Overcoming naïve mental models in explaining the Doppler shift: An illusion creates confusion

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A perceptual auditory illusion is described that may contribute to students' misunderstanding of the physical principles of the Doppler shift. The illusion advances the formation of naïve mental models about the change in observed frequency that occurs as a sound source passes a stationary observer. Factors that may cause misunderstanding are addressed including the following: (i) the semantic distinctions between physical ''frequency'' and perceptual ''pitch,'' (ii) the influence of dynamic loudness on pitch, and (iii) the ambiguity of the word ''rise'' in describing the wave mechanics of the Doppler shift. Implications for teaching the principles of the Doppler shift include addressing the origin of naïve beliefs and using the illusion as a salient and conspicuous example of a breakdown of the correspondence between physics and perception.

I. INTRODUCTION

Despite instruction to the contrary, students in introductory physics and acoustics courses often mistakenly assert that a sound source approaching a stationary observer at a constant velocity will produce an observed rise in frequency at the point of observation. In fact, outside the physics community this erroneous belief appears to be ubiquitous. In a recent study over 90% of the 292 college freshman surveyed believed that the pitch of a train horn would rise as the train approached.[1] Some of these students identified the Doppler effect as the phenomenon accounting for the rise.

The error often made by novices, physics students, and to some extent even those with advanced degrees is the belief that the observed frequency of a sound source traveling at a constant velocity rises as it approaches an observer. It is true that the frequency ahead of the moving source is *higher* than the frequency actually emitted, which in turn is higher than

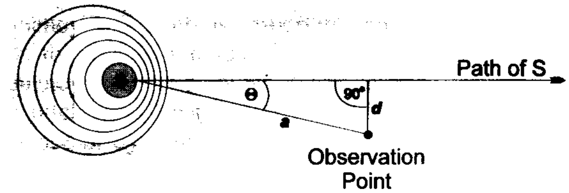

Fig. 1. Path of a moving sound source relative to an observer. **a** is the vector from the source to the observer as the source approaches. **d** is the vector from the source to the observer at the point of the source's closest approach. When S is far away (to the left), Θ is very small, increases to 90° at the point of closest approach, and asymptotically approaches 180° as S recedes to the right.

the observed frequency behind the source. However, when a source approaching a stationary observer at a constant velocity first becomes audible, the observer hears the source at the higher than emitted frequency. As the source draws closer the frequency at the point of observation begins to fall at an increasing rate. When the vector pointing from the source to the observer is exactly perpendicular to the source's direction of movement (see Fig. 1), the observed frequency is equal to the emitted frequency. As the source recedes the observed frequency drops further still. Thus, although the frequency ahead of the traveling source is always higher than the emitted frequency, a stationary observer never experiences a rise in frequency as the source approaches, passes, and recedes.

Despite these facts, the belief that one experiences rising pitch as a source approaches is so widespread that, while many texts accurately describe the phenomenon, some texts[2–10] indicate that the Doppler shift specifies a "rise in pitch" as a sound source approaches followed by a "drop in pitch" as the source departs. The apparent pervasiveness of this belief led us to examine the phenomenon from a perceptual perspective. Perhaps listeners mistakenly believe that frequency rises on approach because they actually hear a *pitch* rise on approach. In a series of experiments reported elsewhere[1] we presented subjects with computer-generated tones that simulated the frequency and intensity changes that would be produced by a passing sound source of constant velocity. Indeed we found that despite the falling frequency of Doppler-shifted tones, listeners perceived rising pitch as the simulated sound source approached and falling pitch as it recessed (see Fig. 2).

In the current paper we discuss this effect which we have termed the "Doppler illusion." We illustrate how the pitch and loudness interact to create the illusion, and discuss its role in creating a naïve mental model of Doppler physics that reinforces the erroneous belief that frequency rises as a sound source approaches an observer.

II. THE PHYSICS OF THE DOPPLER EFFECT

In the domain of acoustics the change in frequency that occurs when there is relative motion between a sound source and an observer is referred to as the Doppler effect. Familiar examples occur when moving sound sources such as ambulances or trains pass us. The frequency at any given observation point is described by the following standard equation which formalizes the higher than emitted frequency in front of the moving source and lower than emitted frequency behind it:

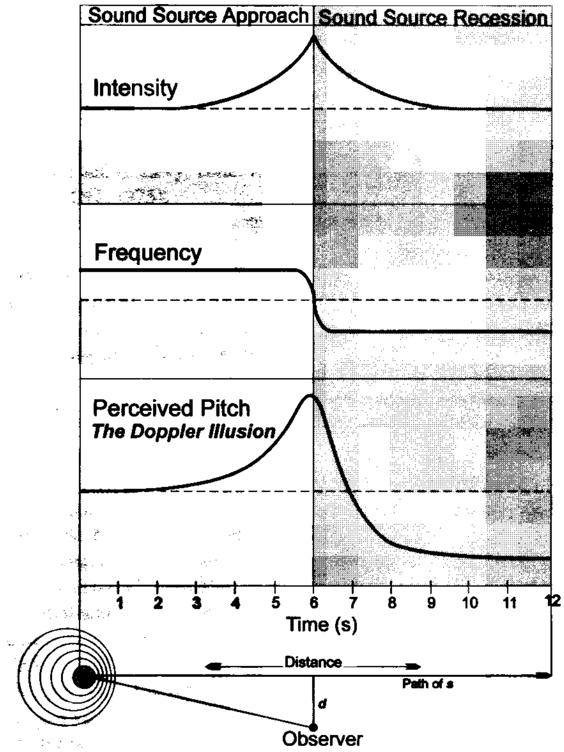

Fig. 2. Characteristic changes in frequency, intensity, and perceived pitch with a Doppler-shifted tone. Pitch change is a typical response obtained with 11 listeners and 54 trials per listener (Ref. 1). The y axis for perceived pitch is an ordinal scale of arbitrary pitch units that corresponds to the amount of displacement of a response wheel.

$$f_D=f_S\left(\frac{v}{v-v_s\cos\Theta}\right). \tag{1}$$

Here 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 Fig. 1).

"Pitch" is defined as "that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from high to low."[11] Pitch is a perceptual variable that typically corresponds largely to the acoustic variable "frequency." The relationship between pitch and frequency is such that they are often treated as functionally equivalent, though intensity and spectral composition have both been found to influence pitch.[12–14] When discussing the Doppler effect these influences are typically considered minor, and functional equivalence is assumed.[15] The correspondence between pitch and frequency implies that the drop in frequency that occurs due to the Doppler shift should be heard as a drop in pitch.

III. THE ILLUSION THAT CONFIRMS THE ERRONEOUS BELIEF

Despite the theoretical expectation of falling pitch, listeners report a rise in pitch as a sound source approaches (see Fig. 2). In the perceptual literature pitch and loudness have been shown to be interacting perceptual dimensions.[1,16–19] In this context the word dimension refers to a characteristic of a sensory modality. Pitch and loudness are dimensions of audition. Selective attention to one dimension that interacts with another cannot be accomplished without a great deal of effort or practice.[20] Therefore, the change in intensity that occurs as a source approaches and recedes influences listeners' perception of the changing pitch.

In work previous to ours the effect of intensity change on pitch was considered to be quite small. Using discrete static tones S. S. Stevens found that in upper frequency ranges (greater than 4 kHz) a discrete increase in intensity produced a higher perceived pitch, and in lower frequency ranges (less than 2 kHz) a discrete increase in intensity produced a lower perceived pitch.[14] Although there is some dispute concerning the magnitude of pitch change due to discrete intensity shifts, the finding itself is robust.[21] Typically, a change in intensity of 40 dB elicits a change in pitch equal to a frequency change of less than 5%.

In our work we found that dynamic intensity sweeps (a directional change in intensity over time) influence the perception of pitch change much more than discrete intensity shifts. In addition, the direction of experienced pitch change follows the direction of the intensity change.[22] Thus the influence of dynamic intensity is both much greater than and often in the opposite direction to that of the discrete intensity shifts. In a stimulus matching task a Doppler-shifted tone with a dynamic intensity change of 16 dB led subjects to estimate the average change in pitch to be 8 semitones (a frequency change of 37%) when in fact the actual change in frequency was only 2 semitones (a frequency change of 11%). Moreover, the dynamic upward sweep in intensity of a Doppler-shifted tone elicits the perception of rising pitch even with a source frequency of 175 Hz, well below 2 kHz where a static intensity increase elicits a decrease in pitch.

The Doppler illusion then, is the perception of an illusory rise in pitch that occurs as a sound undergoes the changes in frequency and intensity that occur when there is relative motion (or simulated relative motion) between a sound source and a listener. The rise in perceived pitch follows the change in intensity and occurs despite the fact that the physical frequency of the stimulus falls.

The illusion occurs because the perceptual processing of frequency and intensity interact. Listeners cannot selectively attend to frequency change in the face of changing intensity without a great deal of effort. That is, judgments about magnitude and direction of pitch change are influenced by changes in loudness. Because the intensity of a Doppler-shifted tone rises as the source approaches and loudness change influences pitch change, pitch is also perceived to rise.[1,22]

When a source passes a listener the observed intensity of the source reaches its highest point when the source is closest to the observer, and then begins to fall. This intensity peak appears to be an important cue for identifying when a source has reached its point of closest approach. In fact, intensity change has been found to be a more effective cue to localizing a passing sound source than either frequency change or interaural time differences.[23] In addition, it has been shown that the pattern of intensity change created by an approaching source provides information that specifies when the source will reach the listener (time-to-contact).[24,25] We found that the point in time where perceived pitch is highest is the point at which intensity is greatest and the source is closest to the listener. It may be then that the perception of pitch change of a moving sound source has evolved to enhance the salient intensity peak that occurs when the source is closest, thus enhancing information about time-to-contact and perhaps providing a selective advantage in dealing with such sources.

IV. THE USE OF THE WORD "RISE"

Relative to a passing sound source, a stationary observer goes from being in front of the source to behind the source as the sound source passes. Consequently, the frequency at the observation point goes from high to low. However, in some ways this might appear counterintuitive. If the frequency in front of the source is higher than the source frequency, then the frequency must at some point rise. Indeed it would as the source accelerates to its final velocity. Once the source reaches a constant velocity a stationary observer will experience only falling frequency as the source approaches and passes. However, if the most salient component in one's understanding of the Doppler shift is that frequency ahead of the source rises, it may be natural to assume that one would experience a rise in frequency as a sound source approached even at a constant velocity.

Thus, in addition to the actual perception of rising pitch, part of the difficulty in understanding the Doppler shift appears to stem from the use of the word "rise." Many textbooks[2–10] imply that the frequency ahead of a moving sound source rises. However, the frequency in front of a source moving at a constant velocity remains constant. Unfortunately, this latter point is often neglected, and the condensed description of the Doppler shift becomes "frequency in front of a moving sound source rises."[6] This erroneous knowledge coupled with the actual perception of rising pitch due to dynamic intensity change, contributes to the belief that the frequency of a source moving at a constant velocity somehow goes from low to high as the source approaches.

V. ASSUMING A FUNCTIONAL EQUIVALENCE OF FREQUENCY AND PITCH

The points of noncorrespondence between the physical dimension of frequency and its perceptual correlate pitch are apparently subtle. Psychologists, physicists, and musicians all commonly use the terms interchangeably. However, the differences are great enough that in English we have different words to describe each dimension. There are similar instances in audition such as the lexical distinction between waveform and timbre, intensity and loudness, and in vision, wavelength and hue, and light intensity and brightness.

These examples stand in contrast to highly corresponding dimensions such as physical and perceived length. There are examples of discrepancy between the actual length of a line and its perceived length (e.g., Müller-Lyer and Ponzo illusions).[26] However, in most situations our perception of length is a relatively close representation of the physical environment. Since there is normally little functional difference between the physical and perceptual dimensions of length, only one word is used to express both concepts.

It appears that the differences between physical frequency and perceived pitch are greater or more salient than differences between physical length and perceived length. Yet, the difference between frequency and pitch is not so great as to prevent their frequent interchangeable use. Given that listeners may actually experience rising pitch as a sound source approaches, the interchangeable use of pitch and frequency probably adds to the difficulty in understanding the mechanics of the Doppler shift. In this case the distinction between frequency and pitch is important, and interchangeable use leads to erroneous conclusions. Listeners may believe that frequency rises as a sound source approaches because they hear pitch rise. What they perceive is rising pitch due to the influence of dynamic intensity change.

VI. IMPLICATIONS FOR TEACHING THE DOPPLER EFFECT

The confusion surrounding the physics of the Doppler shift appears to stem from several sources. We propose that the introductory student and most listeners employ a heuristic in treating pitch and frequency as functionally equivalent. However, when a Doppler-shifted stimulus is encountered, the holistic processing of pitch and loudness and the change in intensity that occurs render the heuristic ineffective. Rising pitch is experienced despite falling frequency. If one assumes a functional equivalence of frequency and pitch, it would be reasonable to believe that frequency rises as a sound source approaches. In addition, texts that erroneously refer to a rise in frequency as a sound source approaches contribute to the confusion; this suggests that even experts experience the illusion.

Previous work has shown that students often exhibit belief in naïve principles of physics (e.g., impetus theories of motion) even after taking college level physics courses.[27] This may occur in part because the naïve beliefs and their origin are infrequently addressed when the principles of physics are taught. We suggest that in teaching the mechanics of the Doppler shift it may be advantageous to forewarn students that an illusion exists. We recommend that teachers acknowledge that pitch can rise despite the fall in frequency. This should dispel some of the confusion since the erroneous mental models are probably based on perceptual experience.

Teachers could explain that while the functional equivalence between frequency and pitch serves us well in most situations, the Doppler shift is a special case in which the equivalence breaks down. The physical principles are contrary to the perceptual experience. Once this is noted the Doppler effect may stand out as a conspicuous example of how the relationship between physics and perception can break down, and at the same time render the actual physics of the Doppler shift more memorable. In short, one could emphasize to students not to believe everything they hear.

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[1]J. G. Neuhoff and M. K. McBeath, "The Doppler illusion: The influence of dynamic intensity change on perceived pitch," J. Exp. Psych. Human Percept. Perform. **22** (4), 970–985 (1996).

[2]J. Bernstein, *Cranks, Quarks, and the Cosmos* (Basic Books, New York, 1993).

[3]R. E. Berg and D. G. Stork, *The Physics of Sound* (Prentice-Hall, Englewood Cliffs, NJ, 1995).

[4]E. C. Grahm, *The Basic Dictionary of Science* (Macmillan, New York, 1965).

[5]S. Levarie and E. Levy, *Tone: A Study in Musical Acoustics* (Kent State U. P., Kent, OH, 1975).

[6]R. Lipkin, "Device measures speed with white light," Sci. News **148**, 215 (1995).

[7]C. Morris, *Academic Press Dictionary of Science and Technology* (Academic, San Diego, CA, 1992).

[8]H. Schneider and L. Schneider, *The Harper Dictionary of Science in Everyday Language* (Harper Row, New York, 1992).

[9]C. E. Speaks, *Introduction to Sound: Acoustics for the Hearing and Speech Sciences* (Singular, San Diego, CA, 1992).

[10]E. B. Uvarov and A. Isaacs, *The Penguin Dictionary of Science* (Penguin Books, Middlesex, England, 1986).

[11]American National Standards Institute, ANSI S1.1-1994, *American National Standard Acoustical Terminology* (Acoustical Society of America, Woodbury, New York, 1994).

[12]E. Terhardt and A. Grubert, "Factors affecting pitch judgment as a function of spectral composition," Percept. Psychophys. **42**, 511–514 (1987).

[13]J. R. Platt and R. J. Racine, "Effect of frequency, timbre, experience, and feedback on musical tuning skills," Percept. Psychophys. **38**, 543–553 (1985).

[14]S. S. Stevens, "The relation of pitch to intensity," J. Acoust. Soc. Am. **6**, 150–154 (1935).

[15]R. E. Kelly, "Musical pitch variations caused by the Doppler effect," Am. J. Phys. **42**, 452–455 (1974).

[16]R. D. Melara, L. E. Marks, and B. C. Potts, "Early-holistic processing or dimensional similarity?" J. Exp. Psychol. Human Percept. Perform. **19** (5), 1114–1120 (1993).

[17]R. D. Melara and L. E. Marks, "Perceptual primacy of dimensions: Support for a model of dimensional interaction," J. Exp. Psychol. Human Percept. Perform. **16** (2), 398–414 (1990).

[18]R. D. Melara and L. E. Marks, "Interaction among auditory dimensions: Timbre, pitch, and loudness," Percept. Psychophys. **48** (2), 169–178 (1990).

[19]L. E. Marks, "On cross-modal similarity: The perceptual structure of pitch, loudness, and brightness," J. Exp. Psychol. Human Percept. Perform. **15** (3), 586–602 (1989).

[20]W. R. Garner, *The Processing of Information and Structure* (Erlbaum, Potomac, MD, 1974).

[21]W. L. Gulick, *Hearing: Physiology and Psychophysics* (Oxford U. P., New York, 1971).

[22]M. K. McBeath and J. G. Neuhoff, "Dramatic auditory pitch change due to dynamic intensity change" (unpublished).

[23]L. D. Rosenblum, C. Carello, and R. E. Pastore, "Relative effectiveness of three stimulus variables for locating a moving sound source," Perception **16** (2), 175–186 (1987).

[24]D. N. Lee, F. R. Vanderweel, T. Hitchcock, E. Matejowsky, and J. D. Pettigrew, "Common principle of guidance by echolocation and vision," J. Comp. Physiol. A. Sensory-Neural, Behavior. Physiol. **171**, 563–571 (1992).

[25]B. K. Shaw, R. S. McGowan, and M. T. Turvey, "An acoustic variable specifying time to contact," Ecol. Psychol. **3**, 253–261 (1991).

[26]R. Sekuler and R. Blake, *Perception* (McGraw-Hill, New York, 1994).

[27]M. McCloskey, "Naive theories of motion," in *Mental Models*, edited by D. Gentner and A. L. Stevens (Erlbaum, Hillsdale, NJ, 1983), pp. 299–324.