# The Octave Illusion and Auditory Perceptual Integration

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## I. INTRODUCTION

A philosophical doctrine stemming from the empiricists of the seventeenth and eighteenth centuries is that objects manifest themselves simply as bundles of attribute values. This doctrine has had a profound influence on the thinking of sensory psychologists and neurophysiologists. For example, it is assumed that when we see an object, we separately appreciate its color, its shape, its location in the visual field, and so on. The different values of these attributes are then combined so as to produce an integrated percept. Similarly, when we hear a sound, we assign values to a set of attributes such as pitch, loudness, and location, and these values are then combined so that a unitary percept results.

With this approach, evidence has been obtained that different stimulus attributes are indeed processed separately in the nervous system. For example, in the case of vision, units have been found that respond to specific shape but are insensitive to color. Other units are sensitive to color but not to shape (Gouras, 1972). Parallel evidence comes from patients with brain lesions. Bilateral ventral prestriate damage has been found to give rise to cerebral achromatopsia (Meadows, 1974), and right hemisphere damage to Brodmann's areas 39 and 40 has been found to produce deficits in visual perceptual classification (Warrington and Taylor, 1973). Further, various studies on human and subhuman species point to an anatomical separation between the pathways mediating pattern discrimination on the one hand and localization on the other (Ingle *et al.*, 1967-1968). For example, Schneider found that ablation of visual cortex in hamsters led to an inability to discriminate visual patterns, with little decrement in the ability to locate objects in space. However, when the superior colliculus was removed, there resulted instead an inability to orient to a visual stimulus, though pattern discrimination remained excellent.

In the case of hearing, Poljak (1926) suggested on anatomical grounds that the lower levels of the auditory pathway are divided into two separate subsystems. The first, a ventral pathway, was hypothesized to originate in the ventral cochlear nucleus and to subserve localization functions. The second, a dorsal pathway, was hypothesized to originate in the dorsal cochlear nucleus and to subserve discriminatory functions. Evans (1974) has advanced neurophysiological evidence supporting such a functional separation (Evans and Nelson, 1973a,



In J. V. Tobias and E. D. Schubert (Eds.), *Hearing Research and Theory,* Vol.1, New York: Academic Press, 1981, pp. 99-142.

b), and he suggests that this division is analogous to the division of the visual system into subsystems underlying the processing of place and form information. Knudsen and Konishi (1978) have presented evidence that two functionally distinct regions exist in the auditory midbrain of the owl: One region appears to mediate localization and the other, to mediate sound identification.

The view that the different attributes of a sensory stimulus are analyzed separately by the nervous system accounts for the processing of single stimuli very well. However, it presents us with a theoretical problem when we consider the case in which more than one stimulus is presented at a time. For example, suppose that we are presented simultaneously with a blue triangle and a green square. The outputs of the color-analyzing mechanism signal "blue" and "green" and the outputs of the form-analyzing mechanism signal "triangle" and "square." But how do we know which output from the color mechanism to combine with which output from the form mechanism? That is, how do we know that the triangle is blue and the square is green? Similarly suppose that we are presented with a 400-Hz tone on our left and an 800-Hz tone on our right. This produces the set of outputs "400 Hz," " 800 Hz," "left," and "right." But how do we know which output from the pitch mechanism to combine with which output from the localization mechanism?

In this review we shall explore the issue of perceptual integration of simultaneous stimuli, considering only two auditory attributes: pitch and localization. We shall first present behavioral evidence showing that the mechanisms determining pitch and localization are indeed separate at some stage in the auditory system, and that at this stage, they operate according to independent criteria. Given certain stimulus configurations, the outputs of these two mechanisms combine to produce a very compelling illusion. By studying this illusion under various parametric manipulations, we can obtain insights into how these two mechanisms operate, and how their outputs are combined so that a unitary percept results.

## II. THE OCTAVE ILLUSION

### A. The Basic Effect

The octave illusion was originally produced by the stimulus configuration shown on Fig. 1a. It can be seen that this consisted of two tones, which were spaced an octave apart, and repeatedly presented in alternation. The identical sequence was presented simultaneously to the two ears; however, when the right ear received the high tone, the left ear received the low tone and vice versa. So in fact the listener was presented with a single continuous two-tone chord, but the ear of input for each component switched repeatedly.

This sequence was found to give rise to various illusions, the most common of which is illustrated on Fig. 1b. It can be seen that this consisted of a single tone that switched from ear to ear, whose pitch simultaneously shifted back and forth from high to low. That is, the listener heard a single high tone in one ear alternating with a single low tone in the other ear.

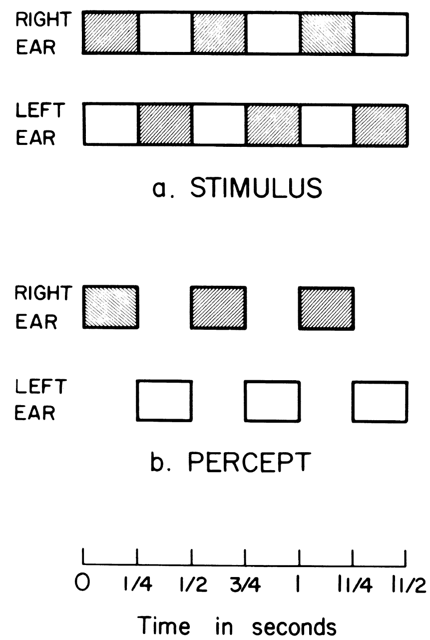


**Figure 1** (a) Representation of the stimulus pattern used in Deutsch (1974 a, b). Shaded boxes represent tones of 800 Hz, and unshaded boxes represent tones of 400 Hz. This pattern was repetitively presented without pause for 20 sec. (b) Representation of the illusory percept most commonly obtained. (From Deutsch, 1974b.)

There is no simple way to explain this illusion. We can explain the perception of alternating pitches by assuming that the listener processes the input to one ear and ignores the other, but then both of the alternating pitches should appear localized in the same ear. Alternatively, we can explain the alternation of a single tone from ear to ear by supposing that the listener suppresses the input to each ear in turn, but then the pitch of this tone should not change with a change in its apparent location. The illusion of a single tone that alternates simultaneously both in pitch and in localization is most paradoxical.

The illusion is even more surprising when we consider what happens when the listener's earphones are placed in reverse position. Now most people hear exactly the same thing; that is, the tone that appeared to be in the right ear still appears to be in the right ear, and the tone that appeared in the left ear still appears to be in the left ear. It seems to the listener that the earphone that had been emitting the high tone is now emitting the low tone, and that the earphone that had been emitting the low tone is now emitting the high tone! This percept is illustrated in Fig. 2, which reproduces the written report of a subject with absolute pitch.

It was further shown that these localization patterns are based on the frequency relationships between the

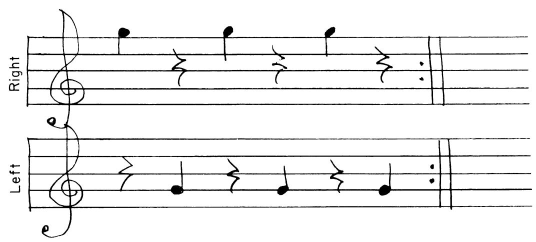


**Figure 2** Percept of the stimulus pattern depicted by a subject with absolute pitch. Her written statement, "same with earphones reversed," shows that the high tones were localized in the right ear and the low tones in the left, regardless of positioning of the earphones. (From Deutsch, 1974b.)

competing tones, and not on a pattern of ear preference at different frequency values (Deutsch, 1974b). Twelve subjects were selected who had consistently localized the 800-Hz tone in the right ear and 400-Hz tone in the left. They were presented with sequences of equal-amplitude tones alternating between 200 and 400 Hz, 400 and 800 Hz, and 800 and 1600 Hz, in counterbalanced order. It was found that with the exception of one report on one sequence, the higher of each pair of tones was always localized in the right ear and the lower in the left. (Thus, for instance, the 800-Hz tone was localized in the right ear when it alternated with the 400-Hz tone, but in the left ear when it alternated with the 1600-Hz tone.)

This illusion cannot be accounted for on any single ground. However, if we suppose that two separate brain mechanisms exist, one for determining what pitch we hear and the other for determining where the sound is coming from, we are in a position to advance an explanation. The model is illustrated in Fig. 3. To determine the perceived pitch, the information arriving at one ear is followed and the information arriving at the other ear is suppressed. However, to determine the perceived localization, each tone is localized in the ear receiving the higher frequency signal, regardless of whether the higher or lower frequency is in fact perceived (Deutsch, 1975a). Thus, in the case of a listener who perceives the frequencies delivered to the right ear, when an 800-Hz tone is delivered to the right ear and a 400-Hz tone to the left, the listener hears a pitch corresponding to 800 Hz, since this is the tone delivered to his right ear. The tone is also localized in his right ear, since this ear is receiving the higher frequency signal. However, when an 800-Hz tone is delivered to the left ear and a 400-Hz tone to the right, this listener hears a pitch corresponding to 400-Hz, since this is the tone delivered to his right ear. However, the tone is localized in his left ear, since this ear is receiving the higher frequency signal, so the entire sequence is perceived as a high tone to the right alternating with a low tone to the left. It can be seen from inspection of Fig. 3 that reversing the position of the earphones would not alter this basic percept (though the identities of the first and last tones in the sequence would reverse). However, in the case of a listener who perceives the sequence of frequencies delivered to the left ear instead, with no change in the localization rule, the same sequence would be heard as a high tone to the left alternating with a low tone to the right.

In order to test this hypothesis, a new dichotic sequence was devised (Deutsch and Roll, 1976). The basic pattern employed is illustrated in Fig. 4a. Here, it can be seen that one ear received three high tones followed by two low tones, and simultaneously, the other ear received three low tones followed by two high tones. This pattern was repeated 10 times without pause.

It was found that, indeed, most subjects reported the pattern of frequencies presented to one ear or to the other; that is, they heard a repetitive sequence consisting either of three high tones followed by two low tones, or of three low tones followed by two high tones. However, each tone was localized in the ear receiving the higher frequency signal, regardless of which frequency was in fact perceived. So when a low tone was heard, it appeared to be emanating not from the earphone that was in fact delivering it, but from the opposite earphone. As illustrated in Fig. 4b, when a subject who consistently followed the pattern of frequencies delivered to his right ear was presented with channel A to his right ear and channel B to his left, he heard a sequence consisting of

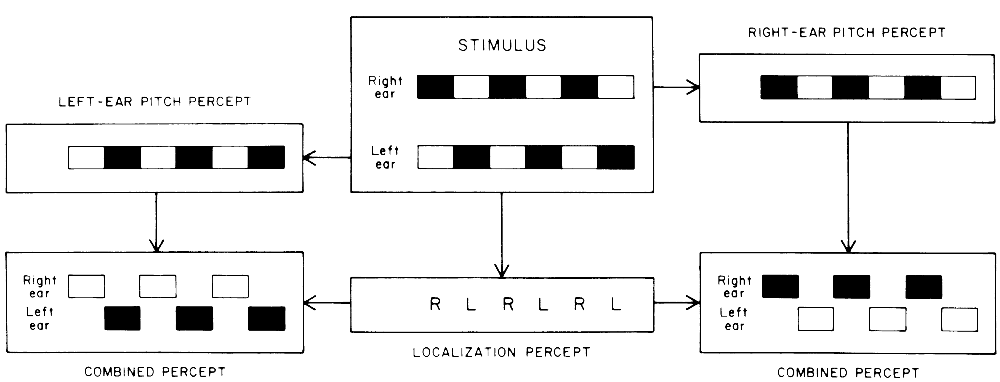


**Figure 3** Model illustrating how the outputs of two decision mechanism, one determining pitch and the other determining localization, combine to provide the illusory percept. See text for details.

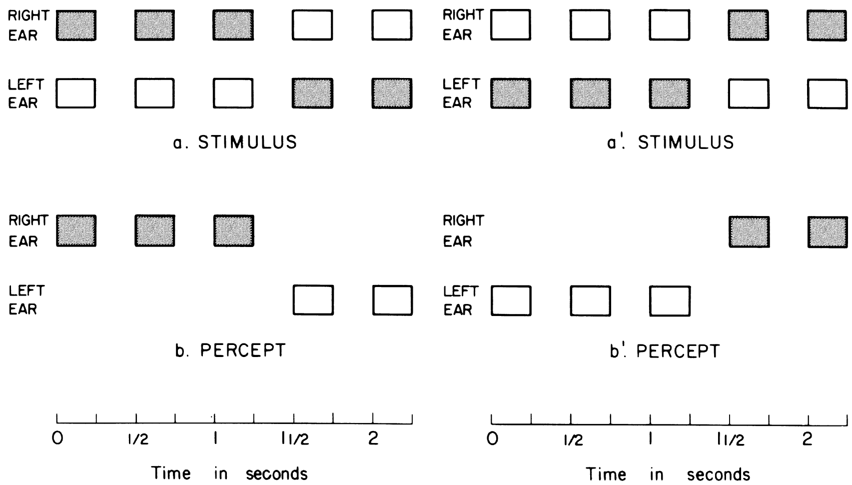


**Figure 4** Representation of the stimulus pattern used by Deutsch and Roll (1976), and the percepts most commonly obtained. Shaded boxes represent tones of 800 Hz and unshaded boxes tones of 400 Hz. (a and b) Stimulus pattern and percept obtained with channel A to the right ear and channel B to the left ear. (a´ and b´) Stimulus pattern and percept obtained with channel A to the left ear and channel B to the right ear.

three high tones to his right, followed by two low tones to his left. When the earphone positions were reversed, this listener now heard a sequence consisting of *two* high tones to his right, followed by *three* low tones to his left. The procedure of reversing earphone positions therefore appeared to cause the channel to the right to drop a high tone and the channel to the left to add a low tone!

## B. Handedness Correlates

By the way of digression, the reader may wish to explore individual differences in perception of the octave illusion and their correlations with handedness. Although such an exploration does not advance the more abstract questions posed above, it does enable us to place the phenomena described in a neurological setting.

When presented with the alternating sequence shown in Fig. 1a, most listeners perceived a single high tone in one ear alternating with a single low tone in the other. However, very different types of percept were obtained by other listeners. Some reported a single tone that alternated from ear to ear, whose pitch either remained constant or changed only slightly as its apparent location shifted. In matching experiments, the pitch of this alternating tone was reported by some listeners to be closest to that of the 400-Hz tone, and by others to be closest to that of the 800-Hz tone. Other listeners obtained a variety of complex percepts, such as two low tones alternating from ear to ear, with an intermittent high tone in one ear, or a sequence in which the pitch relationships appeared to change gradually with time. Listeners with complex percepts often reported striking timbral differences between the tones—for instance, that the low tones had a gong like quality and the high tones a flute like quality. Complex percepts were typically unstable, often changing from one to another within a few seconds.

Significant differences were found between left-handers and right-handers in terms of the relative distributions of these various percepts. In particular, the proportion of listeners obtaining complex percepts was much higher in the left-handed than in the right-handed population (Deutsch, 1974b). A second handedness difference concerned the localization patterns for the high and low tones. Taking those subjects who perceived a single high tone in one ear alternating with a single low tone in the other ear, the right-handers tended significantly to hear the high tone on the right and low tone on the left. They also tended significantly to maintain this localization pattern when the earphones were placed in reverse position. However, the left-handers did not preferentially localize the high and low tones either way, and they were less stable in their localization patterns. A significant tendency to follow the sequence of frequencies presented to the right ear was also found in right-handers in the experiment of Deutsch and Roll (1976) described above.

These results are consistent with the neurological evidence, which shows that the overwhelming majority of right-handers are left-hemisphere dominant; that is, they have speech represented in the left cerebral hemisphere. However, this is true of only about two-thirds of the left-handed population, the remaining one-third being right-hemisphere dominant. Furthermore, although the majority of right-handers have a clear-cut dominance of the left hemisphere for speech, a substantial proportion of left-handers have some speech represented in both cerebral hemispheres (Goodglass and Quadfasel, 1954; Hécaen and Piercy, 1956; Zangwill, 1960; Hécaen and de Ajureaguerra, 1964; Milner *et al.*, 1966; Subirana, 1969).

If we assume that the pathways conveying information from different regions of auditory space are in mutual inhibitory interaction, and that the pathways that convey information from the dominant side of auditory space (i.e., the side contralateral to the dominant hemisphere) exert the strongest influence, then we would expect to obtain the present correlates with handedness. That is, we would expect that right-handers would tend strongly to follow the information presented to their right, but that left-handers would not show this tendency. Furthermore, given the tendency to greater cerebral equipotentiality among left-handers, this group should also be less consistent in terms of which region of auditory space is followed. We can think of the dominant and nondominant pathways as in mutual inhibitory interaction. In the case of individuals with strong dominance, one pathway consistently inhibits the other. However, in the case of people whose dominance is less marked, we can get a type of seesaw effect developing: First the pathway on one side wins out, then the pathway on the other side, and so on. In extreme cases, we can end up with a very high rate of reversal, such as is more commonly found among left-handers. This percept is depicted in Fig. 5 and provides an interesting auditory analog of the Necker cube. It also seems plausible to suppose that the higher proportion of complex percepts found among left-handers reflects the greater cerebral equipotentiality in this group, leading to weaker and less consistent patterns of inhibition between the two pathways.

In a further experiment, the localization patterns for the high and low tones in this alternating octave sequence were examined as a more precise function of handedness and also of familial handedness history. With the handedness questionnaire of Varney and Benton (1974), subjects were categorized as right-handers, mixed handers, and left-handers, and these groups were subdivided into those who had left- or mixed-handed parents or siblings and those who did not.

Subjects indicated on forced choice the perceived locations of the high and low tones in this sequence. A highly significant effect of handedness was found and also a significant effect of familial handedness history. Right-handers with only right-handed parents or siblings were most likely to report the high tone on the right, and left-handers with left- or mixed-handed parents or siblings were least likely to do so. This study therefore reinforces the hypothesis that perception of this sequence serves as a reflection of cerebral dominance (Deutsch, 1981a).

The finding of a substantial right-ear advantage for a sequence that is clearly nonverbal might seem surprising in view of the widely held belief that the dominant hemisphere is specialized for verbal functions and the nondominant hemisphere for nonverbal or musical functions. However, the evidence on patterns of ear advantage for nonverbal stimuli is quite complex, and it is clear that these depend heavily on the stimulus parameters employed.

Left-ear advantages have been obtained in dichotic listening tasks involving materials of complex spectral composition [e.g., melodies generated by musical instruments (Kimura, 1964) or by humming (King and Kimura, 1972), environmental sounds (Curry, 1967; Knox and Kimura, 1970), and musical instrument sounds (Kallman and Corballis, 1975)]. However, Gordon (1970) failed to obtain a left-ear advantage with melodies played on a recorder, yet did obtain such an advantage with chords generated on an electronic organ.

In other dichotic listening experiments involving nonverbal sequences, right-ear advantages have been obtained instead. Thus, Halperin *et al.* (1973) presented listeners with dichotic sequences whose components varied in frequency and duration. They found that as the number of frequency or duration transitions increased from zero to two, the pattern of ear advantage shifted from left to right. Robinson and Solomon (1974) required subjects to recognize dichotically presented rhythms composed of pure tones; they obtained a right-ear advantage also. A complex result was obtained by Papçun *et al.* (1974) using Morse cord signals. They obtained a right-ear advantage in processing these stimuli, except in the case of naive subjects when they were presented with more than seven elements, in which case a left-ear advantage was obtained.

It should also be noted that the bulk of the literature on musical deficit resulting from brain lesions supports the view that music perception is primarily a dominant hemisphere function. A discussion of this evidence is beyond the scope of the present review, and the reader is referred to Wertheim (1977) and Benton (1977) for reviews of this issue.

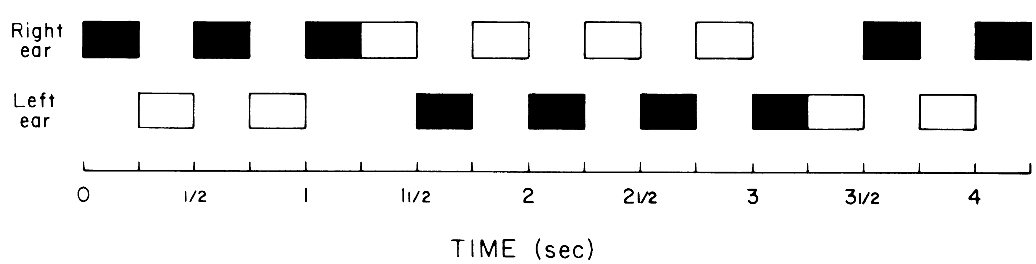


**Figure 5** Percept of the stimulus pattern of Deutsch (1974a, b) obtained by some subjects. The frequent reversals of position of the high and low tones provide an auditory analog of the Necker cube.

### C. Further Complexities: Ears or Auditory Space?

We now turn to a question more germane to the basic theoretical theme—whether the interactions underlying the localization and frequency-suppression effects in the illusion occur between pathways conveying information from the two ears, or whether instead pathways relaying information from different regions of auditory space are involved.

To investigate this question, the sequences depicted in Figs. 1a and 4a were presented to listeners through two spatially separated loudspeakers. The listeners had been selected for showing consistent localization and frequency-suppression effects with stimuli presented through earphones. The experiment was performed in an anechoic chamber, and the listener was placed equidistant between the speakers (Deutsch, 1975a).

It was found that the analogous illusions were obtained under these conditions, even though both sequences were now presented to both ears. When the listener was oriented so that one speaker was exactly on his right and the other exactly on his left, the high tones were heard as emanating from the speaker on the right, and the low tones as from the speaker on the left. When the listener rotated slowly, the high tones remained on his right and the low tones on his left. This percept was maintained until the listener reached the position where he was facing one speaker, with the other speaker directly behind him. The illusion then abruptly disappeared, and a single complex tone was heard as emanating simultaneously from both speakers, as though the information had been passed through a mixer. However, as the listener continued to turn, the illusion abruptly reappeared, with the high tones still on his right and the low tones on his left. So when the listener had rotated 180º from his original position, the speaker that had first appeared to be producing the high tones now appeared to be producing the low tones, and the speaker that had first appeared to be producing the low tones now appeared to be producing the high tones!

This experiment demonstrates that the octave illusion must have a very complex basis. In order for it to be produced with stimuli presented through speakers, the listener must first identify, for each pair of simultaneous tones, which speaker is emitting the high tone and which the low. Following such correct assignments, the information must then travel along pathways that are specific to position in auditory space, and the above interactions must take place between such second-order pathways so as to give rise to the illusory percepts. The mechanism determining what pitch is heard chooses to follow the sequence of frequencies that is emanating from one side of auditory space rather than to the other; thus, the decision as to what is heard is determined by where the signals are coming from. However, the localization mechanism chooses instead to follow the higher frequency signal; thus, the decision as to where the signal is located is determined by what the signal frequencies are.

The finding that the ear advantage obtained with dichotic presentation generalizes to a side advantage when loudspeakers are used parallels results obtained by others with speech stimuli. Morais and Bertelson (1973) and Morais (1975) presented simultaneous pairs of CV syllables through loudspeakers, and found that right-handed subjects recalled more from the speaker on their right than from the speaker on their left. These authors argue that the right-ear advantage obtained in dichotic listening to such materials is due to an advantage for the dominant region of auditory space over the nondominant. This view contrasts with that advanced by Kimura (1961, 1964, 1967) that patterns of ear advantage are due to a prepotency of the contralateral over the ipsilateral pathway from each ear to each hemisphere.

That highly specific regions of auditory space are involved in the present effect is evidenced by the finding that the illusion can be obtained even when the speakers are situated side by side, facing the listener. The reader may determine this by the following simple experiment. Begin by listening to the sequence with earphones placed correctly, and then slowly remove them, bringing them out in front of you. In the case of a listener who obtains a clear and consistent illusion with dichotic presentation, it is possible to remove the earphones some distance before the illusion disappears. (It is interesting that a hysteresis effect operates here: The illusion will be maintained with the earphones at a greater distance from the listener than that required for it to be initiated.[1,2])

For convenience, we shall refer to the following of the pitches presented to one ear rather than the other as "ear dominance." However, the reader should note that the pathways responsible for this effect are specific to region of auditory space and not simply to ear of input.

### D. Dependence of the Illusion on Sequential Interactions

We now turn to the question of whether the inhibitory interactions giving rise to the illusion depend simply on relationships between simultaneously presented tones or whether they depend on sequential relationships also. It will be noted that, in all the sequences so far described, the frequency presented to one side of space was identical to the frequency just presented to the opposite side. It may be hypothesized, therefore, that this pattern of relationship is critical for producing the illusion.

This hypothesis is supported by experiments employing the sequence depicted in Fig. 6a (Deutsch,

1. I am indebted to R. L. Gregory for suggesting this procedure.
2. A curious effect concerning this illusion has recently been observed by McFadden (1977). Upon initial listening to the sequence, a very strong and unambiguous illusion was obtained, and this persisted throughout a prolonged listening session. However, following a period of nonexposure that lasted for several months, the illusion was found to have vanished. This strong example of perceptual unlearning was obtained by two very reliable observers.

1975b). It can be seen that this sequence consisted of a major scale, presented simultaneously in both ascending and descending form. When a component of the ascending scale was delivered to the right ear, a component of the descending scale was delivered to the left ear, and successive tones in each scale alternated from ear to ear. The sequence was played repetitively 10 times without pause.

This configuration was also found to produce a variety of illusory percepts, which fell into two main categories. The majority of listeners heard the correct sequence of frequencies but as two separate melodies, one corresponding to the higher sequence of tones and the other to the lower sequence. Furthermore, the higher tones all appeared to be emanating from one earphone and the lower tones from the other. When the earphone positions were reversed, there was no corresponding change in the percept. Thus, the earphone that had apparently been emitting the higher tones now appeared to be emitting the lower tones, and the earphone that had apparently been emitting the lower tones now appeared to be emitting the higher tones. This percept is depicted in Fig. 6a, which reproduces the written report of a subject with absolute pitch. Other listeners perceived instead only a single melody, which corresponded to the higher sequence of tones, and they heard little of nothing of the lower sequence.

This illusion is discussed in detail elsewhere (Deutsch, 1971b). The point to be noted here, however, is that, in sharp contrast with the alternating octave


**Figure 6** (a) Representation of the dichotic sequence producing the scales illusion. (b) The ascending component separately. (c) The descending component separately. (d) Illusory percept depicted by a subject with absolute pitch. This type of percept was the one most commonly obtained. (From Deutsch, 1975b.)

sequence, no listener perceived the pattern of frequencies presented to one ear rather than to the other. Thus, this sequence produced no ear dominance: When only one melody was heard, this corresponded to the higher frequencies and not the lower, regardless of ear of input. Furthermore, for most listeners, both members of each simultaneous tone pair were perceived and neither was suppressed. It is particularly noteworthy that when two tones in octave relation are simultaneously presented in the octave illusion, generally only one tone is perceived (Fig. 1b). However, when two tones in octave relation are simultaneously presented in the scale illusion, generally both tones are perceived (Fig. 6d). Thus, ear dominance cannot be regarded simply in terms of simultaneous inhibitory interactions; it also depends on sequential interactions. The next section describes several parametric experiments that were designed to explore the sequential conditions giving rise to this effect.

## III. PARAMETRIC STUDIES OF EAR DOMINANCE

### A. Apparatus

Tones were generated as sine waves by two Wavetek function generators (Model No. 155), which were controlled by a PDP-8 computer. The output was passed through a Crown amplifier and was presented to subjects through matched headphones (Grason-Stradler Model No. TDH-49) in sound-insulated booths. In sequences when the tones followed each other without pause, there were no voltage jumps at the frequency transitions, and the voltage slope did not change sign at the transitions. The purpose of this restriction was to minimize transients.

### B. Experiment 1

This experiment was performed as a test of the hypothesis that ear dominance occurs in sequences when the two ears receive the same frequencies in succession, but not otherwise. There were two conditions in the experiment. In each condition, sequences consisted of 20 dichotic chords, each 250 msec in duration, with no gaps between chords.

The basic sequence in Condition 1 consisted of the repetitive presentation of a single chord. As shown in Fig. 7, the components of this chord stood in octave relation and alternated from ear to ear such that when the high tone was in the right ear, the low tone was in the left ear, and vice versa. The frequencies of the low and high tones were always 400 Hz and 800 Hz. Essentially, this is the same sequence as that of Deutsch (1974a,b), and it can be seen that here, the two ears did indeed receive the same frequencies in succession. On half of the trials the sequence delivered to the right ear began with 400 Hz and ended with 800 Hz, and on the other half this order was reversed.

The basic sequence in Condition 2 consisted of the repetitive presentation of two dichotic chords in alter-

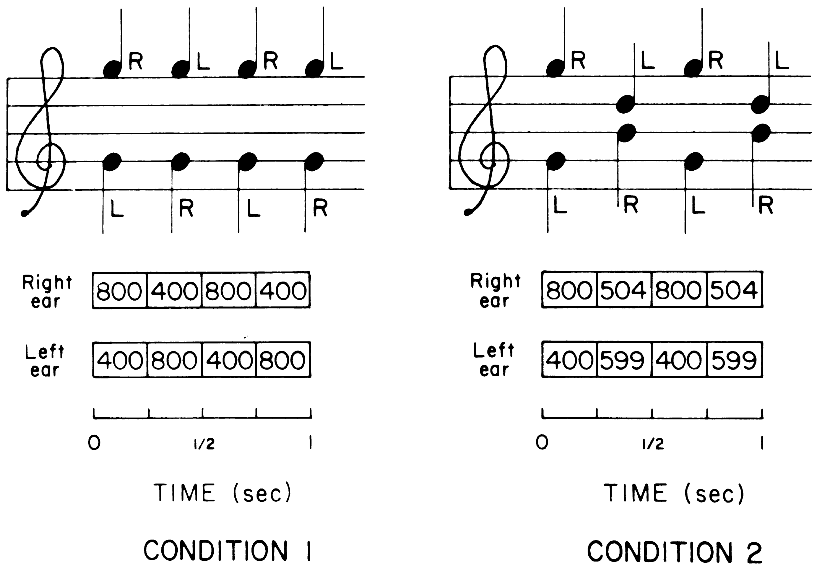


**Figure 7** Examples of stimulus configurations used in the two conditions of Experiment 1. Numbers in boxes indicate tonal frequencies. Musical notation is approximate.

nation. As shown in Fig. 7, the first chord formed an octave and the second chord formed a minor third, so that the entire four-tone combination constituted a major triad. Thus, the two ears did not receive the same frequencies in succession here. The frequencies composing these two chords were 400 and 800 Hz for the octave, and 504 and 599 Hz for the minor third. On half of the trials, the sequence began with the minor third and ended with the octave, and on the other half the sequence began with the octave and ended with the minor third. Further, for each of these subconditions on half of the trials the right ear received the lower component of the first chord and the upper component of the last chord, and on the other half this order was reversed.

In both conditions, for each type of sequence, the amplitude relationships between the tones presented to the two ears varied systematically, so that a left-ear sequence composed of tones at 70 dB SPL was paired equally often with a right-ear sequence composed of tones at 70, 73, 76, 79, 82, and 85 dB. Further, a right-ear sequence composed of tones at 70 dB was paired equally often with a left-ear sequence composed of tones at 70, 73, 76, 79, 82, and 85 dB.

Each condition was presented for three sessions. There were 72 trials per session in Condition 1, and 48 trials per session in Condition 2. The conditions were presented alternately in successive sessions, with the presentation order counterbalanced across subjects. Within each session, sequences were presented in random order in groups of 12. There were 10-sec pauses between sequences within a group, and 2-min pauses between groups. A 500-msec tone of 2000 Hz at 70 dB preceded each group of 12 sequences by 15 sec and served as a warning signal. Subjects judged for each sequence whether it was of the “high-low-high-low” type or the “low-high-low-high” type; and they indicated their judgments by writing “high-low” or “low-high” during the intertrial interval.

Four subjects served in this experiment. They were selected on the basis of consistently hearing a single high tone alternating with a single low tone in sequences designed as in Condition 1, with all tones at equal amplitude. All subjects had normal audiograms. Two of the subjects were right-ear dominant and two were left-ear dominant.

The results of the experiment are shown in Fig. 8. It can be seen that in Condition 1, the frequencies presented to the dominant ear were followed until a critical

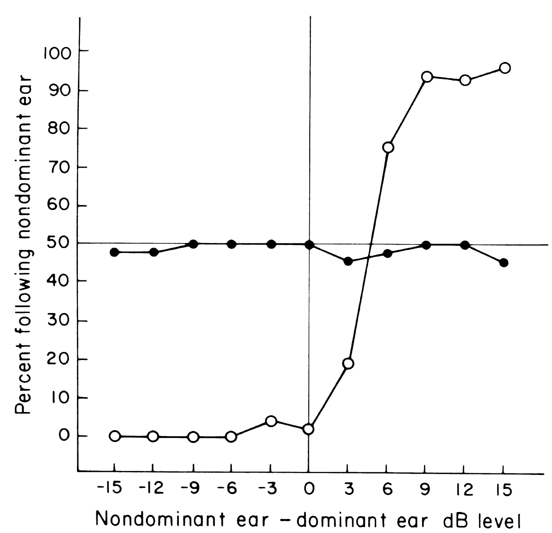


**Figure 8** Percentage following of nondominant ear in Experiment 1 as a function of amplitude differences at the two ears. Open circles: Condition 1. Solid circles: Condition 2. (From Deutsch, 1980.)

level of amplitude relationship between the ears was reached, and the nondominant ear was followed beyond this level. Thus, clear ear dominance was obtained here. However, no such following occurred in Condition 2. Not only was there no ear dominance, but following simply on the basis of relative amplitude did not occur either. However, if we hypothesize that the subjects were following here on the basis of frequency proximity (Dowling, 1973; Deutsch, 1975b, 1981b; Bregman, 1978), a very consistent pattern emerges. The response patterns of all subjects showed consistent following of either the lower frequencies or the higher frequencies, regardless of ear of input or of relative amplitude. As shown in Fig. 9, three consistently followed the lower frequencies, and one consistently followed the higher frequencies.[3]

This experiment therefore strongly supports the hypothesis that ear dominance occurs in sequences when the two ears receive the same frequencies in succession. When this condition was fulfilled, clear ear dominance occurred. However, when this condition was not fulfilled, there was a complete absence of ear dominance, and following occurred on the basis of frequency range instead.

## C. Experiment 2

As a further test of the hypothesis, two conditions were again employed. In each condition, subjects were presented with two dichotic chords, each 250 msec in duration, with no gaps between them.

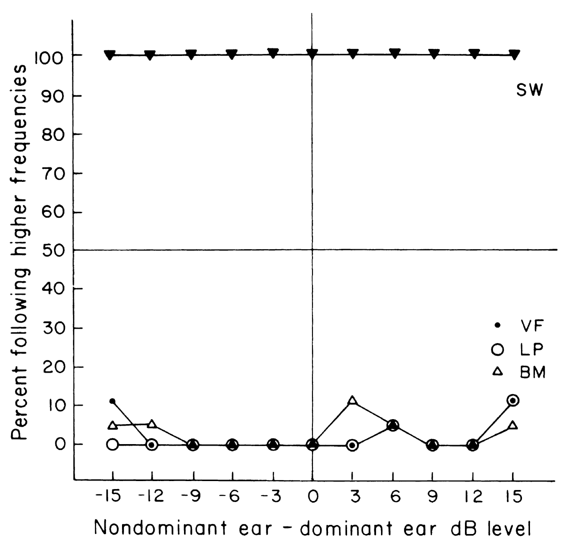


**Figure 9** Percentage following of higher frequencies in Condition 2 of Experiment 1, as a function of amplitude differences at the two ears. (From Deutsch, 1980).

3. The horizontal line at 50% in Fig. 8 simply reflects a consistent following on the basis of frequency proximity, given the counterbalancing procedure of the experiment.

As shown in Fig. 10, the basic sequence in Condition 1 consisted of two presentations of the identical chord, such that one ear received first the low tone and then the high tone, and simultaneously the other ear received first the high tone and then the low tone. The components of the chord stood in octave relation; the frequencies employed were 400 and 800 Hz. On half of the trials, the right ear received the high tone followed by the low tone, and on the other half, this order was reversed.

Also as shown in Fig. 10, the basic sequence in Condition 2 consisted of two chords. The components of each chord formed an octave, but the two chords were composed of different frequencies. On each trial, chords were presented that were formed either by 366 and 732 Hz, and by 259 and 518 Hz; or by 308 and 616 Hz, and by 435 and 870 Hz. These two-chord combinations were presented in strict alternation. Thus, any given chord was repeated only after several seconds, during which other chords were interpolated. For each of the above two-chord combinations, on half of the trials, the sequence began with lower of the two chords and ended with the higher, and on the other half, this order was reversed. Furthermore, for each of these subcombinations, on half of the trials, the right ear received the lower component of the first chord and the upper component of the second chord, and on the other half, this order was reversed.

In both conditions, the amplitude relationships between the tones presented to the two ears varied systematically across sequences, exactly as in Experiment 1. Subjects judged for each chord pair whether it was of the "high-low" type of the "low-high" type.

Each condition was presented for three sessions. There were 72 judgments per session in Condition1 and 96 judgments in Condition 2. The conditions were presented alternately in successive sessions, with the order of presentation counterbalanced across subjects. Within each session, sequences were presented in random order in groups of 12. There were 6-sec pauses between sequences within a group, and 1-min pauses between groups. A warning signal preceded each group of sequences by 15 sec, as in Experiment 1.

Four subjects were selected for this experiment, on the basis of showing clear ear dominance in sequences designed as in Condition 1. All subjects had normal audiograms. Two of the subjects were right-ear dominant and two were left-ear dominant.

The results of this experiment are shown in Fig. 11. It can be seen that, as expected, clear ear dominance occurred in Condition 1. However, also as expected from the hypothesis, there was a total absence of ear dominance in Condition 2. It will also be noted that following on the simple basis of amplitude did not occur either. Assuming, however, that the subjects were responding in this condition on the basis of overall contour, a very consistent result was obtained. As shown in Fig. 12, following on this principle uniformly occurred. That is, responses always indicated a "low-high" sequence when the second chord was higher than the

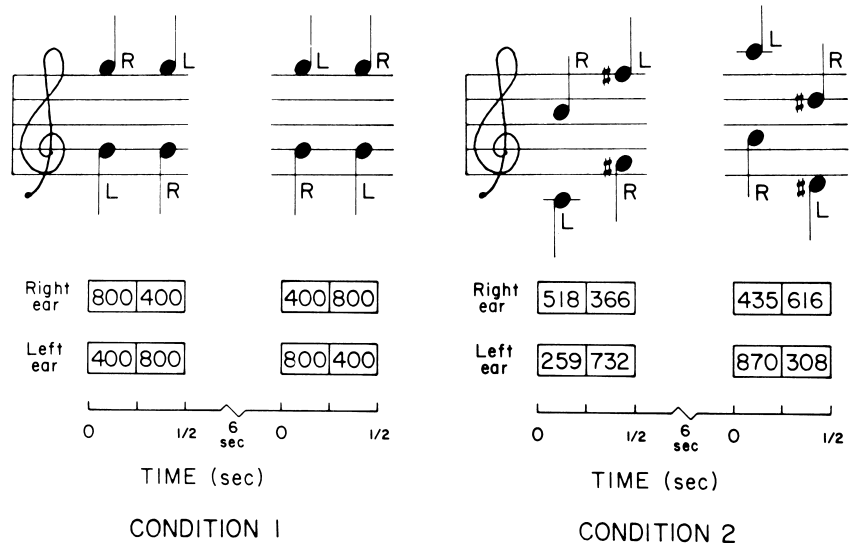


**Figure 10** Examples of stimulus configurations used in the two conditions of Experiment 2. Numbers in boxes indicate tonal frequencies. Musical notation is approximate.

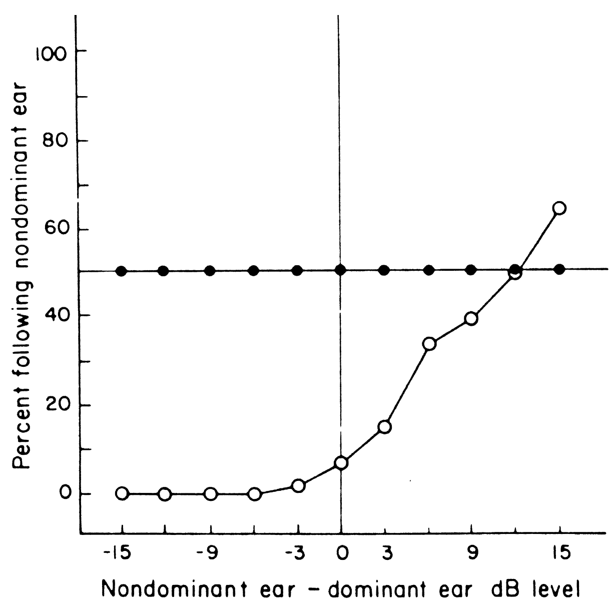


**Figure 11** Percentage following of nondominant ear in Experiment 2 as a function of amplitude differences at the two ears. Open circles: Condition 1. Solid circles: Condition 2. (From Deutsch, 1980.)

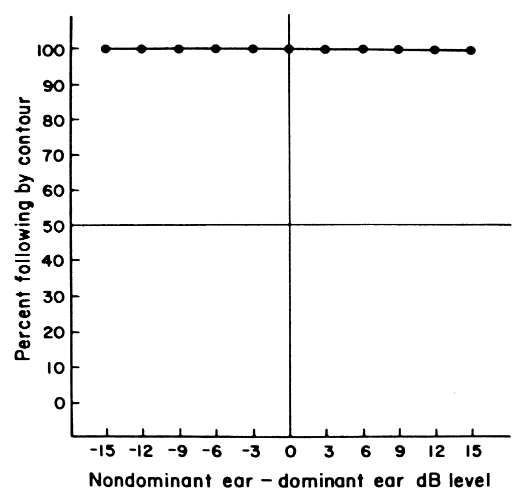


**Figure 12** Percentage following by contour in Condition 2 of Experiment 2, as a function of amplitude differences at the two ears.

first, and a "high-low" sequence when the second chord was lower than the first.[4] This experiment therefore reinforces the hypothesis that ear dominance occurs in sequences when the two ears receive the same frequencies in succession, but not otherwise.

It is interesting to note that relative amplitude was found not to be an important factor in either Experiment 1 or 2. When following was by frequency proximity or by contour, this occurred in the face of substantial amplitude differences between the signals arriving at the two ears. When following was by spatial location, the switch from one ear to the other did not occur at the point where the amplitude balance shifted from one ear to the other, but at a different level of amplitude relationship (and this varied from subject to subject). Thus, amplitude here acted to *set the scene* for following on the basis of spatial location, rather than acting as a primary following principle itself.

## D. Experiment 3

We may next inquire whether the absence of ear dominance found in the second conditions of Experiment 1 and 2 resulted simply from the time delay between successive presentations of the same frequen-

4. The horizontal line at 50% in Fig. 11 simply reflects a consistent following on the basis of contour.

cies to the two ears, from the interpolation of tones of different frequencies, or from a combination of these factors. The question of time delay was explored in Experiment 4 (Section III, E). Experiment 3 was concerned with the effect on ear dominance of interpolating a single tone of different frequency between the dichotic chord pairs, keeping the delay between members of these chord pairs constant.

This experiment employed two conditions, which are shown in Fig. 13. In Condition 1, two dichotic chords were presented, such that one ear received first the low tone and then the high tone, and simultaneously, the other ear received first the high tone and then the low tone. The low tone was always 400 Hz and the high tone, 800 Hz. All chords were 250 msec in duration, and the members of each pair of chords were separated by 750-msec pauses. Condition 2 was identical to Condition 1, except that a single tone was interpolated during the pause between the dichotic chord pairs. The interpolated tone was also 250 msec in duration, and it was preceded and followed by 250-msec pauses. The frequency of this tone was always 599 Hz, and the tone was presented simultaneously to both ears. In each condition, on half of the trials the right ear received the low tone of the first chord and the high tone of the second, and on the other half this order was reversed. Subjects judged for each chord pair whether it was of the "high-low" type or the "low-high" type. They were instructed to ignore the interpolated tone in Condition 2.

In both conditions, the amplitude relationships between the tones presented to the two ears varied systematically across sequences, exactly as in Experiment 1. Each condition was presented for four sessions, and 72 judgments were made per session. The two conditions were presented in alternation, with the order of presentation counterbalanced across subjects. Other aspects of the procedure were as in Experiment 1. The same four subjects participated as in Experiment 2.

The results of the experiment are shown in Fig. 14. It can be seen that a single interpolated tone did indeed reduce the amount of ear dominance. As shown in Fig. 15, this reduction was highly consistent in three of the subjects, and the fourth showed only a small effect in this direction (Deutsch, 1980).

## E. Experiment 4

This experiment studied the behavior of ear dominance as a function of time delay between onsets and offsets of successive dichotic chords. It had appeared from informal studies that the effect was stronger with chords presented in rapid repetitive sequence, and less pronounced when time delays were incorporated between successive chords. A further issue explored was whether the critical factor here was the delay between the offset of one chord and the onset of its successor, or rather the delay between successive onsets.

The experiment employed four conditions, which are depicted in diagram form in Fig. 16. The basic sequence in Condition 1 consisted of 20 250-msec dichotic chords, with no gaps between chords. The components of each dichotic chord were 400 and 800 Hz, and these were presented in strict alternation. On half of the trials, the sequence in the right ear began with 400 Hz and ended with 800 Hz, and on the other half this order was reversed. Subjects judged for each sequence whether it was of the "high-low-high-low" type or the "low-high-low-high" type. Condition 2 was identical to Condition 1, except that only two dichotic chord pairs were presented on each trial, and subjects judged for each pair whether it was of "high-low" type or the "low-high" type. Condition 3 was identical to Condition 2, except, that a 2750-msec gap was interpolated between the members of each dichotic chord pair. Condition 4 was identical to Condition 3, except that each dichotic chord was 3 sec in duration, and there were no gaps between the members of the dichotic chord pairs.

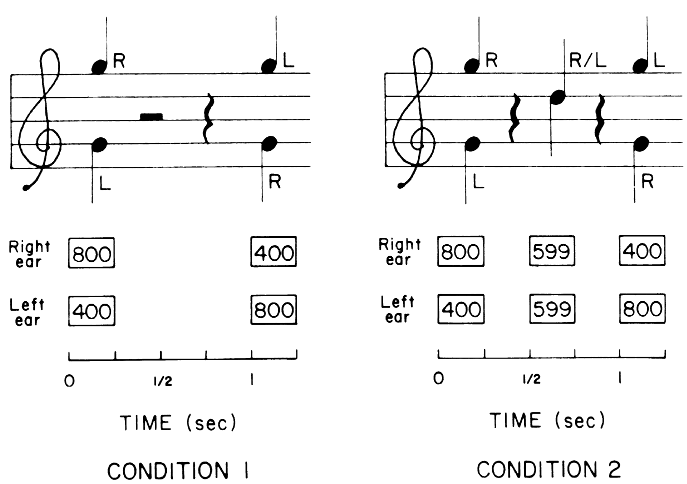


**Figure 13** Examples of stimulus configurations used in the two conditions of Experiment 3. Numbers in boxes indicate tonal frequencies. Musical notation is approximate.

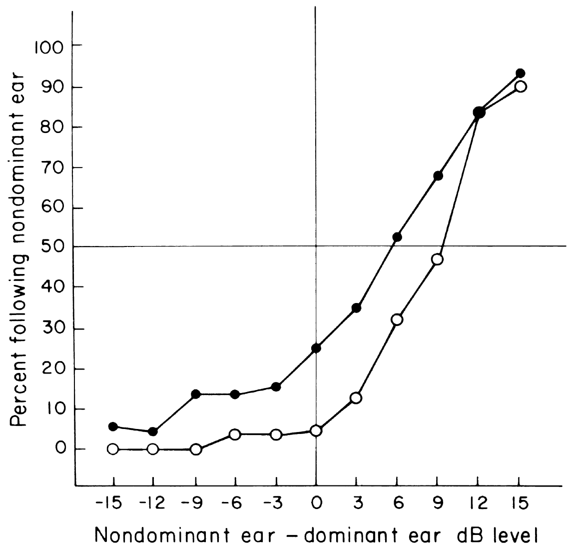


**Figure 14** Percentage following of nondominant ear in Experiment 3 as a function of amplitude differences at the two ears. Open circles: Condition 1. Solid circles: Condition 2. (From Deutsch, 1980.)

Thus, in Conditions 3 and 4, the onsets of successive chords were separated by identical delays; however, these chords differed considerably in duration. In all conditions, sequences were separated by 10-sec intertrial intervals.

In all conditions, for each type of sequence the amplitude relationships between the tones presented to the two ears varied systematically in the same way as in Experiment 1. Each condition was presented for three sessions. The order of presentation of the conditions was randomized, with each subject receiving a different random order. Sequences within each session were presented in random order, and subjects made 72 judgments per session. Other aspects of the procedure were as in Experiment 1.

Four subjects were selected for this experiment, on the same criterion as for Experiment 2. Two were left-ear dominant and two were right-ear dominant. All had normal audiograms.

The strengths of ear dominance under the different conditions of the experiment are shown in Fig. 17. A highly significant effect of conditions was found [$F(3, 9) = 11.59$, $p < 0.01$]. As shown in Fig. 17, the strongest ear-dominance effect did indeed occur in Condition 1, where 20 chords were presented in rapid repetitive sequence on each trial. The next strongest effect occurred in Condition 2, where on each trial, two opposing dichotic chords were presented in rapid sequence. The weakest effects occurred in Condition 3 and 4, where 3-sec delays intervened between onsets of the dichotic chords.

It is particularly interesting to note that the strengths of effect in Condition 3 and 4 were very similar, even

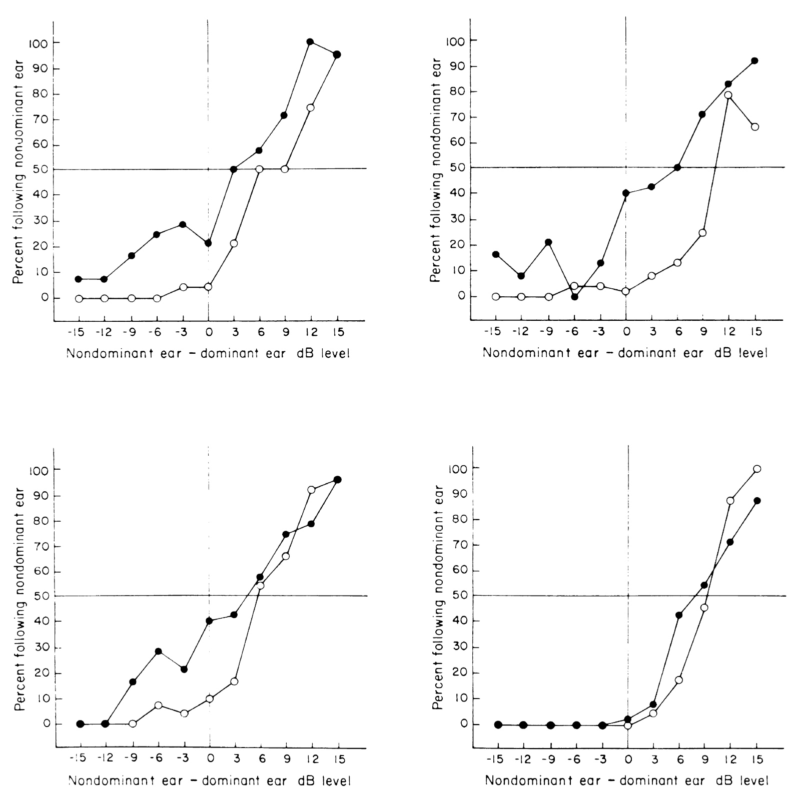


**Figure 15** Percentage following of nondominant ear in Experiment 3, plotted for the individual subjects separately. Open circles: Condition 1. Solid circles: Condition 2. (From Deutsch, 1980.)

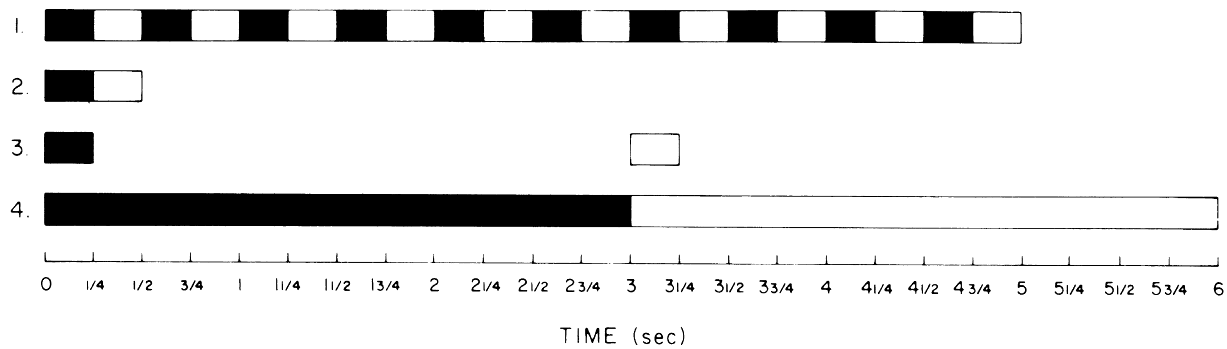


**Figure 16** Examples of stimulus configurations used in the different conditions of Experiment 4. Shaded boxes represent tones of 800 Hz, and unshaded boxes tones of 400 Hz.

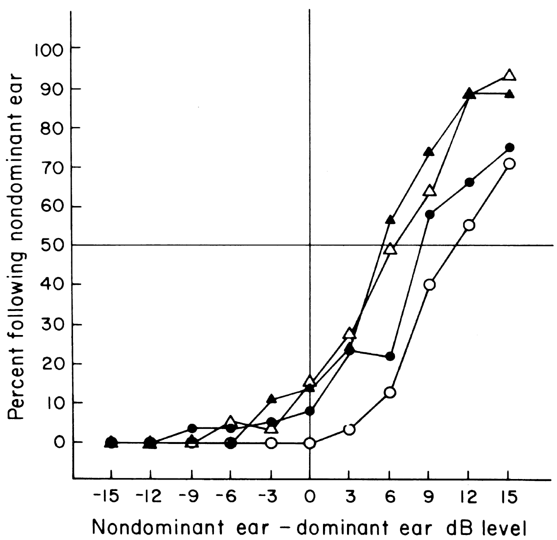


**Figure 17** Percentage following of nondominant ear in Experiment 4 as a function of amplitude differences at the two ears. Open circles: Condition 1. Solid circles: Condition 2. Open triangles: Condition 3. Solid triangles: Condition 4.

though chords of quite different durations were employed. This indicates that the strength of inhibitory interaction underlying ear dominance is determined by the delay between onsets of the successive tones. In contrast, the durations of the tones themselves do not appear of importance, and neither does the delay between the offset of one tone and the onset of the next.

## F. Hypothesized Basis for Ear Dominance

The above experiments lead to the following hypotheses:

1. "Ear-dominance" effects are based on interactions between neural units that are activated by specific values of both frequency and spatial location. Evidence for such units has been found at various levels of the auditory systems, such as the superior olivary complex (Moushegian *et al.*, 1967; Goldberg and Brown, 1969), the inferior colliculus (Rose *et al.*, 1966; Geisler *et al.*, 1969), and the auditory cortex (Brugge *et al.*, 1969). Such studies describe units that have characteristic frequencies, and whose responses are also sensitive either to interaural intensity differences or to interaural time differences. As will be described, it is assumed that other units with such characteristics mediate localization assignments; however, the present units are assumed to mediate pitch assignments.

2. Units that have same (or closely overlapping) frequency-response areas, but that convey information from different regions of auditory space, are linked in mutual inhibitory interaction. The inhibition exerted by one such unit on another acts over relatively long time periods. Such inhibition, when superimposed on the effect of contralateral masking (Ingham, 1959; Sherrick and Mangabierra-Albernaz, 1961; Dirks and Norris, 1966), results in the suppression of the percept of one of the simultaneously presented frequencies.

3. The amount of inhibition exerted by one neural unit on another cumulates with repetitive stimulation, and cumulates more rapidly as repetition rate increases. The duration of the stimulus itself is of little importance in determining the amount of such inhibition. Further, disinhibition occurs when units responding to different frequencies are activated.

4. Units conveying information from the dominant side of auditory space exert a more powerful inhibitory action than units conveying information from the nondominant side (at least under certain condition, as discussed below). The degree of this asymmetry is related to other measures of strength of cerebral dominance.

## G. Discussion

The question arises as to why such a strange and highly specific mechanism should have evolved. It may be suggested that this mechanism helps to counteract perceptual interference due to echoes and reverberation. In everyday listening, when the identical frequency emanates successively from two different spatial locations, the second occurrence may well be due to an echo. This is made more likely as the delay between such occurrences is shortened. However, if other frequencies are interpolated between two such occurrences of the same frequency, an interpretation in terms of echoing becomes less probable. The present phenomenon may therefore fall into the class of phenomena (of which the precedence effect is another example) that function to counteract misleading effects due to echoes and reverberation (Wallach *et al.*, 1949; Haas, 1951; Sayers and Cherry, 1957; Tobias and Schubert, 1959; Schubert and Wernick, 1969; McFadden, 1973).

The effects investigated here may be compared with other studies of ear dominance. Efron and his co-workers—for example, Efron and Yund (1974, 1975) and Yund and Efron (1975, 1976)—have performed a series of experiments that employed the following paradigm. Subjects were presented with a pair of dichotic chords that were separated by an interval of 1 sec. As in certain of the conditions described above, the dichotic chords were composed of the same frequencies throughout an experimental session. For each dichotic chord pair, one ear received first the high tone and then the low, and simultaneously, the other ear received first the low tone and then the high. It was found that a large proportion of subjects tended to follow predominantly the pattern of frequencies presented to one ear rather than the other, even when the tone presented to the nondominant ear was substantially higher in amplitude than the tone presented to the dominant ear.

The patterns of ear dominance found by Efron and Yund did not correlate with handedness. Furthermore, substantial shifts in patterns of dominance occurred as a result of changing the frequency relationships between the tones at the two ears or their frequency region, and such changes were idiosyncratic to the subject. This lack of handedness correlate represents one important difference between the present results and those of Efron and his co-workers, and would imply that the two types of effect are taking place at different levels in the auditory system.

One possible factor leading to the discrepancy between the handedness correlates in the two studies is that the present experiments employed tones standing in octave relation and those of Efron *et al.* did not. It may be that the simultaneous presentation of tones in octave relation is treated by the nervous system under certain conditions as the presentation of a fundamental and its first partial, and that this induces a special processing. This possibility is raised again in the section on lateralization. A second difference that may be critical involves task factors. In all the present experiments exploring handedness correlates, subjects made pitch and localization judgments simultaneously, and it may be that the localization task induces a focusing on the dominant side of auditory space. Haggard (1976) has stressed the importance of task factors in inducing right-ear advantages for verbal materials. A third factor that appears to be of importance is the presentation of the tones in rapid repetitive sequence (Christensen and Gregory, 1977; Deutsch and Gregory, 1978). More work is needed to investigate the boundary conditions producing the handedness correlates found here.

A different basis for ear dominance has been proposed by Yund and Efron (1977). They suggest that pitch perception results from a central summation of excitations arriving simultaneously from monaural frequency channels, and that these excitations may be asymmetric in their effect for any of the following three reasons. First, there may be a difference in sharpness of tuning at the two ears, and the ear with the sharper turning curve may provide the more salient information. Support for this argument was supplied by Divenyi *et al.* (1977), who obtained correlations between patterns of ear dominance and differences between the two ears in monaural frequency discrimination. Second, Yund and Efron (1977) suggest that the two ears may have different intensity - response functions. And third, they suggest that the effect may be due to an asymmetric weighting factor for the excitations arriving simultaneously at the two ears.

This suggestion treats ear dominance solely in terms of simultaneous interactions. Such an interpretation cannot account for the present findings, which show that whether ear dominance occurs depends on the relationships between the tones as they occur in sequence at the two ears. Ear dominance occurs with successive dichotic chords composed of identical frequencies; however, it is absent with successive dichotic chords composed of different frequencies.[5]

A further difficulty raised by the present experiments for the suggestion of Yund and Efron (1977) is that "side-dominance" effects can occur when the stimuli are presented through speakers rather than earphones. Thus, the interactions involved here are between regions of auditory space rather than between pathways from the two ears. The correlations between differences in frequency-resolving power at the monaural level and ear dominance reported by Divenyi *et al.* (1977) could simply reflect a tendency to focus attention on the side of auditory space that provides the more precise information.

The importance of precise spatial information (whether real or apparent) in determining what sounds are perceived is exemplified by the *masking-level difference* (MLD) and related phenomena (Licklider, 1948; Hirsh, 1948; Webster, 1951; Jeffress, 1972; Hafter *et al.*, 1973; Kubovy *et al.*, 1974).

Another related effect has been noted by the author in collaboration with M. Kubovy. A single pure tone is presented continuously to both ears, but alternating in phase so that it appears to move back and forth laterally. Under these conditions, a pitch shift may be perceived such that when the tone appears to be in one spatial location its pitch is higher than when it appears to be in the other location. The perceived pitches of the tones in

5. Informal investigations by the author have indicated that ear dominance may still occur when the frequencies presented in succession to the two ears differ by a few Hz. The exact parameters of this narrow critical region remain to be determined.

these two apparent locations do not change when the earphone positions are reversed. This asymmetry must be based on differences in the response of central neural structures conveying pitch information, whose patterns of activation also depend specifically on the spatial location of the stimulus. This intriguing effect may be termed "central diplacusis."

It should be noted that several other studies have shown also dissociations between "what" and "where" mechanisms in audition. Schubert and Wernick (1969) studied the fusion of dichotic signals where both microstructure and envelope delay were varied. They found that the apparent position of the signal was predominantly determined by interaural envelope delay; however, the singleness of the perceived image was strongly influenced by microstructure. They conclude that "singleness of image and position of image appear to be analyzed separately, the information being combined later into a single perceptual impression" (p. 1525).

In another study, performed by Odenthal (1963), subjects were presented with a dichotic chord that was followed after a silent interval by a diotic or monotic comparison tone. When the components of the dichotic chord were very close in frequency, subjects heard a single pitch, which was termed an intertone. Odenthal found that the pitch of this intertone did not change as the relative intensities of the components of the chord were altered; however, altering these relative intensities resulted in the intertone being lateralized toward the ear receiving the higher intensity signal.

A similar dissociation was described by Efron and Yund (1974). Using their paradigm described above, when the components of the dichotic chord were at equal amplitude, the fused sound was localized in the center of the head. As in Odenthal's experiment, altering the relative amplitude of the components of the dichotic chord produced a lateralization to the ear receiving the higher amplitude signal; however the pitch of the sound often remained constant over a wide range of amplitude variation.

Similar dissociations have been obtained with the use of more complex stimuli. Carlson *et al.* (1976) delivered different formants from a synthetic vowel sound to different ears. It was found that varying the relative formant amplitudes had little effect on the perception of vowel quality, while producing a strong effect on lateralization.

## IV. PARAMETRIC STUDIES OF LATERALIZATION BY FREQUENCY

We next turn to an examination of the second component of the octave illusion: the lateralization or localization of each tone toward the ear receiving the higher frequency signal, regardless of whether the higher or the lower frequency is perceived. We have assumed that this effect is based directly on the use of frequency as a localization cue. On the other hand, it could be due indirectly to other factors. Most studies on the lateralization of dichotically presented pure tones have involved presenting the same frequency to both ears. Under such conditions, amplitude differences will produce a lateralization toward the ear receiving the higher amplitude signal; temporal differences, whether ongoing or transient, will produce a lateralization towards the ear receiving the precedent signal (Mills, 1972; Tobias, 1972). In the single-frequency case, when the two signals are equal in amplitude, assuming that the listener has no ear asymmetry, they will also be equal in loudness. However, when the two signals are unlike in frequency, there may be loudness differences between them at equal amplitude, and we may hypothesize that lateralization occurs toward the louder signal. Second, on the traveling-wave hypothesis (von Békésy, 1960), the receptors on the basilar membrane underlying the 800-Hz tone would initially be stimulated before the receptors underlying the 400-Hz tone, so we might expect an effective precedence of the 800-Hz over the 400-Hz signal at the central neural structures underlying localization decisions. Further support for this view comes from Deatherage (1961), who used filtered clicks as stimuli. He found that when such clicks differed moderately in frequency a single-click image was produced, and it was necessary for the higher frequency click to lag the lower frequency click in order to place the image in the center of the head.

A study was therefore undertaken to investigate this lateralization-by-frequency effect as a function of amplitude and loudness differences between the 400- and 800-Hz tones, and also as a function of onset and offset disparities between them. A further question was considered. Informal studies had indicated that this effect depends upon the repetitive presentation of the alternating tones, and that it is weaker or absent when single pairs of dichotic chords are presented instead. Formal comparison was therefore made between these two conditions.

Four subjects were selected for the study, on the basis of consistently perceiving a single high tone in the right ear alternating with a single low tone in the left ear with sequences composed of 400- and 800-Hz tones at equal amplitude. All subjects had normal audiograms. The apparatus was as in the experiments on ear dominance.

### A. Experiment 1

In experiment 1, the subjects were presented with dichotic sequences consisting of 250-msec tones, which alternated in frequency between 400 and 800 Hz such that when the right ear received 400 Hz, the left ear received 800 Hz, and vice versa. There were 20 dichotic chords in each sequence, with no gaps between chords. The amplitude relationships between the 400-Hz tone and the 800-Hz tone varied systematically across sequences, such that an 800-Hz tone at 70 dB SPL was paired equally often with a 400-Hz tone at 70, 73, 76, 82, and 85 dB. Similarly, a 400-Hz tone at 70 dB was paired equally often with an 800-Hz tone at each of these amplitude values. For each level of amplitude relationship, on half of the sequences the signal in the right ear began with 400 Hz and ended with 800 Hz, and on the other half the signal in the right ear began with 800 Hz and ended with 400 Hz. These sequences were presented in random order. Subjects judged for each sequence whether it was of the "left-right-left-right" type, or the "right-left-right-left" type; and from these judgments it was inferred to which frequency the tones were being lateralized.

Each subject made 72 judgments per day on 4 successive days. Sequences were presented in groups of 12, with 10-sec pauses between sequences within a group, and 2-min pauses between groups. As a warning signal, a 500-msec tone of 2000 Hz at 70 dB preceded each group of 12 sequences by 15 sec.

The results of the experiment, averaged over the four subjects, are plotted by the closed circles on Fig. 18. It can be seen that lateralization toward the 800-Hz tone occurred even when this tone was substantially lower in amplitude than the 400-Hz tone. There were, however, large individual differences in the size of the effect. As shown in Fig. 19, two subjects lateralized toward 800-Hz tone throughout the 15-dB range, one subject showed the effect up to a 9-dB difference, one showed it at equal amplitude only.

## B. Experiment 2

This experiment was performed to determine whether the lateralization effect obtained in Experiment 1 could have been due to loudness differences between

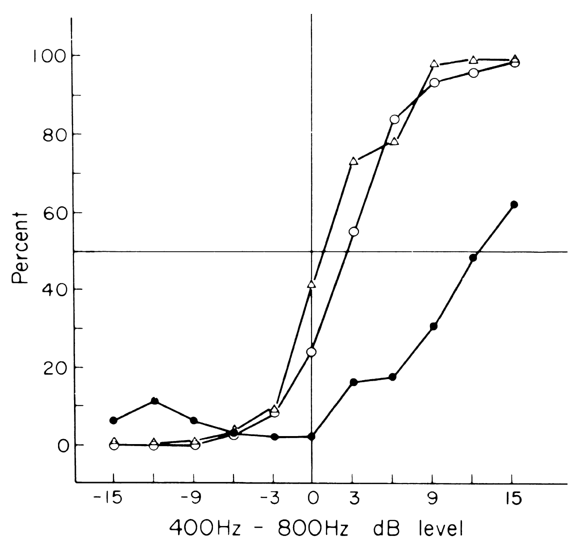


**Figure 18** Results of Experiments 1, 2, and 3 on lateralization. Solid circles: Percentage lateralization to the 400-Hz tone as a function of amplitude differences between the 400-Hz and 800-Hz tones, in sequences of 20 dichotic tone pairs. Open circles: Same function plotted for sequences of two dichotic tone pairs. Open triangles: Percentage judgment of the 400-Hz tone as louder than the 800-Hz tone, as a function of amplitude differences between the 400-Hz and 800-Hz tones, in sequences of 20 dichotic tone pairs. (Adapted from Deutsch, 1978.)

the 400-Hz and 800-Hz tones. The subjects compared the loudness of these tones in a stimulus situation as close as possible to that of Experiment 1. From the other studies of equal loudness judgments in this range (such as by Stevens and Davis, 1938), it was expected that loudness judgments would mirror amplitude relationships quite closely, and not follow the lateralization patterns obtained.

The sequences employed were identical to those in Experiment 1, except that here, only one channel was presented, and this was simultaneously to both ears; that is, an 800-Hz tone presented simultaneously to both ears alternated with a 400-Hz tone presented simultaneously to both ears. The subjects judged for each sequence which of the two alternating tones was louder, and indicated their judgments by writing "high" (referring to the 800-Hz tone) or "low" (referring to the 400-Hz tone) during the intertrial interval. As before, subjects were given 72 trials per session over 4 successive days.

The results of the experiment averaged over the four subjects are plotted by the triangles on Fig. 18. It can be seen that loudness judgments did indeed mirror amplitude relationships quite closely. As shown on Fig. 19, this was true for all subjects. It must be concluded that the lateralization patterns obtained in Experiment 1 were not due to loudness differences between the 400-Hz and 800-Hz tones.

## C. Experiment 3

A further experiment was performed to plot lateralization patterns when, instead of 20 dichotic chords being presented in sequence, two pairs were presented. The paradigm used was exactly the same as in Experiment 1 and subjects were required to judge for each pair of dichotic chords whether it was of the "left-right" type or the "right-left" type. Subjects were again given 72 trials per session over four successive sessions.

The results of this experiment, averaged over all four subjects, are plotted by the open circles on Fig. 19. It can be seen that there was a substantially smaller tendency to lateralize toward the 800-Hz signal, compared with Experiment 1. As shown in Fig. 19, this difference between the long and short sequences occurred in all subjects (Deutsch, 1978).

## D. Experiment 4

A further experiment was undertaken to test the hypothesis that this lateralization by frequency effect is due to an effective precedence of the 800-Hz over the 400-Hz signal at the central neural structures underlying localization decisions. To test this hypothesis, sequences were constructed in which all tones were at equal amplitude (70 dB SPL), but there were onset and offset disparities between the 400- and 800-Hz tones. An example of such a sequence, exaggerating the temporal disparities, is shown on Fig. 20. In the experiment itself, the 400-Hz tone led the 800-Hz tone an equal number of times by 0,

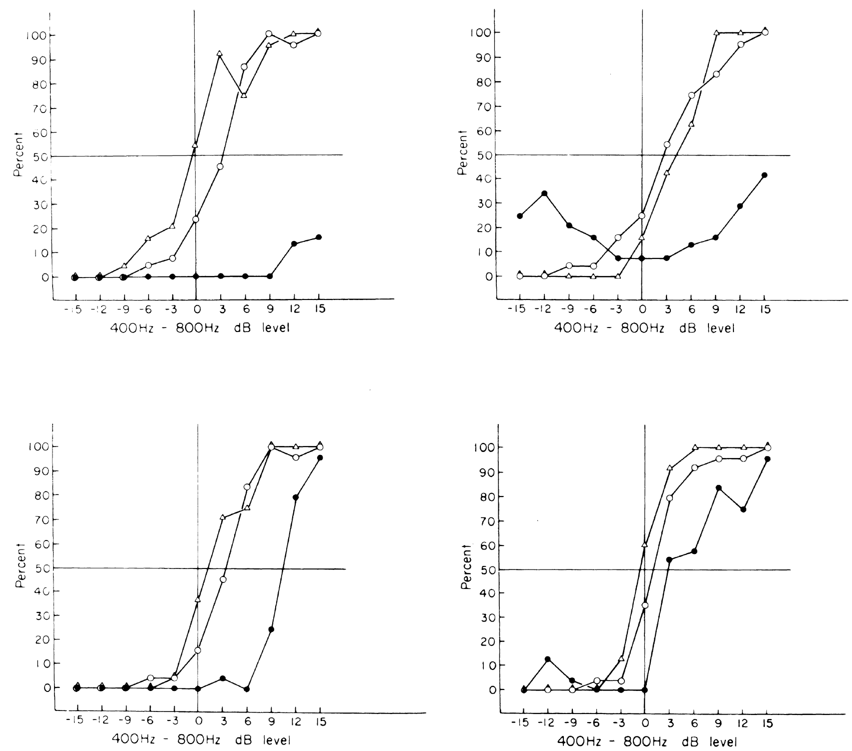


**Figure 19** Results of Experiments 1, 2, and 3 on lateralization, plotted for the individual subjects separately (see Fig. 18 for description of symbols).

1, 2, 3, 4, and 5 msec, and also lagged the 800-Hz tone an equal number of times by each of these values. At a lag of 0 msec, all tones were 250 msec in duration. As in the first experiment, all sequences consisted of 20 dichotic chords, and the other aspects of the procedure were exactly as in the first experiment.

The results of this experiment, averaged over all four subjects, are shown in Fig. 21. It can been seen that substantial lateralization toward the 800-Hz tone occurred under all conditions. Since the range of temporal disparity covered here was substantially greater than that due to the traveling wave, it must be concluded that this lateralization effect cannot be due to differences in arrival time between the 400- and 800-Hz signals at the central neural structures underlying localization decisions.

A further experiment was initiated to study the effect of onset and offset disparities using only 2 dichotic chords in a sequence instead of 20. The range of onset and offset disparities was identical to that of Experiment 4, as were other aspects of the procedure. However, the subjects now reported that percepts were quite ambiguous, and that meaningful "left-right" versus "right-left" judgments could not be made. The experiment was therefore terminated; however, this failure stresses the point that the present lateralization effect develops with sequencing.

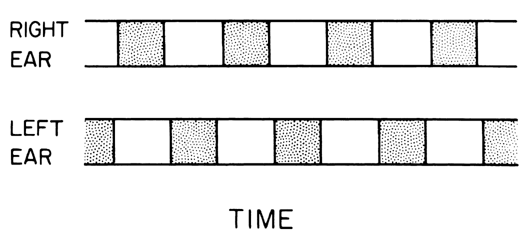


**Figure 20** Representation of stimulus configurations such as employed in Experiment 4 on lateralization, showing onset and offset disparities between the 400-Hz and 800-Hz tones. Shaded boxes represent tones of 800 Hz and unshaded boxes tones of 400 Hz.

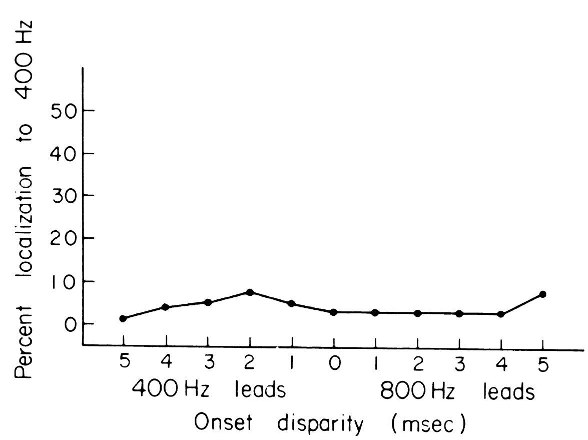


**Figure 21** Percentage lateralization to the 400-Hz tone in Experiment 4 as a function of onset and offset disparities between the 400-Hz and 800-Hz tones.

### E. Discussion

Before speculating on the basis of this lateralization effect, we should note that other experimenters using different stimulus parameters have obtained a variety of results. Von Békésy (1963) obtained an effect in the same direction as the present one. He reports that when a long tone of 750 Hz is delivered to one ear, and a long tone of 800 Hz is simultaneously delivered to the other ear, both tones are perceived and correctly localized. However, when these tones are amplitude modulated in phase with a frequency between 5 and 50 Hz, the two images fuse to form a single percept. Using stimuli that were amplitude modulated in this way, von Békésy found that when the tone in one ear was held constant at 800 Hz and the tone in the other ear was varied between 750 and 880 Hz, this fused tonal percept was lateralized toward the higher frequency signal. (Von Békésy presented this observation as evidence for the traveling-wave hypothesis, since the receptors on the basilar membrane underlying the higher frequency tone would be stimulated before those underlying the lower frequency tone. However, the present lateralization effect cannot be explained on these grounds, as demonstrated by Experiment 4 on onset and offset disparities.)

On the other hand, Scharf (1974), using yet a different paradigm, obtained localization to the lower of two simultaneous frequencies instead. He presented tones of different frequencies through two spatially separated loudspeakers. The frequency separation between the tones from the two speakers was varied between 0 and 4200 Hz around a geometric mean of 2000 Hz, and the tones were adjusted to be equal in loudness. The simultaneous tone pairs were 500 msec duration, and they were repeatedly presented with 2-sec pauses until the subject made a judgment. Under these conditions, subjects tended to localize fused images toward the speaker that was emitting the lower frequency signal. Scharf also reports that analogous effects were obtained when the stimuli were presented through earphones instead of speakers.

When yet other stimulus parameters are employed, the fused sound produced by a dichotic chord with components at equal amplitude appears localized in the center of the head. Changing the relative amplitudes of the components of the chord results in a lateralization toward the higher amplitude component (Odenthal, 1963; Efron and Yund, 1974). Further, Deutsch (1975b) found that with the dichotic scales sequence, subjects who obtained fused percepts did not tend to localize each sound toward the high frequency component. Instead, various idiosyncratic localization percepts were obtained, such as the entire sequence in one ear, or a sequence that traveled from left to right as the pitch of the tones moved from high to low.

The lateralization or localization to the higher frequency signal explored here therefore depends critically on the stimulus parameters employed; more work is clearly needed to establish the boundary conditions for its occurrence. One may, however, suggest a mechanism that takes this flexibility into account. It may be hypothesized that the effect results from interactions between neural units that are specifically sensitive both to frequency and to region of auditory space. Units with such characteristics were hypothesized above as mediating pitch assignments and as underlying "ear-dominance" effects. It is now suggested that units with similar characteristics mediate localization assignments, and that interactions between them underlie the present effect. To obtain the lateralization to the higher frequency signal described here, we need only assume that, under certain conditions, units responding to the higher of the two simultaneous frequencies exert an inhibitory action on units responding to the lower of the two frequencies. Under other conditions, different patterns of inhibition may operate instead.

We may next ask why lateralization or localization to the higher frequency signal should occur under these conditions. One possible explanation lies in head shadow effects. When a complex tone is presented in a natural environment, there is a considerable difference in the relative strength of the partials arriving at the two ears. For instance, if the tone is presented to the listener's right, partial components arriving at the right ear are considerably stronger than those arriving at the left (Benade, 1976). If, as suggested above, the nervous system treats the stimulus in this alternating octave situation as a fundamental together with its first partial, then the signal would be interpreted as coming from the right—that is, as from the side receiving the higher frequency component.

## V. THE WHAT–WHERE CONNECTION

In previous sections, we have explored the mechanism determining what frequencies we hear under conditions producing the octave illusion, and also the mechanism determining where the sounds appear to be coming from. We have seen that these two mechanisms here operate according to quite different rules, with the result that we may end up perceiving a stimulus that does not exist—that is, with its frequency taken from one source and its location from another. The question then arises as to how the outputs of these "what" and "where" mechanisms become linked together. In experiencing the octave illusion, we do not perceive a disembodied location together with a pitch floating in a void; rather we perceive a pitch *at* a location. Thus, some additional mechanism must operate to combine these values of pitch and localization together, so that an integrated percept results. If we wish to confine ourselves to explaining the octave illusion, we need only assume that the outputs of the "what" and "where" mechanisms become linked together. However, this represents a special case, since here we have only one output from each mechanism at any given time. In normal listening we are generally confronted with several sounds that emanate simultaneously from different sources. Thus, we are presented simultaneously with several outputs from both the "what" and the "where" mechanisms. If we are to arrive at a set of veridical auditory descriptions, there must be some rule determining which output to link with which.

We may propose the following solution. Two equivalent arrays are hypothesized, in each of which individual elements are sensitive both to a specific value of frequency and also to a specific value of spatial location, that is, to a specific *conjunction* of attribute values. As shown in Fig. 22, we assume that these two arrays are identical in organization as far as their inputs are concerned; however, the output of one array signals pitch and the output of the other array signals localization.

What we see on these two arrays are the projections resulting from a high tone on the left and a low tone on the right. We here assume that these two tones are veridically perceived (as would be the case, for instance, when both tones are presented continuously for long duration). We can explain this outcome by assuming that there is a linkage between the outputs of those activated elements that are in analogous positions on the two arrays. If there are no outputs from elements in strictly analogous positions, we can assume that outputs from elements in the most proximal positions are linked together.

Figure 23 depicts the situation under conditions giving rise to the octave illusion, for the case of a listener who perceives the sequence of frequencies presented to his right. Thus, interactions within the array that conveys pitch result in the signaling of only a low tone, and interactions within the array that conveys localization result in the signaling of only a localization to the source of the higher frequency signal. Thus, there is only one output from the pitch array, and only one output from the localization array. Since there are no outputs from elements situated in more proximal positions on the two arrays, these two outputs become linked together. We therefore hear a low tone to the left, which was not in fact presented. Thus, the octave illusion results.

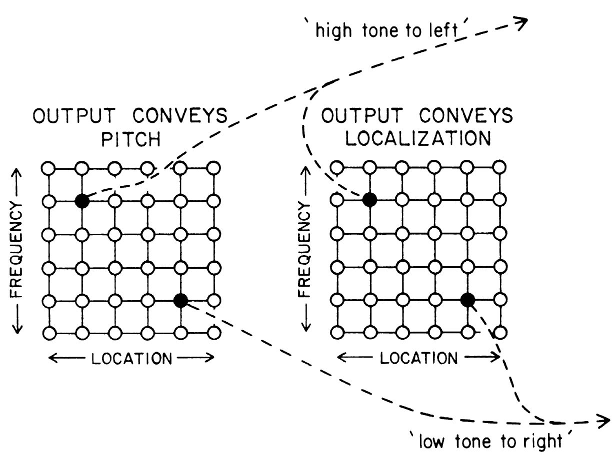


**Figure 22** Hypothesized arrays that mediate selection of pitch and localization values. This figure shows outputs and ther linkages where two simultaneous tones are veridically perceived. See text for details.

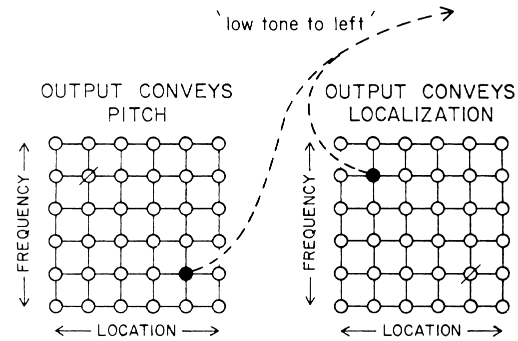


**Figure 23** Hypothesized arrays that mediate selection of pitch and localization values. This figure shows outputs and their linkages under conditions producing the octave illusion. Ø indicates inhibited elements. See text for details.

## Discussion

Jeffress (1948, 1972) has previously hypothesized that units that are sensitive to specific values of both frequency and spatial location mediate both pitch and localization assignments; however, he assumed that a single array of such conjunction units mediates both functions. As explained above, the present results cannot be accommodated on a single array; however, the two arrays hypothesized here could arise as parallel outputs from a single array, such as that proposed by Jeffress.

Our model is advanced as a solution not only to the question how the octave illusion arises, but also to the question of how the attributes of two simultaneously presented stimuli may be correctly conjoined, once they have been pulled apart by the nervous system. This second question presents us with a much more difficult problem than the illusion itself.

Hypotheses have been put forward to solve analogous questions in vision. For example, as described in Section I, suppose that we are presented with a blue triangle and a green square; assuming that the mechanisms analyzing color and form are at some stage separate, how do we know that the triangle is blue and square is green? Attneave (1974) has suggested that such correct conjunctions are achieved by the tagging of attribute values to particular spatial locations, and a similar hypothesis was proposed by Treisman *et al.* (1977). Our present hypothesis bears some similarity to these proposals, since it assumes that both the pitch and the localization mechanisms are composed of elements that respond to specific spatial locations.

## VI. CONCLUSION

Considerable advances have been made in the understanding of how separate attributes of an auditory stimulus are analyzed by the nervous system. Little is known, however, of how the outputs of such analyses are combined to produce an integrated percept. In considering this issue, it is valuable to examine cases where incorrect conjunctions are formed, and the octave illusion presents us with an opportunity to do this.

From the examination of the illusion, it is clear that the mechanisms underlying the selection of pitch and localization values are at some stage separate in the nervous system, and that at this stage, they may operate according to quite independent criteria. It is further clear from analyses of the factors governing pitch and localization decisions that the "what" and "where" mechanisms each operate on both frequency and location information. Building on this knowledge, we have hypothesized that the "what" and "where" mechanisms are each composed of arrays of units that respond to conjunctions of frequency and location values. This hypothesis was elaborated to explain how the outputs of the "what" and "where" mechanisms may be linked together so as to maximize the probability of veridical perception.

### Acknowledgements

This work was supported by U.S. Public Health Service Grant MH-21001. I am grateful to F. H. C. Crick for valuable discussions concerning perceptual organization.

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