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The psychophysical basis of monaural localization

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Listeners were required to locate, monaurally, noise bursts emanating from the horizontal plane ipsilateral to the functioning ear. Loudspeakers were positioned from 0 through 180° azimuth, separated by 15°. Stimulus bandwidth was 1.0 kHz, and centered at 4.0–14.0 kHz in steps of 0.5 kHz. The location judgments were governed by the frequency composition of the stimuli, not by their place of origin. With a miniature microphone positioned at the entrance of the external ear canal, the relative amplification provided by the pinna was obtained for the stimuli employed in the localization tests. For each differently centered noise burst, that loudspeaker position re other positions which was associated with the greatest amplification of the stimulus was the one most likely to have been chosen as the source of that stimulus during the localization tests.

monaural localization, pinna

Introduction

In the absence of interaural differences in time and intensity, listeners can locate a sound proficiently provided its spectrum contains the higher audio frequencies [1]. The pinna, due to its directionally-dependent filtering properties, has been singled out as a critical component in generating spectral cues utilized for these location judgments. Fill it with plasticine, save for an opening to the external auditory canal, and binaural localization of broadband noise in the median sagittal plane (MSP) is severely impaired [6]; monaural localization in the horizontal plane (HP) deteriorates [8]. Nor can narrow bands of noise be located proficiently. What happens is that the apparent location of the stimulus is governed by its frequency composition, not its actual location [2,3,7]. In short, an auditory spatial illusion is created. An interesting question is how this frequency-dependent location judgment relates to location judgments of broadband noise. Blauert [2] in dealing with this question, introduced the concept of directional bands. His research centered on MSP localization and he proposed that if after the pinna filters a sound from a given direction "... the most powerful components of the signal are in those frequency bands that have been boosted, the sound sensation will be formed in a direction that coincides with the direction of sound incidence" (p. 213).

Flannery and Butler [5] investigated the role of the pinna in locating sounds emanating in the HP. Location judgments of narrow noise bands differing in center frequency (CF) were obtained during one session; relative pinna amplification of these same noise bands was obtained during another. There seemed to be a fundamental connection between location judgments and pinna amplification. Unfortunately, the equipment was inadequate for extending the pinna measurements above 9.5 kHz. We know, however, that frequencies higher than this can contribute toward accurate monaural localization [1,3]. With the aid of upgraded equipment and an expanded horizontal arc we were able, in the present study, to (1) incorporate these higher frequencies and (2) extend our measurements to cover a complete hemifield (0–180°) thereby providing a more complete account of the relation between location judgments and pinna amplification.

1. Monaural localization of narrow bands of noise in the HP

Methods

Eight subjects, including the two experimenters, participated. None had a history of otologic problems. Audiometric testing indicated all were within 15 dB of audiometric zero from 0.25 to 8 kHz (ANSI, 1969). In accordance with the experimental design, the right ear was blocked. We inserted an ear plug into the external canal, then covered the ear with a muff. Testing was conducted in a sound-treated room, $4.8 \times 4.1 \times 2.4$ m whose reverberation time was approximately 75 ms. The listeners' task was to report the location of noise bursts originating from one of 13 loudspeakers. The loudspeakers, separated by 15°, were arranged in a semicircle whose radius was 1.5 m. They extended from 0° through 270° to 180° azimuth, being on the side of the subjects' unoccluded, left, ear. Listeners were supplied with a diagram of the loudspeaker arrangement (see Fig. 1). They were asked to hold their head steady and focus their eyes on the loudspeaker positioned at 0°. To promote compliance with our instructions, their chair was equipped with an adjustable headrest.

The stimuli, 1.0 kHz wide noise bands differing in CF, were generated by modulating a 0.5 kHz low-pass noise with a pure tone carrier which defined CF of the band. The low-pass noise was obtained by taking a broadband noise signal generated by a Grason-Stadler noise generator (Model 1285) and filtering it with two cascaded Krohn-Hite filters (Model 3202R). This produced a low-pass noise, symmetrical on each side of the CF, with a slope of 10 dB per 80 Hz. A detailed description of the stimulus generation was published by Ruggero [10]. Repeated trains of 15 noise bursts were presented with a 1 s intertrain interval. Individual bursts were 30 ms in duration with a 10 ms rise–decay time. Interburst interval was 300 ms. CF varied from 4.0 through 14.0 kHz in steps of 0.5 kHz. Subjects could listen to as many stimulus trains as they chose before reporting, via an intercom, the location of the sound source. Unbeknown to those other than the experimenters,

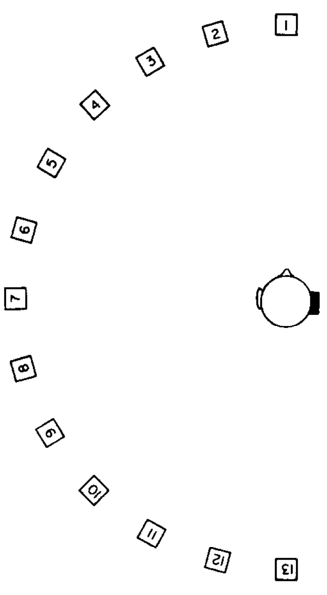

Fig. 1. A diagrammatic sketch of the loudspeaker arrangement.

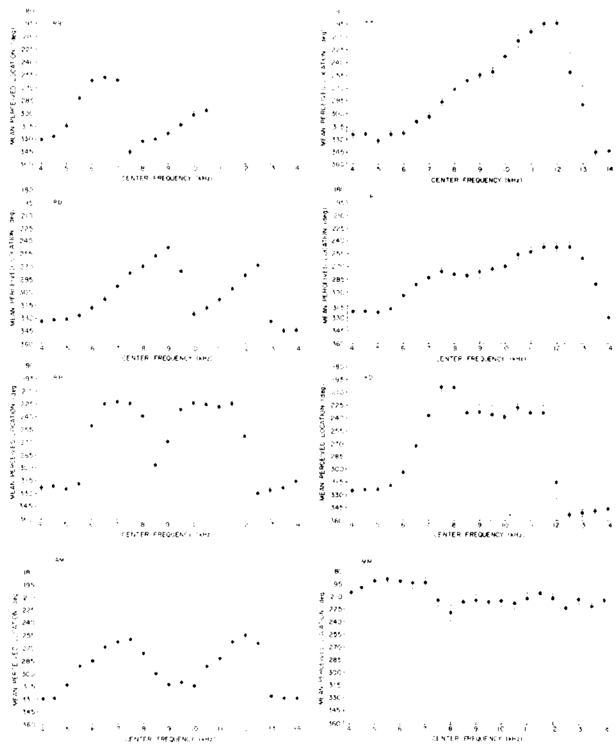

Fig. 2. Apparent location of narrow noise bands as a function of their center frequency. Vertical lines represent 95% confidence levels.

the noise bursts were generated only from loudspeakers positioned at 315°, 270° and 225° azimuth. The stimuli were presented at 18, 20 and 22 dB sensation level (SL). Determination of level was established by taking thresholds (method of limits) for sounds originating from those loudspeakers activated during the tests. Thresholds for noise bands with CFs of 4.0, 6.0, 8.0, 10.0, 12.0 and 14.0 kHz were obtained. Thresholds for the others were estimated via interpolation.

With CF and SL manipulated from trial to trial in an irregular order, stimuli were presented from one of the three loudspeaker positions. Our procedure insured, however, that all CFs were presented 10 times from each loudspeaker. Within the 10 presentations of a CF, SLs of 18 and 22 dB were presented three times; the 20 dB SL was presented four times. Three sessions, each no longer than an hour, were needed to generate the data. Subjects were given a brief rest period at midsessions.

Results

Perceived location of the stimuli was determined primarily by their frequency composition, not their azimuthal location. By inspection, the patterns of location judgments as a function of CF appeared to be highly similar irrespective of which loudspeaker had generated the stimuli. Hence, for each listener, we pooled his/her data from the three loudspeakers (315°, 270° and 225°) and have presented them in Fig. 2. A 1.0 kHz wide band of noise with CF of 4.0 kHz, save for Subject MM, was perceived as originating from 345° or 330° azimuth. As CF increased, perceived location shifted to more lateral and rearward loci. The most rearwardly perceived location of a sound was usually 240° or 225° although Subject KK consistently, and others occasionally, placed stimuli as far back as 195° and 180°. One feature common to the judged location patterns of six listeners was a transition from rearwardly perceived locations to frontally perceived locations occurring around 12.0–14.0 kHz. Of the two remaining listeners, MM perceived all sounds as originating from the rear quadrant. Subject RB's hearing did not extend beyond 11.0 kHz.

2. Relation between the relative amplitude provided by the pinna and location judgments

Method

After collecting the behavioral data, we measured pinna amplification for the various noise bands in the following ways. A Knowles miniature microphone (Model BT 1759) was placed approximately 2–3 mm inside the ear canal entrance of the left pinna (ipsilateral to the sound source) of a subject seated in the normal listening position. The microphone, with a frequency response extending beyond 14.0 kHz, was held in place by a commercially available compound (Audi-Sil) positioned to block the external meatus. The microphone was placed in a vertical position with the diaphragm facing outward. Subjects were cautioned to keep their head resting firmly against the headrest.

CFs of the noise bands ranged from 4.0 through 14.0 kHz in steps of 1.0 kHz. Stimuli were presented from each of the 13 loudspeakers along the arc from 0° through 180°. The microphone output was amplified (Hewlett–Packard amplifier, Model 465A) 20 dB and then filtered in order to eliminate low-frequency extraneous, environmental noise ($<$ 0.4 kHz). The signal was then routed to a vacuum-tube voltmeter (Ballantine, Model 300, measuring true rms voltage) where a reading was taken in decibels. Input voltage to the loudspeakers was maintained at the same level. To facilitate measurements, the sounds were continuous, not pulsed. After recording the output level for each CF at each loudspeaker position (11 CFs $\times$ 13 loudspeakers) the microphone was removed and the subject was asked to move about the room. After a short period, the microphone was replaced as nearly as possible to the same position. Measurements were repeated and the two sets were averaged. Following the second set of measurements, the microphone was removed and attached to a small wooden lever. The lever was then positioned in space so that the microphone occupied approximately the same position as it had when embedded in the ear canal. The complete set of measurements was repeated with the microphone in space. Pinna amplification was determined by subtracting the pressure levels recorded with the microphone in space from those obtained at the entrance of the ear canal.

Our final step was to rank the pinna amplification for each noise band with respect to loudspeaker position. For each subject, we found that loudspeaker associated with the greatest amplification for the noise centered at 4.0 kHz and assigned it a rank of '1'. Then, we identified that loudspeaker associated with the second-most amplification for the 4.0 kHz centered noise, and assigned it a rank of '2'. We continued until we had assigned a rank to each of the 13 loudspeakers based upon the degree to which the pinna amplified the 4.0 kHz centered noise band. The procedure was followed for the remaining noise bands of differing CFs. The result was a set of rankings (1 to 13) for each noise band and for each subject. There were 11 noise bands for 7 of the subjects and 7 noise bands for the listener whose acuity for frequencies above 11.0 kHz was impaired.

Results

To gain insight into the relation between location judgments of the various noise bands and their relative pinna amplification when originating from the different loudspeakers we proceeded as follows: First, we tabulated the number of times a listener identified, as the origin of the 4.0 kHz centered noise band, that loudspeaker position associated with the greatest pinna amplification measured in his ear canal re the other loudspeaker positions for that same noise band. Next, we tabulated the number of times he identified, as the origin of the same noise band, that loudspeaker position associated with the second greatest pinna amplification measured in his ear canal re the other loudspeaker positions. We then entered the number of location judgments to that loudspeaker which was ranked 3rd with respect to amplification measured at his pinna and continued in this way until all 30 location judgments (10 from each of the 3 original loudspeakers used) of the 4.0 kHz centered noise band had been accounted for. We treated the remaining noise bands in the same way. Then, a second subject's data were categorized similarly; the frequency distribution of his location judgments for each noise band was assimilated with the rankings of pinna amplification measured in his ear canal. Upon completion, the

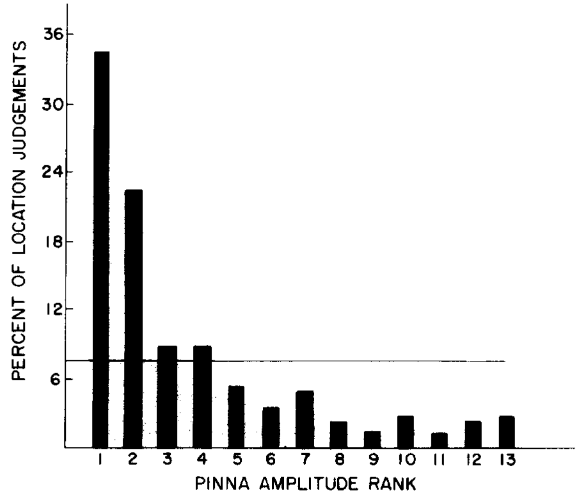

Fig. 3. The percent of location judgments of narrow noise bands differing in CF which was associated with relative amplification furnished by the pinna.

data for each noise band were combined across subjects. Fig. 3 illustrates, in histogram form, the relation between the behavioral and physical measurements for the narrow bands of noise *.

Differences in pinna amplification between adjacent ranks were frequently within 1 dB. Yet, on over half of the trials (57%), listeners chose as the source of the noise band that loudspeaker which they ranked first or second in relative pinna amplification. We should emphasize that listener location judgments were not related to pinna amplification per se. In the majority of cases (71%), the pinna amplification was greatest when the noise band was centered at either 4.0 or 5.0 kHz. This was nearly always the case when noise bands emanated from loudspeakers positioned at 0°–270° azimuth.

* Listener M.M.'s data were not incorporated in Fig. 3. Her pattern of spatial referents deviated widely from those of her cohorts. Her pinna amplification function, on the other hand, was in accord with the rest.

The question arose whether a similar relation can be extracted from a broadband noise stimulus. Since the acoustic effects attributed to the pinna, and to a lesser extent to the head and torso, are part of a linear system, one would expect a high correlation between the pinna amplitude ranks of the narrow bands of noise and the amplitude ranks of these same bands extracted from a broadband noise. Indeed, the reliability of our measurement technique would be suspect were not the two highly correlated. They were. (Spearman's Rho was 0.94; $P < 0.001$.)

3. Monaural localization judgments of narrow noise bands with occluded pinna

Method and Results

We assumed that the reason listeners, in Section 1, were unable to locate the noise bands accurately was due to the restricted width of these bands; the pinna did not differentially amplify frequencies contained within the narrow band. If this were so, then the pattern of each listener's location judgments resulting from changes in CF should be similar with the pinna open or occluded. Seven of our eight original listeners were tested; several months had elapsed since their last test. The Audi-Sil ear molds previously made for the subjects were inserted into their left ear; an opening to the external meatus remained. Their right ear was blocked by completely filling the cavity with Audi-Sil and covering the auricle with an ear muff.

Localization tests were conducted in the same manner as that described in Section 1. This time, however, only the loudspeaker positioned at 270° azimuth was activated. Each of the differently centered noise bands (4.0, 4.5, 5.0, 5.5 ... 14.0 kHz) was presented 10 times in an irregular order. A comparison of mean location judgments as a function of noise band CF between the previous open-pinna condition (loudspeaker at 270° azimuth) and the occluded-pinna condition was carried out for each subject. Pearson's Product-Moment correlations ranged from 0.81 to 0.98. All correlations were significant ($P < 0.001$).

Discussion

The data collected in Section 1 confirm the previous findings that stimulus frequencies possess spatial referents [3] Section 2 data demonstrate that location judgments of narrow noise bands are related to the amplification provided by the pinna. Generally speaking, a stimulus of specific CF was more likely to appear at that azimuthal position from which the sound was amplified most by the pinna re other azimuthal positions. Yet, comparable patterns of location judgements to noise bands differing in CF were obtained with the pinna occluded. We infer from the latter finding that stimulus bandwidth must exceed 1.0 kHz before the pinna differentially amplifies frequency segments within the band. When bandwidth is augmented, however, location judgments commence to bear a closer relation to the actual location of the sound, as reported by Butler and Helwig [4]. They mapped spatial referents in the MSP for 1.0 kHz wide noise bands whose CFs ranged from 4.0 through 14.0 kHz. Then, they required listeners to locate two 4.0 kHz wide noise bands which differed in CF. Although the stimuli originated from loudspeakers widely distributed in the MSP (15° apart, ranging from −15° in front to −15° from behind), listeners' location judgments clustered about that segment of the MSP which encompassed the spatial referents of frequencies contained in the noise bands. Moreover, they could distinguish sounds coming from the front of the segments from those coming from the rear. In a word, a gross level of localization performance emerged with stimulus bandwidths of 4.0 kHz. When the bandwidth is extended to include frequencies whose spatial referents cover a semicircular arc, then maximal proficiency in monaural localization should occur. And, indeed, a 4.0 kHz high-pass noise can be located as accurately as broadband noise [1].

To incorporate the present data into an overall scheme, we propose that listeners perceive a high-pass noise of extended bandwidth as originating from that azimuthal position which is the spatial referent of that frequency segment within the stimulus which is amplified most re other positions. In doing so, the apparent and actual location of the sound coincides. The location judgment is 'correct'. We cannot ascertain the width of this frequency segment from our data; it probably varies as a function of its place in the spectrum as well as from person to person. All in all, our view on the spectral basis of localization without the benefit of binaural difference cues closely resembles that of Blauert's [2].

If spatial referents underlie monaural localization in the HP as well as localization in the MSP, what is their genesis? Listeners may have learned that when a sound originates from a certain azimuth, one frequency region contained within the sound is amplified more at this location than at any other location. So, when presented this frequency region singly, as we did with the 1.0 kHz wide noise bands, they locate it at the azimuthal position where it normally receives its greatest amplification. But, there exists another avenue of speculation. Perhaps the tonotopic organization of the central auditory nervous system serves as the basis for the phenomenon that frequencies possess spatial referents. This explanation is certainly less tortuous than one based on learning and is also consonant with the finding that spatial referents with and without pinna occlusion remained essentially unchanged. Recently, Palmer and King [9] reported finding a monaural spatial map in the superior colliculus of the guinea pig. Its presence allows for the possibility that spectral cues are used to code loci in space. If so, the auditory system shares with the visual and somatic system a basic principle of organization; viz., a place in space bears a one-to-one correspondence with a place in the central nervous system.

Acknowledgment

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