Binaural and Spatial Hearing in Real and Virtual Environments

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Chapter 16

Experiments on Auditory Motion Discrimination

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Temporal aspects of dynamic sound localization were examined in four experiments. Motion was simulated by dynamically changing the interaural delay of a train of high-frequency-filtered, Gaussian clicks. Determining the direction of motion could not be explained by a model that relies entirely on the onset–offset positions of the moving stimulus. The data suggest a lowpass filtering of interaural delay information with a time constant estimated at 60–130 ms. Results from discrimination and descriptive studies of motion are compared.

INTRODUCTION

There is a paucity of research on dynamic sound localization. The reason for this is both the experimental difficulty associated with the physical movement of sound sources[2] and the theoretical complexity of modeling results related to time-varying signals (Stern and Bachorski, 1983). Consequently, there has been little agreement on how the auditory system encodes sound-source movement (Perrott and Musicant, 1977; Perrott, 1989; Grantham, 1986, 1989a; Stern and Bachorskin, 1983; Toronchuk, Stumpf, and Cynader, 1992). The considerable work done in the area of stationary sound localization has provided solid models of binaural hearing (Jeffress, 1948; Colburn and Durlach, 1978; Stern, Xu, and Tao, 1991; Searle, Braida, Davis, and Colburn, 1976), which have found physiological support in the past decade (Carr and Konishi, 1990; Yin and Chan, 1990). Although models of stationary localization provide useful substrates for the study

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[2] Changing the direction and velocity of movement of a loudspeaker between or within trials without introducing extraneous sounds can prove difficult. Few laboratories are equipped with the requisite apparatus. Many have consequently opted to examine dynamic processes by presenting carefully controlled dichotic stimuli through headphones.

of dynamic processes, the psychophysical and perceptual differences between dynamic and stationary localization require recognition in modeling dynamic processing.

One area of discrepancy between results from experiments on stationary and dynamic localization concerns the rapidity with which independent bits of information are processed (Blauert, 1972, 1983; Hafter, Buell, and Richards, 1988). If interaural delays are dynamically changing, the binaural system requires a greater time for sustaining independent processing than if interaural delays are kept constant. Hafter *et al.* (1988) have shown that when the interclick interval (ICI) in a train of high-frequency clicks is about 12 ms, performance based on information derived from n clicks is superior to that based on one click by $n^{0.5}$, denoting optimum summation of interaural information across the n clicks. Increasing the ICI beyond 12 ms does not result in further improvements in performance. As shown later in this chapter, when interaural delays vary between successive clicks, the binaural system cannot make optimum use of interaural information even with an ICI of 130 ms—a value that is more than 10 times greater than that which is sufficient for stationary sources.

The following four experiments were designed to study the temporal aspects of dynamic processing. The first experiment examines the detectability of direction of motion as the interaural delay of a dichotic click train is linearly increased. The second experiment addresses the question of whether the motion mechanism is an onset–offset detector. The third experiment examines the contribution of the ongoing signal to the detection process (as compared to the contribution of the onset and offset of the signal). Finally, the fourth experiment explores the idea of "lag of lateralization" (Blauert, 1972), more commonly referred to as binaural sluggishness (Grantham and Wightman, 1978).

I. EXPERIMENT I

A change in interaural delay may be associated with a change in the lateral distance traveled by a source. The first experiment provides a baseline where an observer's ability to determine the direction of movement of an auditory image is examined as a function of the magnitude of linear change in interaural delay.

A. Design

Signals were trains of dichotic clicks whose temporal envelopes were Gaussian and centered at the cosine phase of a 6-kHz carrier. The trains, presented through electrostatic headphones (STAX-SR5), were used to simulate the dynamic changes in the interaural time difference (ITD) of an intermittent sound source in lateral motion. Figure 1 shows the stimulus configuration. The ITD of each click increased by a constant amount ($\Delta\tau = 10\ \mu\text{s}$) relative to the click immediately preceding it. The starting ITD was randomly selected from a predetermined set of values. The ICI was 13 ms jittered by 10% between trials to eliminate monaural pitch cues. On each trial of a single-interval design, the ITDs either

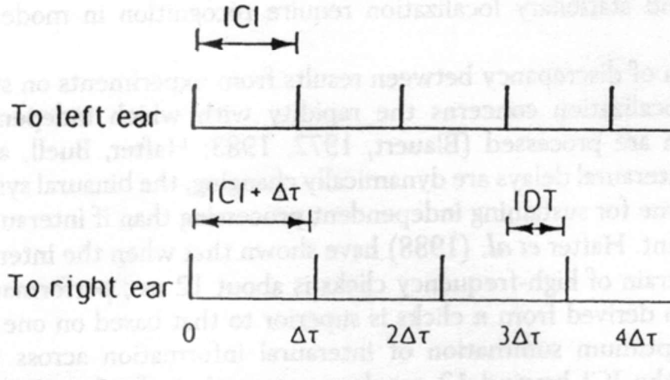

FIG. 1. Stimulus configuration used in experiment I.

progressively increased or decreased. The subject's task was to determine the direction of movement of the auditory image (right or left). The number of clicks in the train was an experimental parameter.

B. Results

Figure 2 shows the results of this experiments for two subjects. The ordinate is a measure of detectability (*d'*) and the abscissa represents the number of clicks. Because the change in ITD between successive clicks and the ICI were constant, one may consider the abscissa to be representative of a scale monotonically related to the distance. Thus, larger numbers of clicks represent a greater distance of simulated lateral movement. Not surprisingly, as the number of clicks increased, the detectability of direction of movement improved. It is noteworthy that subjects had difficulty in correctly identifying the direction of movement when the click train consisted of only six to nine clicks. The duration of the train with only six to nine clicks was 65 to 104 ms. We return to this latter observation shortly.

II. EXPERIMENT II

A. Design

Experiment II was designed to compare the ability of observers to detect the direction of movement when the information required for performing such a task was limited to the onset and offset positions of movement. The stimulus configuration was identical to that used in experiment I except that the middle clicks were eliminated. The temporal relations between the first and last clicks, however, were maintained as before. That is, in this two-click design (onset–offset), the ITD and ICI of the first and last clicks were determined as if the middle clicks were present.

B. Results

Figure 3 shows results for two subjects. The filled symbols are data from experiment I and the open symbols are data from experiment II. The upper abscissa represents the number of clicks used in experiment I and the lower abscissa plots the timing (ICI) between the onset and offset clicks. The two scales are comparable in terms of the total range of ITD covered by each train. For example, the time elapsed between the first and last clicks of a 16-click train when the middle clicks were present was 195 ms.

There was little difference in detectability when the middle clicks were present (experiment I) and when they were eliminated (onset–offset condition). One might presume from these data that the mechanism for the detection of motion relies heavily on information provided by the onset and offset positions of the moving source, and from this argue that the interaural configurations of the middle pulses were inconsequential. Experiment III was designed to address this question.

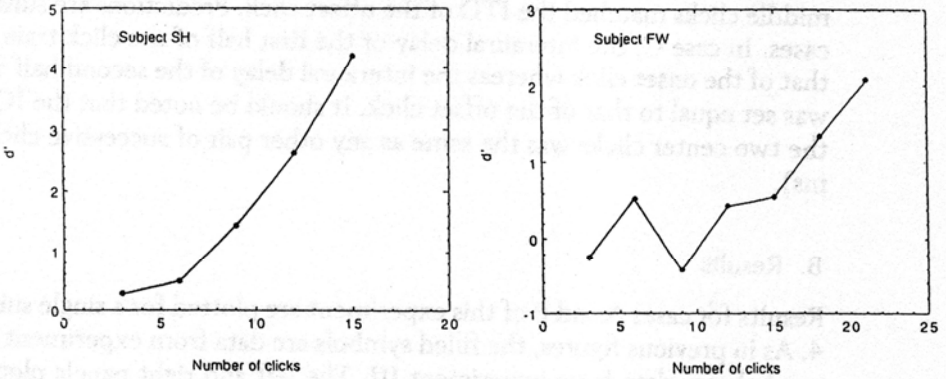

FIG. 2. Results for two subjects from experiment I.

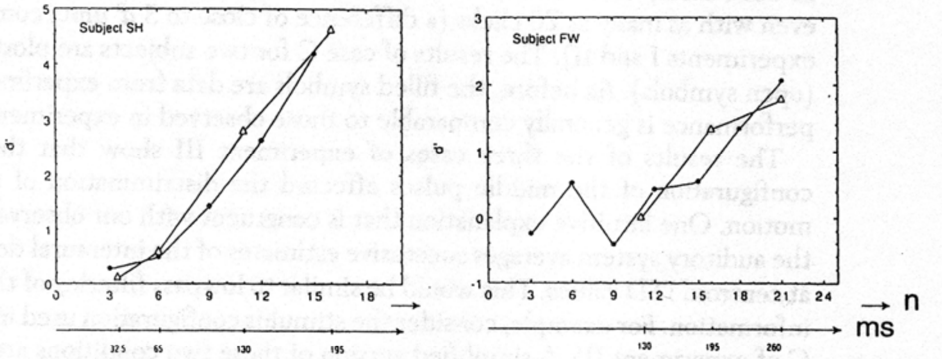

FIG. 3. Results for two subjects from experiment II (open symbols). The filled symbols are data from experiment I and are plotted for comparison. The upper abscissa refers to the number of clicks used in experiment I and the lower abscissa refers to the interclick interval between the two clicks used in experiment II.

III. EXPERIMENT III

A. Design

The purpose of this experiment was to test the idea suggested by the results of experiment II that the mechanism of motion detection is an onset–offset detector. The effective onset duration of an auditory stimulus has been estimated at 2–4 ms (Tobias and Schubert, 1959). Based on these estimates, we consider only the first click in the train to be representative of onset information. The ITDs of the middle pulses were varied according to one of three conditions. In case A, the ITDs of the middle pulses were the same as the ITD of the onset click. One may think of this as presenting the middle clicks from the same location as that of the onset click, while presenting the last click at the same position (ITD) used in experiments I and II. Note that if one accepts the hypothesis devised from the results of experiment II, the middle clicks simply repeat the position of the first click. If the binaural system were a simple onset–offset detector, performance should be identical to that obtained in experiment II. In case B, the ITD of the middle clicks matched the ITD of the offset click. Predictions are similar in both cases. In case C, the interaural delay of the first half of the click train was set to that of the onset click whereas the interaural delay of the second half of the train was set equal to that of the offset click. It should be noted that the ICI between the two center clicks was the same as any other pair of successive clicks (i.e., 13 ms).

B. Results

Results for cases A and B of this experiment are plotted for a single subject in Fig. 4. As in previous figures, the filled symbols are data from experiment I; the open symbols are data from experiment III. The left and right panels plot results for cases A and B, respectively. Comparison of these data to Fig. 3 shows that the interaural configuration of the middle pulses substantially affected performance. In both cases, detectability of the direction of motion dropped to near chance even with as many as 20 clicks (a difference of close to 3 d' units compared with experiments I and II). The results of case C for two subjects are plotted in Fig. 5 (open symbols). As before, the filled symbols are data from experiment I. Here, performance is generally comparable to those observed in experiments I and II.

The results of the three cases of experiment III show that the interaural configuration of the middle pulses affected the discrimination of direction of motion. One intuitive explanation that is congruent with our observations is that the auditory system averages successive estimates of the interaural delay to arrive at centroid ITD values. This would be similar to lowpass filtering of the interaural information. For example, consider the stimulus configuration used in cases B and C of experiment III. A simplified version of these two conditions are plotted for four-click stimuli in Fig. 6. What would our predictions be for these cases if the integration time of the averaging process was long enough to encompass two clicks? A single interaural delay would be calculated for each averaging window.

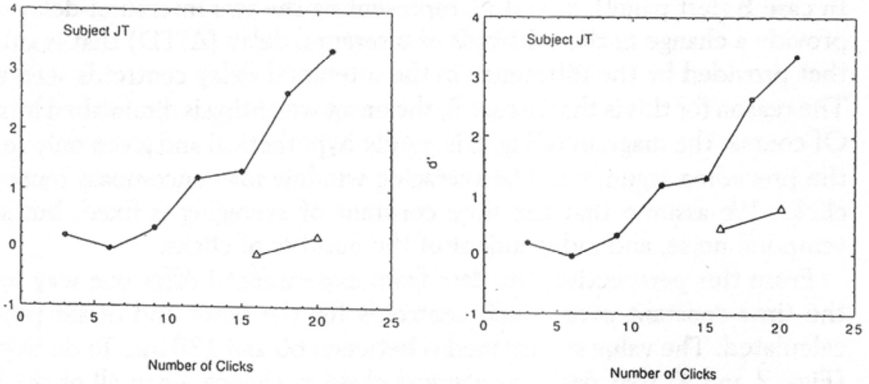

FIG. 4. The left and right panels show results for one subject from cases A and B of experiment III respectively. The filled symbols are data from experiment I and the open symbols from experiment III.

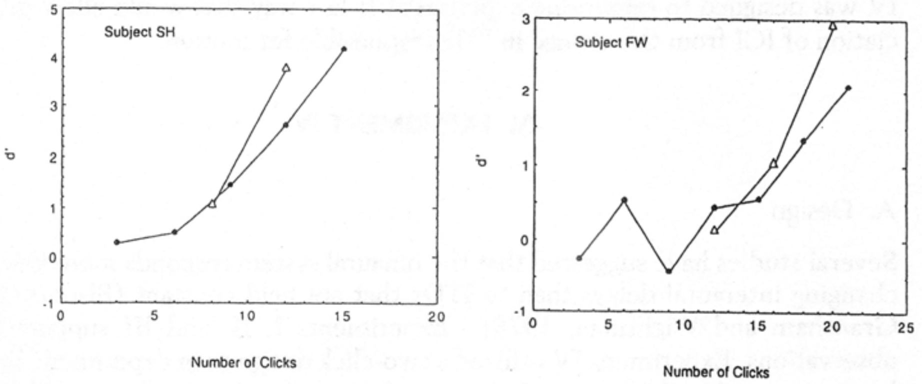

FIG. 5. Data for two subjects from case C of experiment III (open symbols) plotted together with data from experiment I (filled symbols).

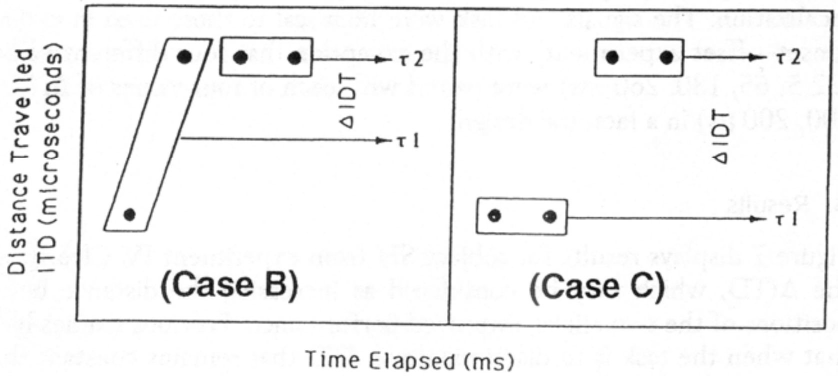

FIG. 6. Hypothetical averaging process for two cases of experiment III. The averaging window in this example has a time constant long enough to encompass two clicks. In case B, ΔITD is diminished by the averaging of interaural delays of the first two clicks.

In case B (left panel), τ_1 and τ_2, representing the two interaural-delay centroids, provide a change in the centroids of interaural delay (ΔITD) that is smaller than that provided by the difference in the interaural-delay centroids seen in case C. The reason for this is that in case B, the onset weighting is diminished by averaging. Of course, the diagram of Fig. 6 is purely hypothetical and given only to illustrate the preceding argument. The averaging window may encompass more than two clicks. We assume that the time constant of averaging is fixed, but subject to temporal noise, and independent of the number of clicks.

From this perspective, the data from experiment I offer one way to estimate the time-constant over which centroids for the onset and offset positions are calculated. The value so obtained is between 60 and 130 ms. To do this, we note (Figs. 2 and 4) that performance was close to chance when all of the clicks fell within a window of this size, implying that for these shorter trains, all of the clicks were averaged to produce a single centroid at the stimulus onset. As such, there was no cue for detecting the direction of motion. In order to obtain further information with regard to the hypothesis of averaging across clicks, experiment IV was designed to reexamine experiment II in a way that would allow disassociation of ICI from the change in ITD responsible for motion.

IV. EXPERIMENT IV

A. Design

Several studies have suggested that the binaural system responds more slowly to changing interaural delays than to ITDs that are held constant (Blauert, 1972; Grantham and Wightman, 1978).[3] Experiments I, II, and III support these observations. Experiment IV utilized a two-click design as in experiment II, only here we varied both the interclick interval (corresponding to the rate of change in interaural delay) and the magnitude of change in interaural delay between the two clicks (corresponding to the spatial distance separating the "locations" of the two clicks). The purpose was to examine spatiotemporal interactions in dynamic localization. The signals and task were identical to those used in experiment II (onset–offset experiment) with the exception that four different values of ICI (32.5, 65, 130, 260 ms) were paired with each of four values of ΔITD (25, 50, 100, 200 μs) in a factorial design.

B. Results

Figure 7 displays results for subject SH from experiment IV. Clearly, increasing the ΔITD, which may be considered as increasing the distance between the positions of the two clicks, improved performance. Previous studies have shown that when the task is to discriminate an ITD that remains constant throughout

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[3] The binaural system's ability to track changing interaural level differences is not as poor as its ability to track ITDs (Blauert, 1972).

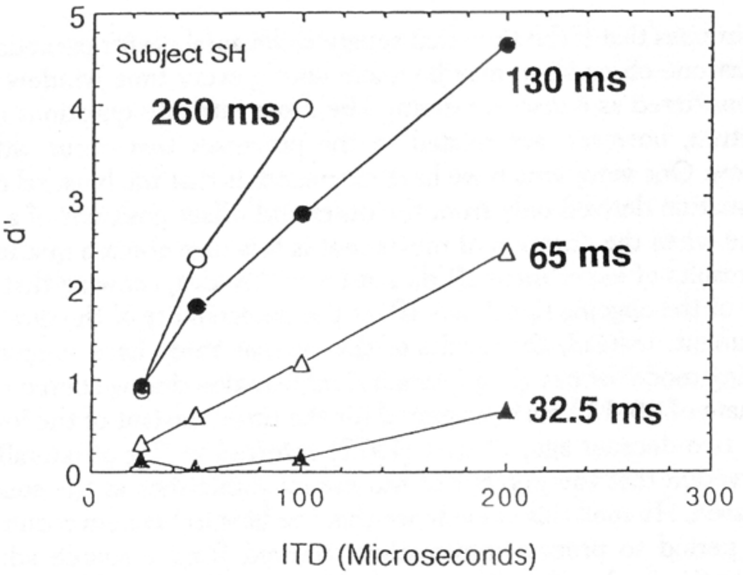

FIG. 7. Results from experiment IV (two-click design) for one subject. The abscissa represents the change in interaural delay from first to second clicks. The parameter is ICI. Filled triangles (32.5 ms), open triangles (65 ms), filled circles (130 ms), and open circles (260 ms).

the train, shortening the ICI leads to a reduction in the effectiveness of each successive click in the train, a process that has been called "binaural adaptation" (Hafter and Dye, 1983). However, if the ICI exceeds about 12 ms the effectiveness of each click is independent of the one immediately preceding it (Hafter *et al.*, 1988). In stark contrast to that result are the data with dynamically changing ITDs. Here we find improvement in the ability to detect the direction of motion when the ICI is increased from 130 to 260 ms, suggesting a lowpass filtering process that enacts an averaging of the individual parts of the stimulus over a duration on the order of 5 to 10 times as long as with the static case. The seeming long time constant of integration for motion is reminiscent of studies on the "lag of lateralization" (Blauert, 1972) or "binaural sluggishness" (Grantham and Wightman, 1978). The latter authors have suggested that the speed with which the binaural system may track interaural delays is limited by an internal noise introduced during the process of taking the time derivative of interaural delays—that is, at the stage where information about position is transformed into changing position. We note that this seeming long time constant for motion is in the range of that estimated earlier from experiment I.

V. DISCUSSION

A. Lowpass filtering of interaural delay information

The time constant of the binaural system is estimated at between 100 to 700 ms depending on psychophysical task, procedures, and stimuli employed (McFadden and Sharpley, 1972; Tobias and Zerlin, 1959; Grantham and Wightman, 1978).

This implies that if the time that separates binaural events exceeds this constant, at least one observation may be made during every time window and each may be considered as a discrete event. The more intricate questions in the binaural literature, however, are related to the processes that occur within this time window. One view, which we have examined, is that the binaural system detects information derived only from the onset and offset positions of a moving sound source when the duration of movement is less than about a quarter of a second. The results of experiment III do not favor this idea, showing that the interaural delay of the ongoing signal may affect the detectability of the direction of source movement. Instead, the results of the current study have supported a lowpass filtering model of changing interaural information during source movement. An estimate of 60–130 ms is suggested for the time constant of the lowpass process. Over two decades ago, Blauert (1972) referred to "lag of lateralization" as the observation that the percept of movement diminishes as the source velocity is increased. He took this as evidence that the binaural system requires a minimum time period to process information received from a source whose interaural information is changing. The assumed lowpass filtering of dynamically changing ITDs shown here is clearly in accord with this "lag" and the "binaural sluggishness" of Grantham and Wightman (1978).

B. Discrimination and descriptive studies of motion and implications for stationary models

Descriptive studies of binaural beats also support the idea that the binaural system lowpass filters or averages changing interaural information. A transition from movement to pulsation is reported as the interaural frequency difference, equal to the beat rate, increases beyond 2–5 Hz (Licklider, Webster, and Hedlun, 1950; von Bekesy, 1960), suggesting that the binaural system cannot track the movement of a signal whose interaural delay is rapidly changing. It is instructive to compare results obtained from these descriptive studies of motion (Licklider *et al.*, 1950; von Bekesy, 1960; Perrott and Briggs, 1972) and those obtained from discrimination experiments (Grantham, 1986; Perrott and Marlborough, 1988). Although discrimination tasks can delineate important features of dynamic processing (e.g., whether the motion mechanism is an onset–offset detector), they cannot fully explore or explain many perceptual aspects of auditory motion. Thus, researchers who have used discrimination tasks have tended to favor stationary models of motion. These models contend that the putative mechanism for coding moving auditory stimuli relies on information derived from successive sampling of positions in space. In most psychophysical motion-discrimination tasks, the observer is required to discriminate either between right and left movements or between a moving and a stationary source. Subjects' performance is then summarized by some measure of detectability, for example, *d*' or threshold for movement. Such experimental designs, by definition, require that subjects detect at least two locations. Subjects' percepts are not of interest but rather their ability to detect a change in location. Consequently, discrimination tasks are an inadequate test of the validity of stationary models, because by definition they cannot subject the theory to being proven false.

Stationary models, embodied in snapshot theory[4] (Grantham, 1986, 1989a), implicitly contend that the spatial information between successive samples of a moving auditory stimulus is lost. As the sampling period of the supposed snapshot mechanism is shortened, however, given the noise inherent in sensory systems, stationary theories become indistinguishable from those that are based on continuous information processing. Thus, snapshot theory may at best be of marginal utility if it cannot demonstrate a quantization of spatial information such that the information between long successive snapshots is lost.

In descriptive studies, qualitative reports of the moving source are solicited, for example, the binaural beat studies described earlier (Licklider *et al.*, 1950; von Bekesy, 1960) or those on apparent motion and the auditory phi phenomenon (Burtt, 1917; Strybel, Manligas, Chan, and Perrott, 1990). These latter studies have shown that when two transient and spatially separated sounds occur within short temporal intervals (<100 ms), a single image is perceived that traverses continuously through the spatial extent between the two sound sources. Our subjects reported similar percepts in experiment IV. It is noteworthy that in the latter type of studies the observer has no *a priori* knowledge of the location of the second sound until it has occurred, and therefore the percept of continuous motion must be generated retroactively; this is a phenomenon not easily explained by the simple static coding of stationary positions. In addition, other behavioral studies, such as those on adaptation (Grantham and Wightman, 1979; Grantham, 1989b, 1992), have examined the effects of prolonged exposure to moving stimuli. Behavioral responses to test stimuli favored a direction opposite to that of the adapting stimulus, suggesting an adaptation of neural elements tuned to motion.

C. Physiological studies of auditory motion

There are several animal studies on the physiology of motion detectors that may be of interest. While one should exercise caution in extending results from animal physiology to human psychophysics, the physiological literature does lend some support to a motion mechanism in at least some species. A listing of these articles is provided in Appendix I. Seventeen articles involved single-cell recording (Table I).[5] All but one article reported neural elements that may be classified as motion detectors. The criterion for classifying a unit as a motion-detector is usually one of the following: (1) it responds to an auditory stimulus moving in one direction and is either inhibitory or responds less vigorously in the opposite direction, or (2) it responds to a moving auditory stimulus but is nonresponsive to a stationary sound-source. The receptive fields of these units are usually sharper at the higher auditory centers relative to the lower centers (Altman, 1978). Some studies have reported on units with preferred velocities at the level of the cortex (Stumpf,

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[4] To our knowledge, the term snapshot was originally coined in the hearing literature by Masters, Moffat, and Simmons (1985) in describing how the bat uses discrete sonar pulses in tracking moving prey.

[5] Some articles were excluded due to insufficient information.

Table I. Summary of studies on animal physiology of auditory motion. The entries in the upper table represent the number of articles concerned with each area. The entries in the lower table represent the number of units studied in each article. For each entry, the left number represents the number of units sensitive to motion (see text) out of the total number of units studied (right number). For example, in the one motion study of the medial geniculate body, 11 out of 50 cells studied were classified as motion detectors (c = cat, g = gerbil, m = monkey). Not all articles in the upper table provided detailed information on the number of units studied.

Articles on the physiology of auditory motion detection

Superior Olive	*Inferior Colliculus*	*Superior Colliculus*	*Medial Geniculate Body*	*Cerebellum*	*Cortex*	*Other (Gross Potentials Reviews and models*
1	5	4	1	1	5	6

Total # of Articles: 23

Reported number of motion-detector units

Superior Olive	*Inferior Colliculus*	*Superior Colliculus*	*Medial Geniculate Body*	*Cerebellum*	*Cortex*
0/21	10/79 (c)	26/39 (c)	11/50 (c)	12/29 (c)	12/50 (c)
	113/145 (g,c)	10/136 (c)			63/180 (m)
	14/100 (c)				61/80 (c)
	52/114 (c)				8/25 (c)

Toronchuk, and Cynader, 1992). Others have reported on units in the superior colliculus responsive to both auditory and visual movement (Wickelgren, 1971). These latter units have the same preferred direction in both modalities. The measurement of gross potentials in human observers has also implicated a physiological mechanism tuned to motion (Ruhm, 1976; Halliday and Callaway, 1978; Altman and Vaitulevich, 1990).

SUMMARY

Although the detectability of the direction of movement of a linearly moving sound stimulus is nearly equivalent to the detectability of a sound source that marks the starting and ending positions of movement, it cannot be concluded that the motion mechanism is a simple onset–offset detector. The equivalence of performance for these two stimulus conditions may be explained if one assumes an averaging or lowpass filtering of interaural information. In support of this latter contention, altering the interaural configuration of the ongoing signal (i.e., middle pulses) demonstrates an adverse effect on detectability. Additional data show that decreasing the ICI between two clicks from 260 to 130 ms degrades the detectability of interaural information, further supporting a temporal lowpass process.

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APPENDIX I: PHYSIOLOGICAL ARTICLES ON MOTION

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