Changes in head position as a measure of auditory localization performance: Auditory psychomotor coordination under monaural and binaural listening conditions[a)]

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(Received 25 July 1986; accepted for publication 28 July 1987)

Two experiments examined the capacity of listeners to turn and face an active sound source. Tests were conducted with sources located in the subject's forward field (an arc extending from 60° to the subject's right to 60° to the left). Localization performance was determined under both monaural and binaural listening conditions, using both brief pulses and sustained pulse trains as target signals. Not unexpectedly, the ability to orient the face to a hidden sound source was very poor under monaural conditions if the listener received only a brief (100-ms) tonal pulse. When continuous pulse trains were employed, localization, even under monaural conditions, became quite accurate. Across conditions, this complex motor response produced results in agreement with those that have been obtained when subjects were only required to report their spatial impressions. In particular, performance with binaural pulse trains was observed to vary as a function of the frequency of the target signals employed. Descriptions of the head movement response, along with a discussion of some of the implications of ear–head coordination, are presented.

PACS numbers: 43.66.Qp, 43.66.Pn

INTRODUCTION

A. Statement of the problem

Static sources and immobile listeners characterize most of the literature that has examined the ability to extract spatial information from the environment using the auditory channel. There is a limited literature that has examined the precision with which static sources can be localized when observers are allowed to move their head (e.g., Wallach, 1940; Thurlow and Runge, 1967; Pollack and Rose, 1967; and Simpson and Stanton, 1973). There is apparently no systematic literature on the inverse question, whether auditory spatial information can be used to regulate changes in head position. In the following section, we will attempt to explain why we feel that this is both a useful and logical question to be considered.

B. Auditory psychomotor coordination

Human auditory spatial acuity is quite poor, at least when compared to foveal acuity. Under optimal conditions, foveal acuity can be measured in seconds of arc (Hecht and Mintz, 1939), whereas auditory acuity is seldom better than a degree of arc (Howard and Templeton, 1966). It is not surprising, then, that the visual system is generally treated as the optimal sensory channel for the acquisition of spatial information. The disadvantages of the visual system are less obvious. First, in humans, the forward placement of the eyes, which allows significant binocular advantage, results in a relatively "narrow window" through which they can sample information from the surrounding environment. Visual resolution is optimal only within a few degrees of the line of gaze. In contrast, the auditory modality provides some spatial information for all remote events in the listener's field, regardless of the current orientation (line of gaze) of the subject. Second, while light travels in straight lines, sounds are able to travel around most objects; thus some spatial information about an acoustic event is generally available to the listener even if a "direct line of sight path" is unavailable. In situations of high spatial uncertainty, that is, when an observer does not know where to look, the potential for the auditory system to provide useful spatial information is excellent. Within this context, one might imagine that the auditory system would provide information that allows the subject to reorient toward a source, thus bringing into play the narrow field but high spatial resolving capability of the eyes. The reorientation of the observer in response to a sound is a familiar observation. In fact, it is one component of the "orientation reflex" (Sokolov, 1963). The fact that auditory stimulation results in a head-turning response toward the source of a sound in infants within minutes of birth (Wertheimer, 1961) is clearly compatible with the hypothesis that the auditory system may have a critical role in the process by which the observer visually examines his environment.[1]

An organism's ability to detect, identify, and respond to environmental events is probably critical to its success. Primates have concentrated much of their exteroceptive resources to the upper half of one plane of the body. Even major organs of manipulation, the hands and mouth, have a primary "frontal" orientation. Only one sensory system appears to provide spatial information about remote events outside this frontal window. The specific goal of the experiments described in this article was to examine the capacity of

[a)] Portions of this article were presented at the 111th meeting of the Acoustical Society of America, Cleveland, May 1986 [J. Acoust. Soc. Am. Suppl. 1 79, S21 (1986)].

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human observers to orient the position of their head based exclusively upon acoustic information. On practical as well as theoretical grounds, assessment of head orientation, not line of gaze (eye/head position), was chosen for these initial experiments, though eventually the latter response must be considered.[2] In addition, these initial experiments were restricted to the forward 120° of the subject's field. Localization in the extreme lateral and rear fields will be discussed in a later article.

I. EXPERIMENT 1. ACCURACY OF HEAD SACCADES RESPONSE UNDER MONAURAL AND BINAURAL LISTENING CONDITIONS

A. Overview

One problem with a novel dependent variable is that it is difficult to distinguish between changes in performance that reflect limits in the subject's ability to use the available sensory information from changes that reflect limits imposed upon the subject by the response. Most research examining auditory spatial function requires the subject to make a decision about the absolute position of a sound source or about the relative positions of two or more sources. The head movement measure requires that the listener translate sensory information into a more complex motor response. In a partial attempt to overcome this difficulty, the first experiment was directed at the most extreme conditions that we could impose: a comparison between localization of sound sources under monaural and binaural listening conditions.

B. Methods

Five subjects were employed. Four of the subjects were experimentally naive. One subject (DRP) had extensive experience on traditional localization problems. No practice on the task was given prior to data collection.

A 3.7-kHz sine wave was led from a voltage controlled oscillator to an electronic switch, programmable attenuator, amplifier, and finally to one of six speakers located in a large audiometric chamber. Signal frequency, amplitude, and all switching parameters were under the control of a microprocessor.

The test chamber had been modified for free-field testing. All interior surfaces of the room were covered with 15.2-cm acoustic foam wedges, creating a relatively "echo-free" environment for audio frequencies above 0.5 kHz. The subject was seated in the center of this room at a distance of 1 m from the speaker array. While the locations of the speakers were varied from session to session, six regions (three to the right and three to the left of the median plane) were sampled on each session: near straight ahead (5°–15°); intermediate lateral positions (25°–35°); and lateral positions (55°–65°).[3]

The subject wore a modified plastic helmet that could be firmly fitted to his head. The helmet, in turn, was attached to a rigid steel frame. Movement of the helmet was possible in one dimension only: rotation about the central vertical axis of the body. Movements of the helmet, relative to the steel frame, resulted in the rotation of a variable resistor element. The voltage changes that resulted from these changes in resistance were, in turn, translated into a digital representation of the current head position, using an analog-to-digital converter. Extensive calibration tests indicated that, for a 200° arc, this system was linear. Resolution was 0.4° within this restricted area.

Since we were concerned that all head movements be based upon only auditory information, a number of precautions were taken. First, the speakers were hidden from view behind a black cloth screen. The screen extended across the entire frontal field (180°). Second, in order to eliminate the use of visual landmarks, all tests were conducted in the dark. Third, feedback was not provided.

The task, from the subject's point of view, was quite simple. A warning noise was sounded at the beginning of each trial (0° azimuth). The subject was required to face forward.[4] Head position was monitored at this time and the warning noise continued until the proper position (defined as the initial head position) was achieved. Upon the head reaching the initial position, the noise was terminated. Head movements greater than 1 deg from this initial position, prior to the onset of the target tone, would automatically reinitiate the warning signal and delay the onset of the stimulus presentation. Since we were interested in an accurate measure of both the initial latency of the head movement response, as well as the initial direction of motion, a variable delay interval of between 0.5–1.5 s was employed. The subject was asked to turn and face the sound source after signal onset. The signal was a 40 dB SPL (*re*: 0.0002 dyn/cm^2) 3.7-kHz tone (signal level calibration was performed by placing a microphone at the same location that the listener's head would occupy during testing). No instruction was given as to the optimal speed of the response to be emitted. Upon completing the movement, the subjects were required to press a button indicating that they felt that they were facing the source.

Within a session, sounds were presented ten times from each of the six sources. The order of presentation was randomized. Four conditions were employed. On two of the sessions, the subjects had the left ear occluded (using a wax plug). The choice of the 3.7-kHz tone was based upon the attenuation characteristics of this ear plug (Ear Saver ®). The remaining trials were conducted without blocking the left ear. On half of the binaural and monaural sessions, a continuous pulse train was employed (a 5-Hz pulse train with a 100-ms on/off duty cycle). On the remaining sessions, a single 100-ms pulse was employed (initial tests indicated that no head movements with a latency shorter than 150 ms would be observed in response to the sound). Rise/decay times of 10 ms were employed with all pulses. From the onset of the warning signal, to the point that the subject terminated the trial, head position was sampled at a rate of 60 Hz.

C. Results and discussion

Figure 1 presents the results under binaural listening conditions. Terminal head position is plotted as a function of the actual location of the sound source. The "ideal performance" presented in this figure indicates the final head position if there were no errors. For both the pulse train and single pulse conditions, no systematic errors were evident for

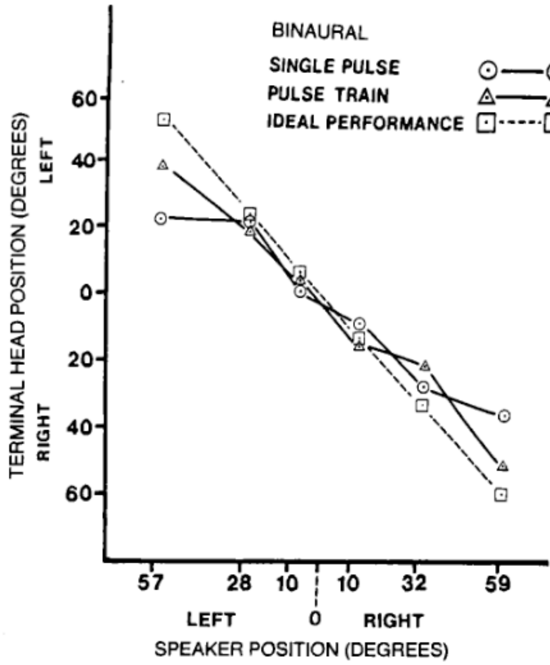

FIG. 1. Head position at the end of a trial (terminal head position) is plotted as a function of the actual location of the sound source. The triangles and circles represent the mean terminal head position under binaural listening conditions. The means were based upon ten observations for each of five listeners. The squares plot the mean location of each source across the 50 trials.

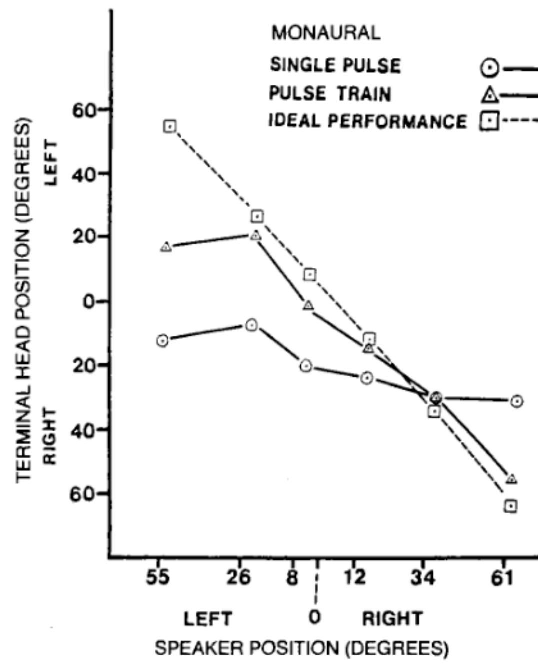

FIG. 2. Terminal head position under monaural listening conditions as a function of the average location of the sound source. Each point represents the mean of 50 observations.

sources located within approximately 30° of the subject's initial head position. Systematic errors occurred under both conditions with the most extreme positions employed, approximately 58°. Systematic underestimation was evident for both pulse and pulse-train conditions in this region, though clearly less for the pulse-train stimulus (e.g., 19° vs 35° with the source in the extreme left position).

Figure 2 presents the mean terminal head position under monaural listening conditions. As expected, given only a single pulse, the monaural listener always faces toward the side of the open ear, regardless of the actual location of the source. While we sampled a 116° range, all of the monaural responses to one pulse were in a region between 8° and 30° to the right. In the most extreme condition, with the source located 55° to the left, the mean terminal head position indicated an average error of nearly 70°. The results under monaural listening conditions with pulse trains are quite different. With the exception of the extreme lateral source on the side of the blocked ear, the terminal head position was typically within 15° of the actual position of the source.

The movement of the head from the onset of the tone until the terminal head position was reached we will refer to as the head movement response (HMR). The HMR can best be described as a series of discrete movements or saccades.[5] In the present study, a saccade was defined as a shift in head position lasting at least 100 ms and representing a minimum change in position of 1 deg. Termination of a saccade was defined as either no change in head position for 100 ms or a reversal of the direction of motion.

Figure 3 presents the distance traveled during the HMR under binaural listening conditions. The lower curve presents the minimum distance that would have been traveled had the subject made a single saccade. For all but the most

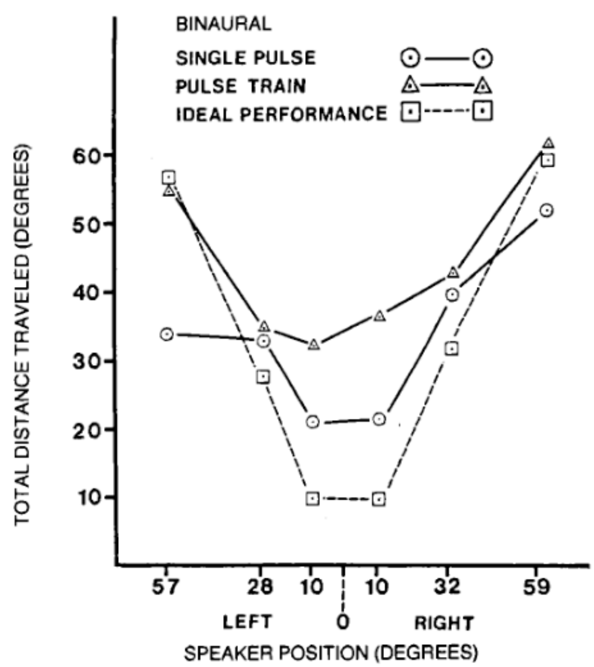

FIG. 3. Total amount of head rotation (in degrees) during a trial under binaural listening conditions as a function of the location of the sound source. Each point represents the mean of 50 trials.

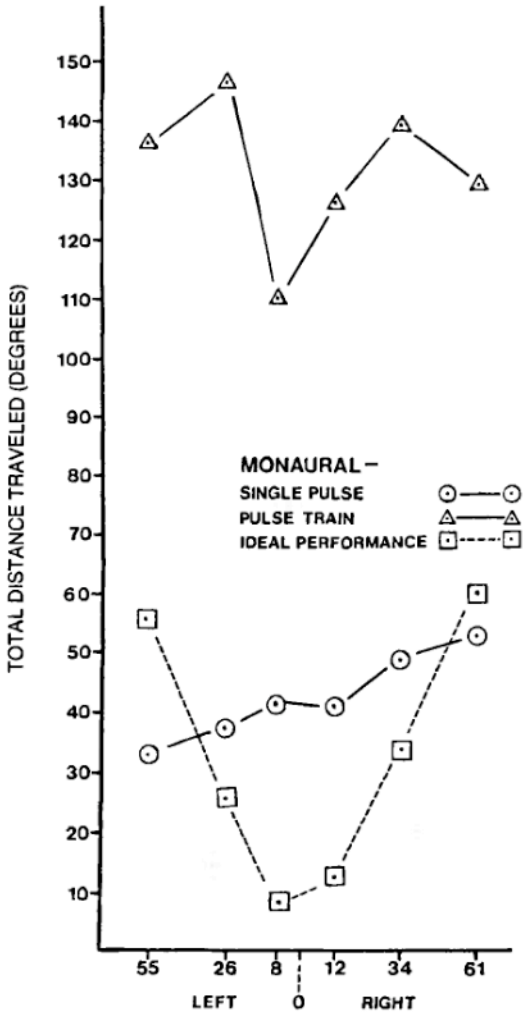

FIG. 4. Total amount of head rotation (in degrees) during a trial under monaural listening conditions as a function of the location of the sound source. Each point represents the mean of 50 trials.

extreme lateral sources, the distance traveled exceeds the minimum distance from the initial to the final head position. For example, with a source located 10° to the subject's left, the mean distance traveled was 33°, more than three times the optimal path. Both the number of reversals and the distance traveled were inversely related to the distance of the source from the initial head position. The HMR was *more* efficient for distant targets than for those located near the subject's median plane.

Under monaural conditions, far more head movement was evident (see Fig. 4). In particular, with the pulse-train condition, it is quite clear that the superior localization performance noted earlier is correlated with extensive head movement (as if the subject were "scanning" the field). Subjects moved over 100° in order to face a source that was only 8° from the initial head position. Such movement takes time. Terminal latencies, that is, the time from the onset of the stimulus until the subject indicated that he was facing the source, frequently exceeded 6 s.

Because these group data tend to mask the details of the HMR, we have included two graphs as representative samples of the trends found within the various conditions. Figure 5 is a plot of the raw data for a single subject (FW) during the first trial in both a binaural and monaural pulse-train condition. The speaker was located 58° to the subject's left. Samples of the head position are plotted every 16.7 ms. In the binaural condition, the latency of the first major saccade was nearly 750 ms. This movement was both the fastest and longest event encountered during the HMR (a ballistic type movement). The second saccade is both shorter in duration and at a lower velocity. There is a long final period in which many small saccades can be identified. The terminal head position error in this trial is about 10°.

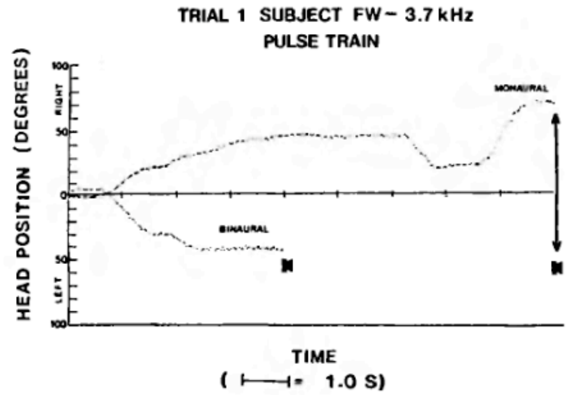

FIG. 5. Head position in degrees as a function of the elapsed time from signal onset for subject FW. Head position was sampled 60 times per second. The speaker symbols indicate the actual location of the source on each of the two trials plotted.

In the monaural condition, the initial latency was nearly the same for this subject. On the other hand, the first major saccade was away from the actual position of the source, that is, away from the occluded ear. The difficulty of this task for this subject is seen in the major reversals in the direction of motion 6 s after signal onset, the exceptionally large error

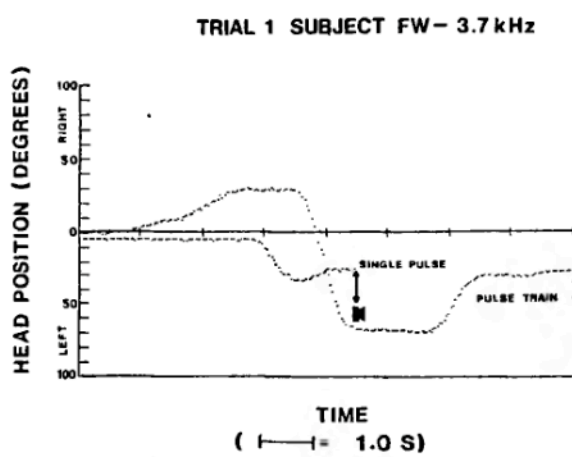

FIG. 6. Head position in degrees as a function of the elapsed time from signal onset for subject FW. Head position was sampled 60 times per second. The speaker symbols indicate the actual location of the source on each of the two trials plotted.

encountered in the terminal head position (in excess of 100°), and the very long period required by the subject to report that she was facing the source (approximately 9 s).

Figure 6 is again a plot of a subject's raw data (FW); both plots are from the first trial in the monaural condition. A comparison of the two HMRs clearly shows that the pulse-train condition allows the subject to update the information by sampling from different positions. In the pulse-train condition, the subject started the trial turning in the wrong direction. After having turned in excess of 30°, the subject made a major reversal in the direction of rotation. The velocity of the second saccade exceeded 150° per second. Additional saccades can be seen after this major readjustment response was completed. The final decision about the apparent locus of the source was not made until 8 s had elapsed. When single pulses were presented, no additional acoustic information was available after the 100-ms pulse was terminated. Both the size of the HMR and the period required to make the response were typically much less than those observed with the pulse-train stimulus.

Several general comments are in order. First, the ability to use auditory spatial information to adjust head position so as to face a sound source is clearly evident in these data. Performance, in fact, seems to follow from what we have obtained in "static" localization tasks in which the subject simply reports the position of a sound source. Errors in localization under monaural conditions, with pure tones and a single short presentation, are extremely large with sources located on the side of the blocked ear. But, as Starch (1905) noted, monaural listeners are able to localize the position of the source, given an opportunity to sample the sound from a number of positions. Conversely, such head movements are not necessary for good localization performance under binaural conditions. In the present paradigm, this effect is reflected in the general similarity of performance between single pulse and pulse-train conditions under binaural conditions.

Second, what might be considered as surprising, is the observation that a gross motor response, movement of the head, is so well determined by the auditory sensory information. In particular, one should note that the HMR to sources located within approximately 30° of the initial head position were, under binaural listening conditions, generally as accurate in the single pulse condition as they were with a continuous pulse train. It would appear that there is something analogous to a "map," which allows the subject to relate the heard position of a source to the position of the head at the end of an HMR. There are some problems with this notion in the extreme lateral portions of the field. Errors in this region were considerably larger in the single pulse mode than they were in the pulse-train condition. The fact that our subjects systematically underestimated the position of the source in the most extreme lateral position, with both types of signals, is particularly interesting. We do not know, for example, what factors determine the "felt position" of "straight ahead." With extreme lateral movements of the head, it seems entirely reasonable that shifts in eye position may exceed the actual shift in head position. If, in fact, straight ahead, at least in the absence of visual information, is determined by the combined information about the degree of rotation of the head and the lateral displacement of the eyes relative to the head, part of this effect would be explained.

II. EXPERIMENT 2. ACCURACY OF HEAD MOVEMENT RESPONSE AS A FUNCTION OF SIGNAL FREQUENCY

A. Overview

The ability to orient to a hidden sound source using only acoustic spatial information should be determined, at least in part, by the spatial resolution of the auditory system. From the preceding study, it was quite clear that the accuracy of the HMR was indeed dramatically attenuated under monaural listening conditions. The following experiment was conducted to determine whether *moderate* modifications in the subject's ability to localize a hidden source could be detected in the head movement response.

Numerous investigators have demonstrated that auditory spatial resolution is dependent upon the frequencies employed. Mills (1958) developed a measure of spatial acuity that he called the minimum audible angle (MAA). He reported that the localization threshold (MAA) as a function of the frequency of the sound generated from the source is at or below 1 deg for frequencies less than 1000 Hz when the sound source was located near the subject's median plane. Resolution decreased as the signal frequency increased; a minimum resolution was observed at 2000 Hz (MAA = 3.0°). Further increases in the signal frequency resulted in a gradual recovery with the MAA approaching only 2.0° at 4000 Hz. On one hand, these results represent a large effect in that a shift from 500 to 2000 Hz, for example, produced a 300% increase in the MAA. On the other hand, would a change of only 3 deg in the resolution be reflected in the accuracy of the head movement response?[6]

B. Method

This experiment was conducted concurrently with the first experiment. The same subjects, apparatus, and procedures as described earlier were employed. Only the binaural pulse train condition was examined. Two additional frequencies were used in the pulse train: 500 and 2000 Hz. The results with the 3700 Hz tonal pulse train, presented in the first experiment, are included for comparison.

C. Results and discussion

In the current paradigm, the subject is required to rotate his head until he believes that he is "facing" the sound source. In classical psychophysics, this would be described as an example of the method of adjustment. Three indices are commonly extracted. First, the point of subjective equality (PSE) is typically the mean of a set of adjustments performed. In the present experiment, the PSE was the *average terminal head position* (THP). The second index, the constant error (CE), is defined as the difference between the actual value of the stimulus and the obtained PSE (in the current experiment, the CE was defined by subtracting the actual location of the source from the THP). Systems in which large CEs occur are, by definition, *not accurate*,

TABLE I. The mean and standard deviation for terminal head position obtained with a 500-Hz pulse train (ten trials). The constant error is the difference between THP and the actual location of the source. Negative values indicate that the source or THP was to the left of the subject's initial head position. Negative constant errors indicate that the THP was to the left of the location of the source.

Subject	Location of source (deg)	Terminal head position Mean (deg)	s. d.	Constant error (deg)
RC	−64.0	−62.7	3.9	1.3
CM	−58.5	−39.8	3.6	18.7
FW	−57.4	−48.5	4.5	8.9
LR	−58.6	−54.5	4.5	4.1
DRP	−58.5	−51.0	5.1	7.5
Mean	−59.4	−51.3	4.3	8.1
RC	−33.1	−31.0	1.7	2.1
CM	−26.1	−21.7	2.1	4.4
FW	−26.2	−27.8	2.2	−1.6
LR	−26.8	−30.6	3.3	−3.8
DRP	−27.0	−21.0	3.8	6.0
Mean	−27.8	−26.4	2.6	1.4
RC	−14.5	−20.0	2.3	−5.5
CM	−8.0	−11.0	1.5	−3.0
FW	−8.9	−11.6	2.2	−2.7
LR	−8.8	−15.6	1.1	−6.9
DRP	−8.0	−7.9	2.6	0.1
Mean	−9.6	−13.2	1.9	−3.6
RC	3.2	4.5	3.3	1.4
CM	12.7	13.4	3.2	0.7
FW	11.8	4.0	3.4	−7.8
LR	12.9	8.1	2.4	−4.8
DRP	10.4	9.9	2.5	−0.5
Mean	10.2	8.0	3.0	−2.2
RC	23.1	18.8	3.2	−4.3
CM	33.6	29.9	3.1	−3.7
FW	33.4	20.0	3.5	−13.4
LR	33.5	22.6	3.2	−10.9
DRP	31.2	30.0	3.6	−1.2
Mean	30.9	24.3	3.3	−6.7
RC	54.9	45.3	2.2	−9.6
CM	61.7	54.1	4.6	−7.6
FW	68.8	61.5	3.9	−7.3
LR	61.0	51.0	1.7	−10.0
DRP	61.1	59.3	3.5	−1.8
Mean	61.5	54.2	3.2	−7.3

TABLE II. The mean and standard deviation for terminal head position obtained with a 2000-Hz pulse-train (ten trials). The constant error is the difference between THP and the actual location of the source.

Subject	Location of source (deg)	Terminal head position Mean (deg)	s. d.	Constant error (deg)
RC	−59.3	−39.0	5.7	20.3
CM	−61.3	−30.9	1.7	30.4
FW	−57.8	−36.9	8.2	20.9
LR	−58.3	−40.2	10.4	18.1
DRP	−53.7	−37.7	6.2	16.0
Mean	−58.1	−36.9	6.4	21.1
RC	−29.7	−25.8	5.1	3.9
CM	−31.1	−23.7	4.0	7.4
FW	−26.3	−26.1	4.3	0.2
LR	−27.9	−30.0	3.9	−2.1
DRP	−28.7	−28.0	6.0	0.7
Mean	−28.7	−26.7	4.6	2.0
RC	−11.1	−6.6	11.3	4.5
CM	−12.1	−21.9	4.3	−9.8
FW	−9.3	−11.9	2.7	−2.6
LR	−8.7	−14.7	3.7	−6.0
DRP	−10.4	−5.9	5.0	4.5
Mean	−10.3	−12.2	5.4	−1.9
RC	8.0	14.4	4.8	6.4
CM	6.9	9.6	3.0	2.7
FW	12.3	2.9	4.9	−9.4
LR	10.8	10.8	4.4	0.0
DRP	10.9	5.7	4.1	−5.2
Mean	9.8	8.7	4.2	−1.1
RC	29.1	23.3	4.0	−5.8
CM	28.7	10.8	3.9	−17.9
FW	34.3	10.8	8.8	−23.5
LR	31.3	24.2	5.0	−7.1
DRP	32.0	21.6	5.0	−10.4
Mean	31.1	18.1	5.3	−12.9
RC	58.0	38.7	5.6	−19.3
CM	57.5	18.8	3.4	−38.7
FW	62.2	32.2	11.0	−30.0
LR	59.3	27.1	16.2	−32.2
DRP	57.2	39.6	2.3	−17.6
Mean	58.8	31.3	7.7	−27.6

though they may be consistent. Consistency is described by an estimate of the variable error (VE). This third index is simply the standard deviation of the THP responses. Neither the CE nor the VE, in themselves, can fully describe "accuracy," though together a relatively clear picture of performance can be obtained (Engen, 1971, pp. 20–23).

Tables I, II, and III present the results on the terminal head position (THP). Since the relative location of the source was based upon the "subjective straight ahead" (thus the location varied slightly for each subject), the relative source location is listed along with the various measures of performance. These estimates of the PSE (the mean THP), VE (the standard deviation of the THP), and the CE are based upon ten trials for each subject.

An analysis of variance performed on the CEs indicates a significant main effect for speaker location ($F = 22.5$; $df = 5/20$; $p < 0.01$). Errors were small with sources located near the initial head position and increased as the distance increased. A significant interaction was obtained between speaker location and the frequency of the signal localized ($F = 7.92$; $df = 10/40$; $p < 0.01$). For the most extreme lateral positions, large CEs were obtained at all frequencies; however, particularly large CEs were evident when the subjects attempted to localize the 2000-Hz signal.[7]

An analysis of variance on the standard deviation of the THP responses (our estimate of the VE) provides a somewhat different picture. While a significant main effect for speaker location was evident ($F = 4.28$; $df = 5/20$; $p < 0.01$), there was no significant interaction between speaker location and the frequency of the signal to be local-

TABLE III. The mean and standard deviation for terminal head position obtained with a 3700-Hz pulse train (ten trials). The constant error is the difference between THP and the actual location of the source.

Subject	Location of source (deg)	Terminal head position Mean (deg)	s.d.	Constant error (deg)
RC	−64.0	−46.3	8.5	17.7
CM	−57.4	−35.7	7.2	21.7
FW	−60.1	−46.7	4.9	13.4
LR	−57.5	−39.1	17.7	18.4
DRP	−55.6	−48.7	5.8	6.9
Mean	−58.9	−43.3	8.8	15.6
RC	−33.4	−27.4	6.8	6.0
CM	−28.1	−19.1	2.8	9.0
FW	−29.8	−15.5	2.0	14.3
LR	−29.0	−32.6	8.6	−3.6
DRP	−27.3	−15.6	2.0	11.7
Mean	−29.5	−22.0	4.4	7.5
RC	−14.4	−10.0	5.6	4.4
CM	−11.2	−0.6	7.9	10.6
FW	−10.4	−4.8	6.1	5.6
LR	−10.6	−20.9	8.5	−10.3
DRP	−9.9	0.3	2.4	10.2
Mean	−11.3	−7.2	6.1	4.1
RC	3.7	9.6	3.3	5.9
CM	8.3	14.3	3.2	6.0
FW	10.4	20.7	2.6	10.3
LR	8.1	3.4	3.0	−4.7
DRP	11.5	13.1	2.4	1.7
Mean	8.4	12.2	2.9	3.8
RC	23.5	15.4	6.1	−8.1
CM	31.0	27.5	2.7	−3.5
FW	30.4	30.6	3.7	0.2
LR	29.1	−3.1	8.2	−32.2
DRP	33.7	17.3	3.3	−16.4
Mean	29.5	17.5	4.8	−12.0
RC	53.5	44.6	9.5	−8.9
CM	57.8	49.4	5.7	−8.4
FW	60.1	65.7	4.1	5.6
LR	56.5	30.7	7.1	−25.8
DRP	56.7	57.3	2.4	0.6
Mean	56.9	49.5	5.7	−7.4

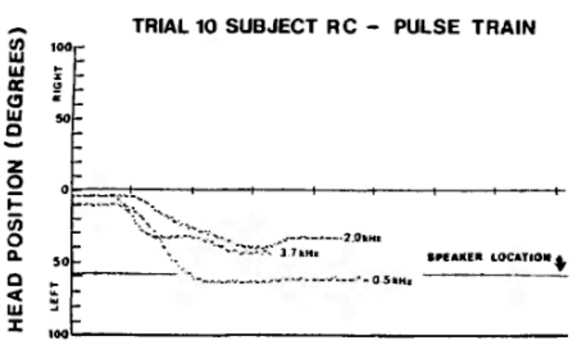

FIG. 7. Head position in degrees as a function of the elapsed time from signal onset for subject RC. Head position was sampled 60 times per second. Note that all three trials were completed with the source at the same location (58° to the subject's left).

ized. The average VE at the lateral extreme was 6.03° as compared to an estimate of VE of only 3.92° for the locations near the initial position of the head. A significant main effect for signal frequency, however, was observed ($F = 4.52$; $df = 2/8$; $p < 0.05$). The average VE was 3.05° for the 500-Hz pulse train, nearly half of the value obtained with the 2000-Hz pulse train (5.63°).

Figure 7 presents the data from one subject (RC) collected on the tenth trial at each of the frequencies tested. Under binaural conditions, a single saccade constitutes the major response at 500 Hz. The terminal positioning of the head with respect to the sound source was generally very accurate. At both 2000 and 3700 Hz, additional saccades were common and the terminal head position, at least with lateral sources, was generally less accurate.

Initial latency, that is, the period between the onset of the tone and the first movement that exceeded 1 deg, was independent of the signal frequency. Location of the source, however, had a significant effect on this variable. The mean initial latency was 371 ms for sources located approximately 60 deg from the initial head position and 453 ms for sources within 10°. This effect could also be seen in the latency from the onset of the tone to the beginning of the largest saccade. With sources located in the most lateral positions of the field, the latency was 639 ms (approximately 270 ms after the initial movement). In the forward field, this latency measure was 1250 ms. In effect, while the terminal head position was more accurate in the forward field, the initiation of the major saccade was considerably delayed under these same conditions. There was no relationship between the latency between the onset of the target tone and the moment that the subjects indicated that they were facing the source. As can be seen in Fig. 7, subjects often remained motionless for several seconds prior to pressing the response button.

With regard to the direction of motion, the largest saccade was always in the correct direction (under binaural listening conditions). The initial saccade, which often preceded the major saccade by 500 ms or more, and often was very small, was generally in the correct direction (87% correct).

III. GENERAL DISCUSSION

The results of both experiments demonstrate good agreement between the ability to face a hidden sound source and the functions that have been defined for sound localization using more traditional dependent variables. Gross errors were evident when the subject was restricted to monaural input and given only a brief sample of the signal. With pulse trains, monaural listeners were able to orient to the source, under most conditions. However, this successful monaural localization required extensive movement of the head. Performance under binaural conditions was not only superior to that obtained in the monaural condition, it was dependent upon the frequency of the sound produced by the source. Given the gross differences between the present task, where the subject was required to translate acoustic spatial information into a motor response, and the more traditional problem that only requires that the subject make a decision regarding the spatial characteristics of an event, these results are quite surprising. It appears that the general features of the response (head movement) can be predicted by existing measures of auditory spatial acuity (MAA).

The agreement between localization performance as measured by the HMR and more traditional indices (e.g., MAA) are far from perfect. Whether one considers the CEs or the VEs, accuracy falls short of the 1°–3° resolution described by Mills (1958) for signals in this same frequency range. Using traditional measures, auditory spatial acuity has been shown to decrease as sources are placed to more extreme lateral positions (Mills, 1958). With the THP measure, while some increase in the VE is evident in the lateral regions, the major effect is seen in the size of the CEs (CEs, even if present, are essentially ignored in the calculation of MAA). Moreover, in the current paradigm, *all* CEs in the most lateral positions were errors of *underestimation*. This latter feature, we believe, may be a unique characteristic of the HMR and not particularly relevant in a description of the auditory spatial function.

Whether there is an intimate connection between the auditory spatial channel and the motor system that allows the organism to "orient" to external events is a question clearly beyond the scope of this article. However, these results in no way conflict with this hypothesis.

ACKNOWLEDGMENTS

This research was supported, in part, by grants from the National Science Foundation (BNS-8512317) and the National Institutes of Health (3S06 RR0801-1452).

[1]Some evidence indicates that auditory spatial information can be utilized to direct saccadic eye movements. Again, as is the case with the head movement literature, most of this research has focused upon the inverse problem, how the visual response affects auditory spatial resolution (Warren, 1970; Platt and Warren, 1972). Some recent work (Zahn *et al.*, 1978; Whittington *et al.*, 1981; and Zambarbieri *et al.*, 1982) provides evidence that saccadic eye movements guided only by the sound from a hidden source were accurate to within 3 deg; however, these observations were restricted to a narrow field directly in front of the observer.

[2]There is growing neurophysiological evidence of an intimate interconnection between visual and auditory spatial function. Studies of a cat's visual cortex (Morrell, 1972; Fishman and Michael, 1973) have shown populations of neurons that are responsive to both modalities and that project to the superior colliculus. Knudsen *et al.* (1979) observed in the optic tectum of the barn owl (the avian equivalent of the mammalian superior colliculus) bimodal, spatially tuned cells. Most of these auditory–visual cells had the same spatial registry. This overlay of receptive fields was lost, of course, as the peripheral extremes of the visual field were exceeded. Such mechanisms could account for the observed capacity of the owl to direct its head (the eyes in this species are relatively immobile) toward a sound source. It seems reasonable to expect the existence of similiar mechanisms in mammals.

[3]These represent "average" locations, since the speakers were repositioned on a random basis. Variations in position did not exceed $\pm 5°$ across sessions and were *fixed* within a session. Subjects did not receive feedback about their performance within or across sessions. By varying the location of the sources actually employed, it was assumed that subjects would not "learn" the position of the sources. We were concerned, of course, that the subject might develop highly practiced motor behavior.

[4]At the beginning of the session, the subject was asked to face forward. While the actual position that the subject assumed was, on the average, 0° azimuth, errors in this facing response often exceeded 3°. This subjective "straight ahead" and not the objective 0° azimuth was used as the initial head position across the trials encountered during a given session. This procedure had two advantages. First, subjects were able to begin each trial in a position in which they felt that they were facing forward. Second, session-to-session variations in this initial head position insured that different objective distances between the initial head position and the speaker "targets" would be encountered across sessions.

[5]The concept of a saccade is a familiar term in the description of nonpursuit eye movements. We believe this concept may have utility in the description of the HMR. Under normal binaural listening conditions, the HMR is composed of a series of discrete movements. Brief movements of relative low velocities are observed at both the beginning and the end of the HMR (usually more at the end). A single, relatively high-velocity movement accounts for the major portion of the response. The velocity of this major saccade was proportional to the distance traveled. The pattern observed with the HMR is quite similiar to that encountered in the eye movement literature. Major differences between the HMR and voluntary eye movements are, however, evident. The maximum velocities observed are much higher with ocular movements and the voluntary changes in fixation occur with much shorter latencies (Hyde, 1959).

[6]If one assumes, as we have, that the capacity to use auditory spatial information to orient the face to the world is the biologically relevant issue, then the current question could be turned around. Are such "small" changes in MAA biologically relevant?

[7]The fact that constant errors of underestimation always occurred in the most extreme lateral locations raised some concern that the constraints imposed by the response apparatus or some other artifact were responsible for this "effect." However, the location by frequency interaction argues against this "artifact" explanation. With the 500-Hz signal, the maximum CE was observed with CM at 58.5° (18.7°). The average CEs for the extreme left and right were only 8.1° and 7.3°. In contrast, with the 2000-Hz signal, a CE of *only* 18.7° was well below the mean CEs observed (21.1° and 27.6°). It is difficult to see how a change in signal frequency could result in a two- to sevenfold increase (and more) in the CEs, if the effect was due to some aspect of the apparatus.

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