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MOTHERS AND THEIR OFFSPRING PERCEIVE THE TRITONE PARADOX IN CLOSELY SIMILAR WAYS

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The tritone paradox is produced when two tones that are related by a half-octave (or tritone) are presented in succession, and the tones are so constructed that their pitch classes (C, C#, D; and so on) are clearly defined but their pitch heights are ambiguous. When listeners judge whether such tone pairs form ascending or descending patterns, their judgments show orderly relationships to the positions of the tones along the pitch-class circle: Tones in one region of the circle are heard as higher and those in the opposite region as lower. However, listeners disagree substantially as to which tones are heard as higher and which as lower, and these perceptual differences correlate with the language or dialect to which the listener has been exposed. In the present study, perceptions of mothers and their offspring were found to be strikingly similar, indicating that the mental representation influencing perception of the tritone paradox is formed early in life and survives into adulthood. It is conjectured that this mental representation is formed during the critical period in which infants acquire the features of their native language.

Keywords: pitch, tritone, paradox, music, speech, illusion.

1. Introduction

The tritone paradox is a musical illusion which reflects an influence of speech sounds on the way that music is perceived [1–6]. The basic pattern that gives rise to the illusion consists of two successively presented tones that are related by a half-octave (or tritone). For example, C might be presented followed by F#, or G# followed by D; and so on. Each tone consists of six sinusoidal components which stand in octave relation, and whose amplitudes are determined by a bell-shaped spectral envelope. Because each complex tone lacks the other harmonics that would generally serve to define its fundamental frequency, its perceived height is ambiguous, while its pitch class (C, C#, D, and so on) is clearly defined.

The tritone paradox has two curious features: First, when one such tone pair is presented (such as C followed by F#) a given listener might hear an ascending pattern; however another listener might hear a descending pattern instead. Yet when a different tone pair is presented (such as G followed by C#), the first listener now hears a descending pattern whereas the second listener now hears an ascending one. Individual differences in perception of this illusion do not correlate with musical training [5].

As a second curious feature, the way any given listener perceives the tritone paradox varies systematically depending on the positions of the tones along the pitch-class circle (Figure 1): Tones in one region of the circle are heard as higher and those in the opposite region are heard as lower. To plot a listener's perceptions of this pattern, tone pairs are presented in haphazard order, such that each of the twelve tones within the octave serves equally often as the first tone of a pair. The tones are generated under envelopes that are placed at four different positions along the spectrum, which are spaced at half-octave intervals. (Varying the envelope positions in this fashion controls for interpretations based on the relative amplitudes of the individual components of the tones). Figure 2 displays some plots that are typical of those obtained. As can be seen, each listener's judgments were related in an orderly fashion to the positions of the tones along the pitch-class circle; however the direction of this relationship differed substantially from one listener to another.

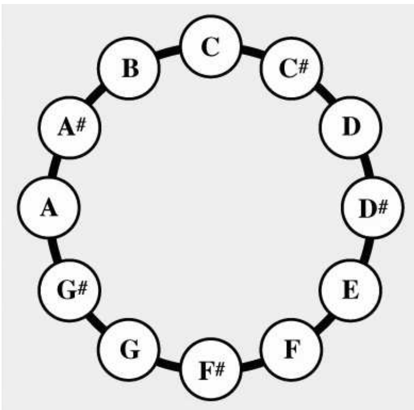

Fig. 1. The pitch-class circle.

To explain these findings, it was conjectured that each listener possesses a representation of the pitch-class circle that has a particular orientation with respect to height, and that this orientation differs from listener to listener. Figure 3 illustrates this point by showing the data from two subjects who perceived the tritone paradox in a pronounced way. As depicted on the righthand part of the figure, for the first subject, G# and A stood at the top of the pitch-class circle, whereas for the second subject, C# and D stood at the top of the circle instead. (For convenience, the tones standing at the top of a listener's pitch-class circle will hereafter be referred to as his or her *peak pitch classes*[1]).

[1] See the Results section for the procedure by which a subject's peak pitch classes are derived.

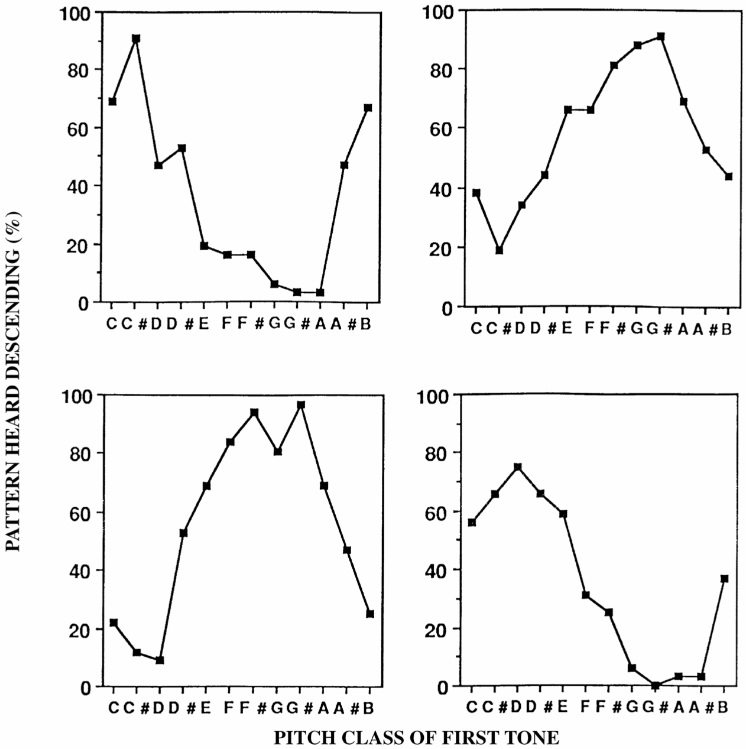

Fig. 2. The tritone paradox, as perceived by four different subjects. The graphs show, for each subject, the percentages of judgments that a tone pair formed a descending pattern, as a function of the pitch class of the first tone of the pair. All subjects showed orderly relationships between pitch class and perceived height; however the form of this relationship differed substantially across subjects.

It was further assumed that the way the circle is oriented is derived from exposure to speech sounds – more specifically, from the octave band containing the largest number of pitch values in the speech sounds to which the listener has been exposed. The pitch classes delimiting this octave band then correspond to the peak pitch classes that are reflected in judgments of the tritone paradox. The octave band also determines the pitch range of the listener's own speaking voice [4, 6].

A number of findings from the speech literature support this conjecture (see [7] for a review). First, it appears that most people confine the pitch ranges of their speaking voices to roughly an octave. Second, within any given linguistic community, the pitch ranges for male and female speech are close to an octave apart. Third, the pitch ranges of speaking voices differ remarkably little within a given linguistic community (controlling for gender); yet there are considerable variations in these pitch ranges across different linguistic communities. Most interestingly, there is a surprising lack of correlation between a person's pitch range for speech and his or her physiological characteristics, such as height, weight, chest size, length of vocal tract, and so on. This evidence, taken together, indicates that a culturally acquired template determines the pitch range of a person's speaking voice, and that this template involves an octave band.

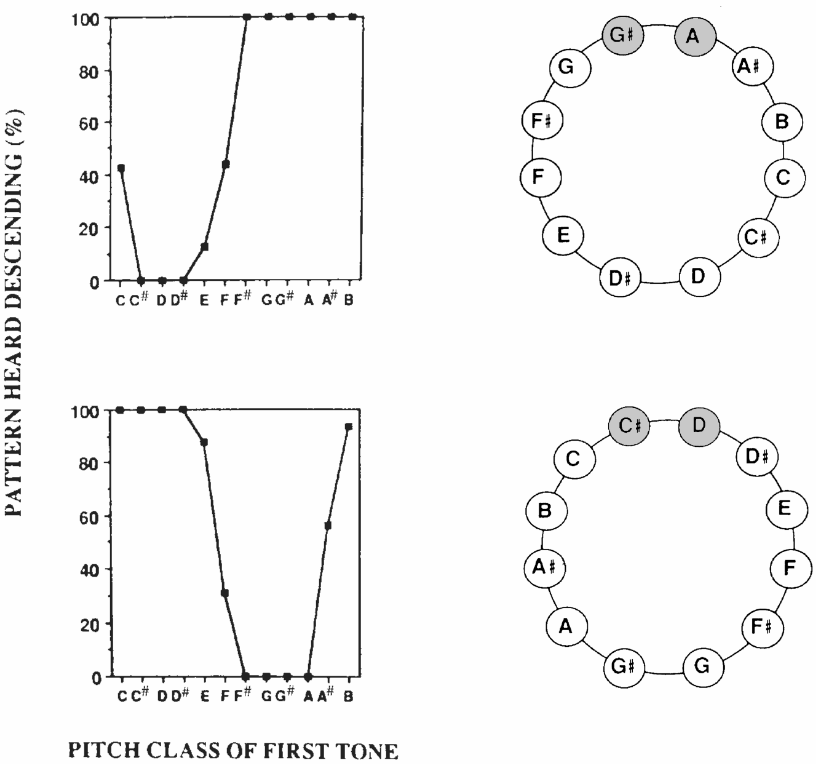

Fig. 3. Perception of the tritone paradox by two subjects who obtained pronounced effects. The graphs on the left show, for each subject, the percentages of judgments that a tone pair formed a descending pattern, as a function of the pitch class of the first tone of the pair. On the right are shown the orientations of the pitch class circle with respect to height, derived from the data shown on the left. The pitch classes that define the highest position along the circle are termed *peak pitch classes*.

An experiment employing speakers of English was performed to test the conjecture that perception of the tritone paradox is related to the pitch range of the listener's speaking voice [6]. Subjects were selected who showed clear relationships between pitch class and perceived height in making judgments of the tritone paradox. Each subject provided a 15-min sample of spontaneous speech, and from this sample the octave band containing the largest number of pitch values was derived. A significant correspondence was indeed found between the pitch classes defining the octave band for speech and those defining the highest position along the pitch-class circle in making judgments of the tritone paradox. In a further study employing speakers of Vietnamese, a significant correlation was again obtained between perception of the tritone paradox and the pitch range of the listener's speaking voice [4][(2)].

(2) In yet another study [27] a different measure of the pitch range of the speaking voice was employed, with no attempt to establish an octave band. Also in this study, the tones were generated under spectral envelopes that differed in shape and position from those employed by Deutsch and colleagues [4, 6]. No relationship was found between perception of the tritone paradox and the pitch range of the speaking voice.

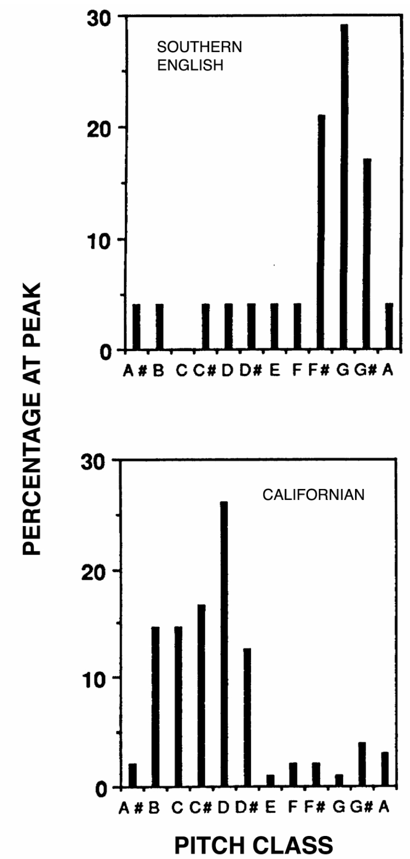

Fig. 4. Distributions of peak pitch classes in two groups of subjects. The first group had grown up in the south of England, and the second group had grown up in California. In large part, when a subject from California heard a pattern as ascending, a subject from the south of England heard it as descending; and vice versa.

A further study was carried out to test the hypothesis that perception of the tritone paradox is determined by a pitch-class template that is developed as a result of exposure to the speech of others. Two groups of subjects made judgments of the tritone paradox: The first had grown up in California and the second had grown up in the south of England. The distributions of peak pitch classes for these two groups is shown in Fig. 4. As can be seen, striking differences here emerged: In large part when a Californian subject heard a tone pair as ascending a subject from the south of England heard it as descending; and vice versa [2].

Further geographical correlates have been obtained by others. Subjects at Florida State University produced results that were similar to those produced from Californi-

However, given the differences in the stimulus parameters, as well as in the procedures for establishing the pitch range of the speaking voice, the relationship of this study to the findings obtained by Deutsch and colleagues cannot be evaluated. See [28] for a detailed critique of this study.

ans [8]. Yet subjects at Macmaster University in Hamilton, Ontario produced a distribution similar to that produced from subjects who had grown up in the south of England [9]. The perceptions of English speakers in Texas differed substantially from those of Korean speakers from Korea [10]. The perceptions of Swedish speakers in Stockholm differed significantly from those of English speakers from Texas and California, and not from those of English speakers from the south of England [11].

The question then arises as to when, during a person's lifetime, the speech-related template that determines perception of the tritone paradox develops. One possibility is that it is acquired gradually over many years through exposure to ambient speech sounds. Another possibility is that the template develops early in life, and that it may be formed during the critical period for speech acquisition [12–14]. In one experiment to explore this question, two groups of subjects were studied; both had both grown up in the region of Youngstown, Ohio [15]. It was found that those subjects whose parents had also grown up in this area produced a distribution of peak pitch classes that was strikingly different from the distribution produced by subjects whose parents had grown up elsewhere within the United States. Since parents exert a particularly strong influence on speech development in early childhood, this study provided evidence for the critical period hypothesis.

A further study compared perception of the tritone paradox among subjects whose first language was Vietnamese, and among those who were monolingual speakers of Californian English [4]. One group of subjects had arrived in the United States as adults ("Vietnamese Late Arrivals") and spoke primarily Vietnamese and little English; another group had arrived in the United States as infants or young children ("Vietnamese Early Arrivals"), and now spoke perfect English but and were not fluent speakers of Vietnamese. The two Vietnamese groups perceived the tritone paradox in very similar ways, and the perceptions of both groups differed significantly from those of the monolingual speakers of Californian English. In a second experiment, it was found that, among a group of "Vietnamese Late Arrivals" there was a strong correlate between the way the tritone paradox was perceived and the pitch range of the listener's speaking voice. These findings, taken together, lead to the conclusion that the pitch of speech heard early in life has a strong influence on perception of the tritone paradox in adulthood, even for people who, as adults, primarily speak a different language.

The present study was undertaken as a direct test of the hypothesis of a developmentally acquired template. The study involved mothers and their offspring. Ten of the offspring were children, and five were adults. The offspring had spent all or most of their lives in California; however, the mothers had grown up in many different geographical regions. On the hypothesis that perception of the tritone paradox is determined by a pitch-class template that develops early in life, it was predicted that perception of this illusion by mothers and their offspring would be closely similar.

2. Method

Eleven mothers participated in the study. They were aged 37 to 56, with a median of 2 years of musical training. Fifteen offspring also participated (including four pairs of siblings). These were 6 male and 9 female, with a median of 0 years of musical training. Ten of the offspring were children, aged 6–11, and five were adults, aged 21–35. The children had spent all their lives in California, and the adult offspring had spent most of their lives in California. However, the mothers had grown up in many different geographical regions, including England, the European continent, and various parts of the United States. All subjects had normal hearing, as determined by audiometry. They were selected on the basis of making no more than 6 out of 48 errors on a screening test in which they judged whether pairs of sine wave tones that were related by a tritone formed ascending or descending patterns. Roughly 40% of the offspring and 85% of the mothers who tried out for the experiment passed the screening test. All subjects were paid for their participation.

2.1. Stimuli and apparatus

Stimulus patterns

The tones all consisted of six sinusoids that stood in octave relation; the amplitudes of the sinusoids were determined by a fixed, bell-shaped spectral envelope. The general form of the equation describing the envelope is:

$$A(f) = 0.5 - 0.5 \cos \left[\frac{2\pi}{\gamma} \log_\beta \left(\frac{f}{f_{\min}} \right) \right] \quad f_{\min} \leq f \leq \beta^\gamma f_{\min}, \tag{1}$$

where $A(f)$ is the relative amplitude of a given sinusoid at frequency f Hz, β is the frequency ratio formed by adjacent sinusoids (so that for tones separated by octaves, $\beta = 2$), γ is the number of $gamma$ cycles spanned, and $f_{\min}$ is the minimum frequency at nonzero amplitude. Therefore the maximum frequency for which the amplitude is nonzero is $\gamma\gamma$ cycles above $f_{\min}$. The values $\gamma = 2$ and $\gamma = 6$ were used throughout, so that the spectral envelope always spanned six octaves from $f_{\min}$ to 64 $f_{\min}$.

In order to control for possible effects of the relative amplitudes of the sinusoidal components of the tones, signals were generated under envelopes that were placed at four different positions along the spectrum. Specifically, the envelopes were centered at 262 Hz (C_4), 370 Hz (F#$_4$), 523 Hz (C_5) and 740 Hz (F#$_5$), so that they were spaced at half-octave intervals. In consequence, the relative amplitudes of the sinusoidal components of tones at any one pitch class, when generated under envelopes centered at C_4 and C_5, were identical to those at the pitch class a half-octave removed, when generated under envelopes centered at F#$_4$ and F#$_5$. For example, the relative amplitudes of the sinusoidal components of tones comprising the tone pair E-A#, when generated under the envelopes centered on C_4 and C_5, were identical to the relative amplitudes of the sinusoidal components of the tone pair A#-E, when generated under envelopes centered at F#$_4$ and F#$_5$. Therefore, when the judgments obtained under these different spectral envelopes were averaged, possible effects of the relative amplitudes of the sinusoidal components of the tones were balanced out.

Twelve tone pairs were generated under each of the four spectral envelopes; these corresponded to the pitch-class pairings C-F#, C#-G, D-G#, D#-A, E-A#, F-B, F#-C, G-C#, G#-D, A-D#, A#-E, and B-F. The tone pairs were presented in blocks of 12, with each block consisting of tones that were generated under one of the envelopes and containing one example of each of the 12 pitch-class pairings. Within a block, the orderings of the tone pairs were random with the restriction that no consecutive tone pairs contained tones of the same pitch class. Sixteen blocks were created, with each of four different orderings employed once for each position of the spectral envelope. All tones were 500 ms in duration, and the tone pairs were separated by 5-sec intertrial intervals. The blocks were separated by 1-min pauses, except that there was a 5-min break between the eighth and ninth blocks. The tones were generated on a Next computer, recorded onto tape, and played back on a tape recorder, the output of which was passed through an amplifier and presented to the subjects via loudspeakers at a level of approximately 72 dB SPL at the subject's ears.

2.2. Procedure

All subjects were tested individually. The mother was tested first, while the offspring was entertained in another room where the sound signals could not be heard. The offspring was then tested. The children were given the choice of having their mothers present while they were being tested, and if they opted for this, the mother sat quietly, out of view of the child. On each trial a tone pair was presented, and the subject judged whether it formed an ascending or a descending pattern. The adults indicated their judgments by drawing upward or downward arrows on answer sheets. The children indicated their judgments by making a "thumbs up" sign when they heard an ascending pattern, and a "thumbs down" sign when they heard a descending one. Several practice trials were administered without feedback at the beginning of the session. In the case of the children, if more time was needed to produce a response, the tape was paused briefly during the intertrial interval. However this was rarely necessary, as the children generally responded rapidly and with confidence.

3. Results and discussion

For each subject, the percentage of judgments that a tone pair formed a descending pattern was plotted as a function of the pitch class of the first tone of the pair. The graphs on Figure 5 show, as examples, the plots obtained from two mother-child pairings. As can be seen, all the subjects' judgments were related in an orderly fashion to the positions of the tones along the pitch-class circle; however the direction of this relationship varied substantially across the two mother-child pairings. The graph on the left shows the judgments made by a seven year old girl, together with those of her mother, who had grown up in the South of England. The graph on the right shows the judgments made by a six year old girl, together with those of her mother, who had grown up in California and Hawaii. As can be seen, both children produced very pronounced patterns, which were strikingly different from each other, and reflected the same orientations of the pitch-class circle as did those of their mothers.

In order to determine the relationship between pitch class and perceived height that was reflected in each subject's judgments, the pitch-class circle was bisected so as to maximize the difference between the subject's averaged scores for the two halves. The circle was then oriented such that the line of bisection was horizontal, and the data

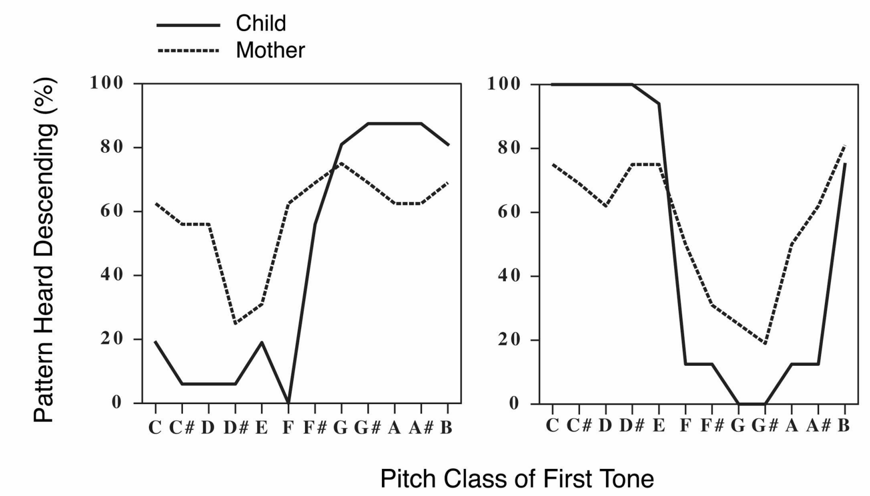

Fig. 5. Perception of the tritone paradox by two mother-child pairings. Both children had been born and spent all their lives in California. The graph on the left shows the judgments of a seven year old girl, together with those of her mother, who had grown up in the south of England. The graph on the right shows the judgments of a six year old girl, together with those of her mother, who had grown up in California and Hawaii.

were retabulated with the leftmost pitch class of the upper half of the circle taking the first position, its clockwise neighbor taking the second position, and so on. The pitch classes that stood at the peak of the normalized circle (i.e., at positions 3 and 4) were then designated the *peak pitch classes* for this subject. (This analysis procedure was the same as that employed previously by the author and co-workers (see, for example, [2, 4–6]).

In order to determine whether there was a significant correlation between the peak pitch classes produced by the mothers and their offspring, two analyses were performed. First, the distance along the circle between the peak pitch classes of each offspring and those of his or her mother was determined. Second, for each offspring, the distances along the circle between his or her peak pitch classes and those of each of the remaining mothers were determined, and these distances were averaged. It was found that for each of the fifteen offspring, the peak pitch classes were closer to those of his or her mother than to those averaged across the remaining mothers. This effect was highly significant ($p < .001$ on a binomial test). The effect was also large in size: The average unsigned distance between an offspring's peak pitch classes and those of his or her mother was 1.3 semitone. However, the average unsigned distance between an offspring's peak pitch classes and those averaged across the remaining mothers was 3.17 semitones. Since unsigned distances were computed, the largest possible distance that could have been obtained was 6 semitones; so the average unsigned distance of 3 semitones was as expected from chance association.

To represent this data in graphic form, the following procedure was adopted. The algorithm that was used to determine the peak pitch classes for each subject (described above) also produced a normalized plot of each subject's judgments. The normalized plots of all the offspring were averaged, and the resultant plot is shown in Figure 6.

The dots on this figure show the positions of the mother's peak pitch classes in relation to those of their offspring, and it can be seen that they clustered strongly around the normalized peak.

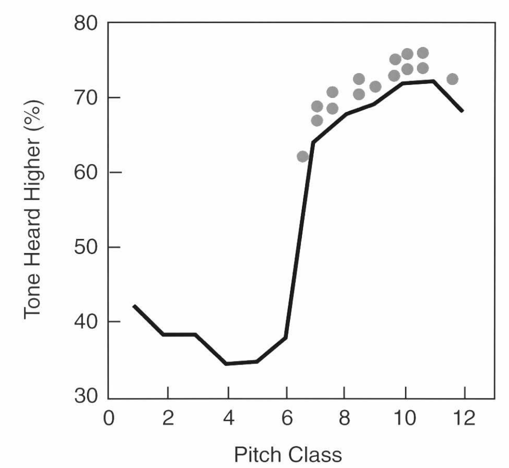

Fig. 6. The graph shows judgments of the tritone paradox, normalized and averaged across all offspring. The dots show the mothers' peak pitch classes in relation to those of their offspring, and as can be seen, they clustered strongly around the normalized peak.

On further analysis it was found that, taking the ten children alone, the effect was still highly significant ($p = .001$ on a binomial test). Taking the five adult offspring alone, the effect was also significant ($p = .031$ on a binomial test). The finding that the correlation held for the adult offspring as well as for the children is in accordance with earlier findings showing that young adults whose first language was Vietnamese but now spoke primarily English perceived the tritone paradox in a way that was strikingly similar to the perceptions of older adults who were primarily speakers of Vietnamese and spoke little English [4]. The two studies, taken together, provide a strong indication that the speech template influencing perception of the tritone paradox is formed in childhood and survives into adulthood. We can further conjecture that this template is formed during the critical period in which infants acquire the features of their native language [12–14]. A further possibility is that exposure to speech sounds in utero, which has been found to influence speech perception in infants [16–18] might also be involved in development of this template.

Finally, it should be noted that the findings reported in the present study were obtained with the use of tones that were generated under four spectral envelopes which were spaced at half-octave intervals, and the results under the four envelopes were averaged. Other work has enquired into the effects of position of the spectral envelope on the perceived relationship between pitch class and perceived height in making judgments of the tritone paradox. This issue was examined in detail in one study employing a small group of subjects [19]. It was found that although the relationship between pitch class and perceived height was sometimes influenced by the overall position of the spectral envelope, and sometimes by the relative amplitudes of the components of the tones, such envelope effects were either absent or small in size in the range employed here. In yet further studies, this effect of envelope position was also found, for most subjects, to be either nonexistent or small in size [8, 9, 20, 21]. In contrast, in one study [22] significant envelope effects were reported from a sizeable proportion of subjects, and the reason for this discrepant finding is unclear. However, it should be emphasized that in the present study, judgments were averaged across envelopes that were spaced at half-octave intervals. As described in the Methods section, this procedure enabled the balancing out of possible envelope effects on the distribution of peak pitch classes, and so rendered the issue of position of spectral envelope irrelevant to the present findings.

In conclusion, the present study contributes to the growing body of evidence on relationships between speech and music. Findings by neuroscientists have indicated that some elements of speech and music are subserved by overlapping neural circuitry [23, 24]. At the perceptual level it has been found that the pitch and durational characteristics of speech are important to language comprehension [25, 26]. The present findings provide more specific information concerning the bases for the relationship between speech and music, by indicating that exposure to speech patterns in childhood can have a strong influence on the way that music is perceived, and that this influence extends into adulthood(3) (4) (5) (6) .

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(4) The author thanks Jeff Hartung, Michael Hurlbert, and Lee Ray for help in data collection.

(5) Part of the work reported here was presented by the author in a paper delivered to the 131st Meeting of the *Acoustical Society of America*, Indianapolis, Indiana, May 1996.

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