Journal of Experimental Psychology:
Human Perception and Performance
1996, Vol. 22, No. 4, 970–985

0096-1523/96/$3.00

The Doppler Illusion: The Influence of Dynamic Intensity Change on Perceived Pitch

John G. Neuhoff and Michael K. McBeath
Kent State University

Four studies illustrate a new auditory illusion associated with the Doppler effect and demonstrate a new influence of dynamic intensity change on perceived pitch. Experiment 1 confirmed the existence of a popular belief that the pitch of a moving sound source rises as the source approaches. Because there is no corresponding rise in frequency, the authors refer to the perceived pitch rise as the *Doppler illusion.* Experiment 2 confirmed that the effect occurs perceptually, so the belief in a "naive principle" of physics has a perceptual basis. Experiment 3 confirmed the effect does not occur under matched static conditions. Experiment 4 showed that the influence of dynamic intensity change on perceived pitch occurs outside the realm of Doppler stimuli. The findings support a dynamic dimensional interaction of pitch and loudness, with marked differences in the perception of pitch and loudness under static and dynamic conditions.

For 2 days in 1845 a locomotive pulled an open car of trumpeters past a group of observers to demonstrate a new principle of wave mechanics derived by Johan C. Doppler (Doppler, 1842). The *Doppler effect,* as it came to be known, refers to the change in frequency that occurs when there is relative motion between a wave-emitting source and an observer. Familiar examples may be the pitch change heard in a train's horn as it passes a crossing or an ambulance siren as it passes on the street. The Doppler effect has since become a valuable tool in various fields that use wave mechanics, including astronomy, communications, meteorology, and medicine. Applications range from tracking the movement of galaxies to monitoring fetal heart activity.

In the auditory domain a sound source traveling at a constant velocity past a stationary observer will drop in observed frequency both as it approaches and departs. Here, the term *observed frequency* refers to the physical frequency of the sound, measured at the point of observation. The present work introduces and investigates a perceived rise in pitch for a passing sound source as it approaches an observer. Because no rise in frequency actually occurs, we call this perception the *Doppler illusion.* In addition, we begin to explore how these findings may relate to auditory localization, current models of pitch perception, and how the dynamic dimensional interaction of pitch and loudness may play a role in producing the phenomenon.

Static Versus Dynamic Models

Like almost all of the sounds we hear, a Doppler shifted sound changes in frequency and intensity over time. Traditional studies examined the dimensions of pitch and loudness by using static stimuli with paradigms such as stimulus-matching, bisection, forced choice, and magnitude estimation (e.g., Falmagne, Iverson, & Marcovici, 1979; Fletcher & Munson, 1933; Garner, 1954; Marks, 1979; Stevens, 1934, 1955; Stevens & Volkmann, 1940; Stevens, Volkmann, & Newman, 1937; see also Shepard, 1982). These investigations have brought about several different approaches to modeling pitch perception. The mel scale, for example, takes into account that two tones in a low-frequency range are less discriminable than two tones the same distance apart in a higher frequency range and provides equal steps of perceived pitch across the frequency range (Stevens & Volkmann, 1940; Stevens et al., 1937). The "helix" model of pitch perception accounts for the perceived similarity of octaves in a musical context (Shepard, 1965). Subsequent modifications of the helix included a double helix, a double helix wound around a torus, and a double helix wound around a helical cylinder (Shepard, 1978, 1981, 1982). These modifications use a more complex geometric structure to better account for the special relationships between harmonic tones when pitch perception occurs in a musical context. Like the one-dimensional models they sought to replace, however, these models are all based on a representation of static tones.

There can be inherent shortcomings in generalizing dynamic perception from findings with static stimuli. For example, a 500 Hz stationary tone can be localized to within ±1° of azimuth (Mills, 1958). Generalizing from the static model to the dynamic case, we would predict then that the

---

John G. Neuhoff and Michael K. McBeath, Department of Psychology, Kent State University.

This work was supported by a Grant in Aid of Research from Sigma Xi and a fellowship from the Applied Psychology Center at Kent State University. We wish to thank Larry Marks, William Merriman, Barbara Neuhoff, John Marazita, and Karen McBeath for their thoughtful comments. We also thank Paul Kiem and Meg Starick for their dedicated help with the data collection.

Correspondence concerning this article should be addressed to John G. Neuhoff, who is now at the Department of Psychology, Lafayette College, Easton, Pennsylvania 18042-1781. Electronic mail may be sent via Internet to neuhoff@lafayette.edu.

motion of a sound source should be detectable when the source has traveled at least 2°. Yet a sound source in motion can travel up to 10 times this distance before the motion can be detected, and the velocity of the source influences the distance required for detection (Harris & Sergeant, 1971; Perrott & Musicant, 1977).

Similarly, informative stimuli that undergo dynamic transformation are remembered better than those that do not (Campbell & Dodd, 1980; Glenberg, 1990; Kallman & Cameron, 1989). In conveying directional information, Kallman and Cameron found an enhanced recency effect for a dynamic stimulus that moved in an upward direction, compared with the static presentation of the word *up*. Thus, models based on static stimuli may not adequately describe dynamic perception. Dynamic stimuli should be used. In audition Doppler-shifted tones are an example of such stimuli.

The Doppler effect is a naturally occurring auditory phenomenon that has received little attention in the psychological literature. Some work has explored its effectiveness as a localization cue (Rosenblum, Carello, & Pastore, 1987). Yet the Doppler shift is also interesting because it presents a situation in which the physical reality of decreasing frequency and the belief or perceived experience of rising pitch may be at odds. Such a naturally occurring auditory illusion might provide a valuable and ecologically valid tool that could be used to investigate the area of dynamic pitch perception and representation. Before illustrating the Doppler illusion, however, we first discuss the physics behind it.

Physics of the Doppler Shift

As a sound source moves forward it emits sound waves in all directions. The source travels in the same direction and in effect chases the sound waves it previously emitted in front of it and travels away from the waves it has emitted behind it. All the while the sound source continues to emit new sound waves. The effect is a decrease in the distance between the wave crests in front of the sound source, and an increase in the distance between the wave crests behind it. These changes in wavelength yield a corresponding difference in frequency in front of and behind the source (see Figure 1).

The frequency at any given observation point can be determined by the following formula:

$$f_D = f_S\left(\frac{v}{v + v_S\cos\theta}\right), \tag{1}$$

where f_D is the observed frequency; f_S is the source frequency; v is the velocity of sound in air; v_S is the velocity of the moving sound source; and θ is the angle formed by the observer, the source, and the direction the source is headed (see Figure 2).

As long as the velocity of the sound source remains constant, the frequency of the waves projected in any given direction does not increase or decrease. The observed frequency in front of the moving source will be higher than the actual source frequency, and the observed frequency behind the moving source will be lower than the source frequency. Assuming the source maintains a constant velocity and emitted frequency, there is no point of observation from which we could obtain a rise in frequency. This may at first seem counterintuitive given that the observed frequency in front of the sound source is higher than the emitted frequency. However, when a moving sound source first becomes audible to an observer, the observer hears this "higher than emitted" frequency, not the actual source frequency. The observed frequency will then gradually decrease as the source approaches, decrease dramatically as it passes, and continue to gradually decrease as the source recedes. This observed fall in frequency occurs because during the passage of the sound source a stationary observer goes from being in front of the source, where the observed frequency is higher than the emitted frequency, to being behind the source, where the observed frequency is lower than the emitted frequency.

Belief in Naive Principles of Physics

The frequency of a sound is the primary (but not sole) determinant of experienced pitch. Generally, as the

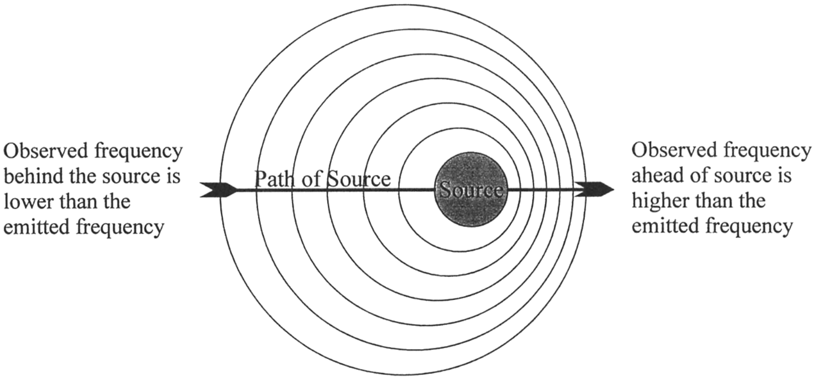

Figure 1. Wave pattern for a sound source in motion at a constant velocity.

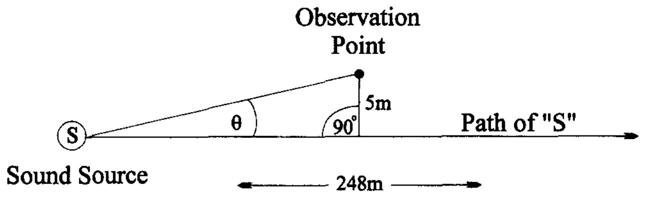

Figure 2. Path of sound source *S* and the straight-line trajectory between the source and observer. This is the source path relative to observer simulated in Experiment 2.

frequency of a sound increases we experience a rise in pitch. In a Doppler-shifted tone, the lack of an increase in frequency at the point of observation suggests that we should not expect observers to experience a rise in pitch as a sound source approaches and passes.

Yet there appears to be a commonly held belief that for a source approaching at a constant velocity, the sound does rise in pitch. This perceptual phenomenon has been consistently characterized in the literature as a *rise* or *increase* in pitch as the sound source approaches, a dramatic fall as it passes, and a gradual fall as the object recedes (e.g., Bernstein, 1993; Graham, 1965; Levarie & Levy, 1975; Morris, 1992; Schneider & Schneider, 1992; Speaks, 1992; Uvarov & Isaacs, 1986). However, the literature lacks a satisfactory explanation as to why such a rise in pitch is heard given that frequency at the point of observation does not increase.

Previous work (Kaiser, Proffitt, & Anderson, 1985; McCloskey, 1983; McCloskey, Caramazza, & Green, 1980) has shown that participants often exhibit erroneous or naive beliefs about physical principles (e.g., impetus theories of motion). Participants use these beliefs both in answering questions about physics problems and in interacting with physical objects (McCloskey & Kohl, 1983). The abundance of literature citing a rise in pitch as a sound source approaches when there is clearly no rise in frequency suggests that the Doppler effect may be another instance in which participants exhibit erroneous beliefs about physical principles.

However, if this is the case, then the Doppler effect differs from other examples of naive physics in that it appears to extend to the presumed experts in the field. Traditionally, studies of naive physics have proposed that the erroneous beliefs are due to intuitive but incorrect theories and that these theories develop over time. Kaiser, McCloskey, and Proffitt (1986) found a U-shaped function in the development of curvilinear theories of motion. Kindergarten and preschool children performed as well as college students when asked to draw the path of a ball exiting a curved tube. Both groups, however, outperformed school-age children. The preschoolers were thought to be operating on a concrete level, whereas the older children had begun to develop general principles of motion (some erroneous) to help them predict the motion of objects. Through experience or formal instruction many older participants had apparently realized that in the absence of an external force, curvilinear motion does not occur. This led to a performance improvement over the school-age children.

If formal instruction and experience are the keys to older participants' improved performance, then we would expect experts to exhibit little if any belief in naive principles of Doppler stimuli. However, as previously pointed out, a notable number of expert sources in both physics and audition cite the rise in pitch of an approaching sound source, thus suggesting several possibilities. First, the experience of Doppler-shifted stimuli may do little to dispel and may even reinforce the belief in rising pitch as a sound source approaches. That is to say that although frequency remains constant and then falls as the source approaches, observers may experience a rise in pitch nevertheless and would have little basis for abandoning their naive beliefs. Second, because this belief has found its way into the literature, perhaps even some experts have been taught that pitch rises as a sound source approaches.

In our first study we surveyed participants to determine if there is, in fact, a popular belief that the pitch of an approaching sound source rises. In our second study participants were presented with Doppler-shifted tones to determine if the pitch rise occurs perceptually. Our third study was a control condition to assess the influence of static amplitude differences that occur as the source approaches the observer. In our fourth and final study we assess perceived pitch change when participants are presented with changes in frequency as intensity is held constant and changes in intensity as frequency is held constant.

Experiment 1

Method

Participants. Two hundred ninety-two introductory psychology students served as participants. All were volunteers who received class credit for participation in a mass testing session.

Procedure. Participants were surveyed in one session in an auditorium. Each participant answered a paper-and-pencil survey that contained the following question:

> 1. Imagine that you are at a railroad crossing waiting for a rapidly approaching train to pass. As the train approaches from the distance it blows its horn, and continues to do so until it is well past you. While the train's horn does not actually change pitch, it may sound as though it does from where you are standing. Which of the following best describes how the pitch seems to change?
>
> The pitch seems to:
> (A) Rise as the train approaches, and rise higher as it passes.
> (B) Fall as the train approaches, and fall lower as it passes.
> (C) Rise as the train approaches, and fall as it passes.
> (D) Fall as the train approaches, and rise as it passes.
> (D) Remain constant as the train approaches, and fall as it passes.
> (F) The pitch does not seem to change.

The word *pitch* was used in the descriptive paragraph instead of *frequency* to make the question less confusing to the participants.

Results

The number of responses for each alternative were as follows: A, 29; B, 5; C, 232; D, 11; E, 9; and F, 6. Because the primary concern was pitch change as the sound source approached, responses A and C were collapsed into one pitch rise on approach category ($n = 261$) and responses B and D were collapsed into one pitch fall on approach category ($n = 16$). A chi-square analysis showed a significant preference for the rise category over the fall category when the no change on approach responses (E and F) were excluded from the analysis, χ^2 (1, $N = 277$) = 206.33, $p < .001$. The preference remained even if the no change on approach responses were grouped with the fall responses in a rise versus no rise comparison, χ^2 (1, $N = 292$) = 181.16, $p < .001$.

Discussion

Experiment 1 confirmed the existence of a popular belief that the pitch of an approaching sound source rises, even though frequency remains constant then falls. That this belief has worked itself into the literature with seemingly no physical explanation for the phenomenon is further evidence that the effect is a robust one. The basis for this belief, however, is still untested. It may be based on a systematic error in memory for pitch change or on some erroneous principle of naive physics. Alternatively, the belief could be based on an illusory rise in pitch that is actually experienced. If this is the case, belief in the rising pitch of approaching objects would differ substantially from previous studies of naive physics in that experiencing the phenomenon would do little to dispel the erroneous belief. One might even have difficulty calling the belief erroneous at all, because broadly construed, pitch is defined as the subjective experience of frequency. In instances in which there is a discrepancy between the physical stimulus and the subjective experience of that stimulus, we typically call the phenomenon an *illusion.*

It should also be noted that an accelerating object approaching an observer could produce a rise in frequency at the point of observation. This is an unlikely explanation for the results of Experiment 1, however, because there is no ostensible reason to believe that accelerating objects would be encountered any more often than decelerating objects or objects of constant velocity.

Experiment 2 was performed to determine if a rise in pitch is an illusion that is actually perceived as a sound source approaches. Participants were presented with computer-generated Doppler-shifted tones, and responses to pitch change were measured in real time. In addition to testing for the existence of the illusion, we wanted to explore the stimulus space to test factors that seemed likely to influence pitch rise. These included source frequency, spectral complexity, and source velocity.

Experiment 2

In a Doppler shift the velocity of the source influences the rate and magnitude of change in observed frequency and the rate of change in observed intensity. Because rate and magnitude of change in either of these dimensions are important factors in the Doppler effect, we hypothesized that velocity may also influence an illusory rise in pitch. We therefore used three velocities of the simulated sound source.

In some instances, the spectral composition (or waveform complexity) of a sound can also affect its pitch (de Boer, 1956; Schouten, Ritsma, & Cardozo, 1962). However, the influence of timbre on pitch is somewhat controversial. Some researchers have found that complex tones are generally perceived as higher in pitch than a pure tone of the same fundamental frequency (Greer, 1970; Lichte, 1941; Platt & Racine, 1985). Bannister (1934) found that this difference in pitch increased as the harmonics in the complex tone became more pronounced. On the other hand, several theories of pitch perception for complex tones predict that the pitch of a complex tone will be perceived as lower in pitch than a pure tone of the same frequency (Goldstein, 1973; Terhardt, 1970; Wightman, 1973). As noted by Terhardt and Grubert (1987), blanket statements concerning the influence of timbre on pitch are probably inappropriate, because the effects can be colored by sound pressure level, frequency, individual differences, and methodology. To assess the influence of timbre on pitch in a dynamic setting, we presented three waveforms that differed in spectral complexity.

Although frequency has by far the most significant influence on pitch perception, it has been shown that the intensity of pure tones can also affect our perception of pitch (Stevens, 1935). For example, a singer who is asked to reproduce the pitch of a tuning fork at middle C (256 Hz) will sing a slightly lower pitch when the tuning fork is held close to the ear than when it is held further away (Miles, 1914). In other words, in this frequency range the louder tone is perceived as lower in pitch. Whereas individual differences in the magnitude of pitch change are great, the direction of pitch change caused by an increase in intensity remains fairly constant across participants and depends on the initial frequency of the pure tone. An 80 dB pure tone at a frequency above 4000 Hz will generally be perceived as higher in pitch than the same frequency pure tone at 40 dB. The opposite holds true for pure tones below 2500 Hz (Gulick, 1971). That is, an 80-dB pure tone below 2500 Hz will generally be perceived as lower in pitch than a 40-dB pure tone of the same frequency. In both cases the degree of change is typically less than 3% (Cohen, 1961; Zwicker & Fastl, 1990). Accordingly, we varied the source frequency of the stimulus tones. A total of three frequencies were tested—all below 2500 Hz, at which an intensity increase should produce a decrease in pitch. Frequencies above 2500 Hz were not tested, because in this range a rise in pitch could simply be attributed to the increase in intensity that occurs as the source draws closer to the observer. It was hypothesized that the higher the initial frequency of the stimuli, the greater the perceived rise in pitch would be, because at lower frequencies any rise in pitch due to the Doppler illusion would be offset by a drop in pitch caused by the increase in intensity. A 3 × 3 × 3 within-subjects design was used with main factors of velocity, spectral complexity, and source frequency. Finally, we hoped to obtain an estimate of the magnitude of the pitch rise relative to the amount of pitch fall. Our dependent variable, therefore, was the ratio of degree of pitch rise to pitch fall.

Method

Participants. Four male and 7 female introductory psychology students between the ages of 18 and 24 years served as participants. All were volunteers who received class credit for participation, and all were naive of the hypothesis being tested. None of the participants were professional musicians, music majors, or had any formal music training past high school.

Apparatus. Stimulus tones were generated by a Korg DSM 1 tone generator. The tones were presented to the participants through Radio Shack Nova 40 headphones. The intensity, frequency, and presentation of the tones were controlled by a Northgate 486 IBM PC compatible computer. Responses were made on the vertically mounted pitch controller wheel of a Casio CZ-1 synthesizer and recorded by the computer. The response wheel had a notched zero point and was spring loaded so that it returned to this zero point after each trial.

Stimuli. The change in intensity and frequency of the stimulus tones were designed to simulate a 108-dB sound source approaching and passing an observer located 5 m above the path traveled by the source, as though the observer was on a bridge overlooking the path of the sound source. The total travel distance simulated by the sound source was 248 m. The observation point was 5 m perpendicular to this path at precisely the halfway point (see Figure 2). For all tones frequency remained constant for a short period, initiated a dramatic downward shift prior to the point of closest approach, then leveled off at a lower frequency after the point of closest approach. Stimulus intensity at onset for each tone was 58 dB, rose to 86 dB at the halfway point, and then returned to 58 dB at terminus. Intensity at each point along the simulated path was determined by the inverse square law, $I = P/2\pi r^2$, where I is acoustic intensity, P is the power of the sound source, and r is distance from the source to the observer. Because all stimulus tones were consistent with the physics of the Doppler effect (i.e., could be produced by an actual sound source in motion), the rate of change in intensity was determined by the simulated velocity for each tone. Frequency change for each tone was determined by the following formula:

$$f_D = f_S\left(\frac{v}{v + v_S\cos\theta}\right), \tag{2}$$

where f_D is the observed frequency; f_S is the source frequency; v is the velocity of sound in air; v_S is the velocity of the moving sound source; and θ is the angle formed by the observer, the source, and the direction the source is headed. Twenty-seven stimuli were composed from three source frequencies (220 Hz, 932 Hz, and 2093 Hz), three waveforms varying in spectral complexity (sine, square, and complex), and three different velocities of the simulated sound source (10 m/s, 15 m/s, and 20 m/s; see Figures 3 and 4).

Design and procedure. Participants were tested individually in a sound-attenuating booth. Each participant heard each stimulus tone twice. Tones were presented in random order constrained by trials. This yielded two sequences of 27 tones for a total of 54 presentations. There were pauses of 3 s between each presentation and a pause of approximately 30 s between Sequence 1 and Sequence 2. Participants were told that they would hear a series of tones that may change in pitch and that may also change in loudness. It was then explained that changes in pitch were changes in the highness or lowness of a tone and that changes in loudness meant that the tone may get louder or quieter. Any further questions about the difference between pitch and loudness were answered. Participants were then instructed to listen carefully to the tones for any changes in pitch and to ignore any changes in loudness. They were also told that while the tone was playing they were to move the response wheel forward (away from them) if they heard the pitch rise and to move the pitch wheel backward (toward them) if they heard the pitch fall. They were instructed that

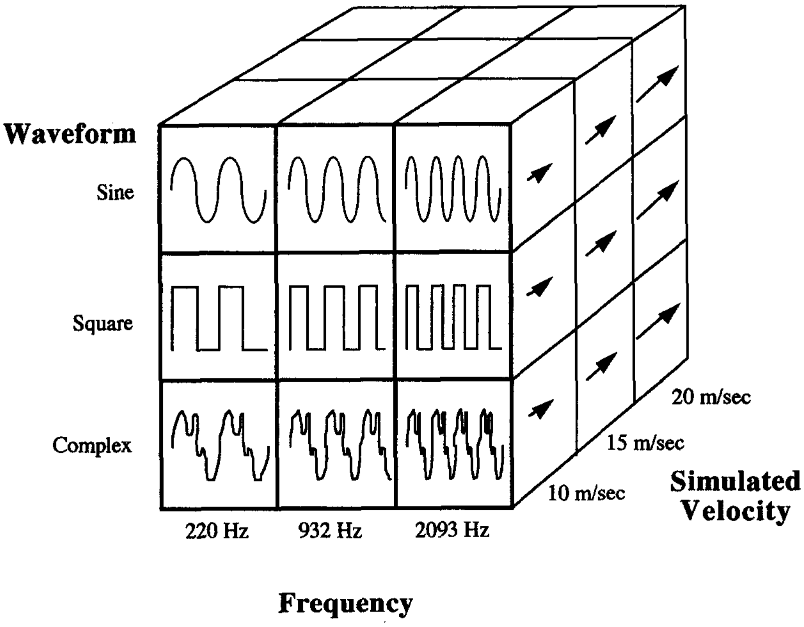

Figure 3. Stimulus characteristics of the Doppler tones used in Experiment 2.

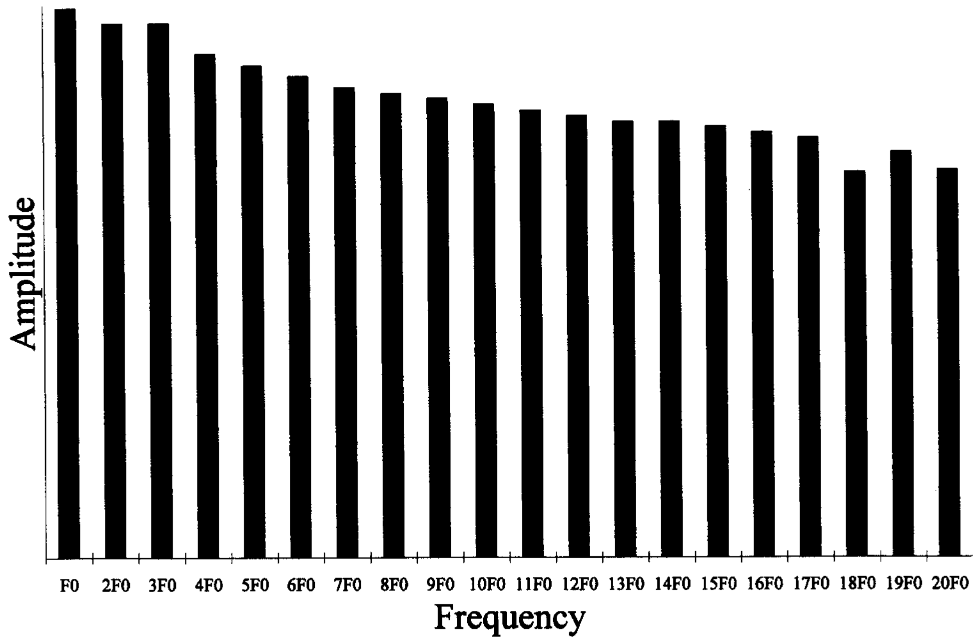

Figure 4. Spectral composition of the complex wave used in Experiment 2; F0 is the fundamental frequency of the tone.

their task was to mimic any changes in pitch they heard by moving the response wheel in the appropriate direction.

Three practice trials were then given to ensure that participants understood what was meant by pitch change and how to operate the response wheel. Practice trials consisted of a 75-dB square wave with an initial frequency of 440 Hz. Frequency was modulated sinusoidally, spanning two musical whole steps over 6 s, with a center frequency of 440 Hz. Practice tones lasted 9 s and so terminated at the same frequency as onset. All participants accurately tracked the direction of pitch change in the practice tones. Following the practice tones, participants were again instructed to concentrate on changes in pitch and to ignore any changes in loudness. Sequence 1 was then presented. After Sequence 1, participants were reminded to concentrate on changes in pitch and ignore changes in loudness. Sequence 2 was then presented.

The response wheel could rotate 180°, 90° to each side of the center notch. The center notch corresponded to a value of zero, and the maximum forward (pitch rise) and backward (pitch fall) wheel displacement corresponded to values of +128 and −128, respectively. A ratio of pitch rise to total pitch fall was obtained by the following formula:

$$\textit{pitch rise ratio} = \frac{P_{\max}}{P_{\max} + |P_{\min}|}, \qquad (3)$$

where $P_{\max}$ is the wheel value corresponding to the highest level of pitch heard during a trial (peak pitch rise) and $P_{\min}$ is the wheel value corresponding to the minimum pitch level after the peak pitch rise. A sample pattern is illustrated in Figure 5.

Results

A *t* test for each condition revealed that a significant rise in pitch occurred in 23 of the 27 conditions ($p < .05$). Three of the four nonsignificant conditions were low-frequency (220 Hz) sine waves; the fourth was a low-frequency complex wave that was significant with a one-tail test. Mean pitch rise ratios for each condition are shown in Table 1.

Participants who experienced a rise in pitch were essentially making inaccurate responses in tracking the direction of frequency change. Across all participants and conditions, the accuracy rate for tracking the direction of frequency change was 30%. This means that participants experienced the Doppler illusion on 70% of the trials, exhibiting a pattern of response analogous to that shown in Figure 5. If the three low-frequency (220 Hz) sine wave conditions are excluded, the illusion occurred on 88% of the trials.

Each participant responded to each tone twice. These responses were averaged to obtain a single pitch rise ratio for each stimulus tone. An analysis of variance (ANOVA) showed a significant effect for frequency range, $F(2, 20) = 5.73$, $MSE = 1.71$, $p < .05$, and for waveform, $F(2, 20) = 3.78$, $MSE = 0.73$, $p < .05$, but not velocity, $F(2, 20) = 0.07$, $MSE = 0.24$, *ns.* Collapsing across velocity and frequency, mean pitch rise ratios for the different waveforms were .77 (complex), .64 (square), and .44 (sine). A Tukey honestly significant difference (HSD) test showed a significant difference between the complex and sine waves. Collapsing across velocity and waveform, mean pitch rise ratios for the different frequencies were .86 (2093 Hz), .73 (932 Hz), and .26 (220 Hz). A Tukey HSD test showed a significant difference between 2093 Hz and 220 Hz and between 932 Hz and 220 Hz. Figure 6 shows how the magnitude of the illusion independently increases with increasing frequency and waveform complexity.

For trials on which a pitch rise occurred, we recorded the point in time of the initial pitch change, or pitch change

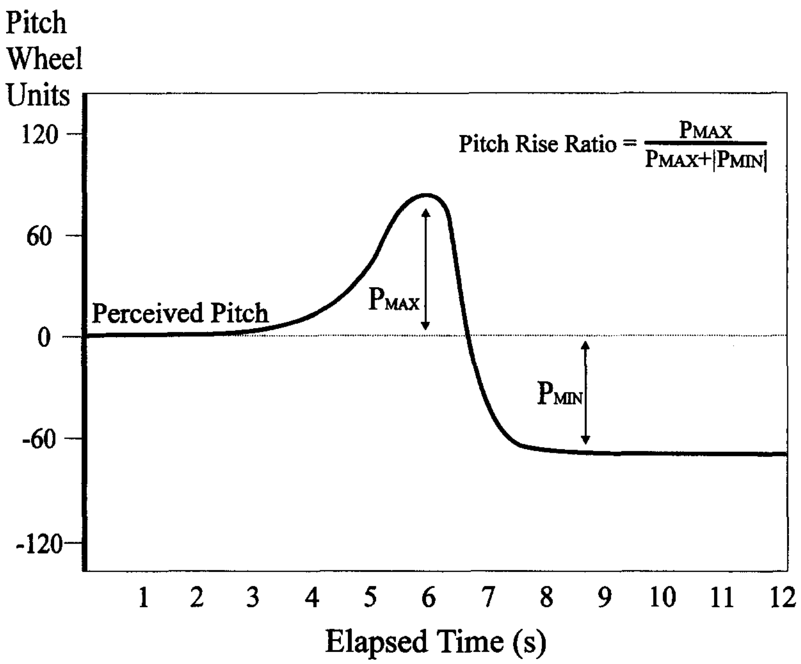

Figure 5. A typical pattern of response found in Experiment 2. P_{MAX} shows the highest pitch experienced. P_{MIN} shows the lowest pitch experienced.

onset time. To compare across velocities, onset time was measured in seconds from the midpoint of each stimulus tone, because the three velocities produced stimuli of different durations. An onset time of -1 corresponds to a peak time 1 s before the intensity peak. An onset time of $+1$ corresponds to a peak time 1 s after the intensity peak. Collapsing across frequency and waveform, an ANOVA revealed a main effect of onset time for $F(2, 20) = 37.97$, $MSE = 0.70$, $p < .001$. Mean onset times for the three velocities were 5.46 (10 m/s), -3.68 (15 m/s), and -2.37 (20 m/s). However, this appears to be a function of the different lengths of time each velocity stimuli required to reach a critical value for intensity change, because in all three conditions onset time for pitch change occurs before any discernible frequency change. We therefore examined the change in intensity that occurred between stimulus onset and pitch change onset. The mean intensity change scores for each velocity were 6.1 dB (10 m/s), 6.4 dB (15 m/s), and 5.3 dB (20 m/s). An ANOVA showed no differences between velocities in the amount of intensity change that occurred before pitch change onset, $F(2, 20) = 1.82$, $MSE = 1.93$, *ns.*

We also recorded the point in time at which the peak pitch rise occurred. Collapsing across frequency and waveform an ANOVA revealed a main effect for velocity, $F(2, 20) = 6.14$, $MSE = 0.26$, $p < .01$. Mean peak times for the three velocities were .88 (10 m/s), .53 (15 m/s), and .12 (20 m/s). Converting peak times to the intensity of the stimulus at those times an ANOVA showed a marginally significant effect for velocity, $F(2, 20) = 3.37$, $MSE = 6.93$, $p = .055$.

Table 1
Mean Pitch Rise Ratios for Each Condition in Experiment 2

	Wave form & frequency (Hz)								
	Sine			Square			Complex		
Condition	220	932	2,093	220	932	2,093	220	932	2,093
10 m/s									
M	0.1	0.51*	0.73*	0.39*	0.68*	0.82*	0.52*	0.87*	1.05
SD	0.2	0.4	0.48	0.49	0.4	0.53	0.52	0.55	1.09
15 m/s									
M	0.05	0.57*	0.71*	0.33*	0.83*	0.74*	0.37*	0.94*	1.04*
SD	0.15	0.43	0.54	0.40	0.73	0.54	0.41	1.11	1.40
20 m/s									
M	0.06	0.51*	0.73*	0.31*	0.66*	0.97*	0.22	0.98*	0.99*
SD	0.19	0.42	0.68	0.39	0.48	1.06	0.36	1.13	1.09

$^{*}p < .05$.

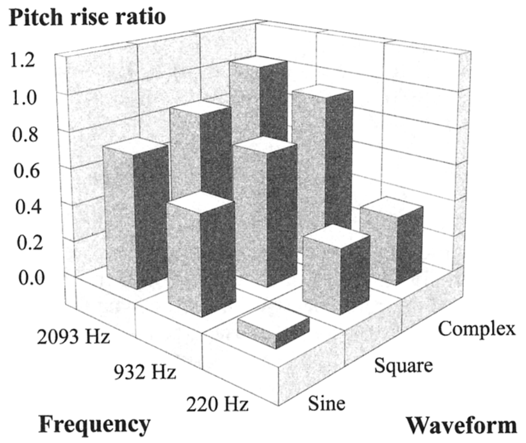

Figure 6. Mean pitch rise ratios by frequency and waveform complexity. As frequency and complexity increase so does the magnitude of the illusion.

The mean intensities at each peak pitch time for velocity were 78.5 (10 m/s), 80.1 (15 m/s), and 81.4 (20 m/s).

Discussion

The results of Experiment 2 demonstrate that a rise in pitch is experienced under various conditions of constant and falling frequency. Specifically, a Doppler-shifted tone in which frequency remains constant and then falls can produce an illusory rise in pitch. These findings indicate that the phenomenon is not merely a case of naive physics, but rather a perceptual illusion. In traditional studies of naive physics, participants generally express and act on erroneous beliefs about the behavior of objects in motion. They are asked to predict the behavior of objects based on their beliefs about the laws of physics or to choose the correct alternative from anomalous ones after viewing a dynamic event (Kaiser et al., 1985; McCloskey & Kohl, 1983). In the present study beliefs were not a factor, nor were participants asked to pick a correct alternative. Participants simply reported their experienced pitch change. By analogy it would be as though we asked them to simply watch the ball as it exited the curved tube and had them assert that its path was curved when in fact it is not. With Doppler stimuli we found a contraposition of the physical dimension frequency and its psychological correlate pitch, and hence called the percept the Doppler illusion.

The main effect and ordered set of means obtained for the three frequencies tested supports the source frequency hypothesis, that the higher the frequency the greater the magnitude of the illusion. This is consistent with previous findings comparing static tones of the same frequency and different intensities. As a general rule, an increase in intensity will make high-frequency sounds sound higher and low-frequency sounds sound lower. In Experiment 2, this effect appears to have attenuated the Doppler illusion somewhat in the lower frequencies tested. However, the fact that a significant pitch rise was still experienced in this range despite this attenuation demonstrates the robustness of the illusion.

The influence of intensity on pitch has been shown to be more pronounced with pure tones, but has also been shown to a lesser extent with complex tones (Fletcher, 1935; Lewis & Cowan, 1936; Zwicker & Fastl, 1990). Our data are consistent with these findings in that the low-frequency (220 Hz) complex tones we tested showed more pitch rise (less attenuation due to intensity increase) than the low-frequency pure tones. The main effect and set of ordered means obtained for waveform suggest that the more complex the waveform, the stronger the illusion. This indicates some support for Bannister's (1934) finding that the more complex a tone, the higher its perceived pitch. However, this evidence is limited due to the restricted range of frequencies, waveforms, and intensities tested, as well as our use of a novel methodology. The lack of a pitch rise ratio main effect for velocity suggests that rate and magnitude of change in frequency and rate of change in intensity, within the range of velocities tested, do not significantly affect the magnitude of the illusion. One interpretation is merely that the range of velocities explored was not broad enough. At much slower velocities the Doppler effect becomes inaudible, and so presumably would the illusion. At the other extreme, as the velocity of the source reaches the speed of sound, we experience sonic booms that would also eliminate the Doppler effect.

In examining the onset time data, the main effect and set of ordered means found is consistent with the interpretation that a critical degree of intensity change is required across conditions before any pitch change is perceived. In other words, we find a main effect for onset times across velocities because a 10 m/s source takes twice as long to produce the same amount of intensity change as a 20 m/s source approaching an observer. When we convert onset times to amount of intensity change, we find no differences between velocities. Thus, across all conditions in Experiment 2, pitch change initiated when the simulated source was approximately 62 m from the observer.

We also found a main effect and ordered means for velocity on the times of peak pitch rise. Whereas all mean peak pitch times were near the intensity peak time of the stimulus, lower velocity stimuli produced significantly later peak times than faster velocity stimuli. The effect remained marginally significant when peak times were converted to intensity values at the peak time. Taken together with the data specifying amount of intensity change required to produce a pitch change, we find that the illusory pitch change, like intensity, may specify relative distance of the source from the observer and relative rate of approach.

The results of Experiment 2 do not explain why participants experience a rise in pitch under the conditions of falling frequency in a Doppler-shifted tone, but they point to the possibility that change in loudness is the mediating factor. In the case of a passing sound source, there are not only continuous changes in frequency at the point of observation, but also continuous changes in intensity due to the changing distance between source and observer. As the sound source approaches observed intensity rises, reaches its highest level at the point of closest passage, and then diminishes as the source recedes. The relationship between the distance from source to observer and the intensity at the point of observation can be expressed by the inverse square law, $I = kr^{-2}$, where I is acoustic intensity, k is a constant determined by the strength of the source, and r is distance. This relationship specifies, for example, that decreasing the distance between source and observer by one half would increase the intensity by a factor of four.

Paradoxically, previous research with static tones, in the frequency range tested, found that an increase in intensity causes a decrease in pitch. Indeed, we found that the differences in intensity, which occur because of the changing distance between source and observer, are responsible for attenuating the illusion in this lower frequency range. Still, we must be careful to differentiate between static differences in intensity and a dynamic change in intensity. In studying the effect of intensity on the Doppler illusion, we can examine the effect of static observed intensity differences between successive points along the source's path. In addition, we can examine the dynamic change in intensity that occurs as the source approaches and passes.

Assessing the effect of this dynamic change requires a control condition that allows measurement of the contribution of the static intensity differences present in Experiment 2. Past research suggests that in the frequency and intensity ranges tested, a static increase in intensity should affect pitch very little, and that any effect would produce a decrease in experienced pitch. If the pitch rise in this frequency range only occurs in a dynamic setting, then the dimensions of pitch and loudness alone are not sufficient for explaining the Doppler illusion. A temporal component would also be necessary. Experiment 3 was conducted to address this issue.

Experiment 3

In Experiment 2, as the sound source approaches, the observed frequency of the sound source falls, and its observed intensity increases. When we examine the average point at which participants in Experiment 2 experienced the peak of the illusory pitch rise (the mean peak pitch rise), we find that it approximates the point at which the peak intensity of the stimulus occurred. If we choose this point O, at which the source is closest to the observer, and compare it with a point P 2 s prior, we find that for the 15 m/s trials the frequency at P is 4% higher than the frequency at O (see Figure 7). However, because O represents the highest pitch heard during the trial, in the dynamic case, participants judge O to be higher in pitch than P.

We also find that the intensity at P is 16 dB lower than the intensity at O. If this 16 dB static difference in intensity alone is sufficient for creating the Doppler illusion found in Experiment 2, then in a comparison using static tones, participants should judge a static tone with the frequency and intensity matching that of point O to be higher in pitch than a static tone with the frequency and intensity of point P, even though P is higher in frequency.

In Experiment 3, participants were presented with pairs of static tones that matched the intensity and frequency of points O and P for the 15 m/s stimuli in Experiment 2 and were asked which tone was higher in pitch.

Method

Participants. Thirty-eight introductory psychology students served as participants. All were volunteers who received class credit for participation, and all were naive of the hypothesis being tested. None of the participants were professional musicians, music majors, or had any formal music training past high school. None had participated in the previous studies.

Apparatus. Stimulus tones were generated by a Korg DSM 1 tone generator. The tones were presented to the participants through Radio Shack Nova 40 headphones. Participants could toggle back and forth between the two comparison tones by using two push buttons on the control panel of a Casio CZ-1 synthesizer.

Stimuli. Nine static stimulus pairs were constructed from the same three waveforms and source frequency ranges as the dynamic stimuli in Experiment 2. One tone in each pair corresponded in intensity and frequency to the static point in time of which the sound source passed closest to the observer (the louder, lower tone). The intensity of this tone was always 86 dB, and its frequency was either 220, 932, or 2093 Hz. The other tone in the stimulus pair corresponded in intensity and frequency to a static point in time 2 s prior to the point of closest passage for a sound source traveling at 15 m/s (the softer, higher tone). The intensity of this tone was always 70 dB, and frequency was either 230, 974, or 2187 Hz, with respect to the first tone in the pair. Because no pitch rise ratio effect was found for velocity in Experiment 2, only the 15 m/s stimuli were represented in the static case.

Design and procedure. Participants were tested individually in a sound-attenuating booth. Stimulus pairs were presented in random order. Participants accessed each tone in a stimulus pair by pressing buttons labeled 1 and 2 that corresponded to Stimulus Tones 1 and 2. Stimulus onset occurred when the participant pressed one of the two stimulus buttons. The tone continued until the participant pressed the other stimulus button or pressed a third button to end the trial. Button assignments were randomized, and participants were free to toggle between the tones as often as necessary. Participants were instructed to listen carefully to the tones for any differences in pitch and to ignore differences in loudness. It was explained that their task was to determine which of the two stimulus tones was higher in pitch, and it was explained that pitch is the highness or lowness of a tone, and not how loud or quiet it is. Any further questions about pitch or loudness were answered.

Results and Discussion

Participants in Experiment 3 essentially compared a loud, lower tone to a soft, higher tone with a difference in pitch of less than a semitone. Accurate responses were those in which the tone that was higher in frequency was judged as higher in pitch. The Doppler illusion demonstrated in Experiment 2, then, is an inaccurate response, that is, judging the loud, lower sound to be higher in pitch than the soft, higher sound.

An ANOVA revealed a significant difference between participant error rate under dynamic conditions in Experiment 2 and the static conditions in Experiment 3 (mean

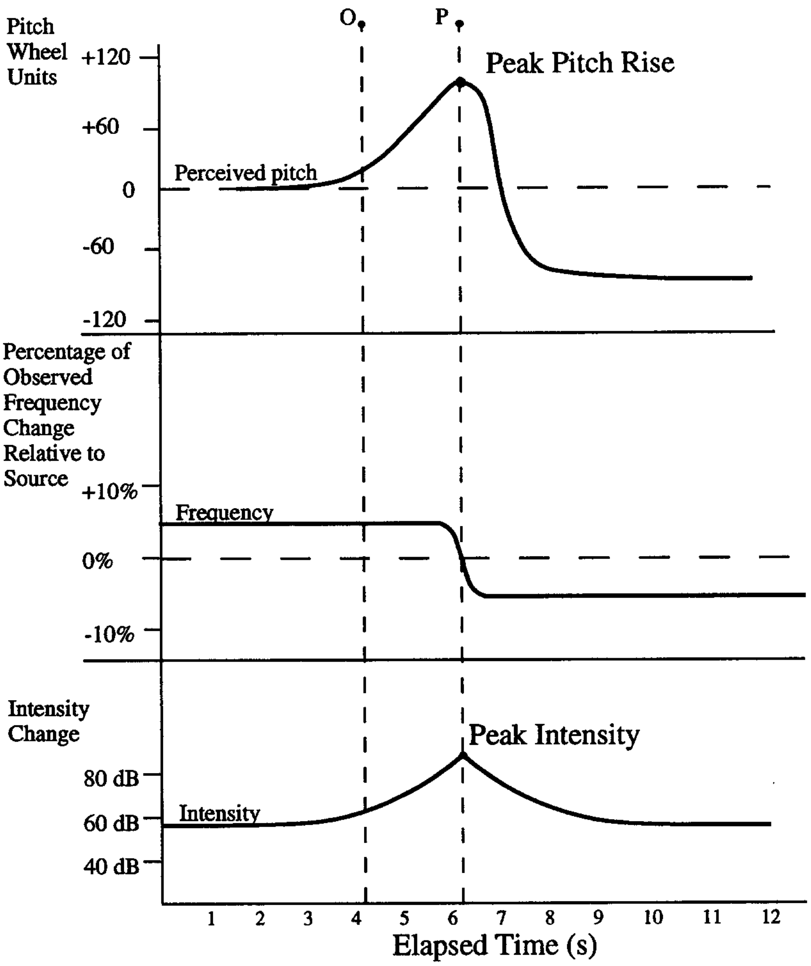

Figure 7. Intensity, frequency and perceived pitch change for a 15 m/s stimulus tone used in Experiment 2. The mean peak pitch rise occurs at the same point in time (*P*) as the peak in amplitude. Point *O* 2 s prior is higher in frequency and lower in intensity.

error rate = 70% and 30%, respectively), $F(1, 102) = 55.49$, $MSE = 0.07$, $p < .001$. Thus, when the component of dynamic change was removed, participants did not experience higher pitch with lower frequency as they did with the Doppler stimuli.

If the inaccurate responses made in Experiment 3 were due to the traditional influence of static intensity on perceived pitch, we would expect fewer errors in the low-frequency conditions in which increasing intensity makes loud, lower tones sound even lower. This would increase the perceptual distance between the two tones and reduce the error rate in the low-frequency range. A Friedman rank test for correlated samples on the number of errors in each condition showed no effect for frequency range, $\chi^2(2, N = 38) = 0.61$, *ns*, or waveform, $\chi^2(2, N = 38) = 1.36$, *ns*. Because previous research has shown the effect of intensity on pitch to be stronger at the extremes of the frequency spectrum, the lack of a main effect for frequency range suggests that the errors in Experiment 3 are due to general task difficulty, not static intensity differences.

The results of Experiments 2 and 3 show that dynamic change is an essential component in the Doppler illusion, and that in the case of Doppler stimuli, dynamic intensity change can influence perceived pitch in a manner opposite that specified by static intensity change. In our final study we explore whether this pitch change due to intensity requires some change in frequency as a catalyst, or if the effect occurs even when frequency is held constant. Also, to determine if the effect is only germane to Doppler-shifted stimuli or if it applies to more general dynamic interactions of pitch and loudness, we use stimuli that could not be produced naturally by steady-state sound sources in motion. Thus, Experiment 4 examines pitch perception using stimuli with dynamic change in intensity and unchanging frequency and with changing frequency and unchanging intensity.

Experiment 4

The complexity of having both frequency and intensity change in a Doppler tone may create errors in judgments of perceived pitch change. Participants may sense a change in frequency, but be uncertain of the direction of change. The rise in intensity may then influence judgments about pitch change, yielding a rise in pitch as the sound source approaches. However, if frequency is held constant the stimulus becomes less complex. Participants may then be better able to selectively attend to frequency in the face of changing intensity.

Additionally, if the influence of dynamic intensity change on perceived pitch is only germane to Doppler-shifted stimuli, then it may be related to localization tasks involving only sound sources or observers in motion. If the finding occurs in other settings, for example, rising or falling intensity when frequency does not change, then it has implications not only for localization, but for our current thinking about the perception of pitch and loudness in more general terms.

To examine these issues we presented participants in Experiment 4 with changes in intensity when frequency was held constant and changes in frequency when intensity was held constant. Participants were instructed to respond to changes in perceived pitch.

Another issue of interest is the effect of headphone presentation on the phenomenon. Typically, participants presented with stimuli through headphones have difficulty externalizing the sound source. The stimuli can seem to originate inside the head. To examine whether externalization of the sound source enhances or diminishes the effect, the stimuli in Experiment 4 were presented through a loudspeaker.

Method

Participants. Five male and 7 female introductory psychology students served as participants. All were volunteers who received class credit for participation, and all were naive of the hypothesis being tested. None of the participants were professional musicians, music majors, or had any formal music training past high school. None had participated in the previous studies.

Apparatus. The instruments used to produce the stimuli and record responses were the same as those used in Experiment 2. The stimuli were presented through a JBL Control 1 studio monitor, located 36 in. (91.44 cm) directly in front of the participant and adjusted to the height of each participant's head. The monitor was powered by a BGW Model 50A power amplifier in mono mode.

Stimuli. Each participant was presented with four types of stimuli: a Doppler change in intensity with constant frequency, a Doppler change in frequency with constant intensity, an inverted Doppler change in intensity (stimulus starts loud, gets softer, then rises to original level) with constant frequency, and an inverted Doppler change in frequency (frequency rises instead of falls) with constant intensity (see Tables 2 and 3). Each type of stimuli was presented in each of the three frequency ranges used in Experiment 2.

Design and procedure. Participants were tested individually in a sound-attenuating booth. Each participant heard each stimulus tone three times. Tones had a duration of 8 s and were presented in random order with an interstimulus interval of 3 s. We used a 2 × 2 × 3 within-subjects design with the main factors stimulus type (changing frequency, changing intensity), direction of change (rising, falling), and initial frequency (220 Hz, 932 Hz, 2093 Hz). Participants were presented with 3 trials of each type of stimuli for a total of 36 trials. Responses were averaged to obtain a single score for each participant in each of the 12 stimulus conditions. Response method, instructions, and practice trial conditions were the same as those used in Experiment 2. Rising stimuli responses

Table 2
Intensity Change Stimuli Used in Experiment 4

Time (s)	Intensity (dB)	Frequency (Hz) 220	932	2093
			Falling[a]	
0.0	86.0	220.0	932.0	2093.0
1.0	73.7	220.0	932.0	2093.0
2.0	67.9	220.0	932.0	2093.0
3.0	64.4	220.0	932.0	2093.0
4.0	61.9	220.0	932.0	2093.0
5.0	64.4	220.0	932.0	2093.0
6.0	67.9	220.0	932.0	2093.0
7.0	73.7	220.0	932.0	2093.0
8.0	86.0	220.0	932.0	2093.0
			Rising[b]	
0.0	61.9	220.0	932.0	2093.0
1.0	64.4	220.0	932.0	2093.0
2.0	67.9	220.0	932.0	2093.0
3.0	73.7	220.0	932.0	2093.0
4.0	86.0	220.0	932.0	2093.0
5.0	73.7	220.0	932.0	2093.0
6.0	67.9	220.0	932.0	2093.0
7.0	64.4	220.0	932.0	2093.0
8.0	61.9	220.0	932.0	2093.0

[a] Intensity rises then falls. Frequency remains constant in all three frequency ranges. [b] Intensity falls then rises. Frequency remains constant in all three frequency ranges.

Table 3
Frequency Change Stimuli Used in Experiment 4

Time (s)	Intensity (dB)	Frequency (Hz) 220	932	2,093
			Falling[a]	
0.0	76.0	233.6	989.6	2222.3
1.0	76.0	233.6	989.5	2222.1
2.0	76.0	233.5	989.2	2221.5
3.0	76.0	233.2	987.9	2218.5
4.0	76.0	220.0	932.0	2093.0
5.0	76.0	208.2	882.1	1980.9
6.0	76.0	208.0	881.0	1978.5
7.0	76.0	207.9	880.8	1978.1
8.0	76.0	207.9	880.7	1977.9
			Rising[b]	
0.0	76.0	207.9	880.7	1977.9
1.0	76.0	207.9	880.8	1978.1
2.0	76.0	208.0	881.0	1978.5
3.0	76.0	208.2	882.1	1980.9
4.0	76.0	220.0	932.0	2093.0
5.0	76.0	233.2	987.9	2218.5
6.0	76.0	233.5	989.2	2221.5
7.0	76.0	233.6	989.5	2222.1
8.0	76.0	233.6	989.6	2222.3

[a] Frequency falls, intensity remains constant in all three frequency ranges. [b] Frequency rises, intensity remains constant in all three frequency ranges.

were scored by recording the highest point of the participant's pitch wheel movement (peak pitch rise). Falling stimuli responses were scored by recording the lowest point of the participant's pitch wheel movement (peak pitch fall). We also recorded the onset time of each pitch change and the time at which each peak pitch rise or fall occurred.

Results

A *t* test for each condition revealed that a significant change in pitch occurred in all 12 conditions ($p < .05$). The means and standard deviations for each condition are shown in Table 4.

Three participants did not experience any pitch change in the intensity fall conditions and 1 of these 3 did not experience a change in pitch in the low-frequency intensity rise condition. They were given a pitch change score of 0 for these trials, and no onset or peak times were recorded for these participants in these conditions. An ANOVA for pitch change score showed a main effect for direction of change (rising, $M = 54.1$, $SD = 34.1$; falling, $M = -51.2$, $SD = 35.2$), $F(1, 11) = 148.15$, $MSE = 487.21$, $p < .001$. To compare the magnitude of pitch change across conditions without regard to whether the stimuli rose or fell, we converted all scores to their absolute values. An ANOVA revealed a significant difference in magnitude of pitch change for stimulus type, $F(1, 11) = 28.57$, $MSE = 2{,}189.68$, $p < .01$, but not for direction of change, $F(1, 11) = 0.37$, $MSE = 759.42$, *ns*, or for frequency range, $F(2, 22) = 0.14$, $MSE = 634.91$, *ns.*

An ANOVA for onset times of the intensity change stimuli revealed a significant main effect for direction of intensity change, $F(1, 8) = 6.95$, $MSE = 1.00$, $p < .05$, but not for frequency, $F(2, 16) = 0.63$, $MSE = 0.17$, *ns.* For frequency change stimuli, we also found a main effect for direction, $F(1, 11) = 5.81$, $MSE = 0.36$, $p < .05$, but not for frequency, $F(2, 16) = 2.59$, $MSE = 0.24$, *ns.*

An ANOVA for peak pitch rise or fall indicated a significant difference for stimulus type, $F(1, 8) = 26.04$, $MSE = 2.04$, $p < .01$, but not for direction of change $F(1, 8) = 1.24$, $MSE = 0.38$, *ns,* or for frequency, $F(2, 16) = 0.72$, $MSE = 0.40$, *ns.*

Discussion

The results of Experiment 4 indicate that a dynamic change in pitch can be obtained when frequency is held constant and dynamic changes in intensity occur. Moreover, the effect of dynamic intensity change on perceived pitch is not an artifact of headphone presentation. The main effect for direction of change indicates that rising intensity elicits judgments of rising pitch and falling intensity elicits judgments of falling pitch. Additionally, the significant difference between rising and falling frequency stimuli indicates that in the absence of such intensity change, participants can accurately track the direction of dynamic frequency change. The lack of a main effect for frequency range with intensity change stimuli suggests that the combination of both upward change in intensity and downward change in frequency enhances differences between frequency ranges.

When the scores were converted to absolute values, we found that changes in intensity did not influence perceived pitch as strongly as changes in frequency. However, there were no differences in the magnitude of pitch change between rising and falling stimuli. So under these conditions participants display a symmetrical pattern of pitch response when presented with rising and falling frequency or intensity.

For the peak time data we found a main effect for stimulus type. This is not surprising because intensity peaks at about 4 s while the frequency continues to change, reaching its maximum displacement at about 5 s. In examining the peak time data for intensity we coded scores in terms of seconds away from the intensity peak, or the midpoint of the stimulus. So a peak time of -1 occurred 1 s before the intensity peak, and a peak time of 1 occurred 1 s after the intensity peak. This permitted us to compare the mean peak time for rising intensity stimuli in Experiment 4 ($M = -.69$, $SD = .74$) with the mean peak time for the analogous condition of 20 m/s stimuli found in Experiment 2 ($M = -.12$, $SD = .54$). The intensity changes exhibited for these two groups were identical. The only difference was that the stimuli in Experiment 2 exhibited a downward Doppler shift in frequency. A *t* test revealed a significant difference between the peak time for Experiment 2 stimuli and the

Table 4
Means and Standard Deviation From Experiment 4

	Intensity rise (Hz)			Intensity fall (Hz)			Frequency rise (Hz)			Frequency fall (Hz)		
Measure	2,093	932	220	2,093	932	220	2,093	932	220	2,093	932	220
Pitch change onset time (s)												
M	3.3	3.1	3.2	3.9	3.9	3.8	3.6	3.4	4.0	4.0	4.1	4.0
SD	0.4	0.7	0.4	0.4	0.9	0.8	0.6	0.8	0.5	0.8	0.5	0.5
Pitch peak time (s)												
M	4.7	4.7	4.7	4.8	5.1	4.4	6.0	5.9	6.6	5.9	6.2	6.1
SD	0.7	0.9	0.7	0.5	0.3	0.8	1.1	1.0	1.1	1.2	0.8	0.9
Pitch peak score (pitch wheel units)												
M	35.4	33.9	33.9	−34.6	−26.3	−26.8	71.4	79.1	70.7	−71.0	−75.6	−73.3
SD	36.4	30.3	38.1	32.3	29.0	25.5	21.6	22.1	16.4	28.6	27.8	25.6

peak time for Experiment 4 stimuli, with the peaks occurring earlier in Experiment 4, $t(45) = 2.36$, $p < .05$.

One possible explanation is the counteracting effect of falling frequency on the illusory pitch rise. The stimuli in Experiment 2 used both changes in frequency and intensity. Frequency begins to fall just before the midpoint of the stimulus tone where intensity peaks. Thus, at the point where frequency begins to fall, intensity is still rising and participants report rising pitch. It would seem then that this falling frequency begins to exert its influence on perceived pitch by counteracting the influence of rising intensity just before the midpoint of the stimulus tone. Participants then report a reversal of pitch change direction as pitch rise peaks and begins to fall. This judgment of pitch change reversal is reinforced by the actual peak and reversal of the intensity of the stimulus that occurs at about this same time.

However, in Experiment 4 frequency was held constant for the changing intensity stimuli. Judgments about pitch change, then, were only influenced by changes in intensity. Because participants could only respond to a reversal in intensity change after they had heard it, and there was no counteracting influence of falling frequency just before the intensity peak, judgments about peak pitch rise occurred later than in Experiment 2. This finding supports the claim that changes in intensity and frequency additively influence pitch perception.

The onset time data show a main effect for direction of change. Participants detect upward changes in frequency sooner than they detect downward changes in frequency. Additionally, they experience changes in pitch for rising intensity stimuli sooner than they experience falling pitch with falling intensity stimuli. In Experiment 2 participants were shown to experience rising pitch with the changes in frequency and intensity that occur as a sound source approaches. Detecting a rise in pitch, then, may be advantageous from an evolutionary standpoint in that early detection would signal the approach of a sound source and give the organism as much time as possible to prepare for the source's arrival. The early influence of rising intensity on pitch would seem to enhance this effect. Because intensity change has been shown to be a more effective cue to localization (Rosenblum et al., 1987), it would also be of interest to determine whether participants detect rising intensity sooner than falling intensity when they are instructed to listen for changes in loudness instead of changes in pitch.

General Discussion

We have demonstrated that there is a popular belief that the pitch of an approaching sound source rises as the source approaches an observer, a percept we named the Doppler illusion. In Experiment 2 we confirmed that the Doppler illusion occurs perceptually and is robust across conditions of source frequency, velocity, and waveform complexity. This finding suggests that the naive belief in rising pitch as a sound source approaches stems from actual experience of the phenomenon. In Experiment 3 we demonstrated that the illusion is not due to the traditional pitch–loudness relationship and only occurs in a dynamic setting. In Experiment 4 we demonstrated the more general finding that dynamic changes in intensity influence perceived pitch change outside the realm of Doppler-shifted stimuli.

In the specific case of Doppler stimuli a possible explanation for the illusion concerns the relevance of information provided by each dimension. As we have noted, at the time of closest passage, intensity is at its peak and frequency is at the midpoint of a rapid downward shift. Of the two, the intensity peak would seem to be the more meaningful feature. From an ecological standpoint, dynamic changes in loudness have been shown to serve a more important role in providing information about the location of approaching sound sources than do dynamic changes in pitch (Rosenblum et al., 1987). It has also been shown that the observed changes in the intensity of an approaching sound source make available an acoustic variable specifying time to contact with the observation point (Shaw, McGowan, & Turvey, 1991). If time to contact or passage is the crucial informative element with this kind of stimuli, perhaps the illusory pitch rise in this specific situation has evolved to enhance (or at least to not undermine) the information provided by the loudness dimension. This type of explanation would be consistent with our data because the mean peak pitch rise in Experiment 2 occurs at the point in time that most closely resembles time to contact.

Still, the results of Experiment 4 show that intensity change can influence perceived pitch even with non-Doppler stimuli. Previous research using static stimuli has shown that when participants evaluate a stimulus on a dimension of interest, they sometimes encounter interference from orthogonal variation of an irrelevant dimension. The two dimensions interact with each other and are considered "integral dimensions" (Garner 1974). For example, using what Garner called "converging operations" (i.e., speeded sorting, restricted classification, and dissimilarity scaling), participants who evaluate the brightness of a stimulus suffer interference (i.e., speed and accuracy deficiencies) if the irrelevant dimension of saturation is varied orthogonally (Garner & Felfoldy, 1970; Handel & Imai, 1972; Torgerson, 1958). Conversely, "separable dimensions" such as brightness and size show no such interference (Attneave, 1950; Garner, 1974; Gottwald & Garner, 1975; Handel & Imai, 1972).

Garner (1974) has suggested and others (Grau & Kemler-Nelson, 1988; Melara & Marks, 1990) have demonstrated that the dimensions of pitch and loudness are integral. According to the traditional view, stimuli consisting of integral dimensions are initially perceived as dimensionless, unanalyzable, holistic "blobs" (Garner, 1974; Lockhead, 1972, 1979). The individual dimensions constituting the stimuli in effect are not perceived. The psychological distance between stimuli can best be described by a Euclidean metric, and stimuli themselves are processed in a holistic, "unitary" manner (Shepard, 1964). In other words the participant does not have primary access to the dimensions in question and cannot selectively attend to one dimension. Rotation of these dimensional axes, therefore, does not change in a meaningful way the psychological distance between two stimuli. This is not to say that a dimensional structure cannot be extracted from integral dimensions, but that it is a more derived and secondary cognitive process (Garner, 1974; Kemler-Nelson, 1993).

Alternatively, Melara and Marks (1990; Melara, Marks, & Potts, 1993) have advanced a model of dimensional interaction that proposes a primary orientation of the dimensional axes and mandatory immediate access to interacting dimensions. This access to primary axes is called *attribute-level processing,* because participants extract individual attributes from the dimensions of interest. With interacting dimensions, the extraction of a dimensional attribute creates a context in which attributes of the other dimension are perceived. This influence of context is called *stimulus-level processing.* In the case of interacting dimensions, then, the perception of an attribute on one dimension is influenced by the context created by an attribute in the other dimension. In the words of Melara and Marks (1990), "The attribute *high pitch* has one perceptual meaning when paired with the attribute *loud* but a different meaning when paired with the attribute *soft.* Context established by loudness values thus acts to weight perceptually the extraction of pitch information; this is stimulus-level processing" (p. 399).

Both the traditional and more recent theories of multidimensional perception have used static stimuli methodologies in identifying interacting and separable dimensions. The results reported here suggest that the properties of interacting dimensions found with static stimuli also apply to the more ecologically valid case of dynamic perception. In the traditional view, for example, if the dimensions of pitch and loudness are processed holistically and participants do not access the dimensions directly, then dynamic changes in intensity would not be initially discriminable from dynamic changes in frequency. Participants would not be able to selectively attend to changes in only one dimension. Instead, the perceptual experience would be the vector sum of the weighted dynamic change in each dimension. So, if the participant's task is to track pitch change, judgments to a certain extent will be influenced by changes in frequency. But if the participant cannot selectively access frequency, judgments about pitch change will be influenced by changes in intensity as well. Depending on the degree to which the participant can selectively access frequency and the relative amount of change in each dimension, the holistic analysis may give way to an experience of changing pitch that is not at all dependent on frequency change, as occurred in Experiment 4.

Similarly, in the more recent view, if we make the assumption that, in the case of dynamic stimuli, a greater degree of dimensional change creates a more influential context, then perceivers who extract the attribute constant pitch in the context of the attribute substantial rising loudness may be so influenced by the context of this rising loudness that they report rising pitch. Although the results reported here do not begin to resolve the debate over the two views, the area of dynamic perception may provide an arena in which the subtleties of the debate can be further tested, and dimensional interaction can be further defined to include dynamic stimuli.[1]

The current work suggests that models of pitch perception that use a static geometric representation may not adequately explain our perception of pitch, and that a model that includes both a dynamic component for intensity and frequency may be more appropriate. The implications for pitch perception in a musical setting, however, must be tempered by the fact that our stimuli were not presented in a musical context. The strength of the helix-type model is that it can account for the special similarities that are perceived between harmonically related, distant frequencies. It is possible that a musical context may constrain the influence of intensity change on perceived pitch, and that the frequencies we hear in a musical context are fit into an existing culturally defined musical schema. What we have shown is that for dynamic stimuli in the psychophysical realm, the relationship between pitch and loudness takes on new characteristics that have not previously been addressed. A full model of pitch perception needs to incorporate our finding that both frequency and dynamic change in intensity influence the perception of pitch.

---

[1] It should be noted that this effect could also be due to congruence between the dimensions of pitch and loudness, for which increasing loudness and increasing pitch are associated. Because the operations defining congruence and integrality use static stimuli, our results do not distinguish between the two at this time. However, because there is a demonstrated integral relationship between pitch and loudness in the static case, and most demonstrated congruency relationships have been cross modal, we suspect that dimensional integrality plays a role in the dynamic interaction of pitch and loudness as well.

References

Attneave, F. (1950). Dimensions of similarity. *American Journal of Psychology, 63,* 516–556.

Bannister, H. (1934). Auditory phenomena and their stimulus correlations. In C. Murchison (Ed.), *Handbook of general experimental psychology* (pp. 880–923). Worcester, MA: Clark University Press.

Bernstein, J. (1993). *Cranks, quarks and the cosmos.* New York: Basic Books.

Campbell, R., & Dodd, B. (1980). Hearing by eye. *Quarterly Journal of Experimental Psychology, 32,* 85–99.

Cohen, A. (1961). Further investigation of the effects of intensity upon the pitch of pure tones. *Journal of the Acoustical Society of America, 33,* 1363–1376.

de Boer, E. (1956). *On the residue in hearing.* Unpublished doctoral dissertation, University of Amsterdam.

Doppler, J. C. (1842). *Ueber das farbridge Lict der Doppelsterne und einiger anderer Gestirne des Himmels: Versuch einer das Bradley'sche aberrations-theorem als integrirrenden Theil in sich schliessenden allgemeineren Theorie* [About the colored light of the double stars and of several other stars in the sky: Attempt to create a general theory including the Bradley aberration theorem as an integrated part]. Prague, Czechoslovakia: K. Bohm, Association of Sciences.

Falmagne, J. C., Iverson, G., & Marcovici, S. (1979). Binaural "loudness" summation: Probabilistic theory and data. *Psychological Review, 86,* 25–43.

Fletcher, H. (1935). Newer concepts of the pitch, the loudness, and the timbre of musical tones. *Journal of the Franklin Institute, 220,* 405–429.

Fletcher, H., & Munson, W. (1933). Loudness: Its definition, measurement and calculation. *Journal of the Acoustical Society of America, 5,* 82–108.

Garner, W. R. (1954). Context effects and the validity of loudness scales. *Journal of Experimental Psychology, 48,* 218–224.

Garner, W. R. (1974). *The processing of information and structure.* Potomac, MD: Erlbaum.

Garner, W. R., & Felfoldy, G. L. (1970). Integrality of stimulus dimensions in various types of information processing. *Cognitive Psychology, 1,* 225–241.

Glenberg, A. M. (1990). Common processes underlie enhanced recency effects for auditory and changing-state stimuli. *Memory & Cognition, 18,* 638–650.

Goldstein, J. L. (1973). An optimum processor theory for the central formation of the pitch of complex tones. *Journal of the Acoustical Society of America, 54,* 1496–1516.

Gottwald, R. L., & Garner, W. R. (1975). Filtering and condensation tasks with integral and separable dimensions. *Perception & Psychophysics, 18,* 26–28.

Graham, E. C. (Ed.). (1965). *The basic dictionary of science.* New York: Macmillan.

Grau, J. A., & Kemler-Nelson, D. G. (1988). The distinction between integral and separable dimensions: Evidence for the integrality of pitch and loudness. *Journal of Experimental Psychology: General, 117,* 347–370.

Greer, R. D. (1970). The effect of timbre on brass-wind intonation. In E. Gordon (Ed.), *Experimental research in the psychology of music* (pp. 65–94). Iowa City: University of Iowa Press.

Gulick, W. L. (1971). *Hearing: Physiology and psychophysics.* New York: Oxford University Press.

Handel, J. D., & Imai, S. (1972). The free classification of analyzable and unanalyzable stimuli. *Perception & Psychophysics, 12,* 108–116.

Harris, J. D., & Sergeant, R. L. (1971). Monaural/binaural minimum audible angle for a moving sound source. *Journal of Speech and Hearing Research, 14,* 618–629.

Kaiser, M. K., McCloskey, M., & Proffitt, D. R. (1986). Development of intuitive theories of motion: Curvilinear motion in the absence of external forces. *Developmental Psychology, 22,* 67–71.

Kaiser, M. K., Proffitt, D. R., & Anderson, K. (1985). Judgments of natural and anomalous trajectories in the presence and absence of motion. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 11,* 795–803.

Kallman, H. J., & Cameron, P. (1989). Enhanced recency effects with changing-state and primary-linguistic stimuli. *Memory & Cognition, 17,* 318–328.

Kemler-Nelson, D. G. (1993). Processing integral dimensions: The whole view. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1105–1113.

Levarie, S., & Levy, E. (1975). *Tone: A study in musical acoustics.* Kent, OH: Kent State University Press.

Lewis, D., & Cowan, M. (1936). The influence of intensity on the pitch of violin and cello tones. *Journal of the Acoustical Society of America, 8,* 20–22.

Lichte, W. H. (1941). Attributes of complex tones. *Journal of Experimental Psychology, 28,* 455–465.

Lockhead, G. R. (1972). Processing dimensional stimuli: A note. *Psychological Review, 79,* 410–419.

Lockhead, G. R. (1979). Holistic versus analytic process models: A reply. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 746–755.

Marks, L. E. (1979). A theory of loudness and loudness judgments. *Psychological Review, 86,* 256–285.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A. L. Stevens (Ed.), *Mental models* (pp. 299–324). Hillsdale, NJ: Erlbaum.

McCloskey, M., Caramazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. *Science, 210,* 1139–1141.

McCloskey, M., & Kohl, D. (1983). Naive physics: The curvilinear impetus principle and its role in interactions with moving objects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9,* 146–156.

Melara, R. D., & Marks, L. E. (1990). Perceptual primacy of dimensions: Support for a model of dimensional interaction. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 398–414.

Melara, R. D., Marks, L. E., & Potts, B. C. (1993). Early-holistic processing or dimensional similarity? *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1114–1120.

Miles, W. R. (1914). Accuracy of the voice in simple pitch singing. *Psychological Review Monograph, 16,* 13–66.

Mills, A. W. (1958). On the minimum audible angle. *Journal of the Acoustical Society of America, 30,* 237–246.

Morris, C. (Ed.). (1992). *Academic Press dictionary of science and technology.* San Diego, CA: Academic Press.

Perrott, D. R., & Musicant, A. D. (1977). Minimum auditory movement angle: Binaural localization of moving sound sources. *Journal of the Acoustical Society of America, 62,* 1463–1466.

Platt, J. R., & Racine, R. J. (1985). Effect of frequency, timbre, experience, and feedback on musical tuning skills. *Perception & Psychophysics, 38,* 543–553.

Rosenblum, L. D., Carello, C., & Pastore, R. E. (1987). Relative effectiveness of three stimulus variables for locating a moving sound source. *Perception, 16,* 175–186.

Schneider, H., & Schneider, L. (1992). *The Harper dictionary of science in everyday language.* New York: Harper & Row.

Schouten, J. F., Ritsma, R. J., & Cardozo, B. L. (1962). Pitch of the residue. *Journal of the Acoustical Society of America, 34,* 1418–1424.

Shaw, B. K., McGowan, R. S., & Turvey, M. T. (1991). An acoustic variable specifying time-to-contact. *Ecological Psychology, 3,* 253–261.

Shepard, R. N. (1964). Attention and the metric structure of the stimulus space. *Journal of Mathematical Psychology, 1,* 54–87.

Shepard, R. N. (1965). Approximation to uniform gradients of generalization by monotone transformations of scale. In D. I. Mostofsky (Ed.), *Stimulus generalization* (pp. 94–110). Stanford, CA: Stanford University Press.

Shepard, R. N. (1978). Externalization of mental images and the act of creation. In B. S. Randhawa & W. E. Coffman (Eds.), *Visual learning, thinking, and communication* (pp. 133–189). New York: Academic Press.

Shepard, R. N. (1981). Psychological relations and psychophysical scales: On the status of "direct" psychophysical measurement. *Journal of Mathematical Psychology, 24,* 21–57.

Shepard, R. N. (1982). Geometrical approximations to the structure of musical pitch. *Psychological Review, 89,* 305–333.

Speaks, C. E. (1992). *Introduction to sound: Acoustics for the hearing and speech sciences.* San Diego, CA: Singular Publishing Group.

Stevens, S. S. (1934). The volume and intensity of tones. *American Journal of Psychology, 46,* 397–408.

Stevens, S. S. (1935). The relation of pitch to intensity. *Journal of the Acoustical Society of America, 6,* 150–154.

Stevens, S. S. (1955). The measurement of loudness. *Journal of the Acoustical Society of America, 27,* 815–829.

Stevens, S. S., & Volkmann, J. (1940). The relation of pitch to frequency: A revised scale. *American Journal of Psychology, 53,* 329–353.

Stevens, S. S., Volkmann, J., & Newman, E. B. (1937). A scale for the measurement of the psychological magnitude pitch. *Journal of the Acoustical Society of America, 8,* 185–190.

Terhardt, E. (1970). Frequency analysis and periodicity detection in the sensations of roughness and periodicity pitch. In R. Plomp (Ed.), *Frequency analysis and periodicity detection in hearing* (pp. 278–287). Leiden, The Netherlands: Sijthoff.

Terhardt, E., & Grubert, A. (1987). Factors affecting pitch judgments as a function of spectral composition. *Perception & Psychophysics, 42,* 511–514.

Torgerson, W. S. (1958). *Theory and methods of scaling.* New York: Wiley.

Uvarov, E. B., & Isaacs, A. (Eds.). (1986). *The Penguin dictionary of science* (6th ed.). Middlesex, England: Penguin Books.

Wightman, F. L. (1973). The pattern transformation model of pitch. *Journal of the Acoustical Society of America, 54,* 407–416.

Zwicker, E., & Fastl, H. (1990). *Psychoacoustics facts and models.* Berlin: Springer-Verlag.

Received April 8, 1994
Revision received March 29, 1995
Accepted June 13, 1995 ■