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The Tritone Paradox: A Link Between Music and Speech

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When William Harvey, in his classic treatise on the circulation of the blood, declared that pulse sounds could be heard in the chest, this assertion was hotly disputed. During the controversy that followed, a Venetian physician jokingly declared that perhaps such sounds were "only to be heard in London" (Hunt, 1978, p. 138).

The idea that certain sounds might be perceived quite differently in different geographic regions appears so unlikely as to form the basis of a joke. Yet this article concerns a sound pattern that, it strongly appears, is indeed heard differently by people in different geographic regions. I explore the properties of this pattern and the basis for this curious geographic association.

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PITCH STRUCTURES

Pitch—the attribute of "highness" or "lowness" of sound—is central to our perception of music. Although many pitches that we encounter outside music are rather blurred (consider, e.g., footsteps, squeaks, and rustling sounds), those produced by most musical instruments and the singing voice are clearly defined. It is from such pitches that melodies and harmonies are formed.

Questions concerning pitch and pitch relationships have intrigued scientists since ancient times. Pythagoras is credited with showing experimentally that the pitch of a vibrating string varies inversely with its length, and that particular musical intervals are produced when string lengths stand in certain ratios. During the 17th century, Galileo and Mersenne showed that these associations are based on the relationship between string length and vibration frequency: The shorter the string, the higher the rate of vibration. Mersenne also discovered that when a body vibrates, it does so not only at the frequency that corresponds to its perceived pitch—the fundamental frequency—but also at frequencies that are integer multiples of the fundamental. Such a set of frequencies is called a harmonic series. Later Seebeck (1843) and Schouten (1940) showed that when presented with a harmonic series, the listener hears a pitch that corresponds to the fundamental, even when the fundamental itself is weak or absent.

How do we abstract relationships between pitches so as to perceive musical patterns? When two tones are presented in combination, we perceive a musical interval, and we perceive intervals as being the same in size when their component frequencies stand in the same ratio. The traditional musical scale is based in part on this principle. Two adjacent notes on a keyboard form a pitch relationship called a semitone; this corresponds to a frequency ratio of approximately 18:17. Intervals that comprise the same number of semitones are given the same name. For example, an interval comprising 12 semitones (a ratio of 2:1) is called an octave, an interval comprising 7 semitones (a ratio of 3:2) is called a perfect fifth, and an interval comprising 5 semitones (a ratio of 4:3) is called a perfect fourth.

Because of the perceptual equivalence of tone pairs that form the same interval, a musical passage can be played by means of different pitches (i.e., it can be transposed to different keys), and provided that the intervals remain the same, its perceptual identity is preserved. Musical patterns are in this respect like visual shapes,

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which retain their perceptual identities when they are translated to different positions in the visual field. Indeed, the notion that such a pattern might be perceived as radically different under transposition is as paradoxical as the notion that a visual shape might undergo a metamorphosis through being moved to a different position in space.

Other pattern analyses are based on the octave. It has long been recognized that tones that are related by octaves have a certain perceptual equivalence. This is acknowledged in the system of notation for the traditional musical scale. The core of this scale consists of 12 tones, corresponding to the division of the octave into semitones, and each tone is given a name (C, C#, D, and so on). The entire scale, as it ascends in height (as in going from left to right up a keyboard), consists of the repeating occurrence of this sequence of note names across successive octaves. Octave placement is designated by subscripts, and tones that stand in octave relation are held to be in the same pitch class. For example, tones C_3, C_4, and C_5 are all in pitch class C, but in successively higher octaves; tones $D\#_3$, $D\#_4$, and $D\#_5$ are all in pitch class D#, but in successively higher octaves; and so on.

We can thus regard the pitch of a tone as varying along two dimensions: The monotonic dimension of height defines its position on a continuum from low to high, and the circular dimension of pitch class defines its position within the octave. We may then ask whether these two dimensions are independent, or whether they interact in some fashion. Common sense would say that surely they must be independent. If a musician were asked, "Which tone is higher, C or F#?" a likely reply is that the question is meaningless: One would need to know *which* C and *which* F# before a reasonable answer could be given.

ENDLESSLY RISING AND FALLING PITCHES

Shepard (1964) performed an experiment that he hypothesized would demonstrate the independence of the dimensions of pitch class and pitch height. He generated a series of tones, each of which consisted of a set of pure-tone components that were separated by octaves.[2] For example, one tone consisted of components . . . , C_2, C_3, C_4, . . . , and so on, and another consisted of components . . . , $C\#_2$, $C\#_3$, $C\#_4$, . . . , and so on. In this way, the tones were clearly defined in terms of pitch class, but their octave placement was ambiguous. For each tone, the amplitudes of the components were determined by a bell-shaped spectral envelope, so that those in the middle of the musical range were highest, and those at the extremes were lowest. Shepard varied the pitch classes of the tones while keeping the position and shape of the envelope constant.

Shepard found that when two such tones were played in succession, listeners heard either an ascending pattern or a descending one, depending on which was the shorter distance along the pitch class circle (Fig. 1). So, for example, the pair D#-E was always heard as ascending, because the shorter distance was clockwise. Similarly, the pair A#-A was always heard as descending, because the shorter distance was counterclockwise. Shepard then produced a fascinating demonstration: A series of tones that repeatedly moved all around the pitch class circle in clockwise direction appeared to be endlessly ascending. When, alternatively, the tones moved around the circle in counterclockwise steps, the series appeared to descend endlessly. This musical paradox has a visual counterpart in the endless staircase devised by Penrose and Penrose (1958), and later popularized by the artist M.C. Escher.

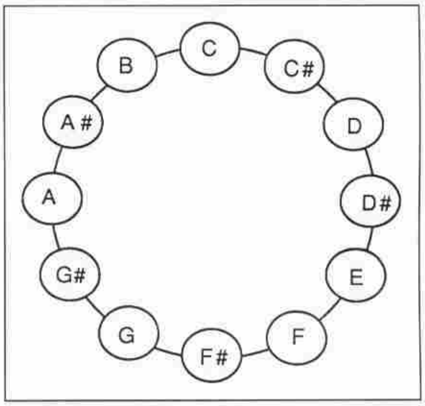

Fig. 1. The pitch class circle, formed by the 12 pitch classes within the octave. To produce the tritone paradox, tones that are in opposite positions along the circle are played sequentially; for example, D followed by G# might be played, or F followed by B.

The composer Jean-Claude Risset produced a number of compelling variants of this pitch paradox (Risset, 1971). In one case, a single tone glided around the pitch class circle in clockwise direction, so that it seemed to ascend endlessly. Counterclockwise movement produced the impression of an endlessly descending glide. In another demonstration, a tone glided clockwise around the pitch class circle while its spectral envelope moved downward, so that the tone appeared both to ascend and to descend at the same time.

At first sight, such demonstrations of pitch circularity appear to confirm the hypothesis that pitch class and pitch height are independent. However, another influence is operating in this situation also. In grouping together elements of a perceptual array, we tend to form linkages between those that are close together, in preference to those that are further apart. There are several well-known illustrations of this principle in vision, such as the tendency to group together dots that are positioned in spatial proximity, or to perceive motion between adjacent lights that come on and off in succession (Rock, 1986). In the case of music, we tend to create perceptual linkages between tones that form small melodic intervals rather than large ones (Bregman & Campbell, 1971; Deutsch, 1975; Van Noorden, 1975). This raises the possibility that in pitch circularity demonstrations, judgments of relative height might be so heavily influenced by proximity that a potential association between pitch class and perceived height would be overwhelmed by this factor.

THE TRITONE PARADOX

Given such reasoning, I wondered how listeners would judge a pair of such tones that were related by exactly a half-octave (this interval is called a tritone), so that they were separated by the same distance along the pitch class circle in either direction. What would happen, for example, if D were played, followed by G#, or if B were followed by F? Because proximity could not then be invoked by the perceptual system, would judgments of relative height be ambiguous, as predicted from the assumption of independence, or would an association between pitch class and perceived height emerge? It occurred to me that in making such judgments, the listener could refer to the absolute positions of the tones along the pitch class circle. If tones in one region of the circle were tagged as higher, and those in the opposite region were tagged as lower, the ambiguity of height would be resolved. Imagine, for example, that the listener represented the pitch class circle as shown in Figure 1, with the vertical axis representing perceived height. If the listener mentally placed pitch class C in the highest position (as in this figure), then he or she would hear C followed by F# as descending. If, however, the listener mentally placed F# in the highest position instead, then he or she would hear the identical pair of tones as ascending.

This reasoning led me to embark on a series of experiments that employed the following procedure. Subjects were presented with tritone pairs such as I have described, and they judged whether each pair formed an ascending or a descending pattern.[3] The percentage of times that the subject heard a pattern as descending was then plotted as a function of the pitch class of the first tone of the pair (Deutsch, 1986, 1987, 1991, 1994, 1996; Deutsch, Kuyper, & Fisher, 1987; Deutsch, North, & Ray, 1990; Ragozzine & Deutsch, 1994).

Each tone consisted of six pure-tone components that were separated by octaves, and whose amplitudes were determined by a bell-shaped spectral envelope. (A spectral representation of such a tone pair is shown in Fig. 2.) The tone pairs were generated under envelopes that were placed at different positions along the spectrum, in most experiments spaced at half-octave intervals. Varying the envelope positions in this fashion controlled for interpretations

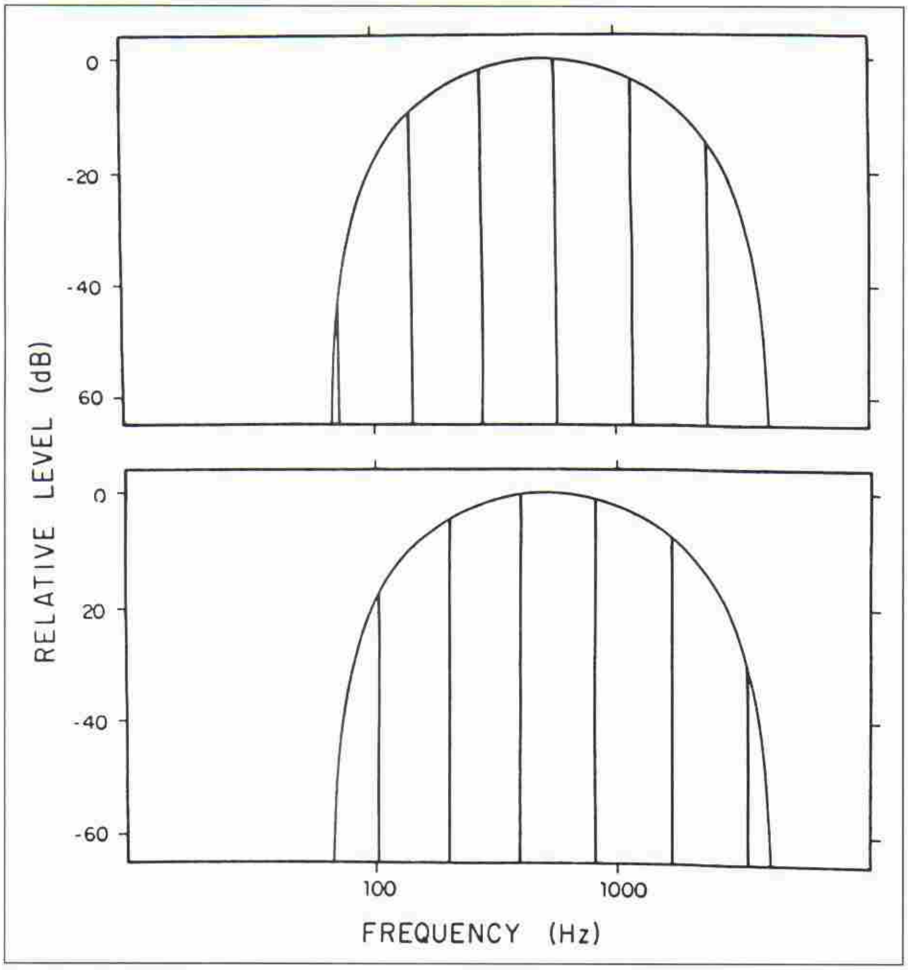

Fig. 2. Spectral representation of a tone pair that produces the tritone paradox. The upper graph represents a tone of pitch class D, and the lower graph represents a tone of pitch class G#.

based on the relative amplitudes or loudnesses of the harmonic components of the tones.

Figure 3 shows the judgments of 4 different subjects using this paradigm. In each case, the data were averaged over four spectral envelopes that were spaced at half-octave intervals. It can be seen that the judgments of each subject depended systematically on the positions of the tones along the pitch class circle. However, the direction of this dependence varied strikingly from one subject to another.

So we can think of the pitch class circle as having a particular orientation with respect to height, and this orientation differs from one person to another. For example, the subject whose data are shown on the upper right of Figure 3 heard tones E, F, F#, G, G#, and A as higher and the other tones as lower. So for this subject, F# and G defined the highest position along the pitch class circle. In contrast, the subject whose data are shown on the lower right heard tones A#, B, C, C#, D, and D# as higher and the others as lower. So for this subject, C and C# defined the highest position along the circle instead. Figure 4 shows the orientations of the pitch class circle for these 2 subjects (derived from the data shown in Fig. 3). I refer to tones that stand at the top of a subject's pitch class circle as his or her *peak pitch classes.*

What can be the basis for this curious association between pitch class and perceived height, and for the individual differences in its manifestation? In one experiment (Deutsch et al., 1987), the effect occurred in a substantial majority of a group of undergraduates at the University of California, San Diego. The subjects in this study all had normal hearing and could judge correctly whether pairs of pure tones that were separated by half-octaves formed ascending or descending patterns. Within this population, the way the tritone patterns were perceived did not correlate with whether or not the subject had musical training, so it appears that the tritone paradox is not musical in origin. Results from other studies argued against explanations in terms of low-level characteristics of the hearing mechanism. For example, the profiles relating pitch class to perceived height in the study of the tritone paradox did not correspond to patterns of relative loudness for the components of the same tones when these were compared with each other individually.

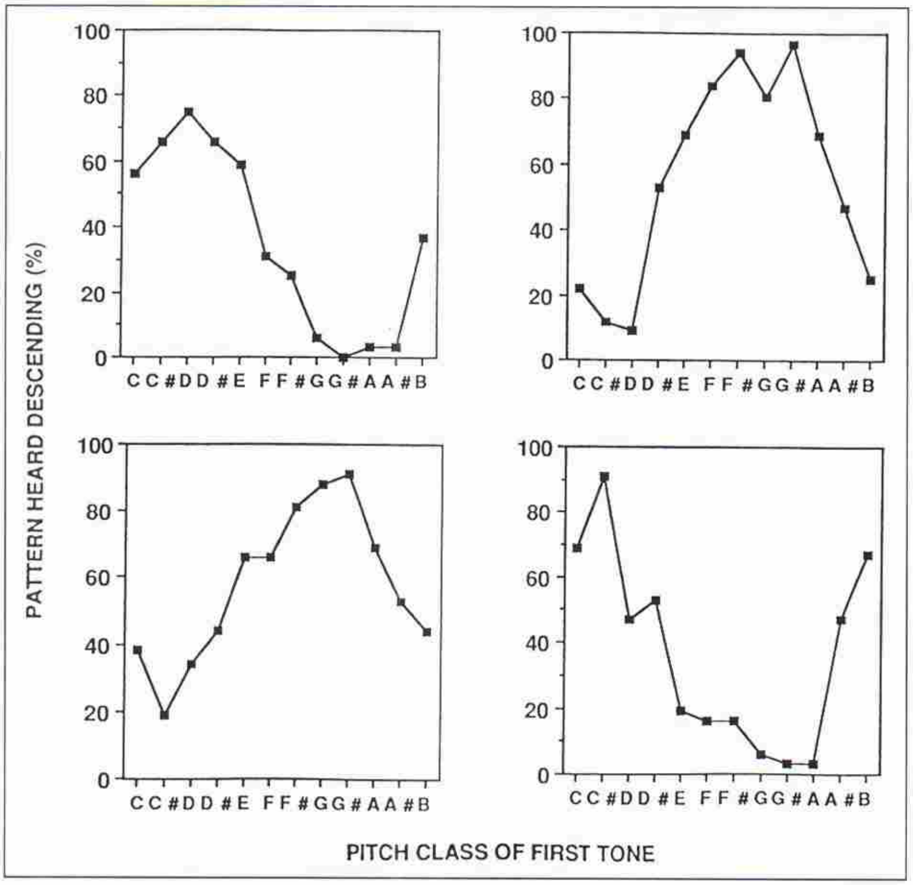

Fig. 3. Perception of the tritone paradox by 4 different listeners. Each graph shows the percentage of judgments that a tone pair formed a descending pattern, plotted as a function of the pitch class of the first tone of the pair.

EVIDENCE FOR AN INFLUENCE OF SPEECH PATTERNS

A number of informal observations led me to conjecture that the tritone paradox might be related to the processing of speech sounds. Specifically, I hypothesized that the listener develops a long-term representation of the pitch range of his or her speaking voice, and that this representation includes a definition of the octave band in which the largest proportion of pitch values occurs. I further hypothesized that the pitch classes delimiting this octave band for speech are taken by the listener as defining the highest position along the pitch class circle, thereby determining the way he or she orients the pitch class circle with respect to height.

Together with Tom North and Lee Ray, I undertook a study to examine this hypothesis. First, we had subjects participate in a full ex-

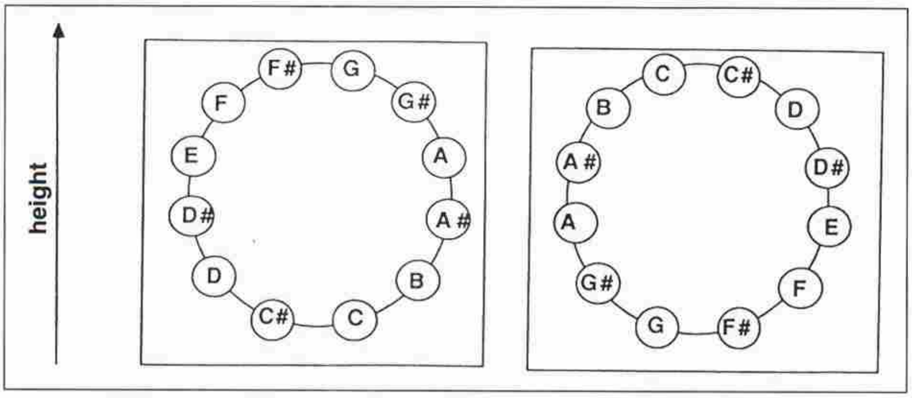

Fig. 4. Orientations of the pitch class circle with respect to height, for 2 different subjects. The circle on the left is derived from the data on the upper right of Figure 3, with peak pitch classes of F# and G. The circle on the right is derived from the data shown on the lower right of Figure 3, with peak pitch classes of C and C#.

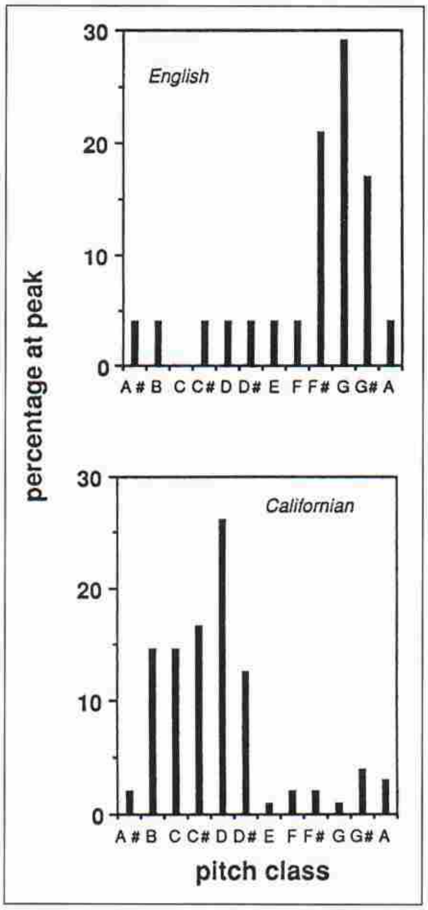

Fig. 5. Distributions of peak pitch classes in two groups of listeners, one from the south of England and the other from California. The percentage of listeners for whom each pitch class is a peak pitch class is graphed. From Deutsch (1991).

periment on the tritone paradox, and we selected a group whose judgments showed clear and consistent relationships between pitch class and perceived height. Then we had each subject speak freely into a microphone for roughly 15 min, and we took pitch estimates of the subject's speech samples at 4-ms intervals. We then determined the octave in which the largest number of pitch estimates occurred and identified the pitch classes that defined the boundaries of this octave band. We then compared, for each subject, the pitch classes delimiting the octave band for speech and those defining the highest position along the pitch class circle, as determined by that subject's judgments of the tritone paradox. For 8 of the 9 subjects, the two sets of pitch classes corresponded closely (Deutsch et al., 1990).

The findings from this study are in accordance with the conjecture that perception of the tritone paradox is based on a representation of the pitch class circle by the listener, whose orientation is related to the pitch range of his or her speaking voice. Two versions of this conjecture can then be considered. The first, and more restricted, version does not assume that the listener's pitch range for speech is itself determined by a learned template, but rather assumes it is determined by some other factor. The second, and broader, version assumes that such a template is acquired through exposure to speech produced by other people, and that the template is used both to evaluate perceived speech and to constrain the listener's own speech output. The characteristics of such a template would then be expected to vary among people who speak different languages or dialects, much as other speech characteristics, such as vowel quality, vary across languages and dialects.

A further study supported the second conjecture. I had noticed informally that Californians and people from the south of England tended to hear the tritone paradox in different ways. In a formal experiment (Deutsch, 1991, 1994), I found that there was indeed a significant difference in the distribution of peak pitch classes between a group of subjects who had grown up in California and a group who had grown up in the south of England. As shown in Figure 5, the Californians tended to have peak pitch classes in the range B, C, C#, D, and D#, whereas the English group showed a different pattern, with the most frequent peak pitch classes being F#, G, and G#.

This experiment supports the view that through a learning process, an individual acquires a representation of the pitch class circle that has a particular orientation with respect to height. This orientation is derived from the speech to which the person is exposed, and varies from one language or dialect to another. Further, we can assume that this template is involved both in the person's own speech output and in his or her evaluation of speech produced by others.

Dolson (1994) has reviewed a number of findings from the speech literature that support the present conjecture. First, it appears that most people confine the pitch of their speech to a range of roughly an octave. Second, within a given linguistic community, the speech of females is close to an octave above that of males. Third, the pitch ranges of speech differ remarkably little within a given linguistic community (except, of course, for the gender difference). In contrast, there are considerable differences in the pitch ranges of speech across different linguistic communities. Finally, there is a surprising lack of correlation between the pitch range of an individual's speech and physiological parameters such as the person's height, weight, chest size, and length of vocal tract.

What could be the evolutionary value of such a template? The pitch of a speaker's voice varies depending on his or her emotional state, and so serves to convey such states to the listener (Fernald, 1992; Scherer, 1985). A template such as this could provide a framework, common to a linguistic community, allowing the pitch of a speaker's voice to be evaluated so that it can signal his or her emotional state. The template could also be used in conveying syntactic aspects of speech (Cutler, Dahan, & Donselaar, 1997).

A number of other laboratories have recently produced additional evidence supporting the idea that the orientation of the pitch class circle varies statistically depending on geographic community. Giangrande (1998), in a study of students at Florida Atlantic University in Boca Raton, Florida, obtained a histogram of peak pitch classes that was quite similar to the one I obtained with Californians (Deutsch, 1991). R. Treptoe (in unpublished work) also produced a similar histogram from subjects at the University of Wisconsin, Steven's Point. In contrast, Dawe, Platt, and Welsh (1998), in a study of students at McMaster University in Hamilton, Ontario, obtained a histogram that was very similar to the one I obtained from subjects from the south of England (Deutsch, 1991).

Further work from my laboratory has indicated that perception of the tritone paradox could well be influenced by a template that is formed early in life. Ragozzine and I found statistical differences in perception of the tritone paradox between two groups of subjects who had all grown up in the area of Youngstown, Ohio (Ragozzine & Deutsch, 1994). We designated those subjects whose parents had also grown up in Youngstown as "locals," and those whose parents had grown up elsewhere as "aliens." The alien group produced a histogram of peak pitch classes that was very similar to the one produced by my Californian subjects (Deutsch, 1991), but the local group produced a very different histogram. Because parents have a particularly strong influence on speech development, this study indicates that an individual's pitch class template might be formed in childhood.

Most recently (Deutsch, 1996), I obtained more direct evidence for such a developmentally acquired template. I studied the perceptions of 15 subjects, together with those of their mothers. Ten of the subjects were children, and 5 were adults. The subjects were all Californian, but their mothers had grown up in many different geographic regions, including England, the European continent, and various parts of the United States. As expected, the mothers perceived the tritone paradox in strikingly different ways. And remarkably, although all the subjects were Californian, their perceptions corresponded closely to those of their mothers, and so also differed considerably from each other. However, because 10 of the subjects were children, it is possible that the correlation between the perceptions of children and their mothers reflects a particularly strong maternal influence in the case of young listeners—an issue that is the subject of ongoing research.

CONCLUSION

Philosophers have argued for centuries that strong linkages must exist between music and speech. This view has been shared by many composers who, in their search for optimal expressivity, have incorporated into their music features that are characteristic of spoken language. From a different perspective, considerable advances have been made in documenting the role of features based on pitch in the comprehension of spoken language (Cutler et al., 1997) and in the recognition of emotional state (Fernald, 1992; Scherer, 1985). The present findings on the tritone paradox indicate that, in addition, experience with speech can influence how music is perceived, and open the door to uncovering other such influences.

Notes

1. Address correspondence to Diana Deutsch, Department of Psychology, University of California, San Diego, La Jolla, CA 92093; e-mail: ddeutsch@ucsd.edu.

2. A sine wave, or pure tone, is composed of a single frequency. The frequency of a tone is the number of times in a second that the waveform repeats itself. This is specified in Hertz, where 1 Hertz (Hz) = 1 cycle per second. The amplitude of a tone is defined as the maximum amount of pressure variation about the mean value. For convenience, amplitudes are converted into decibels (dB). The spectral envelope determines the amplitude of each frequency component.

3. Signals comprising a full experiment on the tritone paradox, together with a description of the procedures for testing subjects and analyzing the data, are available in the following compact disk and accompanying booklet: Deutsch, D. (1995). *Musical illusions and paradoxes* (Available from Philomel Records, P.O. Box 12189, La Jolla, CA 92039-2189).

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Animal Models Reveal the "Psych" in the Psychosomatics of Peptic Ulcers

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Ulcers have been regarded for many decades as the prototypical psychosomatic disease in which psychological strain ("stress") leads to serious erosion and perforation of the stomach wall ("ulcers"). Yet limited empirical evidence for stress as a causal factor in ulcers (until recently) and recent claims that they may be caused by bacterial infection have cast doubts on the psychosomatic view of ulcers. In this article, we examine evidence for the continued validity of the psychosomatic view of ulcers.

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HISTORICAL CONTEXT

Selye (1936) introduced the concept of "stress," including among its sources both biological and psychological factors and among its consequences peptic ulcers in both the stomach (gastrum) and the entrance to the small intestine (duodenum). Selye believed ulcers are caused by many factors and characterized them as "pluricausal." Both the psychological and the biological causes have remained a mystery to this day, despite continued study by physicians, physiologists, and psychologists.

The idea that psychological factors might cause physiological disease was not new with Selye. Indeed, the term "psychosomatic," always much criticized, can be traced to the 19th century. Mesmer, Charcot, Janet, and Freud exploited "psychological treatments" for physical symptoms. In U.S. popular culture, peptic ulcer became a prototype for psychosomatic disease. Wolf and Wolff (1947) directly observed the functioning of the stomach in a patient called Tom; they observed that the stomach responds to psychological challenges. These classic observations confirmed that psychological factors can influence the gastrointesti-