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

Lawrence D Rosenblum †, Claudia Carello, Richard E Pastore
State University of New York at Binghamton, Binghamton, NY 13901, USA
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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 Békésy 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

† Author to whom requests for reprints should be sent. Present addresses: Haskins Laboratories, 270 Crown Street, New Haven, CT 06511, USA; Department of Psychology, University of Connecticut, Storrs, CT 06268, USA.

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:

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

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_i /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

^aThe acoustic parameters are the interaural onset difference (t_i), high-pitch and low-pitch signal frequencies simulating the Doppler effect (f_{Dh} and f_{Dl} , respectively), and amplitude of the signal (P).

^bThe location parameters are time from intercept (t_i), distance from intercept (d_i), and distance from observer (d_o).

^cdB SPL, sound pressure level referred to 20 μ Pa.

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	<i>t</i> /ms	<i>f_D</i> /Hz	<i>P</i> /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
	PDI	or	PDI	or	PDI
Control					
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		