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Relative effectiveness of three stimulus variables for locating a moving sound source

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Abstract. A study is reported in which it is shown that observers can use at least three types of acoustic variables that indicate reliably when a moving sound source is passing: interaural temporal differences, the Doppler effect, and amplitude change. Each of these variables was presented in isolation and each was successful in indicating when a (simulated) moving sound source passed an observer. These three variables were put into competition (with each indicating that closest passage occurred at a different time) in an effort to determine their relative importance. It was found that amplitude change dominated interaural temporal differences which, in turn, dominated the Doppler effect stimulus variable. The results are discussed in terms of two interpretations. First, it is possible that subjects based their judgements on the potential discriminability of each stimulus variable. However, because the stimuli used involved easily discriminable changes, subjects may instead have based their judgements on the independence of a stimulus variable from different environmental situation conditions. The dominance ordering obtained supports the second interpretation.

1 Introduction

The psychoacoustic literature on localization has, for the most part, been concerned with situations in which sound sources are stationary. Under such circumstances, listeners generally rely on interaural temporal (including onset) and intensity differences or, when the source sound is familiar, on the overall intensity of the sound (von Bekesy 1949; Rosenzweig 1961). Outside of experimental settings, however, it is more commonplace for sound sources and listeners to move about. In attempting to understand how a blind person knows when it is safe to cross a city street, for example, one must understand what sorts of acoustic variables reliably indicate when cars, trucks, and so on, that is moving sound sources, have passed by. The stimulus variables that are relevant to the localization of moving sound sources include interaural temporal and amplitude differences, the Doppler effect, (monaural) amplitude change, and the reverberant properties of a sound. In the relatively few investigations that have been concerned with moving sound sources, however, the relative importance of these variables has not been evaluated. For example, Perrott and his colleagues (Perrott et al 1979; Perrott and Musicant 1981) did not attempt a fine-grain analysis of the different stimulus variables that underlie the proficiency of observers at judging the velocity of a sound source moving around their heads (see also Grantham 1986). In the studies that have entailed headphone presentation (Altman and Viskov 1977; Grantham 1983), localization (actually, lateralization) and velocity judgements of only one type of sound-source variable have been tested: temporal disparity between (and thus, interaural phase of) dichotically presented stimuli.

We have chosen to pursue this line of research by examining three types of acoustic variables that might aid observers in locating moving sources: (ongoing) interaural temporal differences, the Doppler effect, and amplitude change. The first step was to

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verify that each type of stimulus variable is, in fact, used by human observers. As we will show, each of the three types of variables is generated lawfully by a particular event. Therefore, each type in isolation ought to be useful to listeners making judgements about particular aspects of that event. Because the location of a moving object changes continually, we assessed 'localization' by asking listeners to judge when a simulated sound source passed them. Assuming that the different variables are used in localization, we then sought to determine whether or not they are differentially effective. In other words do listeners rely more on one type than on the others? This we assessed by putting the three stimulus variables into competition (that is, each indicating that closest passage occurred at a different time) as well as noting their relative usefulness in isolation. We will begin with detailed descriptions of the three stimulus variables in order to set the stage for predictions about their relative importance.

A systematic change in temporal disparity between the onsets of repeated dichotically presented stimuli is sufficient to indicate reliably the movement of a sound source. Thus, if a signal is emitted by a sound source located anywhere on either side of the perpendicular bisector of the line between the two ears, the resulting sound wave reaches one ear before it reaches the other, thus inducing a temporal disparity. As the sound source moves, a change in these interaural temporal differences is generated and, thus, is specific to aspects of the trajectory of the sound source. This temporal difference (t) can be calculated by determining the difference in distance traveled (d) by the sound wave to the two ears ($d_2 - d_1$), and dividing this by the velocity (v) of sound in air (343.5 m s^{-1} at 20 °C). This can be expressed as:

$$t = \frac{d_2 - d_1}{v}\,.$$

If, for example (and anticipating our method), a sound source emits a signal every half second, runs parallel to the line created between the two ears, passes directly in front of the observer at a distance of 15.24 m, and maintains a constant velocity of 48.28 km h^{-1}, a specific change in interaural temporal differences could be calculated across, say, fifteen signals (see table 1).

The second column of table 1 (where the first column contains the signal numbers) shows the temporal differences at the two ears in terms of onset disparity. Of course, interaural phase differences (φ) could just as easily have been shown because the two are directly related:

$$\varphi = 2\pi f_s t,$$

where f_s is the frequency of the signal.

A second type of stimulus variable that can reliably indicate movement of a sound source has been termed the Doppler effect. As a source moves forward there is a shortening of wavelength of waves in front of it and an increase in wavelength of waves behind it. These changes in wavelength alter the frequency of the signal at a stationary point of observation at some distance from the source. The following formulae can be used to determine the frequency of the signal at a distal point at a given moment during the trajectory of the source as it, respectively, approaches and recedes:

$$f_D = f_s\left(\frac{v}{v - v_s \cos\theta}\right), \qquad f_D = f_s\left(\frac{v}{v + v_s \cos\theta}\right),$$

where f_D is the observed frequency, f_s is the original frequency of the source, v is the velocity of sound in air, v_s is the velocity at which the sound source is moving, and θ is the angle between the straight line trajectory of the source and a vector drawn from the source (at a given point in its path) to the point of observation. As the source moves, this angle changes, as does the frequency at the point of observation. Thus, the frequency transformation at the observer is characterized first by a gradual decrease in frequency as the source approaches, followed by a quick downward shift as it passes the observer, and finally a gradual decrease in frequency as the sound source recedes. Based upon the same parameters that were used to calculate the interaural temporal difference transformation, an example of a Doppler effect has been outlined in the third and fourth columns (for a high-pitch and a low-pitch signal, respectively) of table 1.

Amplitude change is the final variable that we will consider. It has been shown that the intensity of a familiar sound can help observers judge the relative distance between themselves and a stationary sound source (von Bekesy 1949; Coleman 1961). The intensity of a signal at a distance r from a source is inversely proportional to r^2. Every doubling of distance, therefore, diminishes sound pressure level by 6 dB. As might be inferred from the above, if a sound source of constant amplitude is moving at a constant velocity and direction relative to a point of observation, then a change in amplitude specifying time of closest passage is generated at that point. An example of an amplitude change transformation is mapped out, based upon the same parameters that were used for the interaural temporal difference and Doppler effect examples, in the fifth column of table 1.

It should be noted that the three types of stimulus variable work together in a very particular way. In the example given, when the sound source is directly in front of the observer, each type of stimulus variable is at a critical moment. At this point the signal: (i) reaches both ears simultaneously (and has a time difference of zero), (ii) is involved in its most significant pitch change relative to the observer, and (iii) is at its peak amplitude for the observer. Thus, all three types of variables are not only related invariantly to the point of closest approach, they are related invariantly to one another. Therefore, although each type of variable should be effective in isolation, we expect the most accurate judgements to occur when all three work together.

Table 1. Acoustic[a] and location[b] parameters of a sequence of signals simulating a sound source moving on a straight line perpendicular to the line of sight of the observer. The sound source moves at a constant velocity of 48.28 km h^{-1} and passes directly in front of the observer at a distance of 15.24 m.

Signal	Acoustic parameter				Location parameter		
	t/ms	f_{Dh}/Hz	f_{Dl}/Hz	P/dB[c]	t_i/s	d_i/m	d_o/m
1	0.557	804.0	602.9	65.0	3.5	46.94	49.35
2	0.547	804.0	601.9	66.0	3.0	40.23	43.02
3	0.533	803.4	601.5	67.5	2.5	33.53	36.83
4	0.509	802.6	600.7	69.0	2.0	26.82	30.85
5	0.467	800.9	599.7	70.5	1.5	20.12	25.24
6	0.387	798.0	597.5	72.5	1.0	13.41	20.30
7	0.236	792.0	593.4	74.0	0.5	6.71	16.65
8	**0.000**	**784.0**	**587.0**	**75.0**	**0.0**	**0.00**	**15.24**
9	0.236	775.7	580.8	74.0	0.5	6.71	16.65
10	0.387	770.5	576.9	72.5	1.0	13.41	20.30
11	0.467	767.7	574.8	70.5	1.5	20.12	25.24
12	0.509	766.3	573.8	69.0	2.0	26.82	30.85
13	0.533	765.0	573.1	67.5	2.5	33.53	36.83
14	0.547	765.0	572.0	66.0	3.0	40.23	43.02
15	0.557	764.6	572.0	65.0	3.5	46.94	49.35

[a]The acoustic parameters are the interaural onset difference (t), high-pitch and low-pitch signal frequencies simulating the Doppler effect (f_{Dh} and f_{Dl}, respectively), and amplitude of the signal (P).
[b]The location parameters are time from intercept (t_i), distance from intercept (d_i), and distance from observer (d_o).
[c]dB SPL, sound pressure level referred to 20 μPa.

Isolation conditions can be used to evaluate the relative effectiveness of the three types of variables. The most effective ought to be associated with the most accurate responses. But if, as is expected, all three types are effective, then this comparison may prove to be insufficiently sensitive. Therefore, in addition to isolation conditions we used competition conditions, in which the critical moments for each type of variables do not occur simultaneously. At issue is whether or not listeners respond to one type of variable over the others.

In all conditions, the subject's task was to indicate the time at which a signal-emitting source (in this case, a simulated two-tone ambulance siren) sounded as if it was just passing him or her.

2 Method

2.1 *Subjects*

Thirteen undergraduates enrolled in an introductory psychology course at the State University of New York at Binghamton participated in this experiment as one means of fulfilling a course requirement. All subjects reported having normal hearing.

2.2 *Stimuli and apparatus*

A European ambulance siren (consisting of alternating high-pitch and low-pitch signals) was simulated with a Wavetek 132 VCG generator. Each simulation contained fifteen signals of 500 ms each alternated between two steady sine-wave tones approximately 197 Hz apart with no time between each signal (a modulation rate of two signals per second). Each signal possessed instantaneous rise and decay times and care was taken to start and end each pulse at zero crossing. Three properties of the signal—interaural onset (and hence, ongoing temporal) differences, Doppler effect, and amplitude—were manipulated in a manner appropriate to an ambulance traveling at 48.28 km h^{-1} along a line 15.24 m in front of the plane of the listener. A Northstar Horizon microcomputer was used to apply the appropriate interaural temporal difference, Doppler effect, and amplitude transformations on digital representations (12-bit at 10k sample rate) of 587 and 784 Hz tones. These transformations can be seen in table 2[(1)].

Five different types of condition were tested (see table 3). In the first condition (control sequences) the three types of variables together indicated passage at the same time (during the fifth, eighth, or eleventh signal). In the second condition (isolation sequences) each variable was presented in isolation, and the other two types were held constant: amplitude was set at 69 dB SPL; frequency alternated between 804 and 602 Hz only; and the interaural temporal difference was zero.

Three different types of competition condition were used (see table 3). In competition type A two variables were kept congruent (both indicating passage at the same signal) while the remaining variable indicated passage either three signals before or after (that is, the transformation of one variable, including the critical moment of passage, was displaced 1500 ms from the other two variables). All possible variable pairings and passage signals (in this case the fifth and eighth signals) resulted in six sequences of this type. In competition type B, all three variables were present within a given trial but each indicated passage at a different time (that is, one at the fifth, one at the eighth, and one at the eleventh signal). Again, all possible orderings of the three variables produced six sequences. Finally, competition type C involved direct competi-

(1) It should be noted that, owing to the limitations of the computer system used, small parts of these synthesized transformations could not perfectly replicate the actual transformations of the 'real-world' event. For example, we could only manipulate the ongoing temporal variable so that changes in this parameter occurred only across, and not within signals. However, table 2 shows that, in general, the deviations from the 'real-world' event were minimal. Moreover, given that subjects were accurate in judging all isolation sequences, it is reasonable to assume that our stimuli sufficiently reproduced all three stimulus variables tested.

tion between two of the three variables on a given trial (the remaining variable was held constant as in the isolation conditions). Here again a temporal disparity of three signals (the fifth and eighth) was used so that the two variables would each indicate passage 1500 ms apart. The permutations and orderings of the three variables produced an additional six sequences.

Table 2. Stimulus variable parameters used for a control sequence. The three stimulus variables simulated an ambulance travelling at 48.28 km h^{-1} along a line 15.24 m in front of the plane of the listener.

Signal	t/ms	f_D/Hz	P/dB
1	0.6	804.0	65.0
2	0.6	602.0	66.0
3	0.5	803.0	67.5
4	0.5	601.0	69.0
5	0.4	801.0	70.5
6	0.3	598.0	72.5
7	0.2	792.0	74.0
8	**0.0**	**587.0**	**75.0**
9	0.2	776.0	74.0
10	0.3	577.0	72.5
11	0.4	768.0	70.5
12	0.5	574.0	69.0
13	0.5	765.0	67.5
14	0.6	572.0	66.0
15	0.6	765.0	65.0

Table 3. Signal during which amplitude (P), interaural temporal difference (I), and Doppler effect (D) indicate passage as a function of condition.

Condition	Signal number in trial				
	5		8		11
Control	PDI	or	PDI	or	PDI
Isolation			P		
			D		
			I		
Competition type A	PD		I		
	I		PD		
	PI		D		
	D		PI		
	DI		P		
	P		DI		
Competition type B	P		D		I
	I		D		P
	D		P		I
	I		P		D
	P		I		D
	D		I		P
Competition type C	P		D		
	D		P		
	P		I		
	I		P		
	D		I		
	I		D		

Each sequence was presented four times. For sequences involving interaural temporal differences, the siren was heard to be moving right to left twice and left to right twice (sequences not involving this variable sounded as if the siren was coming straight at the listener). In order to preclude signal counting, two sequences consisted of fifteen signals and two consisted of thirteen signals. The ninety-six trials were randomly blocked into twelve blocks of eight trials each, and these blocks were presented in a different random order for every two subjects. Each trial was presented directly from the computer through two Ithaco 4302 filters set to low pass the signal at 1000 Hz. The signals were then attenuated (with Charybdis programmable attenuators) and presented through Telephonic TDH-49P headphones to subjects in a sound attenuating chamber(2). When a subject made a button-push response, the computer recorded the signal number within the given trial.

2.3 *Procedure*

Subjects were told that they would hear an ambulance-type siren which would pass from different directions. They were asked to press a button when the ambulance sounded as if it was just passing them. If the siren sounded as if it was coming from the right or the left, subjects were instructed to imagine themselves on a sidewalk facing perpendicular to the flow of traffic. If the siren sounded as if it was coming straight on, they were told to imagine themselves standing on a bridge over the flow of traffic (facing in a direction parallel to the flow). To indicate better what was meant by this task the experimenter traced the imaginary path of the ambulance with his hand. The instructions were repeated between every three blocks (four times in all). Before hearing the critical conditions, subjects heard thirty practice trials including several instances of the control sequence and sequences with two of the variables present and congruent. These trials were used to familiarize subjects with the task and the sound of the presentations and were not included in the analysis. Upon completion of the practice session, subjects heard forty-eight critical trials. At the halfway point subjects were given a 5 min rest. Then, before the critical sequences were continued, subjects again heard sixteen practice trials. The entire experiment took less than 1 h for each subject.

3 Results

For each type of stimulus variable in each trial the number (in the sequence) of the signal at which a given variable specified passage of the sound source was subtracted from the number of the signal during which the subject indicated (by a button press) hearing the source pass. In this way, a 'mean difference from the expected' (MDFE) could be calculated across the four trials constituting each sequence. Sixteen such scores (one for each sequence in which any one variable was involved) were then pooled to find an average signed MDFE per stimulus variable.

Because of the nature of these averaged signed differences (an MDFE of +3 for one condition and −3 for another condition yields a mean difference of 0), they are not useful in an analysis of relative effectiveness and accuracy. However, this measure is informative in that it can portray the degree to which subjects responded either earlier or later than the specified moment of passage for each variable in isolation. These scores were quite low, with average responses to amplitude and interaural temporal

(2) Headphone presentation has notable limitations. Clearly, any role the pinna of the ear might play in structuring the ambient sound is lost in such instances. Also, any changes in head position which might influence the location of the two ears relative to the sound source would be absent with headphones. And, as we discuss in section 4, all naturally occurring reverberant sound which might aid localization judgements is lost when synthetic stimuli are presented through headphones. Nonetheless, the technique is useful because it permits systematic investigation of specific aspects of the stimulus variables.

differences initiated less than one-half signal later than the moment of passage (0.442 and 0.333 respectively), and responses to the Doppler effect stimulus variable occurring just over one-half signal before the moment of passage (yielding a mean of −0.557).

In order to evaluate relative effectiveness and accuracy, two other indices of judgements were considered. First, an average absolute mean difference from the expected was determined for each variable. This metric was calculated in much the same way as the signed means except that the absolute difference between the expected value and actual response was used (table 4). Unfortunately, the distribution of this index failed a Cochran test for homogeneity of variance, thus violating a major assumption of the analysis of variance. The standard deviations for each of the three variables for each subject were also calculated for the competition conditions and these scores were then pooled across all subjects (table 4). Here, low relative variability in responses to a given variable can be taken as an index of high relative strength. That is, because these are differences from an expected value of zero, the standard deviations inform about more than simply the consistency of the responses. Because of this, and the fact that this index did pass the Cochran test for homogeneity of variance, it was decided that the statistical analysis would be carried out on these scores.

It can be seen from table 4 that for all conditions the order of the scores for the different variables was the same both for absolute mean and for standard deviation indices. Amplitude change dominated interaural temporal differences, which, in turn, dominated the Doppler effect when these variables were put into competition. This ordering was found to be significant in an omnibus analysis of variance ($F_{2,24} = 12.71$, $p < 0.002$) and three simple effects analyses (amplitude versus Doppler effect, $F_{1,12} = 38.64$, $p < 0.0001$; amplitude versus interaural temporal differences, $F_{1,12} = 4.85$, $p < 0.048$; interaural temporal differences versus Doppler effect, $F_{1,12} = 8.37$, $p < 0.014$).

Recall that there were three types of competition condition (A, B, and C). The averaged absolute means and averaged standard deviations for each of these are presented in table 4. Because each of these condition types yielded the same dominance ordering of variables, no formal analysis of the interaction of condition type and variable ordering was conducted. These results indicate that the relative importance of a particular stimulus variable holds over a number of different competition-type conditions.

The mean standard deviations of the MDFEs for the three isolation sequences were also calculated, this time representing the accuracy of responses to a variable of a given type. It was found that the three types of variable were ordered in the same way as when put into competition (see table 4): amplitude produced greater accuracy in responses than interaural temporal differences, which, in turn, yielded more accurate responses than

Table 4. Means of the absolute 'mean difference from expected' (MDFE) for each condition, together with the mean standard deviation, SD, of the MDFE.

Condition	Interaural differences		Doppler effect		Amplitude change	
	mean	SD	mean	SD	mean	SD
Competition type A	2.625	2.959	3.224	3.476	1.897	2.001
Competition type B	1.473	1.722	1.834	2.016	1.187	1.322
Competition type C	1.752	1.963	2.074	2.248	1.502	1.571
Competition pooled	1.975	2.255	2.415	2.743	1.532	1.513
Isolation	1.000	1.005	1.858	1.648	0.942	0.693
Control[a]	0.726	0.650	0.726	0.650	0.726	0.650

[a] Because the three variables are congruent, this calculation is the same for each.

the Doppler effect. Since only one type of isolation sequence for each variable was presented to each subject, however, no average standard deviations across subjects could be calculated. Instead, the signed means for each variable were pooled across subjects and the standard deviations of these scores yielded the values presented in table 4. Since an analysis of variance was impractical (only three standard deviations were so produced), a Cochran test of homogeneity of variance was used for analysis of the average standard deviations of the MDFEs. An omnibus Cochran test was shown to be significant ($C_{3,13} = 0.6457$, $p < 0.05$). Three simple effect tests with the ratios of these three variances used for an F test were performed. The amplitude versus Doppler effect comparison ($F_{12,12} = 5.66$, $p < 0.01$) along with the Doppler effect versus interaural temporal differences comparison $F_{12,12} = 2.65$, $p < 0.05$) were found to be significant (only the amplitude versus interaural temporal differences test was not, although their means indicated a trend in which amplitude generally elicited more accurate responses than the interaural stimulus variable).

Finally, the three control sequences (in which all three variables congruently indicated passage of the sound source) were pooled and yielded the lowest average absolute means (0.726) and lowest average standard deviations (0.650). Thus, the most accurate average responses were to the sequences that contained the most—and the most consistent—stimulation.

4 Discussion

The low absolute means and standard deviations of responses to the isolation sequences lend support to the notion that these types of stimulus variables do, in fact, reliably indicate the time of closest approach. Furthermore, when all three types of variables combined to indicate passage of the sound source congruently, subjects were most accurate in their judgements. This result attests to the adequacy of our stimulus simulation; the synthetic 'ambulance' did sound as if it was passing when all of the variables indicated this event.

A comment should be made on how subjects might be able to respond accurately to these stimuli. On first reflection, it might seem that the moment of closest approach is not indicated by the variables until after the moment has passed. For example, in the case of the amplitude variable, one might claim that observers cannot know which signal is the most intense of the series until they hear subsequent signals of lower intensity. However, as is indicated by the low signed means for each isolation condition, subjects did not respond significantly later than the moment of passage. Furthermore, in real-world situations actions must be performed accurately at the moment of closest approach (for example, the predatory behavior of animals that are auditorally guided). How might this be accomplished? One suggestion is that it is not the isolated acoustic structure at the exact moment of passage that acts as information for the time of closest approach as much as the particular changes in the overall acoustic transformations of these stimulus variables. For example, just before closest approach, the rate of change of amplitude begins to decrease relative to the rate of change generated when the sound source is further from the point of observation (for the total rate change patterning of amplitude, refer to table 1). Thus, it might be that observers base their judgements of passage on changes in the rate of change of these different stimulus variables that occur just before passage of the sound source. [For examples of such an interpretation and analysis of optical information, see Lee (1976) and Todd (1981)]. In this way, subjects need not hear the signals after the moment of closest approach in order to make their judgements. Clearly, future research in which more than one amplitude, interaural, and Doppler transformation is used could help to clarify whether or not subjects do use changes in the rate of change of these variables (rather than, say, their familiarity with the changes of particular stimuli) in making their judgements.

What might account for the obtained dominance ordering of variables that we have shown to be so consistent in our results? One conjecture is that subjects rely on whichever stimulus variable is most discriminable within a given presentation. This can be evaluated for each stimulus variable by scaling the total change in the relevant parameter (time, frequency, or intensity) to the difference limen for that parameter. Details of the evaluations for each variable are given in the appendix. It should be noted that these discriminability indices are necessarily approximate in that the discrimination functions used for their calculation were taken from experiments in which highly trained subjects and simple stimuli under conditions of minimal stimulus uncertainty were used (unlike in this experiment). Furthermore, the existence of differential practice effects for the three types of stimulus variables was not considered here. (Owing to the limitations of the apparatus used to generate our stimuli, determination of discrimination functions for the stimuli used here proved impossible.)

In any event, these calculations indicate that, for the stimuli presented to subjects in our experiment, interaural temporal differences have the highest index of discriminability, followed by the Doppler effect, and, finally, amplitude change. If discriminability is the governing principle, then in both isolation and competition conditions the ordering of the variables should follow this pattern. The results, however, do not support this interpretation. In fact the variable calculated to have the fewest potential just noticeable differences (JND) per sequence—amplitude change—dominated in all of the competition analyses and elicited the most accurate responses in the isolation analyses[3]. But it must be reiterated that, although many aspects of our stimuli are taken into account in these calculations (see the appendix), the discriminability interpretation cannot be evaluated fully at this time.

It should be noted that all signals used in the present experiment involved easily discriminable changes. It could be argued that, as long as this was true, finer discriminability would be inconsequential. Thus, as an alternative interpretation regarding differential effectiveness, it might be worthwhile to consider the usefulness of the variables as they are produced by real-world sources that exist in environmental situations involving different velocities, paths, and sound sources[4]. If use of one type of variable is generalized to a wide variety of circumstances—that is, if one type were useful in more situations—then it should dominate. If one considers generalizability to be the principle underlying effectiveness, an ordering different from that predicted by the discriminability interpretation is suggested. In this view, reliance on the Doppler effect (in terms of detectable pitch change) would be undermined because it is likely to be undetectable for certain types of sound sources (those that produce clicks or squeaks lacking the requisite pitch changes) or at extremely slow velocities [where the change of frequency may be so slight as to fall below the difference limen (see Wier et al 1977)].

In contrast, interaural temporal differences are useful regardless of the nature of most (real-world) sound sources. For example, it has been reported that even 1 ms clicks yield good apparent motion (Altman and Viskov 1977). Moreover, even stationary sound sources can be localized through interaural differences (Rosenzweig 1961). An angle of approach in the sagittal plane, however, would produce no inter-

(3) However, it should be noted that the finding that the variables ordered the same way both for isolation and for competition conditions is, in itself, consistent with the discriminability interpretation.

(4) Regarding the nature of the sound source as a situation condition, it is acknowledged that real-world sound sources often do not have constant intensity and frequency properties. However, in most situations these properties tend to change within a relatively limited range. It might be the case that in natural conditions it is the overall change of this range, occurring as a result of movement of the sound source, that subjects detect and base their judgements on. In this way, the three stimulus variables are not affected differentially by this aspect of the nature of a sound source.

aural temporal differences, whereas an approach along the cone of confusion would produce the same interaural temporal differences throughout the path of the sound source thereby limiting the generalizability of this stimulus type.

In the foregoing circumstances where the Doppler effect and interaural temporal differences are equivocal, amplitude change is reliable. It is specific to a source's trajectory irrespective of the angle of approach. It is indifferent to the velocity of the sound source [as suggested by the early localization studies of von Bekesy (1949) with single presentations of a familiar sound source with constant source amplitude]. Also, it is useable for any type of sound source: owing to the difference limens for amplitude (Yost and Neilson 1985) and the fact that intensity of a source decreases so rapidly as one moves away from it, for all intents and purposes if the signal can be detected at all, amplitude change can also be detected.

Based on the above analysis our second interpretation would predict that amplitude change should be the most dominant type of stimulus variable in competition conditions. Also, from this perspective, responses to the amplitude variable in isolation should, on the whole, be more accurate than responses to presentations that include only interaural temporal differences or the Doppler effect variables.

Clearly, the results are consistent with the generalizability interpretation. In all cases, the stimulus variable independent of the three situation conditions that we considered (amplitude) dominated the type dependent on one condition (interaural temporal differences), which dominated the stimulus variable dependent on two situation conditions (Doppler effect). Furthermore, this same ordering was found for accuracy judgements when each variable was presented in isolation.

These results provide a successful first pass at understanding the relative contributions of different types of stimulus variables for localization of moving sound sources. The variables used here, however, do not faithfully mimic what listeners would encounter in natural circumstances. Judgements of the position of a sound source are most often based on stimuli that are structured by the reflecting surfaces of the environment as well as on the moving sound source event itself (Warren 1982). Hence, the amplitude, interaural temporal difference, and Doppler effect variables are commonly much more intricate than was true of the synthetic stimuli used here. Whether or not this consideration would influence the relative dominance of the stimulus variables remains to be seen. Nonetheless, the same methodological strategy ought to be useful in evaluating other types of acoustic information so that a better understanding of how humans localize moving sound sources can be pursued.

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APPENDIX

Indices of discriminability for each stimulus variable

Indices of discriminability were calculated using the parameters provided in table 2. Discriminability of changes in interaural temporal differences is a function of the frequency of the signal as well as of the initial temporal disparity. For example, Mills (1958) has shown that for a 700 Hz signal with an initial baseline interaural onset disparity of 600 μs, a change of 22.5 μs (yielding an interaural temporal disparity of either 622.5 μs or 577.5 μs) is needed for highly trained listeners to hear a change in the relative location of that signal. Using this criterion, and taking into account the changing baseline disparity (or simulated lateral extent), inspection of table 2 reveals no JND between signals 1 and 2, 4.4 (100 μs/22.5 μs = 4.4) potential JNDs between signals 2 and 3, and so on for each signal step (3 to 4, 4 to 5, ..., 14 to 15). Adding these scores yields a rough index of the potential discriminability of interaural temporal difference changes. For the stimuli used here, a score of 80.2 total potential JNDs was calculated.

The difference limen for frequency of steady sine-wave tones depends on the duration, intensity, and initial frequency of the signal (Freyman and Nelson 1986; Wier et al 1977). Furthermore, it has been found that in simulated Doppler shift contexts, the corresponding intensity change can affect significantly discrimination of frequency changes(5) (Jorasz 1982; Ryffert et al 1979). Given equal durations and intensities, however, the difference limen for frequency increases with initial frequency. For example, it has been found that for highly trained subjects, an 800 Hz frequency of 500 ms has a difference limen of 1.2 Hz, whereas a 600 Hz tone is discriminable with a change of only 1 Hz [using $\log \Delta f$ proportional to $f^{\frac{1}{2}}$ (after Wier et al 1977)]. Keeping this in mind, an index of discriminability was calculated for the Doppler effect variable for the signal steps outlined in table 2. Because the stimulus presentation alternated between high and low tones, however, a scaled JND was found for every other signal step. Hence, the changes from 804 Hz to 803 Hz (signals 1 and 3) and from 602 Hz to 601 Hz (signals 2 and 4) were evaluated separately. The summed scores yielded a rough discriminability index of 62.5 for the Doppler effect stimuli. Although it has been shown that both recognition and discrimination of pitch can be affected by the presentation of intervening tones between the tones to be judged (Deutsch 1975), it is not clear whether this need be the case with the stimuli used in this study. Here, although either the high or low tone sets can be thought to 'intervene' and therefore hinder the discrimination of the other, it should be noted that both sets change frequency at the same general rate (unlike the stimuli used by Deutsch), which could potentially aid in overall pitch discrimination.

Finally, it has been shown that the difference limen for amplitude change is dependent on the duration, frequency, and initial amplitude of a signal (Florentine 1986; Yost and Neilson 1985). If we simplify and consider our 500 ms tones to be a constant 700 Hz (a difference of 200 Hz at these levels matters little), however, and calculate the number of potential JNDs for each signal step, we obtain a summed rough index of amplitude change discriminability of 31.4 for our stimulus set.

(5) Given the potential discriminability interpretation, it would seem that these findings might have implications for the potential relative effectiveness of pitch change in competition conditions (where intensity change is involved). However, they are not relevant to our finding about the relative accuracy of judgements when the Doppler effect frequency change was presented in isolation (where intensity change is not involved). In this case, although the potential discriminability interpretation predicts that judgements using this type of stimulation alone should be more accurate than judgements based on intensity change, table 4 shows that this is clearly not the case.