frequencies below 4.0 kHz are located most imprecisely (Belendiuk & Butler, 1975); and, the outer ear must not be distorted or blocked—otherwise, all sounds seem to originate from a restricted region in the horizontal plane (Butler, 1975; Gilse & Roelofs, 1930). It appears, then, that the pinna modifies the sound field, and the resulting spectrum is dependent on the azimuthal position of the sound source. Assuming that the sound spectrum is a primary cue for monaural localization, an obvious extension to a research program centered about monaural localization is to define the relevant spectral cues more precisely. In this connection, Butler and Planert (1976) reasoned that since a sinusoid cannot be located monaurally, but wideband noise can, then a progressive increase in the stimulus bandwidth should result in a corresponding improvement in localization proficiency. Accordingly, the bandwidth of an 8.0-kHz centered noise stimulus was increased from 2.0 to 6.0 kHz in steps of 1.0 kHz. While performance in locating sounds positioned in the vertical plane improved in an orderly fashion when stimulus bandwidth was augmented, the monaural performance data for horizontal plane localization were inconsistent. The results of a further experiment also indicated that increasing the stimulus bandwidth may or may not lead to improved performance when listening monaurally to sounds in the horizontal plane (Belendiuk & Butler, 1977). In this latter study, bands of noise, 2.4 kHz wide and centered at 5.0, 7.4, or 9.8 kHz, were presented singly and in pairs or triplets. The combined noise bands were not consistently located more accurately than one of the single noise bands. Listeners' location judgments of the single noise bands showed strong position biases—certain loudspeaker positions would be chosen routinely as the sound source, irrespective of its actual location. On close inspection of the data for single and combined noise bands, the following rule appeared to account for the observed performances: "The addition of a noise band,

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centered at one frequency, to another noise band centered at a different frequency will result in improved localization performance if the distribution of loudspeaker choices for each noise band when presented singly differs from one another in a pronounced manner." If, on the other hand, the choice of loudspeaker distribution for each noise band overlaps appreciably, then combining the two noise bands will not result in improved localization performances (p. 356). An additional monaural test on one subject led us to suspect that the apparent location of a narrow band of noise differing in center frequency may move sequentially from in front toward the side of the functioning ear as its center frequency is increased. In other words, different stimulus frequencies may possess different spatial referents.

Two experiments will be reported here: Experiment 1 was designed to map, for the horizontal plane, spatial referents for various stimulus frequencies. In Experiment 2, we sought to find out how these spatial referents might enter into the process of accurate monaural localization.

EXPERIMENT 1

The first experiment dealt with apparent location of 1.0-kHz-wide noise bands with different center frequencies.

Method

Twelve normal-hearing persons participated. Their left-ear thresholds for frequencies ranging from .25 through 8.0 kHz were within 15 dB re audiometric zero (ISO; see Davis & Kranz, 1964). The subjects were seated in the test room such that the left ear was approximately 5 ft from each of the loudspeakers positioned at eye level on a semicircular arc. The test room was sound-treated by means of sound-absorbent material on the walls and ceiling and carpeting covering the floor. Reverberation time, as determined by tracing the decay of an impulse sound photographed on an oscilloscope screen, was estimated to be approximately 75 msec.

The subjects were asked to report, via an intercom system, the loudspeaker from which the sound appeared to emanate. The transducers consisted of six KLH loudspeakers, 4 in. in diameter and housed in wooden cabinets. They were positioned at 345, 330, 315, 300, 285, and 270 deg azimuth. Each was identified by a number, 1 through 6, with 1 assigned to the loudspeaker stationed to the left of a visual fixation point, at 345 deg, and 6 assigned to that stationed at 270 deg azimuth (see Figure 1). The loudspeakers were chosen from the laboratory supply for their comparable frequency response characteristics. The subjects were aided in maintaining a stationary head position throughout the testing by means of a headrest affixed to the chair and a visual fixation point that defined 0 deg azimuth.

A monaural listening condition was established by inserting a Mine Safety Appliance (MSA) ear defender into the right ear canal and then covering the same ear with an MSA muff, which was strapped to the head. Thresholds (Method of Limits) for all stimuli used in the experiment were measured with the right ear occluded. The stimuli were then presented at 20 dB re threshold for the loudspeaker positioned at 315 deg azimuth. At this SL, a stimulus, while clearly audible to the left ear, is below threshold for the right ear when occluded by an ear defender and muff (Belendiuk & Butler, 1975). After each test session, however, a threshold for each stimulus condition that had been presented was measured with both ears occluded in the manner described above. Thresholds were taken for all loudspeaker locations. The precaution was taken to insure that the stimuli were, in fact, audible only to the left, or open, ear during testing. Rarely did listeners report hearing a stimulus when both ears were occluded; when they did, the data for the test session were discarded. Since variation in the loudness of the stimulus can vary as a function of the loudspeaker position with respect to the listener's head, and since this might influence the listener's judgment of sound location even though it would not serve as an adequate cue, we manipulated the intensity level ±2 dB re 20 dB SL. Larger increases were not employed since we wanted to be sure that the stimulus remained below threshold for the blocked ear. The stimuli, noise bands 1.0 kHz in width, had a rise-fall time of 10 msec, a duration of 30 msec, and were presented approximately 3 times/sec. The train of bursts continued until a location judgment was reported.

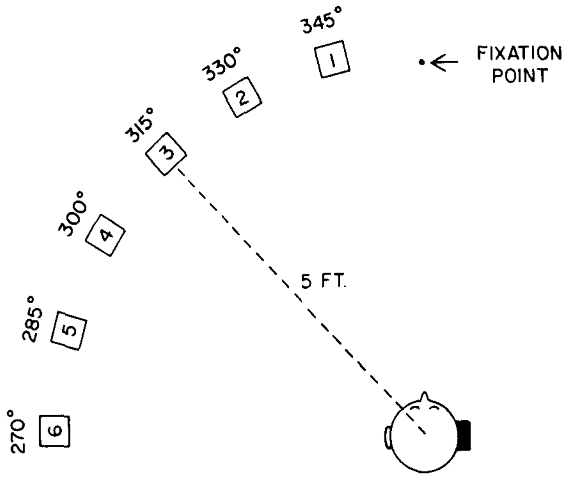

Figure 1. A diagrammatic sketch of the listening situation.

Center frequency (CF) was varied in .5-kHz steps from 4.0 to 14.0 kHz. These narrow bands of noise were generated by a ring modulator circuit in which the carrier (i.e., the CF) was modulated by a .5-kHz low-pass noise. Two filters, one Spencer-Kennedy Laboratories (Model 302) and one Krone-Hite (Model 320R), with rejection rates of 18 dB/octave and 24 dB/octave, respectively, were cascaded to filter the output of the noise generator, thereby providing a reasonably restricted band of noise. The spectra of the narrow noise bands were monitored by a Hewlett-Packard Spectrum Analyzer (Model 348A) and displayed on a Hewlett-Packard X-Y Recorder (Model 7035B). Since there was little acoustic energy in the 1-20-Hz band of the noise stimulus, a gap appeared at each side of the CF extending for 20 Hz; its depth was approximately 20 dB. With two exceptions, the subjects were given 189 localization trials extending over at least three test sessions. Preliminary observations indicated that the actual location of the sound source within the segment of the arc under investigation does not influence apparent location of the narrow bands of noise; hence, each stimulus condition was presented three times in a haphazard order from only three loudspeakers. They were positioned at 330, 300, and 270 deg azimuth. However, we requested that the listeners choose from among the six loudspeakers positioned at 345, 330, 315, 300, 285, and 270 deg azimuth. Other than the two experimenters who also participated as listeners, the subjects were not aware that just three loudspeakers were being activated.

Results

The frequency composition of the stimuli, not their actual azimuthal position, primarily determined

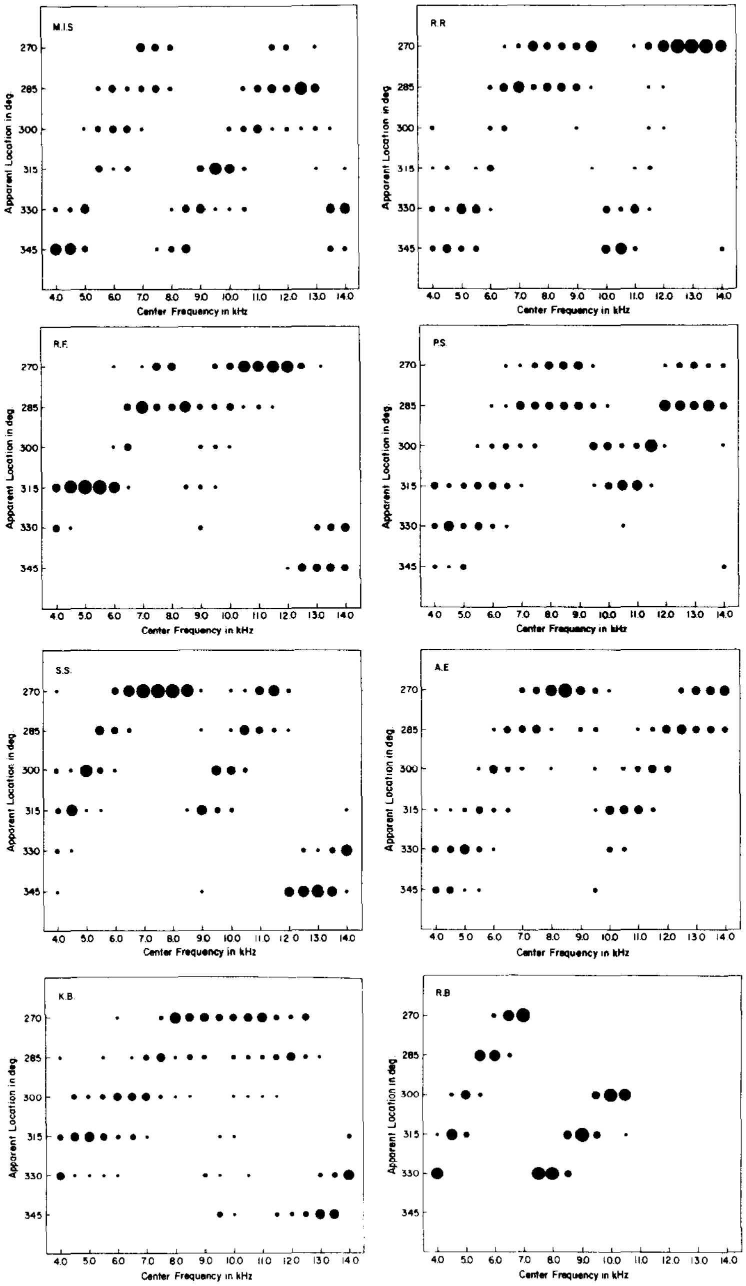

Figure 2. Apparent location as a function of the center frequency of a 1.0-kHz-wide noise burst. The area of the circles represents number of location judgments, with the largest circle in the figure indicating nine judgments and the smallest circle indicating one judgment. Subjects are identified by their initials.

perceived location. The pattern that emerged was as follows: A band of noise centered at 4.0 kHz was located in front (345 or 330 deg azimuth), and as the CF was increased to about 8.0 kHz, the apparent locations of the sounds moved progressively from in front to a position abreast the test ear (i.e., 270 deg azimuth). With continued increases in CF, the sounds appeared to shift back to the front and then move again toward the side with still further increases in CF. This pattern of spatial referents as a function of stimulus frequency composition is illustrated in Figure 2—a composite of the data from eight listeners. Although the details differ from one listener to the next, their general pattern of apparent location vs. frequency composition was comparable. At around 12.0 kHz, and above, the plots for listeners shown in the left column indicate that the apparent location of the noise bursts appeared again in the frontal segment of the horizontal plane. Perhaps this would have occurred for listeners whose data are represented in the right column had the CF been increased even further. So it appears, then, that two—and for some listeners, three—maps of spatial referents exist. We shall refer to these as Spatial Referent Maps (SRMs) 1, 2, and 3, with SRM 1 consisting of the spatial referents for the stimulus frequencies beginning around 4.0 kHz and extending to approximately 8.0 kHz, SRM 2 consisting of the spatial referents for the frequencies ranging from approximately 8.0 to 12.0 kHz, and SRM 3—a partial array of spatial referents—beginning with frequencies of about 13.0 kHz. We did not present noise bands whose CFs exceeded 14.0 kHz. Of the four subjects whose data are not represented in Figure 2, the plots for three resembled those already illustrated. The location judgments of the fourth seemed to be scattered indiscriminately as the CFs were increased from 4.0 to 14.0 kHz. Some listeners, notably K.B., R.R., and S.S., reported an inordinately large number of stimuli as emanating from 270 deg azimuth (see Figure 2). This clustering of location judgments may have reflected a defect in our experimental design. Specifically, sounds that seemed to originate from locations just beyond 270 deg (i.e., toward the rear) were reported as coming from the loudspeaker positioned at 270 deg, since this loudspeaker was nearest to the apparent location of the stimulus. Only after the study was underway did some listeners comment on an occasional "rearward" impression of the sound source.

EXPERIMENT 2

The role of spatial referents in monaural localization was the subject of the second experiment.

Once the general correspondence between apparent location and the frequency composition of 1.0-kHz-wide noise bands was established, we investigated the influence of SRMs on the monaural localization of wider bands of noise. We reasoned that a phenomenon as ubiquitous as that of spatial referents for stimulus frequencies must somehow enter into perceiving sounds at their actual rather than at their illusory locations. Otherwise, why should they exist?

Method

The same listeners participated. Their ability to locate, monaurally, noise bursts emanating from the loudspeakers positioned at 345, 330, 315, 300, 285, and 270 deg was tested. Again, an ear defender was inserted in the right external ear canal and the pinna was covered by a circumaural muff. With bandwidth (BW) set at 3.0 kHz, we systematically varied CF in steps of 1.0 kHz for each group of 60 trials. Individual loudspeakers were activated 10 times within a test run in an irregular, but planned, order. Listeners reported, via an intercom, the loudspeaker number (1 through 6) from which they judged the sounds to originate. If they showed no evidence that they could locate the sound sources regardless of the CFs employed, we increased the BW to 4.0 kHz. In cases in which we wished to investigate more closely the effect of BW at specific CFs, we varied the BW from 2.0 to 5.0 kHz in steps of 1.0 kHz. In short, we were searching for a relation between SRMs and localization proficiency. We assumed that if a noise band contained all the spatial referents within the arc covered by the array of loudspeakers, the listener would be able to locate the sound with reasonable accuracy. Throughout these series of tests, sensation level was 20 dB ± 2 dB re threshold for the stimuli originating from the loudspeaker positioned at 315 deg azimuth. Rise-fall time, duration, and repetition rate remained unchanged from those described in Experiment 1.[1]

We analyzed three aspects of performances: (1) number of correct responses; (2) error score, that is, the magnitude by which a listener was incorrect in his/her choice of loudspeakers (if the listener's choice of loudspeaker was once, twice, or thrice, etc., removed from the loudspeaker that generated the sound, the error score for that trial would be 1, 2, 3, etc., respectively); (3) distribution of loudspeaker choices. Since each loudspeaker was activated 10 times, a distribution significantly different from a rectangular distribution would suggest that the listener was biased in the choice of loudspeakers.

Results

The question was whether SRMs, which by themselves are nothing other than a pattern of auditory spatial illusions, have anything to do with locating accurately a sound in space. The answer is "yes, they do"—at least for the narrow bands of noise that we used. Armed with information about a listener's SRMs, one can select a CF for a restricted noise band that will enable the listener to locate this stimulus at maximal proficiency. For, what we observed repeatedly was this: A noise stimulus whose frequency composition connected one SRM with the next, that is, SRM 1 with SRM 2, or SRM 2 with SRM 3, could be located considerably more accurately than one whose frequency content fell within a single SRM. We calculated for each of 11 subjects—the SRMs of 8 being shown in Figure 2—the number of correct responses and error score for a stimulus whose frequency content (1) bridged adjacent SRMs and (2) fell within an SRM. (SRMs for the 12th subject of our group showed no recognizable pattern of apparent location as a function of CF; we could not distinguish noise bands whose frequency composition connected SRMs from those that were contained within a single SRM. Consequently, the data were not used.) BW was either 3.0 or 4.0 kHz, remaining constant for any one listener. Without exception, the number of correct localization responses was higher for the stimuli that bridged the SRMs than for those that did not; error score was less in 10 of the 11 cases. Also instructive is to observe how the error score increased and the number of correct responses decreased as the CF of a noise band was moved in steps of 1.0 kHz away from the frequency that best connects adjacent SRMs (see Table 1). Shown on the left side are mean error scores and mean correct responses per 60 trials when the CF was placed at the most abrupt transition between SRMs and when the CF was removed from this position by ±1.0 and ±2.0 kHz. Clearly, the mean error score was least when CF was fixed at the transition zone, and the reason for this is that subjects made more correct location judgments. The ANOVA results in the data, shown in the left side of Table 1,

Table 1
Mean Error Score (ES) and Mean Number of Correct Responses (CR) for Noise Bands Whose CFs Were Centered at the Transition Between Adjacent SRMs (Left Side) and Whose CFs Were Centered at a Representative Midfrequency of All CFs Presented in the Study (Right Side)

Transition Zone Data			Midfrequency Data		
CF	ES	CR	CF	ES	CR
−2.0	103.5	13.0	−2.0	104.0	15.5
−1.0	109.6	13.7	−1.0	99.5	14.2
.0	59.4	23.2	.0	82.4	13.7
+1.0	91.1	12.1	+1.0	84.1	15.1
+2.0	99.6	12.3	+2.0	107.2	12.1

Note–An ES of approximately 117 and a CR of 10 would be expected by chance. CF is given in kilohertz.

indicated that differences among the CFs with respect to both error score and number of correct responses were significantly beyond the .01 level of confidence. A post hoc analysis (Scheffé Procedure) implied that the error score and number of correct responses for the CF fixed at the transition zone were significantly different from those calculated for all other conditions ($p < .05$). None of the other conditions differed significantly from one another ($p > .05$). Since subjects differ among themselves with respect to the CF at which the transition between SRMs occurs, there is no fixed CF at which all subjects would best locate the narrow noise band. Note what happens when the analysis just described was carried out among a range of CFs that covered most of those employed in this study (see Table 1, right side). For some subjects, the mid-frequency of this range was represented by a 9.0-kHz CF; for others, it was represented by a 9.5-kHz CF. Whether the CF was a whole number or a fraction depended on which one best fitted the transition between adjacent SRMs for any given listener, since this was the primary aim of our search. The results for the data on the right side of the figure were negative for both error score and number of correct responses ($p > .05$). Admittedly, the error score decreased when CF was set at the mid-frequency re CFs 1.0 and 2.0 kHz above and below this value. There was, however, no concomitant increase in correct responses. Inspection of the data revealed the reason for the decrease in error score for the mid-frequency point—viz., subjects exhibited a strong tendency to choose those loudspeakers near the center of the array as the sound source, thereby reducing the opportunity to make a large error score on any one trial. Distribution of loudspeaker choices differed significantly from a rectangular distribution ($p < .05$), thus reflecting this judgmental bias.

To more richly convey how a listener utilized the available spectral information given his or her particular configuration of SRMs, we will present individual data. For each set selected for exposition, we will present a plot of the apparent location of a 3.0- or 4.0-kHz-wide noise band against its actual location, and display a graph of the relative strength of the various spatial referents for 1.0-kHz-wide noise bands that were contained within the broader band. To find out whether this constellation of spatial referents influenced the location judgments, we will include a graph of the relative distribution of loudspeaker choices for the broader noise band. These data will be shown for noise bands whose frequency composition connected adjacent SRMs and for noise bands whose frequency composition was contained within an SRM. Consider, first, the data of M.I.S. (Figure 3). Localization performance for the noise band whose spectrum lay within SRM 1 is shown on the left side of the figure. The right side shows localization data for a noise band whose spectrum connected SRM 1 with SRM 2. The numbers 1 through 6 represent loudspeakers that were positioned every 15 deg from 345 to 270 deg azimuth, respectively. His SRMs are shown in Figure 2, and upon examination one can

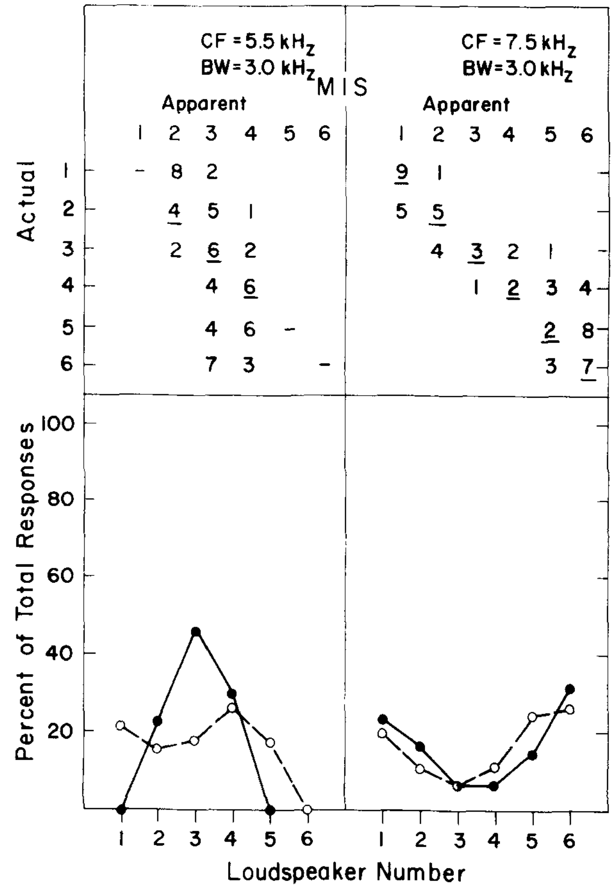

Figure 3. Upper half: A plot of the apparent vs. the actual location of a 3.0-kHz-wide noise band for M.I.S. at two different CFs—5.5 and 7.5 kHz. Numbers represent frequency of loudspeaker choices. Lower half: Solid lines represent frequency distribution of loudspeaker choices; dashed lines represent relative strength of spatial referents (see text).

see that the spectrum of a 3.0-kHz-wide noise band centered at 5.5 kHz lies within SRM 1. By increasing the CF to 7.5 kHz, the spectrum of a 3.0-kHz-wide noise band extends from the upper frequency region of SRM 1 to the lower frequency region of SRM 2. When using these two stimuli, we can compare localization performance for a sound whose frequency content is confined to a single SRM with that of a sound whose frequency content bridges adjacent SRMs. Figure 3, upper half, plots apparent vs. actual location for the 3.0-kHz BW centered at 5.5 and 7.5 kHz. With the CF fixed at 5.5 kHz, M.I.S. perceived all sounds as originating within a restricted region of the arc, 300 to 330 deg azimuth. In all, he made 16 correct location judgments; error score was 68. With the CF set at 7.5 kHz, his location judgments were distributed over the 75-deg arc extending from 270 to 345 deg azimuth; his location judgments were correct on 28 of 60 trials; his error score was 37. Clearly, the performance for the 7.5-kHz centered stimulus was superior to that observed for the 5.5-kHz centered stimulus. The solid lines at the lower part of Figure 3 simply show the relative distribution of loudspeaker choices over the 60-trial test. These data are taken directly from the plots shown in the upper part of the figure. The dashed lines represent what we suggest to be the relative strength of those spatial referents contained within the 3.0-kHz-wide noise bands. Again, we went to the data upon which Figure 2 is based. Our procedure for arriving at a value for relative strengths is illustrated by the following example: The 3.0-kHz-wide noise band centered at 7.5 kHz contained those 1.0-kHz-wide noise bands centered at 6.5, 7.0, 7.5, 8.0, and 8.5 kHz—all narrow band stimuli whose apparent locations were recorded in Experiment 1. Forty-five location judgments were made, nine for each of the five CFs. We summed the number of times the loudspeaker at each azimuthal position was selected as the source of the sound. The relative strength of a spatial referent, say, 285 deg, was defined as the percent of total number of location judgments that the loudspeaker positioned at 285 deg was chosen as the sound source. When the noise band was centered at 5.5 kHz, the spatial referents of 345, 330, 315, 300, and 285 deg azimuth were presumably present (see dashed curve, left side of figure). M.I.S.'s location judgments, however, were clustered around 315 deg. No sounds appeared to originate from 345 and 285 deg, even though the stimulus contained frequency regions which, if presented alone, possessed these referents. The correspondence between the dashed and solid line curves was much closer when the CF was 7.5 kHz. (Recall, also, that the localization performance was more precise.) Note, in particular, that those stimuli emanating from Loudspeakers 1 and 2 were never perceived as coming from Loudspeakers 5 and 6, and vice versa. Note also that the spatial referents corresponding to the extreme positions of the loudspeakers (345 and 285 deg azimuth) were well represented. In summary, M.I.S. performed best when the sound's spectrum connected SRM 1 with SRM 2; the distribution of loudspeaker choices for this sound followed closely the distribution of relative strengths of the spatial referents presumably contained within the stimulus.

K.B.'s data, shown in Figure 4, illustrate the importance of a clear-cut transition between SRMs insofar as employing this region of the spectrum for the localization task. Again, referring to Figure 2, the transition between SRM 1 and SRM 2 occurred at about 9.5 kHz; that between SRM 2 and SRM 3 occurred at 12.5 kHz. The former was indistinct; the latter was abrupt. In K.B.'s case, we scanned the frequency spectrum with a 4.0-kHz-wide noise band; we considered 6.5 kHz as the most appropriate CF for the stimulus falling within a SRM—the basis for our decision is open to inspection (see K.B.'s SRMs in Figure 2). As the data on the left side of Figure 4 illustrate, K.B. could not locate sounds whose frequency components fell within SRM 1. She made only 10 correct responses in 60 trials and her error score was 109. She also performed poorly when the stimulus composition encompassed the blurred transition between SRM 1 and SRM 2 (see middle section of Figure 4). Number of correct responses was 8; error score was 95. When the CF was set at 12.5 kHz, the frequency composition of the sound bridged the sharp transition between SRM 2 and SRM 3. For this sound, K.B. located 33 of the 60 presentations correctly, and her error score was only 32. The spatial referents within the 12.5-kHz centered noise band that corresponded to the extreme positions of the arc (345 and 270 deg) enjoyed greater representations than those that corresponded to the middle positions (315 and 300 deg). A final point, and one that we consider fundamental, is: The distribution of loudspeaker choices for this 4.0-kHz noise band closely paralleled the distribution of relative strength of spatial referents contained within this noise band (see curves in lower right column of figure).

It was not that subjects were completely unable to locate sounds whose frequency composition was confined to a single SRM; rather, their performances, in nearly all instances, were much less proficient than when the stimulus frequency composition served to connect one SRM with the next. Consider, as an example, the performances of P.S. (Figures 5 and 6), whose SRMs are shown in Figure 2. With the noise band centered at 6.5 kHz—a CF that placed restricted BWs within SRM 1—localization accuracy, as assessed in terms of number of correct responses, increased from 7 to 12 to 13 to 22 as the BW was increased from 2.0 to 5.0 kHz in steps of 1.0 kHz. Error score decreased from 88 to 84 to 61 to 45 for the same BWs.

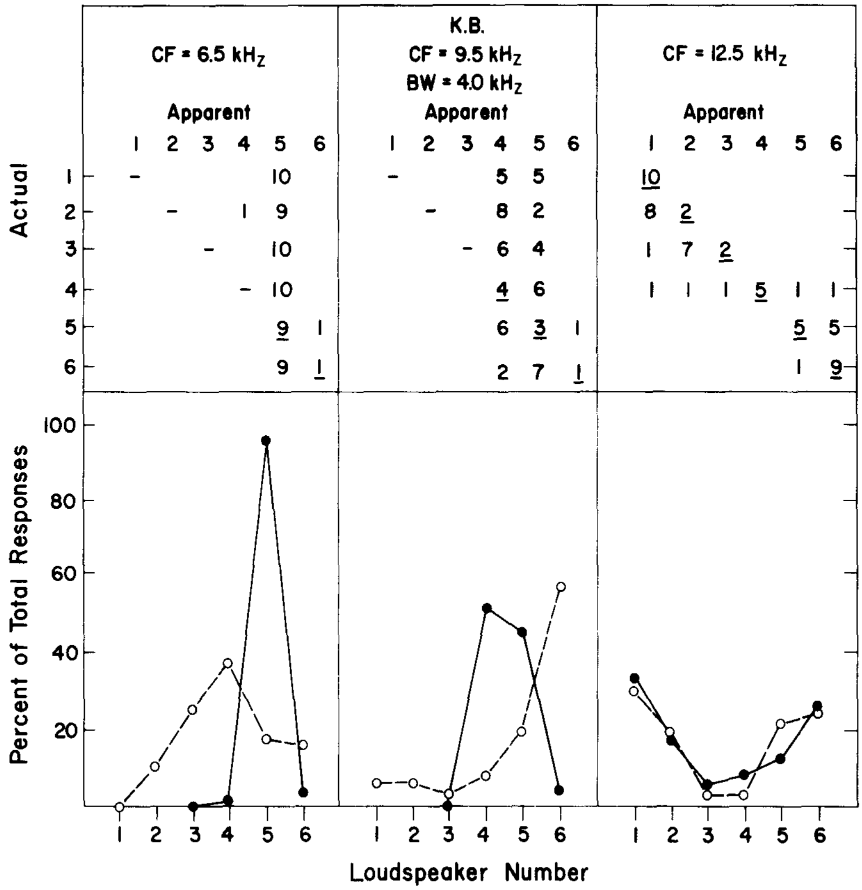

Figure 4. Localization data for K.B. with CFs at 6.5, 9.5, and 12.5 kHz: BW is 4.0 kHz. See Figure 3 for further description.

We also have data on P.S. for a 3.0-kHz BW centered at 9.5 kHz—a stimulus whose frequency content connected SRM 1 with SRM 2. On this test, P.S. made 26 correct responses out of 60 presentations; an error score of 50 was recorded. Data of other listeners in this study were consistent with the trend that we have emphasized: Sounds are located more proficiently when their spectra connect SRMs rather than when they lie within them.

DISCUSSION

When binaural differences in stimulus arrival time and intensity are abolished, as they were in this study, phenomena emerge that may bear directly on the question of how we locate sounds monaurally. These phenomena are: (1) Stimulus frequencies have spatial referents, and (2) localization proficiency depends closely on the frequency composition of the noise bands. With respect to the first, noise bands, 1.0 kHz in width, appear to move from in front toward the side of the functioning ear when the CF is increased above 4.0 kHz, only to return to the front and begin the sideward migration again at CFs around 8.0 or 9.0 kHz. Granted, the location judgments by most subjects showed considerable variability, yet apparent location as a function of CF followed the same general pattern for all but one listener. We could have converted our listeners into experienced ones by providing a series of practice sessions. As it was, R.B. (lower right of Figure 2) was the only experienced listener; his data are clearly more orderly than the others. But our main concern, to be discussed later, was finding out how these spatial referent patterns of stimulus frequency were related to proficient monaural localization.

These patterns of location judgments illustrated in Figure 2 most likely arise from the filtering characteristics of the pinna. And within this context, the data of Mehrgardt and Mellert (1977) are of special relevance. They plotted the transfer functions from free field to the ear canal entrance along the azimuth continuum for a wide range of frequencies. The data reflected the mean values for 20 subjects. By shifting the curves along the abscissa (log frequency) to achieve a greater overlap, they were able to retain much of the fine structure that would otherwise have been washed out. When viewing their family of curves for frequencies ranging from 4.0 to 9.0 kHz (their Figure 18), one observes that the peak amplitude

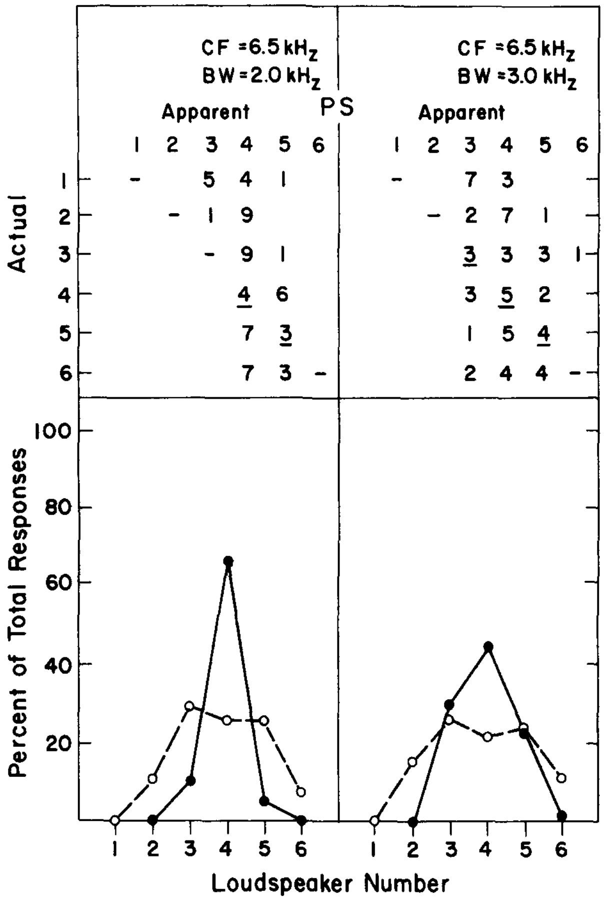

Figure 5. Localization data for P.S. with BWs at 2.0 and 3.0 kHz; CF is 6.5 kHz. See Figure 3 for further description.

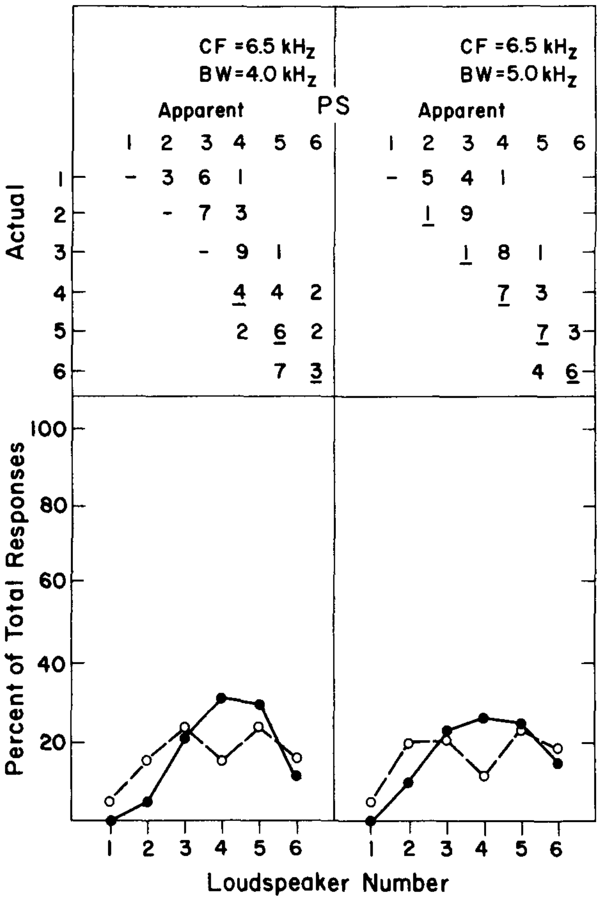

Figure 6. Localization data for P.S. with BWs at 4.0 and 5.0 kHz; CF is 6.5 kHz. See Figure 3 for further description.

measured at the near ear moves progressively from about 40 to 100 deg from midline. This parallels our SRM 1. Their measurements at higher audio frequencies roughly correspond to our SRM 2; specifically, the peak amplitudes appeared at 60 and at 90 deg, respectively, for the 10.0- and 12.0-kHz curves. But, when the frequency was increased to 14.0-kHz, the amplitude peaked at 15 deg off midline. This would parallel the beginning of our SRM 3. Shaw's (1974) data on transfer function from free field to ear canal when the angle of incidence was changed (frequency served as the parameter) compares somewhat less well with our performance data. But, again, he averaged over several studies from various laboratories in order to show the main features of the transfer function when different frequencies originated at various angles of incidences. In the Mehrgardt and Mellert study, which also contains data on transfer function when the stimuli of different frequencies emanated from the median sagittal plane, they pointed out that the peak amplitude recorded for specific angles of elevation corresponded to apparent location of differently centered one-third octave noise bands as reported by Blauert (1969/1970). In fact, they considered their data as "objective verification" of Blauert's psychophysical findings. Should they be correct, the azimuthal distribution of peak amplitudes over the range of frequencies we employed for monaural localization in the horizontal plane may well represent the physical correlates of the SRMs exhibited by our listeners.

How do the SRMs enter into the task of locating a horizontally positioned sound correctly when listening with only one ear? At first glance, they seem to be maladaptive—apparent location and actual location of stimuli are largely independent of one another. But, as we manipulated CF over a wide range, we observed time and again that when the frequency composition of the stimulus connected adjacent SRMs, localization performance improved, often dramatically. What was also necessary for proficient performance was that the transition between SRMs be abrupt—a point illustrated in Figure 4.

How do these data fit with the proposed rule of Belendiuk and Butler (1977)? As stated in the introduction, they contended that two narrow bands of noise simultaneously presented can be located if the apparent location of one band, when presented alone, differs appreciably from the apparent location of the other. Should the two noise bands appear to come from the same location when presented singly, the sound resulting from a mixture of the two will also appear from the same place. This rule is not violated by our results if one is willing to consider a band of noise, say, 3.0 or 4.0 kHz wide, as consisting of two noise bands, one-half the width, with contiguous frequency compositions. For example, suppose the band of noise covered a frequency range that fell within a SRM. The CFs of each half-bandwidth, close to one another along the frequency continuum, would possess spatial referents that would also be near one another. The combined sound would be located poorly. On the other hand, with a noise band whose frequency composition linked adjacent SRMs, the CFs of each half-bandwidth would possess spatial referents that would be widely separated from one another. We suggest that the latter accounts for the superior performances of the listeners. More specifically, we speculate that the relative strengths of the spatial referents *govern* the location judgments, but the listener must be able to discriminate among the contending referents. This discrimination is facilitated when adjacent frequency regions have widely different spatial referents; it is impaired when adjacent frequency regions have adjacent spatial referents. Also to be noted is that when the stimulus is "map connecting," it is the azimuthal borders of a listener's spatial framework that are established; the space is perceptually anchored at two points. With increasing BW, the center is filled in. When the sound's spectrum falls within a SRM, location judgment approaches a mean value of the various spatial referents and the listener's choice of loudspeakers represents a compromise among those referents contained in the sound. Data from Figures 3 through 6 are consistent with this suggestion.

One final comment: Dependency on monaural cues to localize sounds in space is not restricted to those thousands of unilaterally deafened persons. Persons with normal hearing rely on monaural localization for the initial orientation to sounds that are subthreshold for the "far" ear. And, in the case of high-frequency transients, those occasions are ubiquitous. The data of our study suggest that spectral information essential for proficient monaural localization is encoded in relatively narrow bands within the high-frequency region. The specific characteristics of these bands presumably depend upon the configuration of the individual pinna.

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NOTE

1. Experimenter feedback following each localization judgment was not provided. While feedback probably could have improved performance, it is unclear whether this improvement would have reflected increased localization accuracy or increased ability to differentiate among different spectra without regard to their locations.

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