Auditory spatial orientation¹

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An experiment is reported on the effect of six consecutive days of exposure to distortions of binaural time and intensity cues on the localization function for tones of 350, 1000, and 4000 Hz. Tests were conducted under "free-field" conditions. The changes in auditory spatial orientation indicate that adjustments to binaurally distorted temporal and intensive cues can occur. Reorientation does not appear to depend upon the existence of veridical auditory cues.

It is frequently observed, in studies of visual spatial orientation, that under conditions of distorted visual cues (inverted lenses, prisms, etc.) an individual can regain orientation with experience (Stratton, 1897). These observations have provided strong support for the view that perceptual processes associated with spatial orientation are highly adaptive and readily molded by experience. The evidence for parallel effects in auditory spatial orientation does not fulfill this expectancy. For example, the acoustical transposition of the ears with pseudophones, produces a complete reversal of the apparent sound field, yet extensive exposure to the reversed field fails to result in a dramatic reorientation to the reversed sound field (Young, 1928; Willey, Inglis, & Pierce, 1937). The pseudophone experiments, in which distortion of the field was radical (180-deg shift), indicated a dissociation of visual and auditory localization functions. After prolonged exposure to this condition the listener is no longer aware of discrepancies between visual and auditory localization cues. This is often reported as a reorientation of the auditory field. However, in situations in which only auditory cues are relevant, the apparent reorientation is lost. The failure to observe reorientation of the auditory field may, however, be a function of the radical shift produced by the pseudophones. Held (1955) demonstrated adaptation to moderate changes in auditory input produced by pseudophones. Adaptation occurred to a 22-deg translation of the auditory field. Although shifts in localization occurred to a 45-deg rotational displacement of the auditory field, the shifts were more erratic. Held interpreted the latter effect as a difficulty in the listener's ability to make compromise judgments. This consideration might explain the failure to observe adaptation to radical (180-deg) displacement by pseudophones.

Pierce (1901) noted that unilateral attenuation produced by plugging one ear results in a tendency to shift all sounds toward the open ear. This apparent shift in the auditory field has been repeatedly observed in listeners with both artificially produced and inherent interaural differences in sensitivity (Bauer, Maturza, & Blackmer, 1966; Butler & Naunton, 1967). As one would expect from the pseudophone experiments, the distortion of the sound field is most evident when the sound source is concealed (i.e., no visual cues). One would expect that a person suffering from a unilateral hearing loss would learn to compensate for the interaural sensitivity difference. The observations on this point are mixed. Some individuals with unilateral loss show considerable improvement over time but a complete return is rare.

Attempts to study the reorganization of auditory spatial "habits" have been most successful with normal-hearing listeners who have been provided with an artificial hearing loss. Bauer et al (1966) reported that a listener can reorient to the distorted localization cues spontaneously in about three days

(that is, without specific training). If the listener is provided with training, reorientation occurs in less than half a day. If, in fact, the listener has undergone a reorganization of auditory localization habits, the sudden removal of the plug should produce a temporary localization shift in the opposite direction. Although Bauer's results demonstrated postshifts that were modest or negligible and not consistently different from pretest performance, they were in the above-indicated direction.

The present study is an attempt to study the recovery of localization function following an extended exposure to a monaural hearing loss in an environment in which the available temporal and/or intensive cues are limited or distorted.

METHOD

Subjects

Six Ss with normal hearing and an ability to localize an auditory image in a free field were employed in the study.

Procedure

Initially, three daily sessions under normal listening conditions, were run to establish baseline data for later comparisons. Absolute thresholds for signals of 350, 1000, and 4000 Hz were determined for each ear. The testing was performed in a soundproof room (IAC, Model 1201A) using an audio oscillator (Hewlett-Packard, Model 241A) and earphones (TDH-49). Localization tests were also conducted during these baseline sessions. The S was seated in the center of an anechoic room facing a semicircle of lights arranged on a radius of 4 ft from the center of the room. The lights were spaced to enable a measurement every 2 deg of angle along the arc. The light array extended 100 deg on each side of the S's median plane. The S manipulated a knob which allowed him to turn on any light in the array. Four-inch speakers (Quam, Model 4A05) were hidden behind a black cloth screen, one directly in front of S, one 45 deg to the right, and one 45 deg to the left of this position. The S was never informed as to the actual locus or number of speakers. The room was darkened during test sessions and the only visual object in the room was the particular indicator lamp turned on by S. An analog array in the control room was used to monitor the position indicated by S.

The localization test sequence was as follows: Either a 350-, 1000-, or a 4000-Hz signal was presented from one of the three speakers. The signal was sounded for a period of 15 sec, during which S was instructed to turn on the various lights in the array until he felt that the light which was illuminated corresponded to his perception of the source of the sound. Each presentation was made with a fast rise-decay signal at a level of 60 dB SPL, minimum audible field. During each localization session, four presentations of each speaker and frequency combination were made in random order. Each session lasted approximately 15 min.

Throughout the localization test, S's head was held in place by a headrest. The S was instructed not to move during the test trials. No feedback was given with regard to performance during or after the sessions throughout the duration of the study.

Following the three baseline sessions, a plug was inserted in the right ear of three Ss and in the left ear of the remaining three. The plug was constructed by placing a small wad of

Fig. 1. Mean indicated position of sound sources at 45 deg right, mid-line, and 45 deg left for 350 Hz signal. Each point represents algebraic mean of responses from three Ss. (Left Ear Plug Condition.)

cotton in the ear canal, then a gram of plastic clay was inserted and molded to the shape of the external meatus. The specific effects of the plug were as follows: (1) The range of attenuation for the 350-Hz signal was 0-3 dB, for the 1000-Hz signal, 10-15 dB, and for the 4000-Hz signal, 20-30 dB. (2) Binaural presentation of 4000-Hz signal by earphones produced a centered image when the signal was presented simultaneously at each ear matched for SL. A 350-Hz signal, similarly presented, produced a lateralized image and a 105- μ sec delay at the open ear was required to center the image. A 1000-Hz signal also produced a lateralized image and a 90- μ sec delay was required at the open ear to center the

Fig. 2. Mean indicated position of sound sources at 45 deg right, mid-line, and 45 deg left for 1000 Hz signal. Each point represents algebraic mean of responses from three Ss. (Left Ear Plug Condition.)

image. The phase shift values were calibrated on two of the experimental Ss and should be considered only as gross estimates of the phase shift produced by the plug.

From the above it can be seen that the plug produced distortion of auditory input specific to the frequency of the signal. The 350-Hz signal was distorted along the temporal dimension (phase) but little distortion was present on the intensity dimension. The 1000-Hz signal was distorted on both the temporal and intensive dimensions. The 4000-Hz signal was distorted on the intensive dimension and free of measurable distortion on the temporal dimension.

Absolute threshold determinations and localization tests

Fig. 3. Mean indicated position of sound sources at 45 deg right, mid-line, and 45 deg left for 4000 Hz signal. Each point represents algebraic mean of responses from three Ss. (Left Ear Plug Condition.)

Fig. 4. Mean indicated position of sound sources 45 deg right, mid-line, and 45 deg left for 350 Hz signal. Each point represents algebraic mean of responses from three Ss. (Right Ear Plug Condition.)

Fig. 5. Mean indicated position of sound sources 45 deg right, midline, and 45 deg left for 1000 Hz signal. Each point represents algebraic mean of responses from three Ss. (Right Ear Plug Condition.)

were made immediately after insertion of the plug. Both tests were made daily on each of the next six days during which the plug was worn continuously. Immediately after the plug was removed and on the following two days, the tests were again run.

RESULTS

Results of the localization tests for Ss with the plug in the left ear for signals of 350, 1000, and 400 Hz appear graphically in Figs. 1, 2, and 3, respectively. Similar graphic representation for localization tests on Ss with plug in the right ear appear in Figs. 4, 5, and 6. (A between-within analysis of variance of the preplug data demonstrated no significant difference between the right-ear plug and the left-ear plug localization judgments.) It is readily apparent that the insertion of the plug produces an immediate shift in the apparent location of the sound source toward the open ear. Maximum shifts of the apparent source are observed for the 4000-Hz signal. Localization of the 350- and 1000-Hz signals seems to be affected similarly, but less extensive shift is noted. Maximum initial shifts are generally observed on localization of a source on the plugged ear side, slightly less for a source directly in front of the listener, and least for a source located on the open ear side. For the 4000-Hz signal on the plugged ear side, the apparent locus of the source is shifted to such an extent that it is initially located on the opposite side of the midline. This consistent lateral reversal is rarely observed under normal listening conditions. The results of an analysis of variance on the data obtained during the seven days of continuous exposure to distorted auditory input, show the following effects to be significant: (1) stimulus frequency, (2) hours of exposure to the distortion, (3) frequency by hours of exposure interaction, (4) speaker locus, (5) frequency by locus, and (6) frequency by hours of exposure by locus. A trend analysis of the hours of exposure effect demonstrated a reliable overall linear trend.

Although all localization functions showed a return toward baseline values, only in the case of the 4000-Hz signal was a systematic shift noted as a function of source locus. For this signal, the mean apparent return, for locus on the plugged ear

side, was 34.5 deg, for locus in front of S the shift was 25 deg, and for locus at the open ear side the shift was only 9.5 deg. These changes in locus were positively correlated with size of the initial shift. For the other frequencies, although initial shifts were greatest on the plugged side, the amount of recovery was not related to size of the initial shifts.

On the last day of exposure to the monaural plug, indicated positions of the sound sources were still significantly different from baseline values. After 144 h, the amount of recovery from the initial shifts ranged from 30% to 70%.

The postexposure data shows that a considerable shift, toward the previously plugged ear side, occurs immediately after removal of the plug. All localization shifts are significantly different from baseline performance and in the direction opposite that observed immediately after insertion of the plug. Forty-six of the 54 localization estimates exhibited this reverse shift. Twenty-four hours after removal of the plug, no significant difference from baseline performance was noted for the 4000-Hz signal. Forty-eight hours after removal of the plug only the 350-Hz signal showed significant deviation from baseline values.

An analysis of variance on the postexposure data indicates that only the hours of exposure, and the frequency by hours of exposure by locus effects are significant. The significant interaction effect is evident in the differences in postexposure shift between the high (4000-Hz) and the low (350-, 1000-Hz) frequencies. For the high frequency large initial mean shifts from baseline are observed on the open ear side (24 deg), less for the source in front of S (12 deg), and least for the source on the previously plugged ear side (3 deg). Postexposure shifts for the low frequencies are smaller but tend to last longer, as indicated above.

The absolute threshold data for the 4000-Hz signal at both the plugged and unplugged ear appears in Fig. 7. Over the period of exposure there was a decrease in the interaural difference in sensitivity. The initial mean interaural intensity difference of 33 dB had decreased to 25 dB by the end of the exposure period. Immediately after removal of the plug, thresholds returned to baseline values. Absolute thresholds for

Fig. 6. Mean indicated position of sound sources 45 deg right, midline, and 45 deg left for 4000 Hz signal. Each point represents algebraic mean of responses from three Ss. (Right Ear Plug Condition.)

Fig. 7. Mean absolute threshold for a 4000 Hz signal.

the 350- and 1000-Hz signals showed no regular deviation from baseline values.

DISCUSSION

The results of the present study indicate that listeners can adapt to distortion of binaural input. The gradual return of localization toward baseline performance (even though incomplete), and more strikingly, the postexposure shift, demonstrate this effect. Reorientation does not appear to be dependent upon the existence of a "correct" auditory cue since the reorientation of the localization function occurred in the presence of distorted temporal and intensive cues in the case of the 1000-Hz signal. The shifts in localization function exhibited to continuous pure tones in the present study are similar to those reported by Bauer et al (1966) and by Held (1955) for continuous and interrupted noise signals and for filtered clicks.

While there was a considerable distortion of the intensive cue for the 1000-Hz signal, the changes in the localization function for this signal parallel those observed with the 350-Hz signal which was little attenuated by the plug. From what is known of the physical limitations imposed upon the utilization of interaural intensive cues in the "free field" situation (limited head shadow effects), it seems likely that interaural intensity cues are of limited relevance to the localization of pure tones below 3000 Hz (Mills, 1960). The failure to observe differences between the 1000-Hz and 350-Hz signals seems reasonable in view of these physical limitations.

The more dramatic shifts in localization on the plugged side than on the unplugged side may be explained in that localization depends upon monaural and binaural intensity cues and dichotic time cues. The prolonged exposure to imbalances simply involves a re-weighting of the effectiveness of the above cues.

The observation of the tendency to return to a more veridical localization function following prolonged exposure to the plug and the postexposure shift of the function, implies some underlying process. One could speculate that S simply learns to compensate for the distortions of the interaural cues. S, in fact, received considerable feedback, during the 144 h the plug was in the ear, in situations outside of the laboratory. For the 4000-Hz signal there are difficulties with the compensation notion. Assuming that the return in the localization function was the result of this process, while the return was extensive for the source on the opposite side of the midline, the

postexposure shift shows just the opposite relationship. The results could be appreciated as a function of at least two processes. The first is the compensation or re-weighting of the binaural cues. This could account for the relatively slower and yet longer-lasting effects noted with the 350- and 1000-Hz signals. A second process, an adaptation-to-level effect, in the auditory system, is typically described as "auditory fatigue," which in turn is defined as the effects of prolonged or intense stimulation on absolute threshold and loudness (Békésy, 1960). It is reasonable to expect that prolonged exposure to reduced input could also produce adaptation effects but in the opposite direction. Adaptation effects or auditory fatigue have been observed in a localization situation without parallel changes in absolute threshold (Elfner & Perrott, 1967). Such a sensitization of the plugged ear or at least a readjustment of normal interaural level differences could account for the postexposure shifts which appear to be just the opposite of the return shifts. Because of the situational limitations upon the utilization of intensity cues and the attenuation characteristics of the plug, the adaptation level hypothesis is limited to the 4000-Hz signal. Given sufficient stimulation of both ears (i.e., above absolute threshold) interaural level differences appear to be of limited significance to the low-frequency signals.

An explanation of the low-frequency adaptation effect is provided by Held (1955). That is, a directional localization is an equivalent response for a translational displacement of the head in the same direction. "Continued recurrence of the combination of a certain direction of head translation with a given time-difference will eventually result in the recapitulation of that translational displacement when S is asked to localize a sound source producing the given time-difference at his ears." The presence of preexposure directional responses (normal localizations) complicates the situation. In most cases S compromises the directions of response as evidenced by small shifts of localization. Held also states that prolonged exposure to atypical stimulation finally builds the strength of the new response (compromise response) to the point that a double localization is obtained. The failure to find double localizations in the present study may have been due to the relative paucity of temporal cue in the tonal stimuli employed during localization testing.

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NOTES

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