MUSICAL ILLUSIONS

by Diana Deutsch
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Presenting certain sequences of tones simultaneously to both ears produces paradoxical auditory illusions. Surprisingly, right-handed subjects and left-handed subjects perceive the illusions differently.

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When we listen to music, we do not merely hear a set of independent tones; we perceive the tones as being linked together in combinations such as melodies and chords. One of the central problems in the study of the perception of music is how the human brain sorts and organizes a complex set of tonal stimuli into such combinations. When I set out to investigate the principles by which we link successive tones into musical sequences, I obtained some surprising results, including a series of paradoxical auditory and musical illusions. Even more surprising, right-handed and left-handed subjects perceive the auditory illusions in different ways.

In these experiments a computer was programmed to control two sine-wave generators so that the tones could be precisely regulated in terms of amplitude, duration and frequency. The technique used is known as dichotic presentation. The tonal sequences were presented to the listener through earphones so that when one ear received one tone, the other ear received another tone.

In the first experiment the listener heard a sequence consisting simply of a high tone alternating with a low tone. The tones were in octave relation and their frequencies were 400 and 800 hertz on the musical scale these are closest to G₂ (392 hertz) and G₃ (784 hertz). The sequence was presented simultaneously to both ears at equal amplitude. The sequence at one ear, however, was out of phase with the sequence at the other: when one ear received the high tone, the other ear received the low tone, and vice versa.

Although the listener was presented with a single, uninterrupted two-tone chord, I have found only one individual in the 100 or so I have tested who was able to describe the two-tone chord correctly. Most listeners heard only a single tone that shifted from one ear to the other, and as it shifted, its pitch simultaneously shifted from the high tone to the low one. In other words, the listener alternately heard the high tone in one ear and the low tone in the other. When the earphones were reversed, most people experienced exactly the same thing: the ear that had previously heard the high tone would hear the low tone, and the ear that had heard the low tone would hear the high tone. It seemed, however, that the earphone that had originally emitted the high tones was now emitting the low tones and that the earphone that had emitted the low tones was now emitting the high ones (see two illustrations on opposite page).

Right-handed subjects tended strongly to hear the high tone in their right ear and the low tone in their left ear and to maintain this percept when the earphones were reversed. Left-handed subjects were just as likely to localize the high tone in their left ear as in their right. In right-handed people the left hemisphere of the brain is dominant, and its primary auditory input comes from the right ear. In left-handed people either hemisphere may be dominant. The difference in the localization of the tones in right-handed and left-handed subjects suggests that high tones are perceived as coming from the ear that provides the strongest input to the dominant hemisphere, and that low tones are perceived as coming from the ear that provides the strongest input to the nondominant hemisphere.

Although most listeners showed a preference for localizing the high tone in one ear and the low tone in the other, it often happened that after continued listening the high and the low tones suddenly reversed position. Such reversals occurred without warning in the middle of a sequence, but they were most likely to occur when the sequence was abruptly discontinued and then started again. Some subjects experienced frequent reversals. We have here, I believe, an auditory analogue of reversing visual figures such as the Necker cube (see illustration on page 3). In both the auditory illusion and the visual one the perceptions alternate spontaneously and never occur simultaneously.

The two-tone illusion presents a paradox for theories of pitch perception and auditory localization. If we assume that the listener attends to one ear and ignores the other, then the alternating pitches should both seem to be localized in the same ear. Alternatively, if we assume that the listener attends to each ear in turn, the perceived tone should not change in pitch as it shifts from ear to ear. The fact remains that for most people the high tone is heard as though in one ear and the low tone as though in the other. The paradox is that the low tone is localized in an ear that is actually receiving a high tone at that moment.

Some people did perceive the two-tone chord as a single tone that alternated from one ear to the other, with the pitch either remaining the same or changing only slightly. Others reported complex percepts, such as two low tones alternating from ear to ear together with an intermittent high tone in one ear, or a sequence in which the pitch relations seemed to change gradually over a period of time. Some listeners remarked on striking differences between the timbres of the tones, for example that the low tones sounded like a gong and the high tones like a flute. These complex percepts tended to be unstable and often
HOLLOW MOLD OF A HUMAN FACE is shown in the photograph at the left. When the hollow mold is viewed from the back, the face appears to project outward even though the features of the face are actually projecting inward. Hence our perception that all faces project outward is so strong, we unconsciously infer that the hollow mold of a face here must be projecting outward. Unconscious inference may also be the basis of the illusion created by the paradoxical musical sequence (see upper illustration on page 8).

TWO-TONE AUDITORY ILLUSION is created when a sequence consisting of a high tone (colored squares) alternating with a low tone (white squares) is presented so that when one ear receives the high tone, the other ear simultaneously receives the low tone, and vice versa. Each tone was a quarter of a second in duration. The frequencies were 400 and 400 hertz. The sequence is presented for 20 seconds. Most right-handed subjects hear a high tone in the right ear alternating with a low tone in the left ear. The surprising thing is that the low tone is localized to the left ear while that ear is actually receiving a high tone. When the earphones are reversed (right), most people continue to hear the high tone in the right ear and the low tone in the left ear. To the listener it seems that the earphone that previously emitted the high tone was now emitting the low tone and that the earphone that had emitted the low tone was now emitting the high tones. Most left-handed subjects hear a high tone in one ear alternating with a low tone in the other ear, but the high tone is just as likely to be localized in the left ear as in the right. Some listeners hear a single tone that alternates from ear to ear. Others, particularly left-handers, report complex percept consisting of several tones.

REPRESENTATION IN MUSICAL NOTATION of the two-tone sequence is given at the left. The most common illusionary percept is depicted at the right. The closest notes in the musical scale to the actual 400- and 400-hertz tones are G₂ (392 hertz) and G₃ (396 hertz).
A sudden reversal of the high tone and the low tone occurs for some subjects with prolonged listening to the tone/rhythm sequence. The high tone seems to shift from the right ear to the left, and simultaneously the low tone shifts from the left ear to the right.

In the alternating-tone illusion based on the absolute pitch levels in the stimulus sequence or on the relative pitch levels? To find out I selected a group of listeners who had consistently localized the high tone in the right ear and the low tone in the left ear and who showed no tendency to reverse the pattern. I presented three different sequences of tones to these subjects: the first dichotic sequence alternated tones of 390 and 400 hertz; the second, tones of 400 and 800 hertz, and the third, tones of 800 and 1,600 hertz. Virtually all the subjects reported hearing the higher tone of each sequence in the right ear and the lower tone in the left ear. The results clearly show that the illusion is based on the pitch relation between the competing tones.

How can we account for this auditory illusion? There is clearly no simple explanation, but we may suppose separate brain mechanisms exist for determining what pitch we hear and for determining where the tone appears to be coming from. Indeed, these two mechanisms may even be differentiated anatomically. Barry et al. (1965) and the neuroanatomist S. Pollock have proposed that there is an anatomical separation in the lower levels of the auditory system between the mechanisms serving discriminatory functions and those serving localization functions. Recently E. F. Profas and E. G. Nelson of the University of Kentucky in England have provided neurophysiological support for this scheme. There seems to be a similar separation in the visual system.

Gerald E. Schneider of the Massachusetts Institute of Technology has found that if the part of the brain known as the superior colliculus is removed from a hamster, the animal can discriminate between patterns, but cannot tell where an object is. On the other hand, if the visual cortex of the brain is removed, the hamster shows poor pattern discrimination but can easily locate objects in space.

If we suppose there are two separate auditory mechanisms, one for determining the pitch we hear and another for determining where the sound is coming from, we are in a position to explain the illusion. An additional hypothesis that is needed in that although under the conditions of the illusion only one ear follows the sound for pitch, the perceived tone is localized by the brain toward the ear receiving the higher tone. Let us take the case of a listener who follows the sound for pitch to the right ear, but then, because the lower tone is coming from the left ear, localizes it toward the left ear.

In most right-handed people the left hemisphere of the brain is dominant for speech. Studies have shown that there is a high degree of hemispheric specialization in the right-handed group. These studies have shown that the left hemisphere is more involved in tasks requiring verbal and sequential processing, while the right hemisphere is more involved in tasks requiring spatial and non-verbal processing. This specialization of the hemispheres is thought to be responsible for the auditory illusion described above.

PRINCIPLES OF PROXIMITY plays an important role in the perception of melody. Two excerpts from classical music show how tones from two frequency ranges are grouped into separate melodic lines. In Capriccio for Recorder and Bassoon Continuo (top) by Georg Philipp Telemann the sequence creates two separate melodies, each in a different frequency range. In Telemann's Senzas in C Major for Recorder and Bassoon Continuo a repetitive single pitch in the lower range forms a ground against which the melody is heard (bottom).
the two melodies were in different pitch ranges, recognition was much easier. Dowling interpreted his findings in terms of the tendency to group tonal stimuli into separate pitch ranges so that tones in different ranges do not interfere with one another.

Albert S. Bregman and John Campbell of McGill University have investigated the paradoxical musical sequence and the associated perceptual property of very rapid sequences of tones that are drawn from two separate frequency ranges. Listeners found it difficult to perceive the order of tones in such sequences, although the problem did not arise when the tones were close together in pitch. It appears that if the rate of presentation is very rapid, we cannot form order relations between the elements of different tonal streams.

Why do many listeners, on hearing the paradoxical musical sequence I have described, localize all the higher tones in one ear and all the lower tones in the other? Since all the tones are perceived, the illusion must have a basis different from that of the two-tone-chord illusion. The musical illusion is created by tones from overlapping pitch ranges. In everyday life similar sounds are likely to emanate from the same source and different sounds from different sources. Hence the best interpretation of the dichotic musical sequence, in terms of the real world, is the assumption that sounds in one frequency range are emitted from one earphone and sounds in the other frequency range are emitted from the other earphone. The power of unconscious inference is so strong that it overrides the actual localization cues.

Unconscious inference is based on the assumption that the sequence of pitches that is delivered to his right ear. When the high tone is presented to the right ear and the low tone to the left, the listener should hear a high tone in his right ear, since the right ear is both determining pitch and receiving the higher tone. When the low tone is presented to the right ear and the high tone to the left, the listener should hear a low tone, since it is the tone presented to his pitch-determining ear, but the tone should seem to be coming from both ears because the brain localizes the perceived tone at the ear that is receiving the higher tone. The entire sequence should therefore be a high tone in the right ear alternating with a low tone in the left. It is obvious that reversing the position of the earphones would not alter the perceived sequence.

In the case of a listener who follows the sequence of pitches that is delivered to his left ear, the dichotic sequence would be perceived as a high tone in the left ear alternating with a low tone in the right ear and the reversals experienced by some listeners would be due to a change in which ear is following pitch.

In collaboration with P. L. Bell, a graduate student in the department of psychology at the University of California at San Diego, I devised an experiment to test that hypothesis. These consecutive high tones were presented to the listener’s right ear and three low tones to the left ear, again simultaneously. Listeners heard the pattern 10 times without pause and then reversed their earphones and listened to it again [see lower illustration on next page].

The results confirmed the hypothesis. The perceived tones, regardless of whether he was high or low, appeared to come from the ear that was receiving the higher frequency. As for the pattern of tones, subjects who were right-handed tended significantly to hear the pattern degraded in the left ear rather than the pattern delivered to the left ear. That is, when the right ear received three high tones followed by two low tones, the listener reported hearing three high tones in his right ear followed by two low tones that appeared to be coming from his left ear.

When the earphones were reversed, the person who always followed pitch with the same ear experienced a new illusion. He could hear three high tones before the reversal of the earphones now heard only two high tones and the ear that heard two low tones now heard three low tones. Reversal of the earphones then seems to cause the listener to hear the high tones to disappear and to create an additional low tone, even though there is absolutely no change in the dichotic sequence being presented.

In another experiment I presented the two-tone sequence through loudspeakers rather than earphones. The subject stood in an anechoic (echo-free) room, equidistant between two loudspeakers, one on his left and one on his right. When a low tone came from the loudspeaker on the left, a high tone came simultaneously from the loudspeaker on the right that alternated with a set of low tones from the speaker on the left. As the listener turned slowly to hear the high tones on his right and the low tones on his left until he was facing one speaker and the other speaker was directly behind him. He then heard a single tone of constant pitch that seemed to be coming from both speakers. If the listener continued to turn in the same direction until he had rotated 180 degrees from his original position, the speaker that had originally seemed to be emitting the high tones now seemed to be emitting the low tones, and the speaker that had been emitting the low tones now seemed to be emitting the high tones.

The illusion also occurs when the loudspeakers are placed side by side, both facing the listener, and even when they are placed at some distance. This indicates that the illusion is based on simple competition between the ears but rather on competition between different regions of perceived auditory space.

The illusion I have been describing is based on two alternating tones. What happens if the listener is presented with three tones? As for the pattern of tones, subjects who were right-handed tended significantly to hear the pattern reversed in the left ear rather than the pattern delivered to the left ear. That is, when the right ear received three high tones followed by two low tones, the listener reported hearing three high tones in his right ear followed by two low tones that appeared to be coming from his left ear.

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they were asked to ring along with the sequence, they sang the higher tones and not the lower ones. Interestingly enough, a third of these listeners correctly identified the switching of individual notes between ears. The other two-thirds reported a variety of effects, such as hearing the entire sequence in one ear, or having the sequence travel from the left ear to the right as the tones went from high to low and reverse back again to the left ear as the tones went from low to high.

When I analyzed the reports of the subjects who had listened to this musical sequence, I found that all the listeners, regardless of how they perceived it, formed perceptual groupings of tones based on frequency range. That is, they either heard all the tones as two simultaneous non-overlapping pitch sequences that ascended or descended in opposite directions, or they heard the higher tones and little or nothing of the lower ones. Since most people in our culture are much more familiar with the major scale than they are with the melodic patterns reported by the subjects, it is particularly surprising that not one of the subjects reported hearing a full ascending or descending scale.

In a further test of the effect I presented the dichotic musical sequence to a group of subjects and then had them listen to only the ascending-scale component of the sequence. When the subjects were asked if the ascending scale had been a part of the total sequence, all of them replied that it had not. It appears that the mechanism responsible for grouping tonal stimuli by their frequency range is so powerful that it can mask the perception of a familiar musical scale present in the total sequence.

An important part of listening to music involves the linking of tonal stimuli into sequences. When more than one tone is presented at a time, the listener is forced to decide which successive tone to link with which. Knowledge of the rules underlying how such linkages are made is of crucial importance if we are to understand the perception of music.

A century ago Max Wertheimer, one of the founders of the Gestalt school of psychology, proposed several principles of perceptual organization. One of them is the principle of proximity, which states that nearer elements are grouped together in preference to elements that are spaced farther apart. Another is the principle of good continuation, which states that elements that follow each other in a given direction are perceived as belonging together. Wertheimer’s principles are easily demonstrated by visual examples, and indeed two principles can be set in opposition in a single demonstration. When that is done, one principle of organization often proves to be stronger than the other (see top illustration on page 9).

The paradoxical musical sequence is another example of conflict between two principles of perceptual organization. If the principle of good continuation is applied, we should perceive either the full ascending scale or the full descending one. On the other hand, if the principle of proximity is applied, we should group the higher tones together and the lower tones together. As we have seen, a subject who listens to the paradoxical sequence always applies the principle of proximity.

The grouping of tonal stimuli by frequency range is often found in traditional music. When a solo instrument plays a melody and its accompaniment, the two elements are generally presented in different frequency ranges; more often than not the melody is in the higher range.

An interesting musical technique used by classical composers is the presentation of a sequence of notes in rapid succession, alternating between two frequency ranges, with the result that they are heard as two melodic lines (see bottom illustration on page 9). W. J. Dowling, who was then at the University of California at Los Angeles, has investigated the effect under experimental conditions. He presented pairs of well-known melodies so that successive melodies came from different melodies. When the pitch range overlapped, recognition of the melodies was very difficult. When
they were asked to align along with the sequence, they sang the higher tones and not the lower ones. Interestingly enough, a third of these listeners correctly identified the switching of individual notes between ears. The other two-thirds reported a variety of effects, such as hearing the entire sequence in one ear, or having the sequence travel from the left ear to the right as the tones went from low to high and travel back again to the left ear as the tones went from low to high.

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Albert S. Bregman and John Campbell of McGill University have investigated another interesting perceptual property of very rapid sequences of tones that are drawn from two separate frequency ranges. Listeners found it difficult to perceive the order of tones in such sequences, although the problem did not arise when the tones were close together in pitch. It appears that if the rate of presentation is very rapid, we cannot form order relations between the elements of different tonal streams.

Why do many listeners, on hearing the paradoxical musical sequence I have described, detect all the higher tones in one ear and all the lower tones in the other? Since all the tones are perceived, the illusion must have a basis different from that of the two-tone-chord illusion. The musical illusion is created by tones from overlapping pitch ranges. In everyday life similar sounds are likely to emanate from the same source and different sounds from different sources. Hence the best interpretation of the dichotic musical sequence, in terms of the real world, is the assumption that sounds in one frequency range are emitted from one earphone and sounds in the other frequency range are emitted from the other earphone. The power of unconscious inference is strong enough to override the actual localization cues.

Unconscious inference as the basis of pitch assignment.

In summary, the three main observations are:

1. When high tones are presented to the right ear and the low tones to the left, the listener hears pitch as arising from a high tone in his right ear and a low tone in his left ear. When the high tones are presented to the left ear and the low tones to the right ear, the pitch is perceived as arising from a high tone in the left ear and a low tone in the right ear.

2. The pitch of the upper tone is seen as originating in the ear corresponding to its frequency range, even when the earphones are reversed. The perceived pitch is heard as arising from the ear closest to the frequency range of the tone. When the high tones are presented to the right ear and the low tones to the left ear, the pitch is perceived as arising from the right ear. When the high tones are presented to the left ear and the low tones to the right ear, the pitch is perceived as arising from the left ear.

3. When the high tones are presented to the right ear and the low tones to the left ear, the pitch is perceived as arising from the ear corresponding to its frequency range, even when the earphones are reversed. The perceived pitch is heard as arising from the ear closest to the frequency range of the tone. When the high tones are presented to the right ear and the low tones to the left ear, the pitch is perceived as arising from the right ear. When the high tones are presented to the left ear and the low tones to the right ear, the pitch is perceived as arising from the left ear.

In conclusion, the paradoxical musical sequence is an example of a case where the perceived pitch is not determined by the actual location of the tones, but rather by the frequency range of the tones.

The paradoxical musical sequence can be used to demonstrate the power of unconscious inference in the perception of pitch. The sequence consists of two sets of tones, one set of higher frequencies and one set of lower frequencies. When the higher frequencies are presented to the right ear and the lower frequencies to the left ear, the listener perceives a pitch that is higher than the actual pitch of the higher frequencies. This is because the perceived pitch is determined by the frequency range of the tones, not by their actual location in space.
Sudden Reversal. The high tone seems to shift from the right ear to the left, and simultaneously the low tone shifts from the left ear to the right.

The pitch relation between the competing tones.

How can we account for this auditory illusion? There is clearly no simple explanation, but we may suppose separate brain mechanisms exist for determining what pitch we hear and for determining where the tone appears to be coming from. Indeed, these two mechanisms may even be differentiated anatomically. Half a century ago the neuroanatomist S. Pollock proposed that there is an anatomical separation in the lower levels of the auditory system between the mechanisms serving discriminatory functions and those serving localization functions. Recently E. F. Evans and E. G. Nelson at the University of Keele in England have provided neurophysiological support for this scheme. There seems to be a similar separation in the visual system. Gerald E. Schneider of the Massachusetts Institute of Technology has found that if the part of the brain known as the superior colliculus is removed from a hamster, the animal can discriminate between patterns but cannot tell where an object is. On the other hand, if the visual cortex of the brain is removed, the hamster shows poor pattern discrimination but can easily locate objects in space.

If we suppose there are two separate auditory mechanisms, one for determining the pitch we hear and another for determining where the sound is coming from, we are in a position to explain the illusion. An additional hypothesis that is needed is that although under the condition of the illusion only one ear follows the sound for pitch, the perceived tone is localized by the brain toward the ear receiving the higher tone. Let us take the ease of a listener who follows the sequence:

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Patients with damage to the dominant hemisphere show deficits in identifying the temporal order of auditory stimuli and in processing rhythms. Auditory listening studies with normal individuals have found that right-handers process sound sequences better through the right ear than through the left. George M. Robinson and D. J. Solomon of Duke University presented pairs of rhythmically patterned tonal sequences simultaneously, one to each ear. Right-handers identified the sequences presented to the right ear better than those presented to the left. Y. Halperin, L. Nachshon and A. Caruson of the Heichal Musical School in Jerusalem employed dichotic sequences made up of tones of different pitches and also found that better identification of the sequences presented to the right ear. These findings are in agreement with the results I obtained with the two-tone-chord illusion in which right-handed listeners tended to follow the sequence of pitches delivered to the right ear.

Since listening to music involves many aspects, including the appreciation of timbre and the organization of tonal sequences, it would appear that both the cerebral hemispheres play important but somewhat different complementary roles in musical perception. The degree of involvement of each hemisphere would depend on both the type of music and the perceptive strategy of the listener.

It is clear from the studies with auditory and musical illusions that there are substantial differences among human beings in how even the simplest tonal sequences are perceived when different spatial locations are involved. The musical experience of the listener may well play an important role. The finding that differences in the perception of tonal sequences are correlated with handedness, however, indicates that variations in auditory perception are also very liable to result from differences between individuals at a basic neurological level. Such differences may be responsible for many variations in musical taste and appreciation. Indeed, certain controversies in musical aesthetics may have as their source fundamental differences in the nervous systems of the listeners rather than differing evaluations of a common auditory percept.

HOLLOW MOLD OF A HUMAN FACE is shown in the photograph at the left. When the hollow mold is viewed from the back, the face appears to project outward even though the features of the face are actually projecting inward. Because our percept that all faces project outward is so strong, we unconsciously infer that the hollow mold of a face here must be projecting outward. Unconscious inference may also be the basis of the illusion created by the paradoxical musical sequence (see upper illustration on page 8).