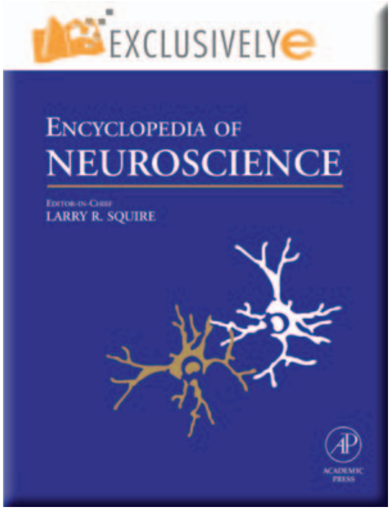

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Musical Illusions

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Introduction

Over the past decade, there have been significant advances in understanding the brain mechanisms underlying music perception. Functional imaging studies of normal individuals have provided considerable information concerning the anatomical structures involved. Studies of patients with musical deficits resulting from brain lesions have supplied much complementary information, as have studies of individuals with congenital amusia. Investigations of musical illusions – misperceptions of music by normal individuals – provide further insights into the brain circuitry underlying music perception. This entry reviews those musical illusions which have clear implications for the neuroscience of music. In exploring these illusions, we focus in particular on three issues:

1. *Innate differences in music perception.* Can we assume that music perception is the function of innate brain circuitry that is common to most individuals, or are there widespread and substantial differences in music perception that reflect innate differences in brain organization? Some of the illusions to be described point to widespread individual differences in the perception of music that correlate with handedness; these indicate that there are substantial variations in the innate brain circuitry underlying music perception.
2. *Neural plasticity in the development of music perception.* Recent imaging studies have indicated that musical practice produces alterations in brain organization, and that this happens particularly at an early age, when the effects of experience on brain function are particularly strong. In addition, a musical illusion to be described here has been shown to be heavily influenced by the speech patterns to which the individual has been exposed, particularly in childhood. The characteristics of this illusion indicate that the brain circuitry underlying music perception can be influenced by extramusical input, particularly at an early age. More specifically, it points to a strong influence of exposure to speech patterns in childhood on how music is later perceived.
3. *Modularity in musical processing.* Findings from neurophysiological and neuropsychological studies have indicated that there are distinct 'what' and 'where' pathways in the auditory system. In accordance with these findings, certain musical illusions indicate that there are separate decision mechanisms underlying what pitches we hear and underlying where the tones appear to be coming from, and that the combined outputs of these decision mechanisms can lead to illusory conjunctions. More specifically, we can think of a musical tone as a bundle of attribute values – having a pitch, a location, a loudness, a timbre, and so on, with the different attributes being subserved by distinct neural pathways. When more than one tone is presented at a time, the different outputs of these pathways must be correctly conjoined in order to produce veridical percepts. Some of the illusions described here can be explained as due to incorrect conjunctions of attribute values.

Stereo Illusions

Powerful musical illusions can be produced when two streams of tones arise in parallel from different regions of space. There are striking differences among listeners in the way these illusions are perceived. These differences have been found to correlate with the handedness of the listener, and so can be taken to reflect innate differences in brain organization.

The Octave Illusion

The octave illusion is produced by the pattern shown in the upper portion of Figure 1. Two tones which are spaced an octave apart (at 400 and 800 Hz) are repeatedly presented in alternation. The tones are 250 ms sine waves at equal amplitude, and they follow each other without pause. The identical sequence is presented via headphones to both ears simultaneously; however, when the right ear receives the high tone the left ear receives the low tone; and vice versa.

Surprisingly, this simple pattern is almost never perceived correctly, and instead gives rise to a variety of illusions. The type of illusion varies substantially across listeners, and the one most commonly obtained is shown in the lower portion of Figure 1. A single tone appears to be switching from ear to ear while at the same time its pitch appears to be switching between high and low. In other words, the sequence as heard at the right ear consists of 'high tone – silence – high tone – silence' while the sequence as heard at the left ear consists of 'silence – low tone – silence – low tone.'

The illusion becomes even more surprising when the listener's earphones are placed in reverse position. Now most people experience exactly the same thing – the tone that had appeared in the right ear still appears in the right ear, and the tone that had

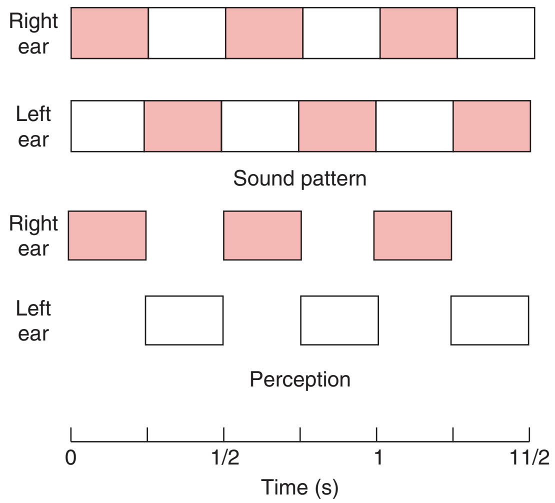

Figure 1 The sound pattern that gives rise to the octave illusion, and the percept most commonly obtained by right-handers. Filled boxes indicate tones of 800 Hz and unfilled boxes indicate tones of 400 Hz. When this pattern is played continuously through headphones, most right-handed listeners perceive an intermittent high tone in one ear that alternates with an intermittent low tone in the other ear. Adapted from Deutsch D (1974) An auditory illusion. *Nature* 251: 307–309.

appeared in the left ear still appears in the left ear. This gives rise to the peculiar impression that the earphone that had been producing the high tone is now producing the low tone, and that the earphone that had been producing the low tone is now producing the high tone.

There is clearly no simple explanation for this illusory percept. However, if we assume that there are two separate decision mechanisms, one determining what pitch we hear, and the other determining where the sound is coming from, we are in a position to advance an explanation. The model is shown in Figure 2. To provide the perceived sequence of pitches, the frequencies arriving at the dominant ear (i.e., the right ear in most right-handers) are followed, while those arriving at the nondominant ear are suppressed from conscious perception. However, to provide the perceived locations, each tone is localized at the ear that receives the higher frequency signal, regardless of whether a pitch corresponding to the higher or the lower frequency is perceived.

More specifically, we can consider a listener who perceives the pitches corresponding to the frequencies delivered to the right ear. When the high tone is delivered to the right ear and the low tone is delivered to the left, this listener hears a high tone, since it is delivered to the right ear, and localizes the tone in the right ear, since this ear is receiving the higher frequency signal. However, when a low tone is delivered to the right ear and a high tone is delivered to the left, this listener now hears a low tone, since it is delivered to the right ear, but hears the tone in the left ear instead, since this ear is receiving the higher frequency signal. So the full sequence is heard as a high tone to the right, alternating with a low tone to the left. It can be seen from Figure 2 that reversing the position of the headphones would not alter this basic percept. However, given a listener who perceives the pitches corresponding to the frequencies arriving at the left ear instead, holding the localization rule constant, the same sequence is heard as a high tone to the left, alternating with a low tone to the right.

Evidence for this model has been obtained in a number of studies. The octave illusion therefore provides a strong indication, at the perceptual level, that the neural pathways underlying what pitch we hear, and those underlying where the sound is located, are at some stage distinct and separate, and operate in accordance with different rules. The combined outputs of these two mechanisms can then result in striking illusory conjunctions.

As another aspect of the octave illusion, it has been found, on a statistical basis, that right-handers and left-handers show different patterns of localization for the high and low tones at the two ears. Right-handers tend strongly to hear the high tone on the right and the low tone on the left; however, left-handers as a group do not show the same tendency. This handedness difference is in accordance with the literature showing that while most right-handers have clear left-hemisphere dominance, patterns of cerebral dominance among left-handers vary considerably. In one study individuals were categorized as strongly right-handed, mixed-handed, or left-handed, and these groups were subdivided into those who had only right-handed parents and siblings, and those who had a left-handed parent or sibling. As shown in Table 1, this categorization produced an orderly pattern of results: subjects who were strongly right-handed and with no left-handers in their family were most likely to hear the high tone on the right and the low tone on the left, while left-handers with left-handers in their family were least likely to do so. These findings are as expected from neuropsychological studies relating hemispheric dominance of function to patterns of handedness and familial handedness background, since those individuals with left-handers in their family are less likely to be strongly left-hemisphere dominant than are those with only right-handers in their family. As a further handedness correlate, left-handers as a group tend more than right-handers to obtain complex percepts on listening to the octave illusion. This is in accordance with studies showing that left-handers, on a statistical basis, tend to have weaker patterns of cerebral dominance than do right-handers.

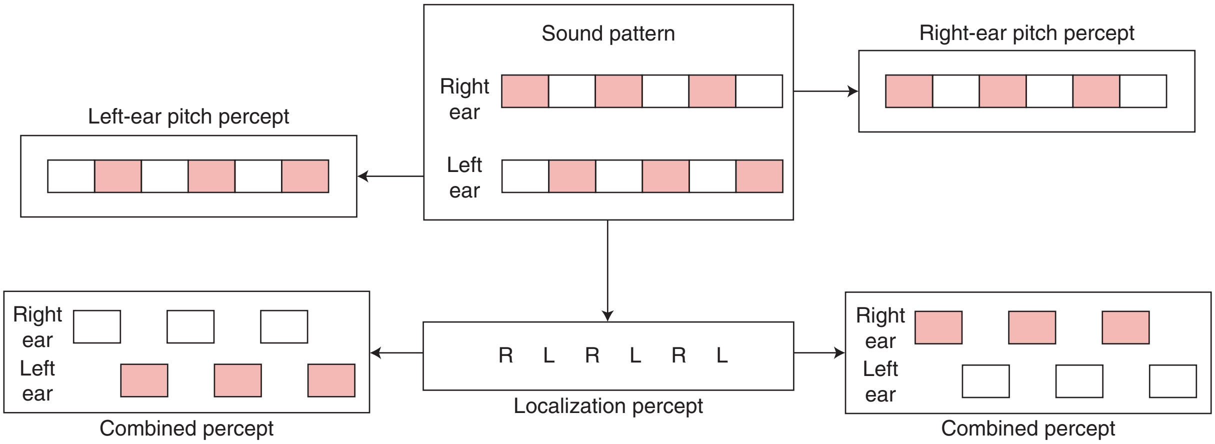

Figure 2 Model showing how the outputs of two decision mechanisms, one determining perceived pitch and the other determining perceived location, combine to produce the octave illusion. Filled boxes indicate tones of 800 Hz and unfilled boxes indicate tones of 400 Hz (R, right; L, left). Adapted from Deutsch D (1983) Auditory illusions, handedness, and the spatial environment. *Journal of the Audio Engineering Society* 31: 607–618.

Table 1 Percentages of individuals reporting the high tone on the right and the low tone on the left on listening to the octave illusion, tabulated by handedness and familial handedness background

	Dextral	*Left- or mixed-handed parent*	*Left- or mixed-handed sibling*
Right-handed	87.2% ($N=86$)	64.0% ($N=25$)	79.3% ($N=29$)
Mixed-handed	67.7% ($N=31$)	44.4% ($N=9$)	58.3% ($N=12$)
Left-handed	55.6% ($N=9$)	50.0% ($N=16$)	33.3% ($N=6$)

From Deutsch D (1983) The octave illusion in relation to handedness and familial handedness background. *Neuropsychologia* 21: 289–293.

The Scale Illusion

We next inquire what happens when a pattern is presented that consists of more than two tones. The scale illusion provides an example. As shown in the upper portion of Figure 3, the sequence that produces this illusion consists of a major scale, with successive tones alternating from ear to ear. The scale is presented simultaneously in both ascending and descending form, such that when a tone from the ascending scale is in the right ear, a tone from the descending scale is in the left ear; and vice versa. In consequence, the right ear receives one disjunct pattern of pitches, while the left ear receives a different, and overlapping, disjunct pattern of pitches. The tones are 250 ms sine waves at equal amplitude, and the sequence is repeatedly presented without pause.

This scale pattern also produces a number of illusions, which vary strikingly across listeners. The illusion most commonly obtained by right-handers is shown in the lower portion of Figure 3. A melody that corresponds to the higher tones appears to be coming from the right earphone, and melody corresponding to the lower tones appears to be coming from the left earphone. When the earphone positions are reversed, the higher tones continue to be heard as in the right ear

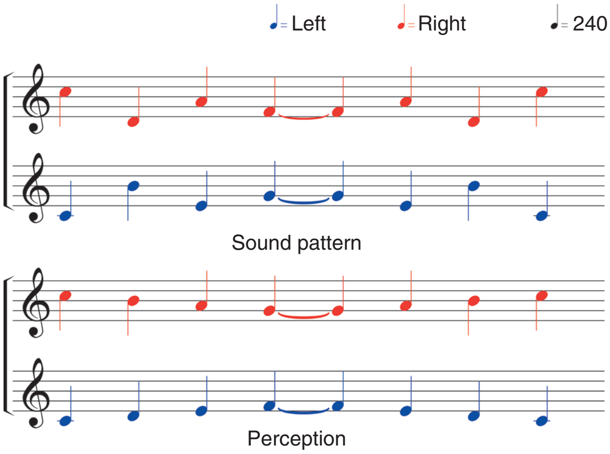

Figure 3 The sound pattern that gives rise to the scale illusion, and the percept most commonly obtained by right-handers. A major scale is presented simultaneously in ascending and descending form. The components alternate between earphones such that when a component of the ascending scale is delivered to one ear a component of the descending scale is delivered to the other ear. The pattern is played continuously without pause. Most right-handers perceive a melody that is composed of the higher tones in the right ear and a melody composed of the lower tones in the left ear. Adapted from Deutsch D (1999) Grouping mechanisms in music. In: Deutsch D (ed.) *The Psychology of Music*, 2nd edn., pp. 299–348. San Diego: Academic Press.

and the lower tones as in the left ear. This produces the strange impression that the procedure of reversing earphone positions has caused the higher tones to migrate from one earphone to the other, and the lower tones to migrate in the opposite direction. As with the octave illusion, right-handers and left-handers differ statistically in the way they perceive the scale illusion: right-handers tend to hear the higher tones on the right and the lower tones on the left; however, left-handers as a group do not show the same tendency. This indicates that there is a perceptual tendency to perceive higher tones as coming from the dominant side of space and lower tones as from the nondominant side.

Variants of the scale illusion are easily produced. Figure 4 depicts a version involving a two-octave chromatic scale. In reality, the sounds coming from each earphone leap around in pitch; however, listeners instead hear two smooth melodies that correspond to the higher and lower tones in the combined pattern, and they perceive the higher tones as coming from one earphone (in right-handers, this is usually the right earphone) and the lower tones as from the other.

The scale illusion can also occur with the sounds presented to the listener via two loudspeakers in a normal room environment. In one experiment, piano tones were used as signals, and differences in timbre were introduced for the tones presented through the two loudspeakers. The differences in timbre gave rise to yet another perceptual dissociation: a new sound quality was heard, but it appeared to be coming simultaneously from both loudspeakers. This perceptual dissociation of timbre from pitch and location may be related to findings indicating that brain lesions can give rise to deficits in timbre perception with spared pitch perception.

Why, then, should the illusory conjunctions that give rise to perception of the scale illusion occur? One approach involves the notion of unconscious inference. When faced with a complex sound configuration the brain engages in a process of inference concerning the sources that produced the sounds. In everyday life, similar sounds are likely to be coming from the same source and different sounds from different sources. So the best interpretation of this implausible musical pattern, in terms of the real world, is that the higher tones are all coming from one source and the lower tones from a different source. We therefore mislocalize the tones in accordance with this interpretation.

A related approach derives from the writings of the Gestalt psychologists, who argued that we form perceptual configurations based on certain organizational principles such as proximity. In the case of vision, for example, we group together dots that are positioned in spatial proximity, and we perceive motion between neighboring lights that are turned on and off in succession. The principle of proximity is a useful heuristic, since in the real world elements that are proximal in an array are likely to be coming from the same source. In the scale illusion we group

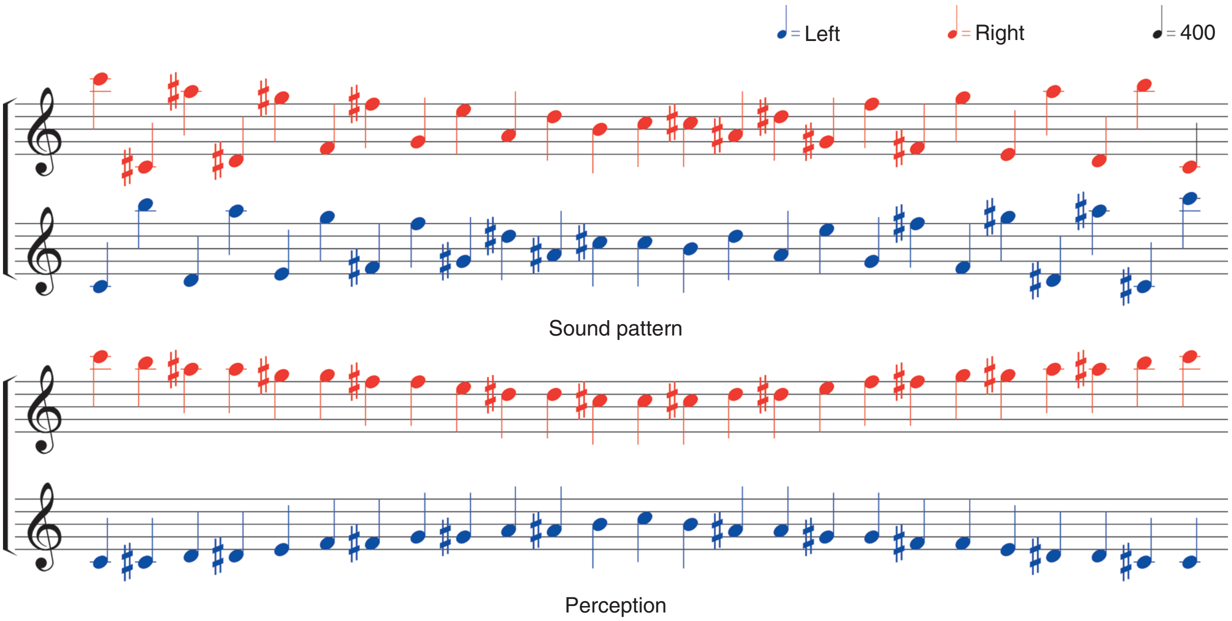

Figure 4 The sound pattern that gives rise to the chromatic illusion, and a way it is often perceived by right-handers. A two-octave chromatic scale is played simultaneously in ascending and descending form. The components alternate between earphones such that when a component of the ascending scale is presented to one ear a component of the descending scale is presented to the other ear. Most right-handers perceive a melody that is composed of the higher tones in the right ear and a melody composed of the lower tones in the left ear.

together successive tones that are related by pitch proximity, and separate out those that are further apart, and we mislocalize the tones on this basis, so overriding low-level localization cues.

The Glissando Illusion

The glissando illusion is best heard with the listener seated in front of two stereophonically separated loudspeakers, with one to the left and the other to the right. The pattern that gives rise to the illusion consists of two components; the first is a synthesized oboe tone of constant pitch, and the second is a sine wave that glides up and down in pitch. As illustrated in Figure 5, these two components are presented simultaneously via the two loudspeakers, and constantly switch between the speakers such that when the oboe tone is emanating from the speaker on the right a portion of the glissando is emanating from the speaker on the left; and vice versa. A fragment of the pattern producing this illusion is shown in Figure 5. When each channel is presented separately, the listener correctly hears the oboe tone in alternation with a portion of the glissando. However, when both channels are presented together, the percept changes dramatically. The oboe tone is heard correctly as switching back and forth between the loudspeakers. However, the portions of the glissando appear to be joined together quite seamlessly, so that a single, continuous tone is heard that appears to move around in space in accordance with its pitch motion. When the switching rate speeds up and slows down, the speed at which the glissando appears to move around in space does not change, but instead remains tied to its pitch motion.

Handedness correlates again emerge in terms of the apparent spatial positions of the higher and lower portions of the glissando: right-handers tend strongly to hear the glissando move from left to right as its pitch moves from low to high, and then back from right to left as its pitch moves from high to low. However, non-right-handers as a group do not show the same tendency. In this sense, the glissando illusion is similar to the octave and scale illusions, since it reflects a tendency to hear higher tones as on the dominant side of space and lower tones as on the nondominant side. However, in the octave and scale illusions the apparent spatial positions of the higher and lower tones generally remain fixed for the duration of the pattern, whereas in the glissando illusion the gliding tone is perceived as moving slowly in space, in accordance with its pitch motion.

In considering why the glissando illusion occurs we can refer to the same principles as were discussed with respect to the scale illusion. In this case we link together portions of the glissando that are proximal in pitch, and that follow smooth trajectories. In the real world this perceptual strategy is likely to lead to the best conclusion in interpreting our auditory environment, since it is very unlikely that a sound which is changing smoothly in pitch is switching abruptly between two widely different locations.

Illusions Based on Octave Ambiguity

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, which correspond to the division of the

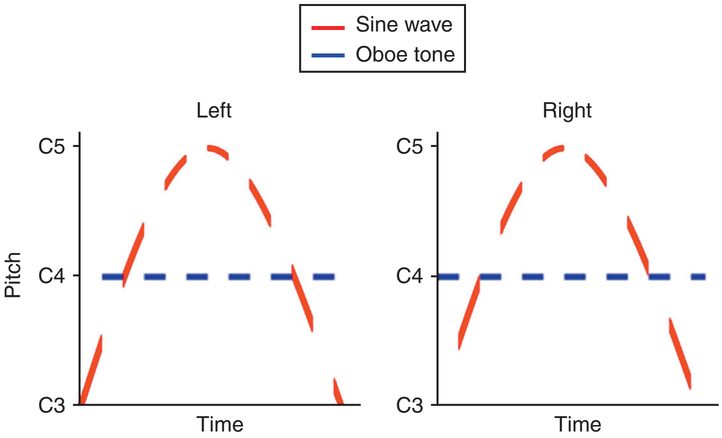

Figure 5 The sound pattern that produces the glissando illusion. This consists of an oboe tone of constant pitch and a sine wave that glides up and down in pitch, with the two repeatedly switching between loudspeakers. Listeners perceive the oboe tone correctly as alternating between loudspeakers; however, the glissando appears to be joined together quite seamlessly, and to be moving around in space in accordance with its pitch motion.

octave into semitones, and each tone is given a name (C, C#, D, D#, E, F, F#, G, G#, A, A#, and B). The entire scale, as it ascends in height, consists of repeating the same sequence of note names across successive octaves. Because all Cs sound in a sense equivalent, as do all C#s, all Ds, and so on, pitch can be characterized as varying both along a monotonic dimension of height and also along a circular dimension of pitch class (or note name). The circular dimension is illustrated in Figure 6. The two dimensions can be largely separated by the use of computer-produced tones with pitch classes that are clearly defined, but that are ambiguous in terms of height. For example, one can employ tones consisting only of components that are related by octaves. With the use of such ambiguous tones, striking illusions are produced.

Illusions of Pitch Circularity

When two octave-ambiguous tones are played in succession, the listener hears either an ascending pattern or a descending one, depending on which is the shorter distance between the tones along the pitch class circle. So, for example, the tone pair consisting of C# followed by D is always heard as ascending, since the shorter distance between these tones is clockwise. Similarly the tone pair consisting of F# followed by F is always heard as descending, since the shorter distance between these tones is counterclockwise. So when a series of octave-ambiguous tones is presented that repeatedly traverses the pitch class circle in clockwise direction (C, C#, D, and so on) listeners perceive a sequence that appears to ascend endlessly in pitch. When, instead, the tones repeatedly traverse the pitch class circle in counterclockwise direction (C, B, A#, and so on) listeners hear a sequence that appears to descend endlessly. So just as with the scale illusion, this circularity illusion provides an example of the perceptual tendency to link together elements of an array of tones on the basis of pitch proximity.

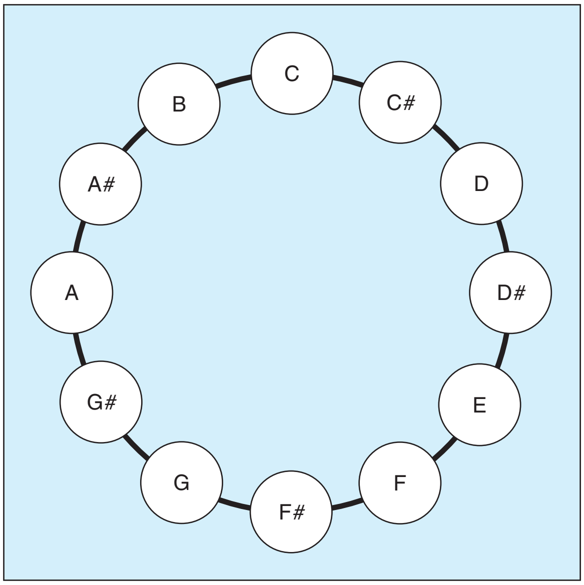

Figure 6 The pitch class circle. The notes of the Western musical scale are formed by dividing the octave into 12 semitone steps, and each note is given a name: C, C#, D, and so on. The entire scale is formed by repeating this sequence of note names across octaves.

The Tritone Paradox

We can then ask what happens when listeners are presented with pairs of octave-ambiguous tones that are related in such a way that proximity cannot be used as a cue in judging their relative heights. For example, what happens when listeners are presented with two tones in succession that stand in opposite positions along the pitch class circle, so that the same distance between them along the circle is traversed in either direction? Such tones form an interval of six semitones, known as a tritone. When such tone pairs are presented, striking perceptual differences among listeners emerge. For example, when D is presented followed by G#, some listeners clearly hear an ascending pattern, while other listeners clearly hear a descending one. Yet when, instead, A is presented followed by D#, the first group of listeners now hears a descending pattern, whereas the second group now hears an ascending one. Furthermore, for any given listener the pitch classes generally arrange themselves perceptually with respect to height in a systematic way: tones in one region of the pitch class circle are heard as higher, and tones in the opposite region as lower. This is illustrated in Figure 7, which reproduces judgments of the tritone paradox made by four different listeners. It can be seen that the judgments of each listener showed an orderly relationship to the positions of the tones along the pitch class circle; however, the direction of this relationship varied substantially across listeners. As a result, extended patterns formed of such tone pairs are heard by listeners in entirely different ways, as depicted in Figure 8.

It has been shown that the way the tritone paradox is perceived correlates with the pitch range of the listener's speaking voice. Perception of this illusion also varies with the language or dialect to which listeners have been exposed. For example, striking differences have been found between listeners who had grown up in California and those who had

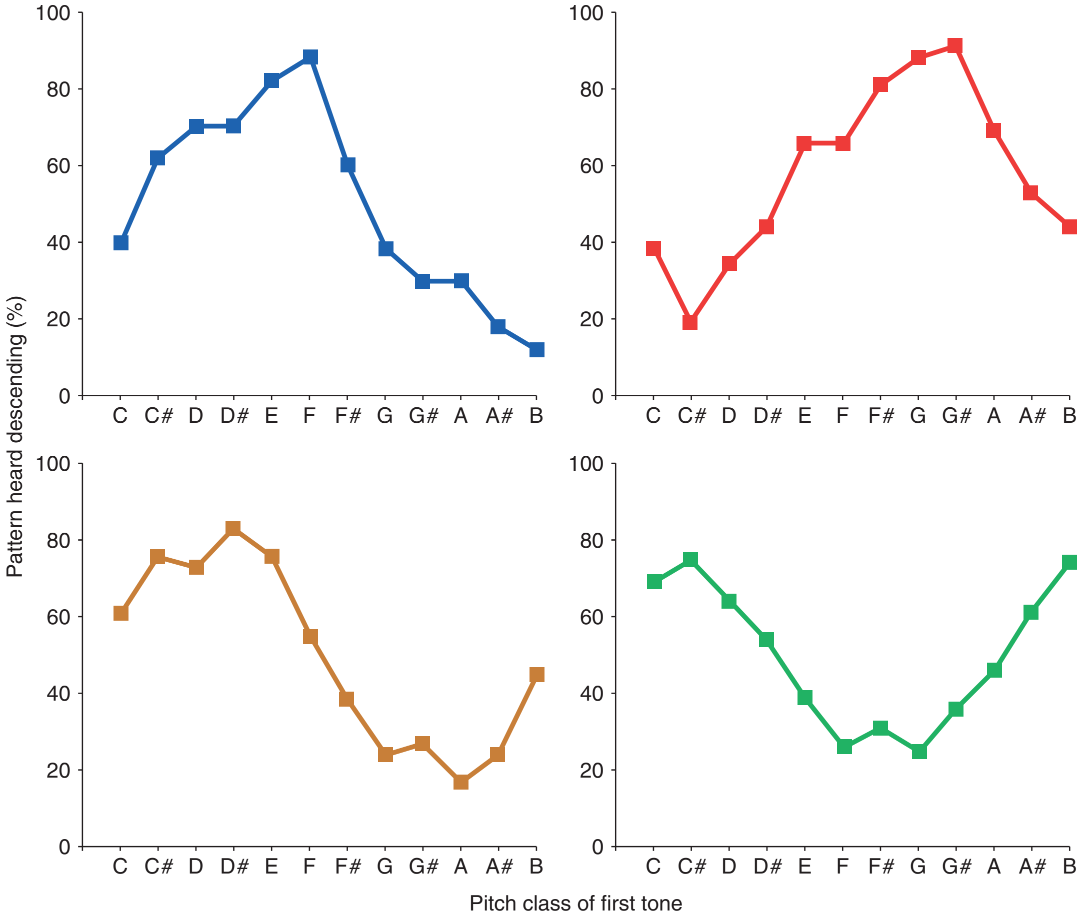

Figure 7 Judgments of the tritone paradox made by four different listeners. Each graph shows the percentages of judgments that a tone pair formed a descending pattern, plotted as a function of the pitch class of the first tone of the pair. The judgments of all listeners showed orderly relationships to the positions of the tones along the pitch class circle; however, the direction of this relationship varied substantially across listeners. Data supplied by the author.

grown up in the south of England: in general, when the California group tended to hear a pattern as ascending, the English group tended to hear it as descending, and vice versa. It appears, therefore, that perception of the tritone paradox is based on an acquired pitch template that is used primarily for speech communication.

Further work has provided evidence that the pitch representation that influences perception of the tritone paradox is formed early in life. On study explored perception of the tritone paradox in mothers and their children. The children were all Californians; however, the mothers had grown up in many different geographical regions, including England, the European continent, and various parts of the United States. As expected, the group of mothers perceived this pattern in ways that differed considerably; however, although the children were all native Californians, their percepts were very similar to those of their mothers. In a further study, perception of this illusion was explored in individuals who were born in Vietnam, as well as in a group of English-speaking Californians. The Vietnamese group was divided into two subgroups: those who had arrived in the United States as adults and spoke fluent Vietnamese but little English, and those who had arrived as infants or young children and now spoke perfect English, though most were not fluent in Vietnamese. Perception of the tritone paradox by the two Vietnamese groups was very similar, and clearly differed from the paradox's perception by English-speaking Californians. The study therefore indicates that exposure to speech sounds during an early critical period can have a substantial influence on perception of music in adulthood.

Conclusion

The perceptual phenomena described in this article demonstrate that the auditory system is very prone

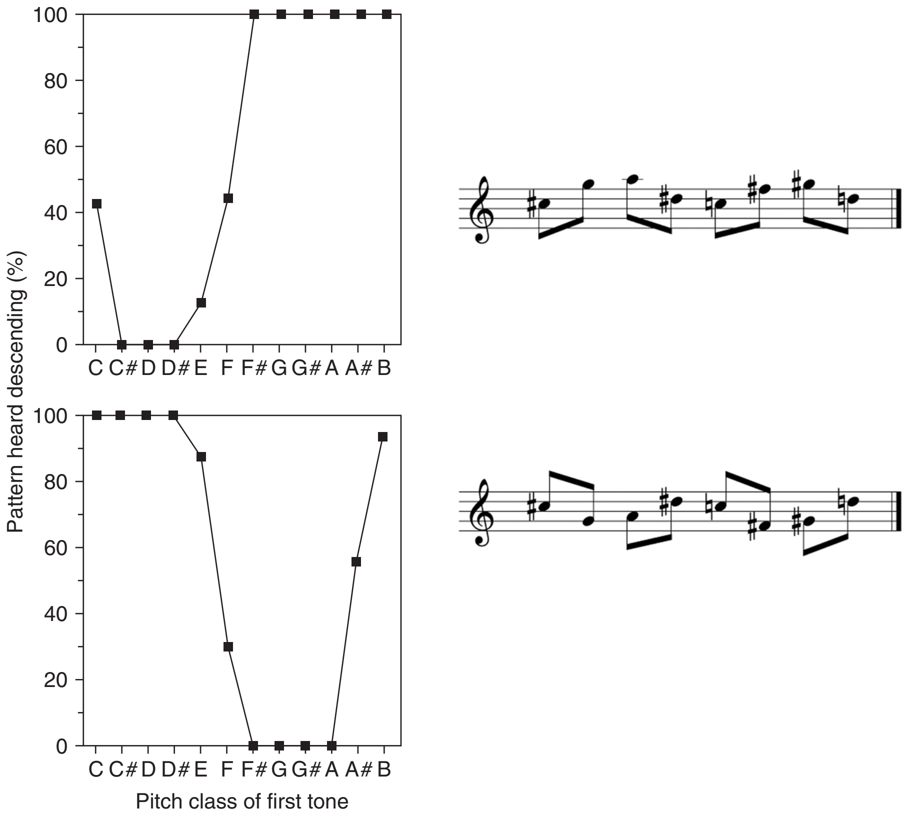

Figure 8 Perception of the tritone paradox by two listeners who experienced the illusion in a pronounced way. Each graph shows the percentages of judgments that a tone pair formed a descending pattern, plotted as a function of the pitch class of the first tone of the pair. The notations show how the identical series of tone pairs was perceived by these two listeners in entirely different ways. From Deutsch D (1999) Processing of pitch combinations. In: Deutsch D (ed.) *The Psychology of Music,* 2nd edn., pp. 349–412. San Diego: Academic Press.

to illusion. This is not surprising, considering the paucity of information that is supplied by the peripheral auditory system. There are roughly 16 000 peripheral receptors in each ear, compared with roughly 125 million receptors in each eye. In addition, the amount of brain tissue devoted to hearing is far less than is devoted to vision. As a further consideration, sound signals are mixed together and are subject to numerous distortions as they travel from their sources to our ears, so that the brain is faced with the very difficult task of reconstructing the original signals from the mixture of sounds that arrive at the ears. The musical illusions described here provide valuable information concerning the strategies adopted by the nervous system in interpreting our auditory environment, and they reflect the operation of both innate mechanisms and neural plasticity in the process.

See also: Language: Auditory Processes; Music; Speech Perception: Adult; Speech Perception: Cortical Processing; Speech Perception: Development; Speech Perception: Neural Encoding.

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