# Detection of Dynamic Changes in Interaural Delay

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#### Summary

The ability to detect a dynamic change in interaural time difference (ITD) was examined for rates of change from 3.125 to 32,000  $\mu$ s/s, for stimulus durations from 0.025 to 16 seconds, and for extent of change in interaural delay from 50 to 800  $\mu$ s. The stimulus was a sinusoidal tone of frequency f = 500 Hz presented to one ear and  $f + \Delta f$  to the other ear, where  $\Delta f$ , the frequency difference, was varied to simulate different motion velocities. In a single-interval two-alternative forced-choice design, observers were required to discriminate between a stationary tone (same frequency to both ears) whose ITD was randomly selected between trials, and a tone with a dynamic interaural delay. Results showed that performance decayed at high and low velocities, although the specific cutoff velocities were dependent on distance traveled (i.e., total change in ITD). Higher velocity cutoffs were associated with greater distances. A minimum integration time of 100–400 ms was required for most observers before peak detection was reached. Stimulus durations greater than 4 seconds led to a decline in detection of movement, presumably due to a decay of trace memory and/or lapses in attention.

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## 1. Introduction

This is a report on the role of interaural delays in auditory motion detection. A number of previous studies have investigated the roles of velocity [1, 2, 3, 4], trajectory [5], stimulus spectrum [6, 7, 8], as well as other stimulus features [9] in motion perception. Few, however, have focused on the isolated contribution of individual binaural cues. Those studies that have investigated individual cues have revealed distinctions between auditory motion systems based on interaural time differences (ITDs) and those based on interaural level differences (ILDs). Motion perception at high velocities of movement is less salient when based on dynamic ITDs. This finding has been referred to as "lag of lateralization" [10] or "binaural sluggishness" [11, 12].

The majority of ITD-based studies of auditory motion have employed sinusoidal changes in ITD either in noisebands [12] or in a binaural-beat paradigm, in which a tone of frequency f is presented to one ear, and a tone of frequency  $f + \Delta f$  is presented to the other ear [13, 14]. The difference frequency  $\Delta f$  is usually confined to within a few Hertz. The observer's task in such studies is to discriminate a perceptually beating or moving percept from a stationary one, i.e., the same tone presented to two ears. While such studies have contributed greatly to our understanding of the perception of dynamic changes in interaural delay, their focus has usually centered on the temporal lowpass characteristics of the binaural system. Discrimination in such tasks may be based upon a number of perceptual features other than perception of motion, such as loudness fluctuations, split images when tones are antiphasic, and roughness of the sound quality, all of which are valid cues. Studies that have restricted the available cues to motion are scarce [12, 9].

The current study had three specific goals. When tones of different frequencies are presented to the two ears, a beating or loudness fluctuation may be perceived for some frequency differences as the tones enter in and out of phase. Furthermore, as the interaural phase difference between tones at the two ears approaches an antiphasic condition, a percept of a dual or split image is sometimes perceived (phase wrapping). The first goal of the experiment was to examine for pure-tone stimuli, sensitivity to ITDbased motion under conditions that control for loudness variations and phase wrapping at extreme lateral positions along the interaural axis, and thus conditions that restrict detection to cues that emphasize a percept of motion. To this end, we randomized both the initial ITD of motion, as well as the ITD of stationary control tones to eliminate absolute position cues, and restricted the range of peak ITD to within less than half the period of the tone stimulus. The second goal was to investigate sensitivity to dynamic interaural delays for a very wide range of veloc-

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ities (a factor of ~10,000 between lowest and highest velocities), durations (a factor of 640 between shortest and longest stimulus durations), and "distances" (from 50 to 800  $\mu$ s total change in *ITD*). The third goal was to establish time constants for *ITD*-based motion detection. Minimum integration times were derived and an upper bound on duration was estimated where motion detection began to deteriorate, presumably due to a decay in short-term sensory memory [15, 16]. A further goal was to determine if these time constants are dependent on stimulus features other than duration per se. As will be described, some surprising interactions emerged.

# 2. Method

Four subjects participated in this experiment. Two were males and two females. All had normal hearing based on self-report, and they were paid an hourly wage for their participation. Experiments were conducted in an acoustically isolated steel chamber (Industrial Acoustics Company). Stimuli were pure tones generated in a Dell OptiPlex-Gx1 computer and presented binaurally through digital-to-analog converters (Sound Blaster Live, -120 dB noise floor) and Sony Headphones (MDR-V1) at a sampling rate of 10 kHz. They were lowpass filtered at 5 kHz, and had linear rise-decay times of 10 ms for stimulus durations of 100 ms or longer, and 5 ms for stimulus durations less than 100 ms. On a given block of trials, a combination of distance by velocity was selected from a set of predetermined values. The velocities ranged from 3.125 to 32,000  $\mu$ s/s, and the distances, measured in *ITD* units, were 50, 100, 200, 400, and  $800 \,\mu s$ . For convenience we will refer to a change in ITD as "distance" traveled, partly because a change in angular displacement in the freefield produces a corresponding monotonic change in ITD, and partly because a change in ITD is usually associated with a perceptual change in the lateral position of an intracranial image along the interaural axis. The combinations of distance and velocities led to stimulus durations from 25 ms to 16 seconds. Not all velocities were paired with all distances, but rather, velocity-distance pairs to be used were determined based on pilot data to ensure a wide range of performances leading to reliable measurements of subjects' psychometric functions. Table I shows the combinations of velocity, distance, and duration used in this study.

The experiment was conducted in a block design. On a given block of trials, one combination of velocity by distance was randomly selected from Table I. Each block of trials consisted of 50 trials and required from a few minutes for the shortest-duration stimulus, to approximately 20 minutes for the 16-s stimulus. A minimum of 4 runs were completed by each subject for each velocityby-distance condition. Subjects completed between 5 to 10 runs in a two-hour session, and there were three sessions per week. They were allowed to take breaks between blocks at anytime. They were practiced for several hours on various conditions of the experiment until their performance appeared to have stabilized. Data collection beTable I. Range of velocities V and distances (total change in ITD) tested. The entries are the durations in seconds required for the combination of velocity and distance.

	Total change in $ITD$ ( $\mu$ s)				
$V~(\mu { m s/s})$	50	100	200	400	800
3.125 6.25 12.5 25 50 100 200 400 800 1600 2000 4000 8000 16000 32000	$ \begin{array}{r} 16\\ 8\\ 4\\ 1\\ 0.5\\ 0.25\\ 0.125\\ 0.0625\\ 0.03125\\ \end{array} $	8 4 2 1 0.5 0.25 0.125 0.0625	4 2 1 0.5 0.25 0.125 0.1 0.025	8 4 2 1 0.5 0.25 0.1 0.025	16 8 4 2 1 0.5 0.1 0.025

gan after this practice period, which lasted two to three days. The experimental design was a single-interval twoalternative forced-choice paradigm. On each trial, with equal *a priori* probabilities, either a stationary tone was presented or a tone that simulated movement toward the right at the specified velocity and distance. The latter was accomplished by presenting tones of different frequencies at the two ears. The waveforms to the two channels were:

$$X_l(t) = \sin (2\pi f_l t + \phi),$$
  
 $X_r(t) = \sin (2\pi f_l (1 + V/10^6)t),$ 

where  $f_l = 500 + \varepsilon$  Hz is the frequency to the left ear,  $\varepsilon$  is a 25-Hz random perturbation on each trial to eliminate monaural pitch cues (the perturbation was applied to both the stationary and motion stimuli), the time t is in seconds, V is the rate of change in interaural delay (i.e., velocity) in  $\mu$ s/s, and

$$\phi = 2\pi f_l \ ITD_i / 10^6, \qquad 0 < ITD_i < ITD_m,$$

where  $ITD_m$  in  $\mu$ s is the maximum allowable ITD for that run, equal to distance traveled, and  $ITD_i$  is the initial interaural time difference.

When the interaural delay was dynamic, the right ear always received the higher frequency (i.e., motion toward the right ear) and the range of change in *ITD* was restricted to the region bound by +/- "distance'  $\mu$ s. The start point (i.e., initial *ITD*) was always randomized by  $\phi$  to reduce the potential cueing on absolute position. For example, if the distance traveled was 200  $\mu$ s, then the start point could be anywhere from -200 to 0  $\mu$ s. Such a randomization severely degraded fixed-location cues, forcing observers to rely on a *change* in *ITD*. Subjective reports solicited from observers suggested that in fact they relied on spatial movement cues. When the interaural delay was



Figure 1. Index of detectability, d', as a function of velocity of motion, i.e., rate of change in interaural delay. Each panel shows data from one observer. The dashed line at d' = 0 represents chance performance. A ceiling value of 3.5 was imposed on each d' calculation for conditions in which no errors were made during the 200trial run (see text). The parameter is "distance" of movement measured in interaural delay units of  $\mu$ s. Each point is based on four blocks of 50 trials each.

constant (i.e., no-motion trial), the *ITD* was randomly selected from the range of +/- distance in  $\mu$ s, again, in order to eliminate absolute-position cues (e.g., in the previous example, the *ITD* of the tone in the no-motion trial was randomly selected from -200 to  $+200 \mu$ s). The duration of the sound in the no-motion trials was always matched to that of the motion trials (from 25 ms to 16 seconds). The observer's task was to respond either "no-motion" or "motion" by pressing one of two keys on the computer keypad. If the frequencies of the tones to the two ears were the same and the subject responded no-motion, a correct-response feedback was displayed on the monitor. Similarly, if the frequencies were different and the subject responded motion, a correct-response feedback was displayed. Otherwise, an incorrect-response feedback was displayed.

The measure of performance was the index of detectability, d' [17]. Each value of d' for each condition and subject was based on 200 trials, pooled across 4 blocks. To calculate d', we estimated the hit rate from the number of "motion" responses given a dynamic interaural delay divided by total number of trials with a dynamic ITD. The false-alarm rate was calculated as the number of "motion" responses given a static ITD trial (i.e., no motion) divided by total number of trials with a static ITD. d's were then estimated by transforming hit and false-alarm rates to zscores and finding their difference [18]. It is difficult to derive reliable estimates for very high values of d' when the number of trials is not very large (usually 200 trials per point per subject in our study). This is partly because inattention often leads to chance responses on a very few trials, leading to high variability in estimates of d' above 3.5. In addition, some observers on some conditions did not make response errors in the 200 trials (i.e., a d' of infinity). Therefore, as is customary in such cases, we assumed a small inattention rate [18, 19] and imposed a ceiling value of 3.5 on d' estimates.



Figure 2. Averaged data from Figure 1.

## 3. Results

Figures 1 and 2 show data from individual subjects and mean results, respectively. The abscissa represents the velocity of movement (i.e., the rate of change in interaural delay) in  $\mu$ s/s on a logarithmic scale, and the ordinate represents d'. Figures 3 and 4 show the same data as in Figures 1 and 2, respectively, but with the abscissa representing stimulus duration. Each panel in Figures 1 and 3 presents data from one observer. The parameter in each panel is the "distance" traveled which is the change in *ITD*, in microseconds, during the presentation of the stimulus. The horizontal dashed line is plotted at d' = 0 and represents chance performance.

The data of Figures 1 and 2 show that increasing distance improved motion detection throughout the wide range of velocities and distances tested. Furthermore, performance appears to have declined at high as well as low velocities. At velocities of movement greater than about



Figure 3. Index of detectability, d', as a function of duration of the stimulus. Each panel shows data from one observer. These are the same data as in Figure 1 plotted in different coordinates. The dashed line represents chance performance and the parameter is distance. A ceiling value of 3.5 was imposed on each d' calculation for conditions in which no errors were made. Each point is based on four blocks of 50 trials each.

800  $\mu$ s/s, motion detection deteriorated, although this cutoff velocity was different for different observers. It is also noteworthy that the cutoff velocity for which motion detection began to decline was different for the various distances (parameter in Figure 1). The greater the distance traveled (and the shorter the stimulus duration), the higher was the cutoff velocity associated with a decline in performance. At the shortest distances of 50 and 100  $\mu$ s, the decline began at velocities of 200  $\mu$ s/s or less. At the longest distance of 800  $\mu$ s, the decline occurred at the higher velocities. For two subjects (DP and CL) this cutoff was, in fact, the highest velocity tested 32,000  $\mu$ s/s.

One possible explanation for these observations is the well-known multiple-looks model [20, 21] which assumes that the auditory system samples the signal at fixed intervals. The longer the duration of the signal, the more looks are taken, thereby improving performance. Note, however, that the ratios of distance (total change in *ITD*) to velocity for the shortest and longest distances (50 and 800  $\mu$ s) are approximately a factor of 10 different (i.e., 1/4 vs. 1/40). Differences in thresholds were, of course, expected since the peak *ITD* excursion was different for the two cases. However, the upper velocity cutoff at which performance declines cannot simply be attributed to duration or the multiple-looks model.

As a simple quantitative rule, for each distance traveled, there is a straightforward relation between velocities corresponding to  $d'_{\rm max}$  and  $d'_{\rm max}/2$ . The log-difference between the two velocities in Figure 2 corresponding to  $d'_{\rm max}$  and  $d'_{\rm max}/2$  is approximately constant  $k = \log_{10}(V_{d'_{\rm max}}/V_{d'_{\rm max}/2})$ . The mean value of this constant is about k = 1.3 averaged across distances, with a standard deviation of 0.2. Given that the range of velocities used is 4 log units, this variability is negligible.

As velocity was decreased to very low values, three of four observers (excluding NE) showed a decline in



Figure 4. Averaged data from Figure 3.

motion-detection ability. This was particularly evident for the shortest distance of 50  $\mu$ s, but also for two subjects at a distance of 100  $\mu$ s. For the range of velocities tested, two observers (PT and CL) showed a decline in performance at low velocities when the distance was large, i.e., greater than 200  $\mu$ s.

## 4. Discussion

Several features of our findings are worth further consideration. When motion velocity was very low, performance deteriorated. This may be attributed partially to memory decay and partly to momentary lapses of attention. At extremely low velocities the memory for an absolute position decays [22, 16] and detection of a continuous change from that location becomes more difficult. For comparison, one may consider that a source in motion at the slowest velocity ( $3.125 \,\mu$ s/s) traveling a distance of  $50 \,\mu$ s, is approximately moving at an angular velocity of  $0.3^{\circ}$ /s. While for visual stimuli this velocity is not very low, for the auditory

system which has a coarse angular-resolution ability, this rate of change in position is quite small. If it takes several seconds (i.e., 16s) to travel a small distance, then such displacement may not be easily detected. Subjects may have also lacked vigilance during these long runs, as will be discussed below. In addition to these, another explanation for poor performance given long-duration and slowly moving stimuli may be neural adaptation. Previous psychophysical reports have shown that repeated exposure to moving sound sources reduces thresholds for motion detection [23] and may produce motion afterimages in a direction opposite to the motion of the adapting stimulus [24]. A trial-by-trial analysis of error patterns for the 16-s runs showed that while there were clusters of errors, they did not necessarily occur at the ends of runs, but were scattered throughout. This pattern is more suggestive of momentary inattention than of neural adaptation.

An interesting feature of the data of Figure 1 is the shift in the upper bound on velocity for motion detection as distance was varied (i.e., the shift in the optimum velocities). This shift suggests that the cue to motion detection may have been based on distance-by-velocity interactions. To gain better insight into such interactions, it is useful to consider the effects of stimulus duration. We have replotted in Figure 3 each observer's performance as a function of duration. Figure 4 shows the mean of these data. The parameter is, again, distance traveled. Similar to what was described for Figure 2, there is also a simple quantitative relationship between  $d'_{\text{max}}$  and  $d'_{\text{max}}/2$  for each curve, in that the logarithm of the ratio of these two numbers is constant across conditions. This constant is approximately 1.2 log units, very near the value reported for Figure 2. Although performance deteriorated at short durations for all distances, distance itself played an important role in motion detection even for constant-duration stimuli. Grantham [4] has suggested that the auditory motion system requires a minimum integration time of 150 to 300 ms, above which an asymptotic performance level is reached. The data of Figure 3 support this estimate. Depending on subject, the average requisite integration time varied from about 100 ms (subject CL) to approximately 400 ms (DP). Note, however, that even though for most observers and distances, an asymptote, or at least peak performance was reached after this integration period, there were exceptions. For instance, the data of subject NE show that for the three shortest distances of 50, 100, and 200  $\mu$ s, performance continued to improve with increased duration up to several seconds. For this subject, even after the initial 400 ms, performance was not solely based on distance traveled but also on duration.

As described earlier, for very long-duration stimuli, memory decay may play a role in the slight decline in performance, at least for some subjects and conditions (Figures 3 and 4). If, however, the distance of movement is large enough, a decay of sensory memory will not substantially degrade judgments that are based on long-term memory. The small effect of long durations at larger distances may, therefore, be attributed to momentary lapses in attention since it is difficult to maintain vigilance during fifty 16-second trials. We examined the trial-by-trial data of subjects for long-duration stimuli and found that errors appeared to occur in clusters. For example, subject PT's data for 16-second duration and  $800-\mu$ s distance showed error-free runs as long as 40 trials, and points in her run where 4 errors occurred within six trials. Other subjects showed similar error clusters, as well as isolated errors, though these clusters could occur with equal likelihood at any point of a 50-trial run.

For the long-duration stimuli, subjective descriptions from our listeners were not that of an image in motion, but rather one that was slowly changing positions. This may be a subtle distinction, but as several previous studies have indicated [25], one may perceptually distinguish between a sense of motion and a perceptual experience that is better described as a change in location. These descriptions may be perceptual correlates of the responses of neural motion detectors [26, 27, 28], some of which are tuned to an optimum velocity and do not respond to non-moving sounds or respond with a decreased rate to non-optimum velocities.

In summary, we have reported data on motion detection based on dynamic changes in interaural delays for a large range of velocities (a factor of  $\sim 10,000$ ) as well as a large range of distances (50 to  $800 \,\mu s$ ) and durations (a factor of 640 between shortest and longest durations). The study was designed to restrict the range of dynamic ITD cues to within the range of natural delays, avoiding phase wrapping at the extreme lateral regions of the interaural axis, as well as cues based on loudness fluctuations, or absolute position. Using such controls emphasized cues based on a percept of motion. Our findings showed that performance deteriorated for high velocities in the range of 1600 to 32,000  $\mu$ s/s, depending on distance. Greater distances traveled were associated with a higher velocity cutoff. A decline in performance was also observed for very low velocities. This may be attributed to a number of factors including a decay of trace memory, limits imposed by internal position noise, and inattention. When plotted as a function of duration, performance was dependent on distance as well as non-monotonically on duration, inconsistent with the idea that the primary determinant of motion detection is distance traveled. The results further showed that a minimum integration time is required for asymptotic detection. For three observers, this time constant was between 100 and 400 ms consistent with previous psychophysical [4, 14] and neurophysiological reports [29]. This latter study has shown that neural motion detectors encode a sound sources' location but not its motion during the first 50 to 100 ms of stimulation. We did, however, observe a considerably longer integration time, in the order of a few seconds, for one observer (NE). An upper bound on the effects of duration on motion detection may also be observed in the order of about 4 seconds. Such long time constants are consistent with involvement of higher brain center in motion processing, as have been reported in fMRI studies of human motion perception [30, 31, 32, 33].

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