566
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by Diana Deutsch

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MUSICAL ILLUSIONS

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

by Diana Deutsch

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 G_4 (392 hertz) and G_5 (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.

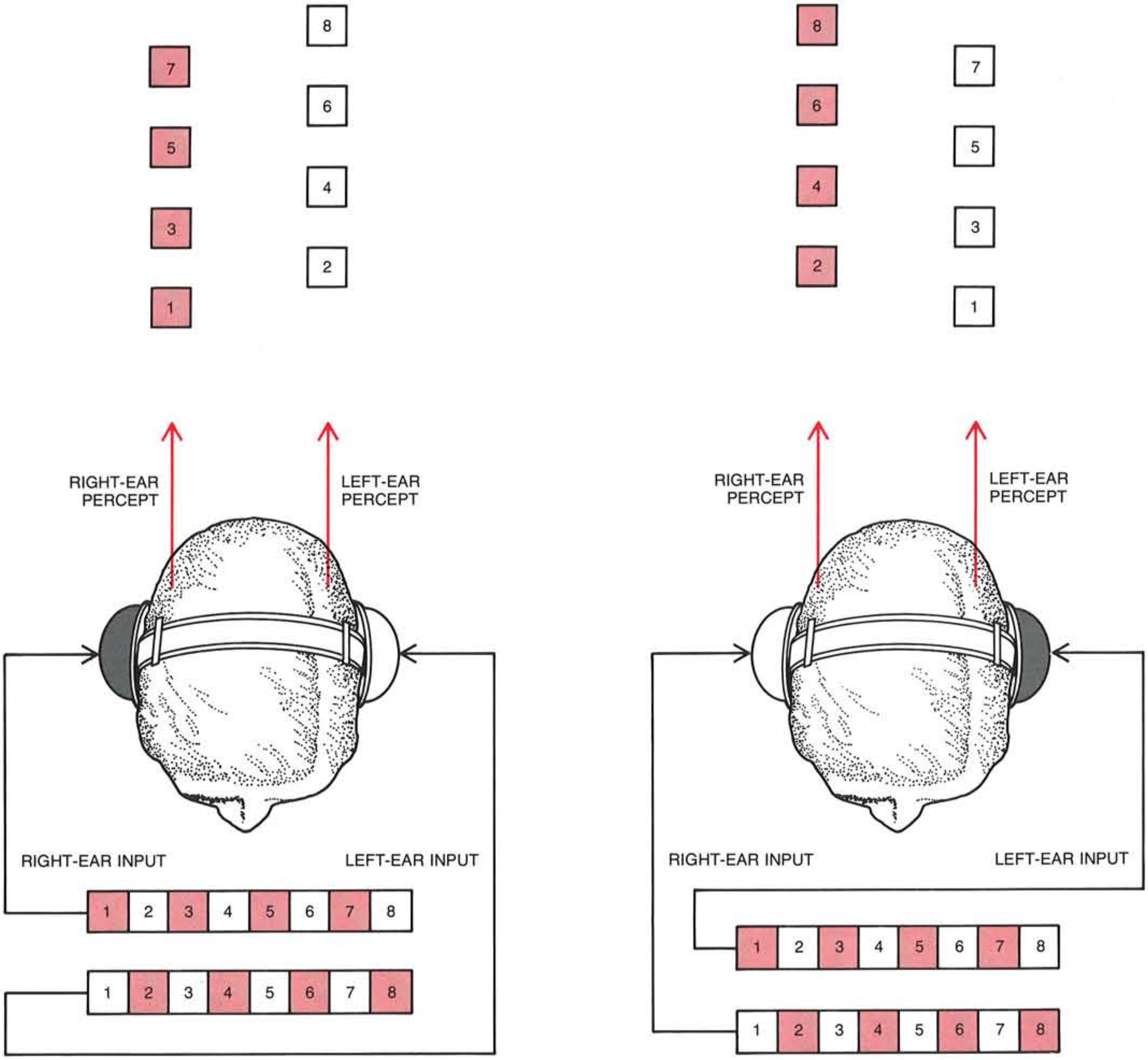
Although the listener was presented with a single, uninterrupted two-tone chord, I have found only one individual in the 100 or so I have tested who was able to describe the two-tone chord correctly. Most listeners heard only a single tone that shifted from one ear to the other, and as it shifted, its 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 still heard it, and the ear that had heard the low tone continued to hear the low 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 top illustration 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.

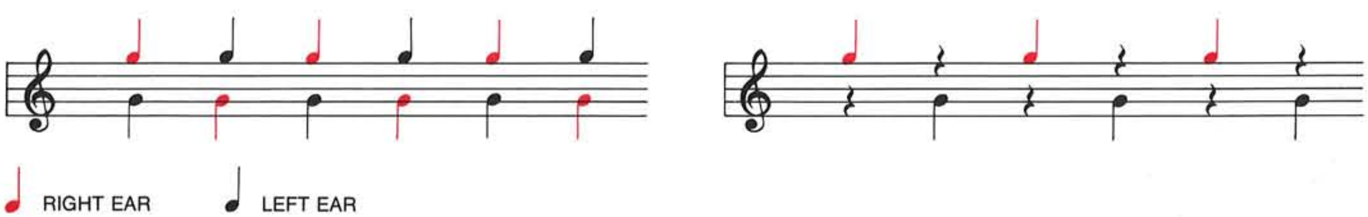
Although most listeners showed a preference for localizing the high tone in one ear and the low tone in the other, it often happened that after continued listening the high and the low tones suddenly reversed position. Such reversals occurred without warning in the middle of a sequence, but they were most likely to occur when the sequence was abruptly discontinued and then started afresh. 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 5*]. In both the auditory illusion and the visual one the percepts 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.

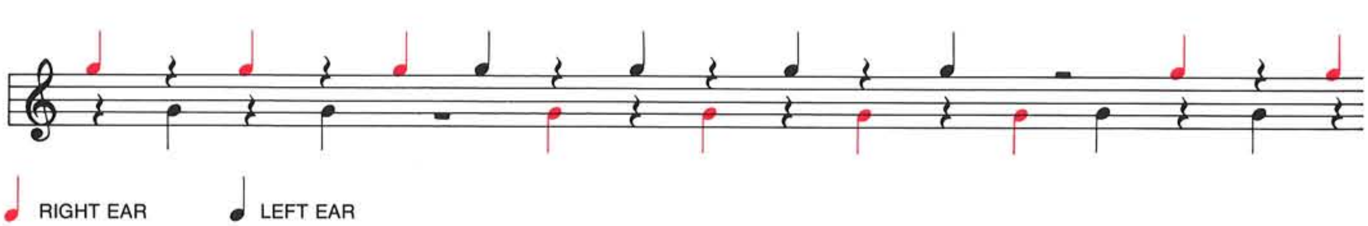
Some people did perceive the two-tone chord as a single tone that alternated from one ear to the other, with the pitch either remaining the same or changing only slightly. Others reported complex percepts, such as two low tones alternating from ear to ear together with an intermittent high tone in one 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



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 800 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 tones was now emitting the low tones and that the earphone that had emitted the low tones was now emitting the high tones. Most left-handed subjects also 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 percepts consisting of several tones.



REPRESENTATION IN MUSICAL NOTATION of the two-tone sequence is given at the left. The most common illusory percept is depicted at the right. The closest notes in the musical scale to the actual 400- and 800-hertz tones are G_4 (392 hertz) and G_5 (784 hertz).



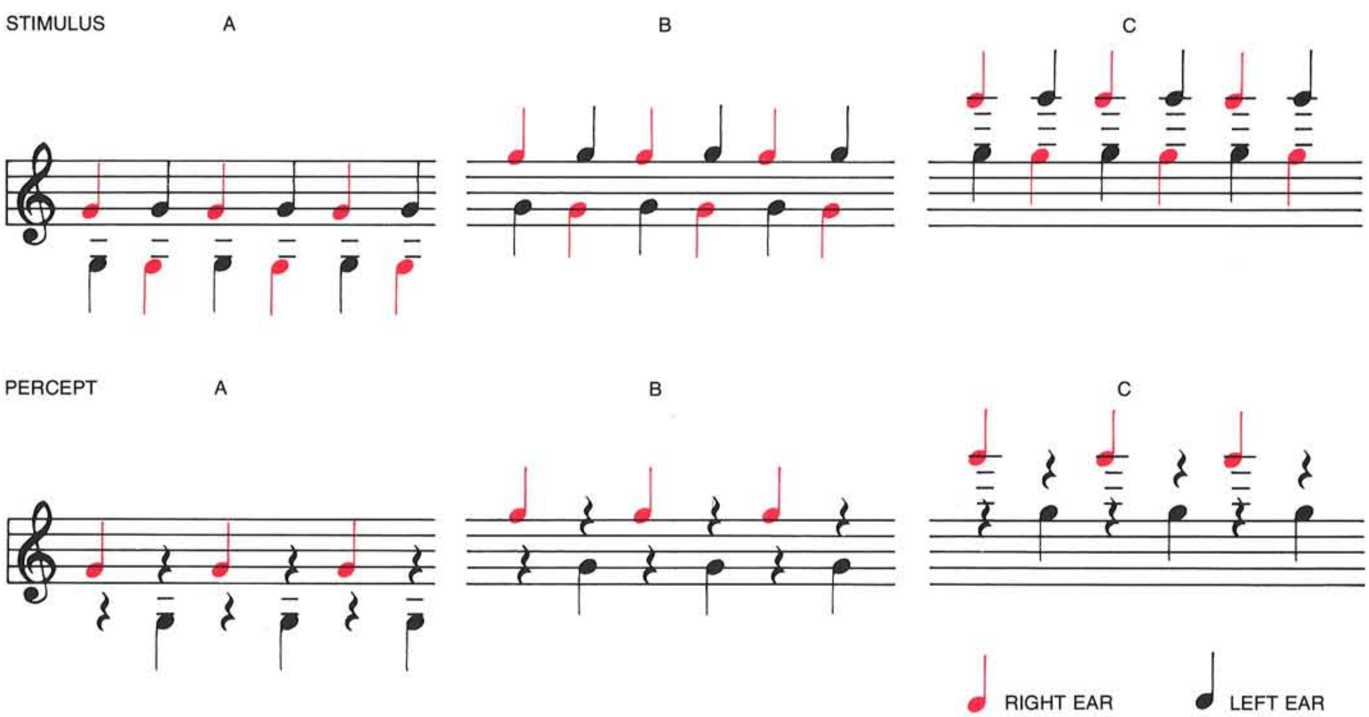
SUDDEN REVERSAL of the high tone and the low tone occurs for some subjects with prolonged listening to the two-tone sequence. The high tone seems to shift from the right ear to the left, and simultaneously the low tone shifts from the left ear to the right.

changed within a few seconds. Complex percepts were reported by a higher proportion of left-handed subjects than right-handed ones.

Is 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 200 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. Half a century ago the neuroanatomist S. Poljak 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 P. G. Nelson of 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 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 se-



THREE SETS OF PAIRED TONES were tested to determine whether the two-tone illusion is based on absolute pitch levels or on the pitch relation between the tones. The subjects were listeners who had previously localized the 800-hertz tone in the right ear and the 400-hertz tone in the left ear. The first set (*Stimulus A*) had tones of 200 and 400 hertz, the second set (*B*) had tones of 400 and 800 hertz and the third set (*C*) had tones of 800 and 1,600 hertz. In each set one ear received a high tone while the other ear simultaneously received a low tone. The results were clear: the higher of the two tones was almost always localized in the right ear and the lower of the two tones in the left ear. This indicates the illusion is based on the pitch relation between competing tones.

quence 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 the left ear 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. And the reversals experienced by some listeners would be due to a change in which ear is following pitch.

In collaboration with P. L. Roll, a graduate student in the department of psychology at the University of California at San Diego, I devised an experiment to test that hypothesis. Three consecutive high tones were presented to the listener's right ear and three low tones were simultaneously presented to the left ear. Then two low tones were presented to the right ear and two high 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 tone, regardless of whether it was high or low, appeared to come from the ear that was receiving the higher frequency. As for the pattern of the tones, subjects who were right-handed tended significantly to hear the pattern delivered to the right 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.

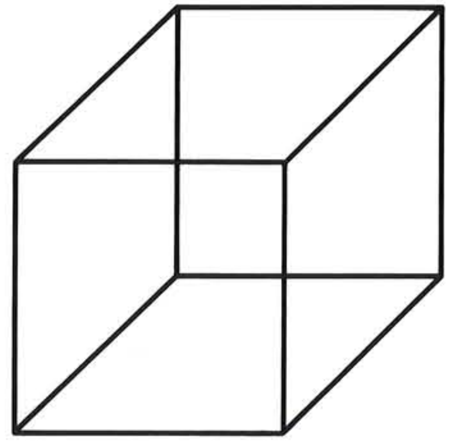
When the earphones were reversed, a person who always followed pitch with the same ear experienced a new illusion. The ear that heard three high tones before the reversal of the earphones now heard only two high tones, and the ear that heard two low tones now heard three low tones. Reversal of the earphones thus seems to cause one of 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, and vice versa. The subject heard a set of high tones apparently emanating 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 he continued 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 not on simple competition between the ears but rather on competition between different regions of perceived auditory space.

The illusions I have been describing are based on two alternating tones. What happens if the listener is presented with more elaborate musical sequences instead? In one experiment I devised a dichotic sequence consisting of the C-major scale in its ascending and its descending forms. When a note from the ascending scale was presented to one ear, a note from the descending scale was simultaneously presented to the other ear, with the successive notes in each scale alternating between ears [*see illustration on page 7*].

This musical sequence generates another set of illusions. About half of the right-handed subjects heard the correct sequence of pitches but heard them as two separate melodies, a higher one and



REVERSAL OF NECKER CUBE, in which the back face periodically becomes the front one, is analogous to the sudden reversals experienced in listening to the two-tone sequence (*see upper illustration on opposite page*). In both this visual illusion and the auditory one reversals occur spontaneously.

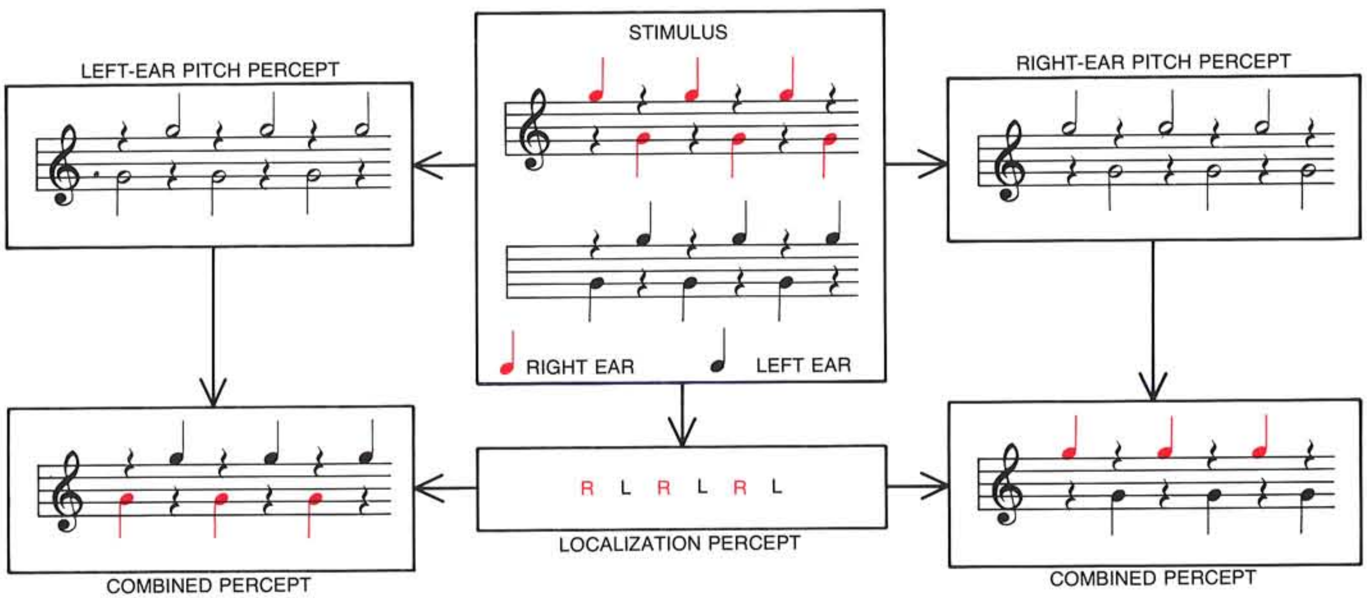
a lower one. The two melodies appeared to be moving in opposite directions with respect to pitch. Moreover, the higher tones all seemed to be emanating from the right earphone and the lower tones from the left earphone. When the earphones were reversed, there was no change in what was perceived. I should add that my own percept is the same. The higher tones appear quite unambiguously to come from the right earphone and the lower tones from the left, however many times I reverse the earphones.

Other subjects perceived the sequence differently. A few reported hearing all the higher tones in the left ear and all the lower tones in the right ear, regardless of how the earphones were positioned. For still other subjects, when the earphones were reversed, the apparent location of the tones was reversed also. Right-handers and left-handers were found to differ in terms of these localization patterns. Right-handers showed a strong tendency to hear the higher tones on the right and the lower tones on the left; left-handers, however, displayed no such tendency. Thus it appears that we tend to refer the higher tones to the dominant side of auditory space and the lower tones to the nondominant side.

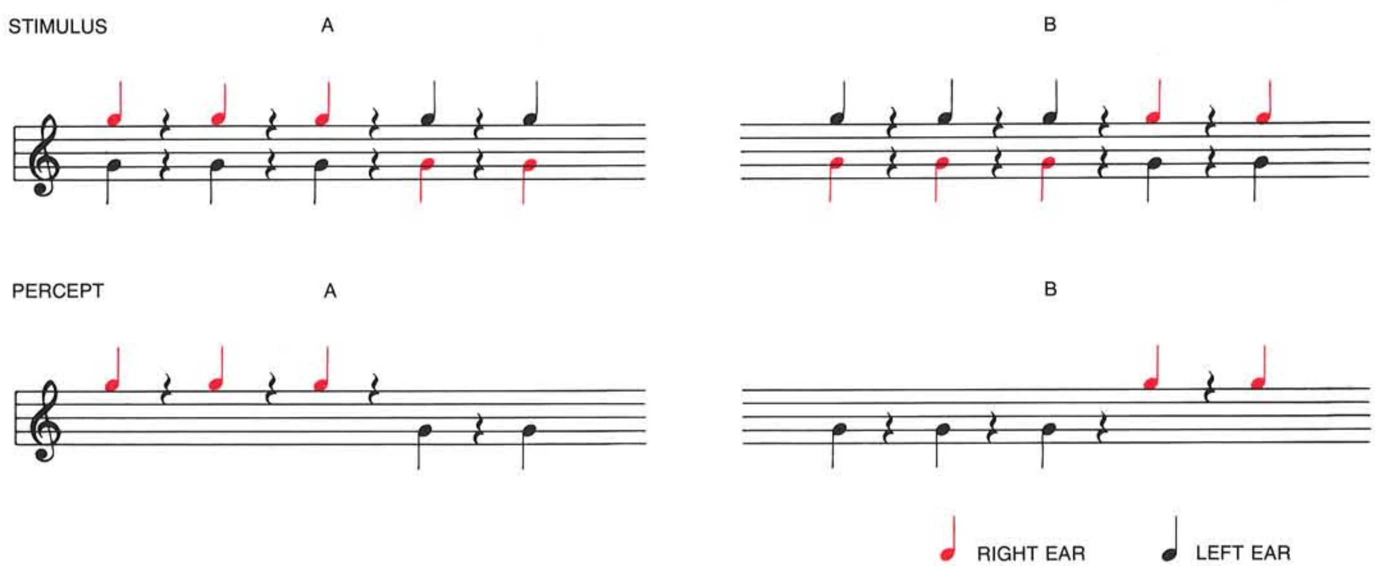
A few listeners perceived the sequence as being composed of higher and lower melodic lines moving in opposite directions, but they localized the individual tones in a variety of unpredictable ways.

Some subjects reported hearing only one sequence of four tones that repetitively descended and ascended. When they were asked to sing 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 travel 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 nonoverlapping pitch sequences



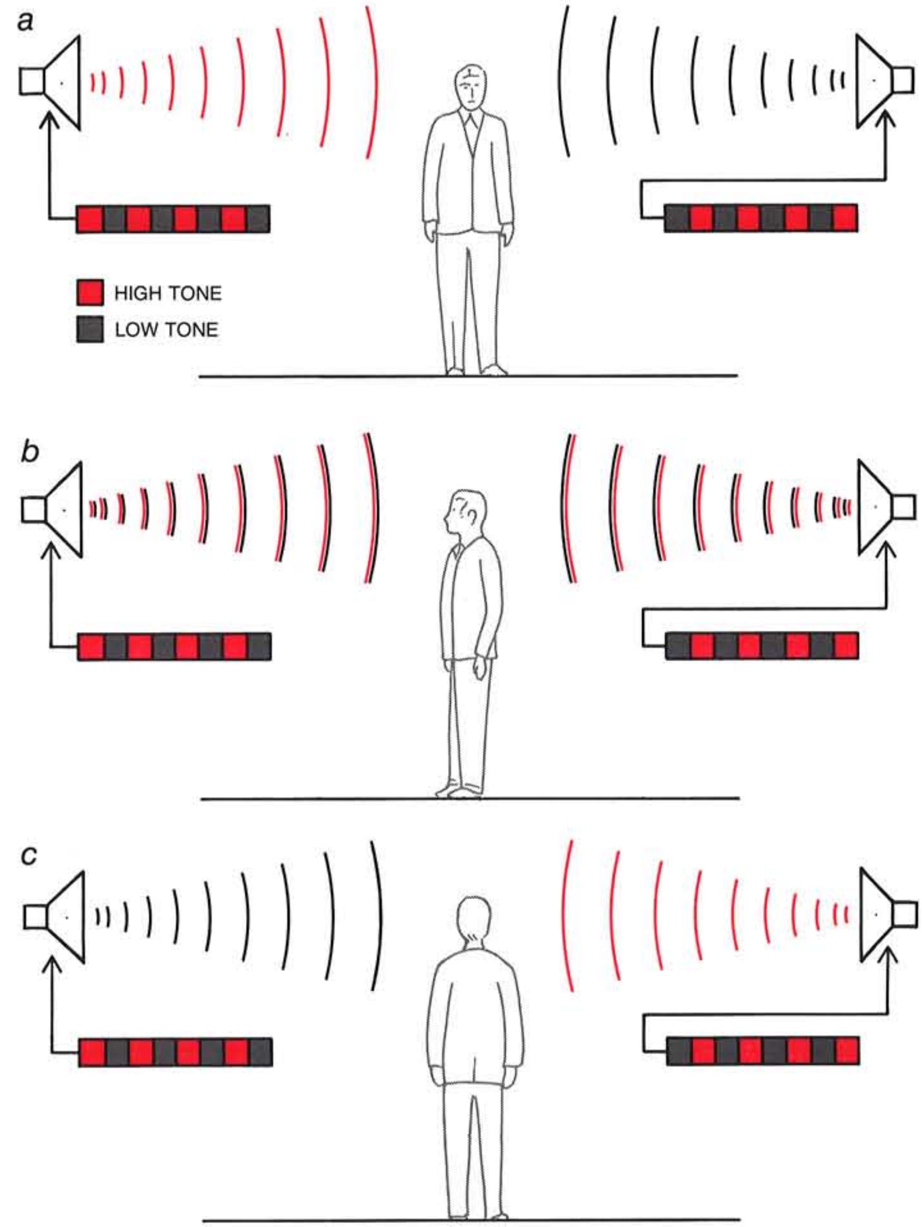
TWO AUDITORY DECISION MECHANISMS, one for determining apparent pitch and the other for determining where the sound appears to be coming from, could interact to create the two-tone illusion. It is hypothesized that the perceived tone is always localized in the ear that is receiving the higher tone but that only one ear follows the sound for pitch. If the listener follows the sequence of pitches delivered to his right ear, the combined operation of the two auditory decision mechanisms results in the percept of a high tone in the right ear followed by a low tone in the left ear (*percept at lower right*). If the listener follows the sequence of pitches delivered to his left ear, however, high tone is heard in the left ear and low tone is heard in the right ear (*percept lower left*).



TONAL SEQUENCE that presents a different pattern of pitches to each ear was devised to investigate the mechanisms determining apparent pitch and the localization of sound. The pattern to the right ear consisted of three high tones followed by two low tones; the pattern to the left ear consisted of three low tones followed by two high tones (*Stimulus A*). The sequence was presented simultaneously to both ears and was repeated 10 times. Most right-handed subjects perceived three high tones in the right ear followed by two low tones in the left ear (*Percept A*). In other words, they heard only the pattern presented to the right ear, but each tone was localized to the ear receiving the higher frequency. When the earphones were reversed (*Stimulus B*), subjects now heard three low tones in the left ear and two high tones in the right ear. Again the pattern presented to the right ear was the one that was followed.

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.



EXPERIMENTAL ARRANGEMENT for creating an auditory illusion with loudspeakers instead of earphones is depicted. The listener stands between two loudspeakers in an echo-free room (*a*). When one speaker is playing a high tone, the other speaker is simultaneously playing a low tone, and vice versa. To the listener, however, it appears that the speaker on his right is emitting only high tones (*colored arcs*) that alternate with low tones (*black arcs*) from the speaker at his left. When the listener turns to face one of the speakers (*b*), he now hears a single tone of constant pitch apparently coming from both speakers. If the listener turns again so that he has rotated 180 degrees from his original position, the speaker that originally appeared to be emitting the high tones now appears to be emitting the low tones, and the speaker that had emitted low tones now appears to be emitting high tones (*c*).

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 critical importance if we are to understand the perception of music. Half 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. And 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 in different frequency ranges; more often than not the melody is in the higher range.

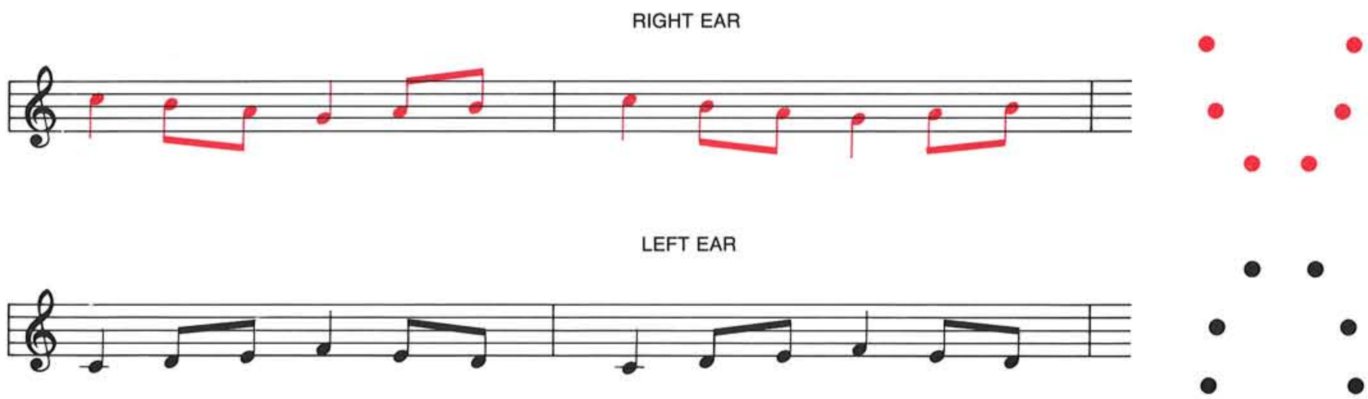
An interesting musical technique used by classical composers is the presentation of a sequence of tones in rapid succession, alternating between two frequency ranges, with the result that they are heard as two melodic lines [*see bottom illustration on page* 9]. W. J. Dowling, who was then at the University of California at Los Angeles, has investigated the effect under experimental conditions. He presented pairs of well-known melodies so that successive notes came from different melodies. When the pitch ranges overlapped, recognition of the melodies was very difficult. When 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 another interesting perceptual property of very rapid sequences of tones that are drawn from two separate frequency ranges. Listeners found it difficult to preceive 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 as the basis of

PARADOXICAL MUSICAL SEQUENCE consists of the C-major scale in its ascending and descending forms (*a*). When a component of the ascending scale is presented to one ear, the matching component of the descending scale is presented to the other ear. Successive notes in ascending scale (*b*) and in descending scale (*c*) actually alternate from ear to ear. The most common illusion reported is two melodies, a higher one and a lower one (*d*). The higher melody is heard in the right ear and the lower one in the left ear.



PERCEPTION OF PARADOXICAL SEQUENCE by a right-handed subject who was musically sophisticated and had absolute pitch is depicted in musical notation (*left*). When he reversed the earphones, he wrote: "Same result: high in right ear." A subject who had no musical training depicted the illusion in diagram form (*right*). Asked to sing the two melodies, she sang them correctly.

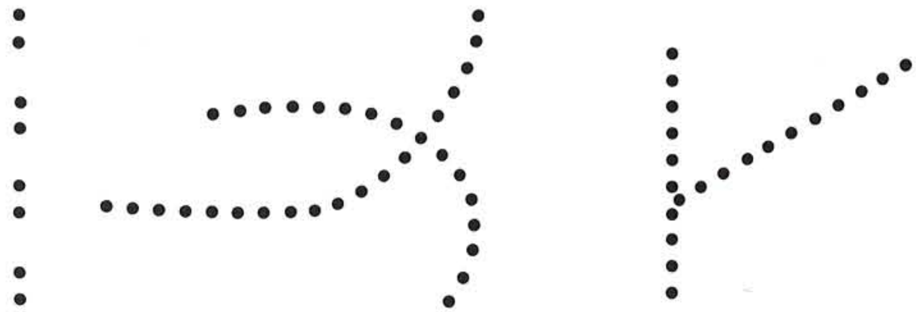
illusions has been well documented in visual perception. A familiar example is the Ames room, which appears to be rectangular when it is viewed monocularly from a certain position but actually is not rectangular at all. Our percept that all rooms are rectangular is so strong that objects or people placed in the Ames room appear to be larger or smaller than they actually are. Another striking example of unconscious inference in visual perception is presented when we view a picture of a mold of a human face [*see illustration on next page*]. Even though the nose and other features of the mold are projecting inward, they always look as though they are projecting outward in the usual orientation. The illusion holds even when we view the actual mold from a distance.

In most right-handed people the left hemisphere of the brain is dominant for speech. Studies have shown that the right hemisphere, which often is called the nondominant hemisphere, also has specialized functions. Studies by neurologists of deficits in music perception resulting from brain injury indicate that such deficits are more likely to exist when there is damage to the dominant hemisphere. The evidence for musical deficits, however, is much less clear-cut than that for speech deficits. It is likely that some musical functions are mediated by both hemispheres. Further, it seems that some musical attributes are processed mainly in the dominant hemisphere and others in the nondominant hemisphere.

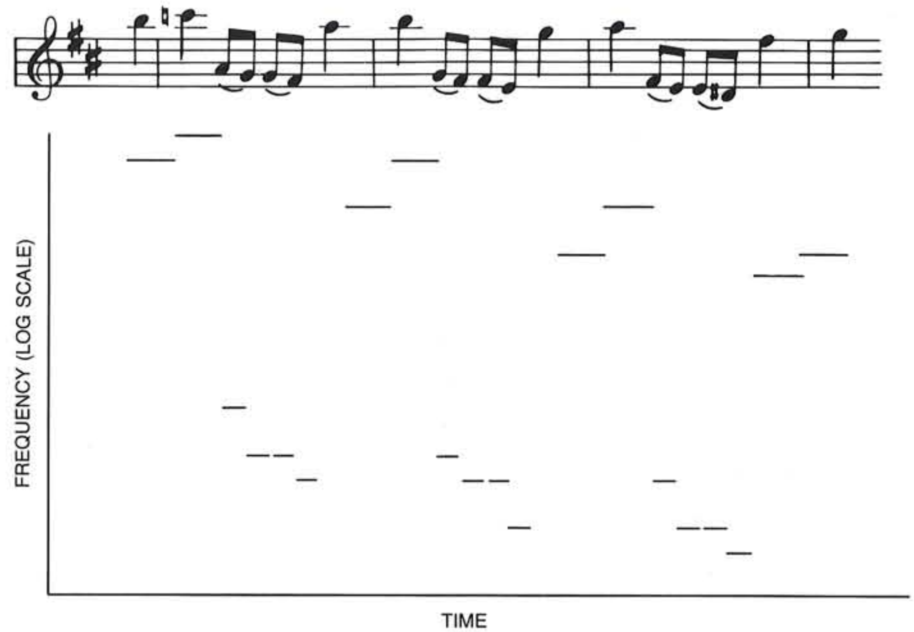
The nondominant hemisphere appears to play a more important role in processing the quality of nonverbal sounds. People with damage to the nondominant hemisphere show deficits in discriminating complex sounds and timbres. Dichotic-listening studies with normal individuals have found that right-handers process complex sounds better through the left ear than through the right.

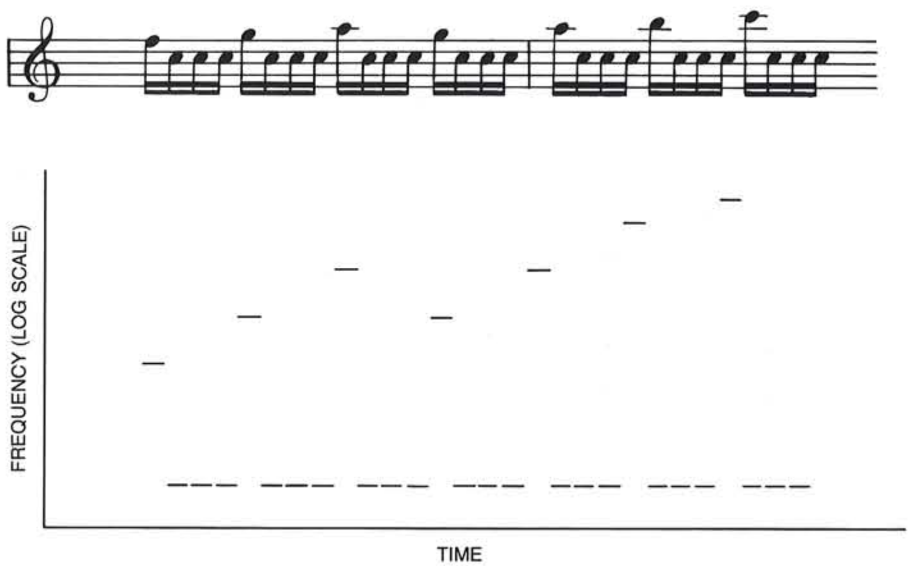
For example, H. W. Gordon, who was then at the California Institute of Technology, presented pairs of two-tone chords generated by an electric organ simultaneously, one to each ear. Right-handers showed better recognition of the chords they heard in their left ear. Since the left ear has stronger connections to the right hemisphere, it appears that the right, or nondominant, hemisphere has a stronger involvement in the recognition of complex tones or chords.

On the other hand, the processing of sound sequences appears to take place chiefly in the dominant hemisphere. Pa-



PRINCIPLES OF PERCEPTUAL ORGANIZATION, proposed by Max Wertheimer, are demonstrated in these visual examples. The dots that are closer together are perceived as pairs (*left*), illustrating the principle of proximity. Dots that follow each other in a given direction are perceived as lines (*middle*), which demonstrates the principle of good continuation. When these two principles are set in opposition (*right*), one may be dominant. Even though the dot at the junction is closer to the vertical row, it is perceived as belonging to the oblique row. In this instance the principle of good continuation is the stronger.



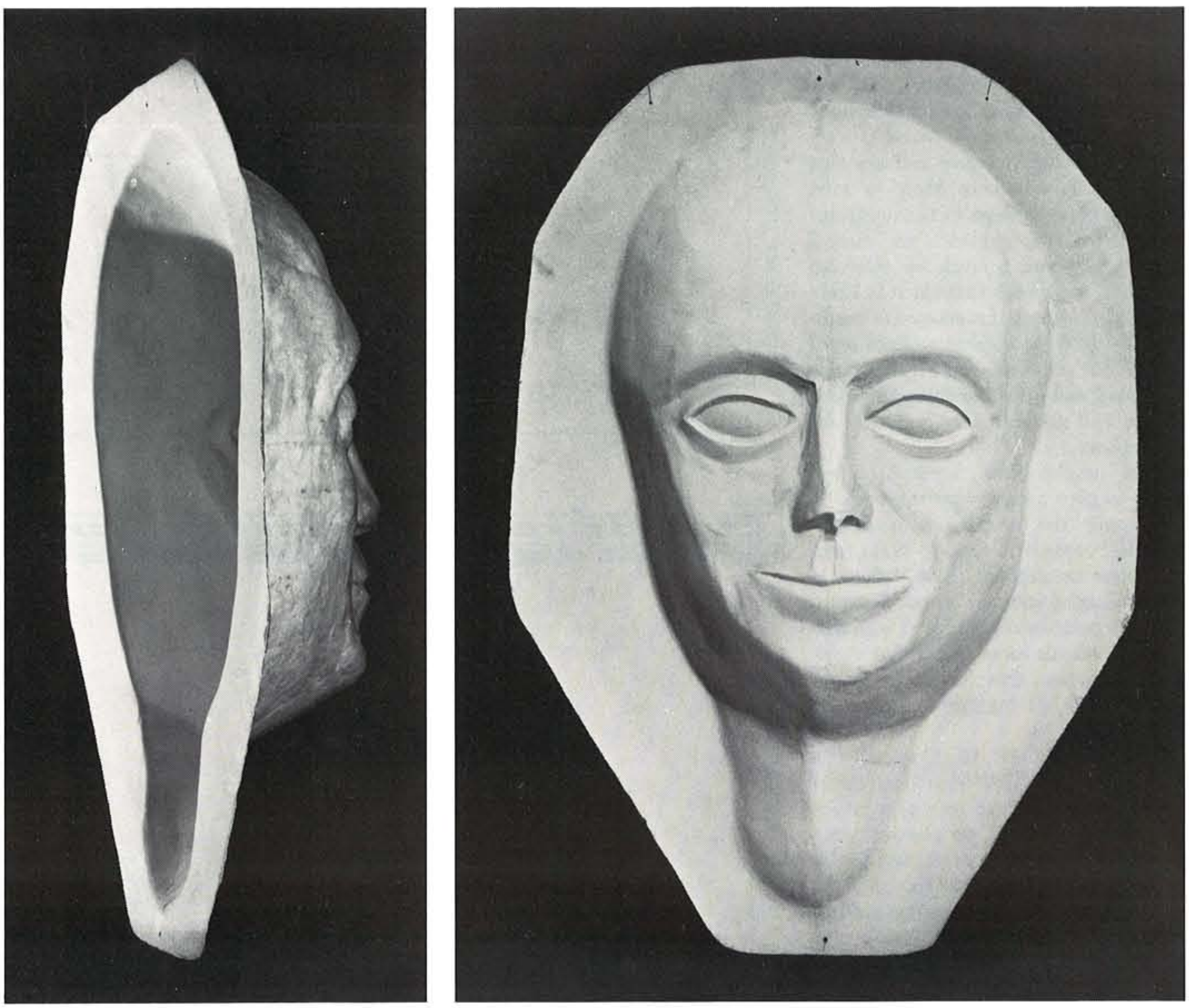


PRINCIPLE OF PROXIMITY plays an important role in the perception of melody. Two excerpts from classical music show how tones from two frequency ranges are grouped into separate melodic lines. In *Capriccio for Recorder and Basso Continuo* (*top*) by Georg Philipp Telemann the sequence creates two separate melodies, each in a different frequency range. In Telemann's *Sonata in C Major for Recorder and Basso Continuo* a repetitive single pitch in the lower range forms a ground against which the melody is heard (*bottom*).

tients with damage to the dominant hemisphere show deficits in identifying the temporal order of auditory stimuli and in processing rhythms. And dichotic 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, I. Nachshon and A. Carmon of the Hadassah Musical School in Jerusalem employed dichotic sequences made up of tones of different pitches and also found 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 functions, including the appreciation of timbre and the organization of tonal sequences, it would appear that both cerebral hemispheres play important but to some extent complementary roles in musical perception. The degree of involvement of each hemisphere would of course depend on both the type of music and the perceptual 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 likely 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 system 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)*.