Lateralization and sequential relationships in the octave illusion

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Subjects made lateralization judgments concerning sequences of dichotic chords whose components stood in octave relation. In condition 1, each ear received a sequence consisting of 400- and 800-Hz tones in alternation, such that when one ear received the 400-Hz tone, the other ear simultaneously received the 800-Hz tone. Condition 2 was identical to condition 1, except that the alternating tones were at 600 and 1200 Hz instead. In condition 3, dichotic chords at 400 and 800 Hz alternated with dichotic chords at 600 and 1200 Hz. In all conditions, the amplitude relationships between the higher and lower tones were varied, and the percent lateralization to the higher frequency signal was plotted as a function of these amplitude relationships. In all conditions, when the tones at the two ears were equal in amplitude, lateralization tended to be toward the ear receiving the higher frequency signal. Averaged across subjects, this tendency in condition 1 was overcome only when the lower frequency signal was 12 dB higher in amplitude, and, in condition 2, when it was 9 dB higher. However, in condition 3, the tendency was overcome when the lower frequency signal was 3 dB higher in amplitude. The lateralization effect was thus shown to be influenced by the sequential relationships between the frequencies presented to the two ears.

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INTRODUCTION

In general, lateralization studies have focused on interaural differences between signals consisting of the identical frequency components. Such studies have shown that differences in amplitude result in lateralization toward the higher amplitude signal, differences in temporal envelope result in lateralization toward the leading signal, and, for sounds below roughly 1500 Hz, differences in temporal microstructure result in lateralization toward the leading signal (Mills, 1972; Durlach and Colburn, 1978; Blauert, 1983). Analogously, models of binaural interaction generally assume that lateralization decisions result from interactions between units that have identical or near-identical frequency selectivities (Jeffress, 1948; Scharf *et al.*, 1976; Colburn and Durlach, 1983).

In contrast with the identical-frequency case, the dichotic presentation of two different frequencies generally results in the perception of two different pitches, which are separately lateralized. A number of studies have examined the threshold frequency separation for obtaining two pitch images in this situation; in general, this has been found to be of the order of a critical band or less (Thurlow and Bernstein, 1957; Perrott and Barry, 1969; Perrott *et al.*, 1970). Other studies have measured the threshold frequency separation required to influence lateralization judgments here; this has been found to be roughly of the same order (Thurlow and Elfner, 1959; Perrott and Williams, 1970; Scharf *et al.*, 1976).

However, while we might expect frequencies that stand in arbitrary relation to be treated as independent by the auditory system, we might also expect perceptual fusion to occur between frequencies whose relations indicate that they are likely to be emanating from the same source. Indeed, it has been shown that frequencies that stand in simple harmonic relation tend to give rise to fused pitch sensations (Tobias, 1972; De Boer, 1976; Mathews and Pierce, 1980). We may, therefore, expect that such complexes would tend to fuse dichotically also, so as to produce unitary lateralized images.

The octave illusion (Deutsch, 1974) provides a case in point. Here, two sine wave tones, at 400 and 800 Hz, are repeatedly presented in alternation. The identical sequence is delivered to both ears simultaneously; however, when the right ear receives the high tone, the left ear receives the low tone, and vice versa. Thus the listener is presented with a single dichotic chord, but the ear of input for each component switches repeatedly.

This pattern gives rise to a number of percepts, which vary from one listener to another. The percept most commonly obtained consists of a single high tone in one ear, which alternates with a single low tone in the other ear. This has been shown to result from two factors. First, the perceived sequence of pitches corresponds to the frequencies delivered to one ear or to the other (ear dominance); second, each fused sound is lateralized toward the ear receiving the higher frequency signal, regardless of whether a pitch corresponding to the higher or the lower frequency is perceived (Deutsch and Roll, 1976).

The lateralization component of the illusion has been found to be robust in face of amplitude differences between the 400- and 800-Hz tones (Deutsch, 1978, 1981). In some cases, lateralization to the higher frequency signal occurs even when the lower frequency signal is more than 12 dB higher in amplitude. This is only true, however, when long repetitive sequences are employed. When two dichotic tone pairs are presented instead, lateralization judgments closely follow patterns of relative loudness. This lateralization effect has also been found to be robust in face of onset–offset differences between the 400- and 800-Hz tones, when long repetitive sequences are employed. Varying the relative onsets and offsets of these tones up to 5 ms in either direction does not affect the strength of lateralization toward the higher frequency signal (Deutsch, 1981).

The present study investigated the behavior of this lateralization effect as a function of sequential relationships between the signals at the two ears. One characteristic of the pattern givning rise to the octave illusion is that the frequency presented to one ear is identical to the frequency that has just been presented to the other ear. This factor has previously been shown to be critical to the ear dominance component of the illusion (Deutsch, 1980), and it was hypothesized that it might influence the lateralization component also.

Accordingly, three conditions were compared. These employed the pitch patterns illustrated in Fig. 1. The basic sequence employed in condition 1 consisted of the repetitive presentation of a single chord, whose components 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 lower and higher tones were 400 and 800 Hz. The basic sequence in condition 2 was identical to that in condition 1, except that the frequencies of the lower and higher tones were 600 and 1200 Hz instead. In condition 3, dichotic chords formed of 400 and 800 Hz alternated with dichotic chords formed of 600 and 1200 Hz.

In order to evaluate the strength of the lateralization effect under these different conditions, the relative amplitudes of the higher and lower tones were varied, and the percent lateralization to the higher frequency signal was determined as a function of the amplitude relationships. It was reasoned that, if the frequency relations between successive tones had no influence on the lateralization effect, then performance in condition 3 should fall somewhere between performance in conditions 1 and 2. If, however, such a result were not obtained, an influence of sequential relationships on the lateralization effect would be demonstrated.

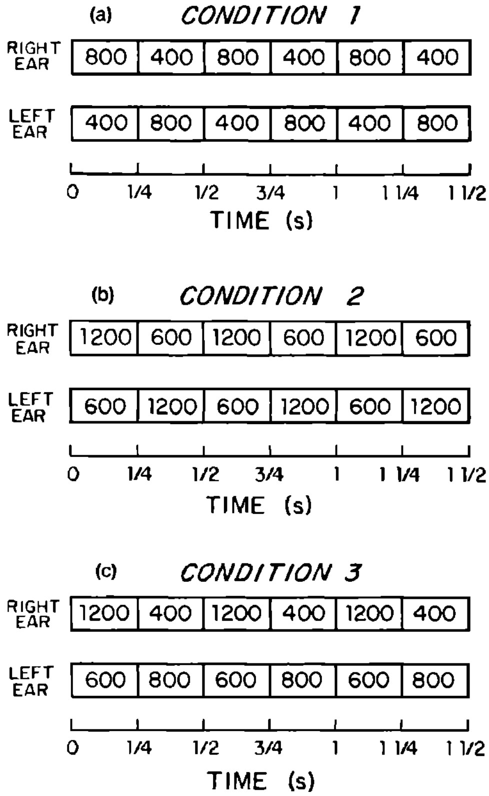

FIG. 1. Examples of stimulus patterns employed in the different conditions of the experiment. Numbers in boxes indicate frequencies (Hz).

I. METHOD

A. Apparatus

Tones were generated as sine waves by two function generators (Wavetek model No. 155), which were controlled by a PDP 11/23 computer. The output was passed through a Crown amplifier, and presented to subjects through matched headphones (Grason-Stadler TDH-49). Subjects were seated in sound-insulated booths.

B. Stimuli and procedure

The experiment consisted of three conditions, and all subjects participated in all conditions. Throughout, subjects were presented with sequences consisting of 20 dichotic chords. Each chord was 250 ms in duration, and there were no gaps between chords. In order to minimize transients, there were no voltage jumps at the transition between tones, and the voltage slope did not change sign at the transitions.

The basic sequence employed in condition 1 is illustrated in Fig. 1(a). It can be seen that this consisted of a single chord, whose components were at 400 and 800 Hz, and alternated from ear to ear such that, when the 400-Hz tone was in the right ear, the 800-Hz tone was in the left ear, and vice versa. Subjects judged on each trial whether the sequence was of the "right–left–right–left" type, or the "left–right–left–right" type, and from these judgments it was inferred to which frequency the tones were being lateralized.

In order to evaluate the strength of the lateralization effect, the amplitude relationships between the 400- and 800-Hz tones were varied systematically across sequences. Thus a 400-Hz tone at 70 dB SPL was paired equally often with an 800-Hz tone at 70, 73, 76, 79, 82, and 85 dB. Further, an 800-Hz tone at 70 dB SPL was paired equally often with a 400-Hz tone at 70, 73, 76, 79, 82, and 85 dB. For each level of amplitude relationship, the signal to the right ear began with 400 Hz and ended with 800 Hz on half the trials, and began with 800 Hz and ended with 400 Hz on the other half.

All subjects were tested in this condition for three sessions, with 72 trials per session. Specifically, for each of the eight subjects, there were 36 replicates for the equal amplitude subcondition (18 for each temporal order), and there were 18 replicates for each of the othe relative amplitude subconditions (9 for each temporal order). Sequences within a session were presented in random order.

The basic sequence in condition 2 is illustrated in Fig. 1(b). It can be seen that this consisted of a single chord, whose components were at 600 and 1200 Hz, and alternated from ear to ear such that, when the 600-Hz tone was in the right ear, the 1200-Hz tone was in the left ear, and vice versa. This condition was otherwise identical to condition 1.

The basic sequence in condition 3 is illustrated in Fig. 1(c). It can be seen that this consisted of the alternating presentation of dichotic chords at 400–800 Hz and at 600–1200 Hz. One ear received a pattern consisting of a 400-Hz tone alternating with a 1200-Hz tone, while the other ear received a pattern consisting of an 800-Hz alternating with a 600-Hz tone. Thus, just as in conditions 1 and 2, the two ears received the higher component of each chord in alternation. However, in contrast with conditions 1 and 2, the two ears did not receive the same frequencies in succession.

Again, in order to evaluate the strength of the lateralization effect, the amplitude relationships between the higher and lower components of the dichotic chords were varied across sequences. Thus 400- and 600-Hz tones at 70 dB SPL were paired equally often with 800- and 1200-Hz tones at 70, 73, 76, 79, 82, and 85 dB. Analogously, 800- and 1200-Hz tones at 70 dB SPL were paired equally often with 400- and 600-Hz tones at 70, 73, 76, 79, 82, and 85 dB. For each level of amplitude relationship, on half the trials the sequence began with the 400- to 800-Hz chord and ended with the 600- to 1200-Hz chord, and on the other half this order was reversed. Further, for each of these orderings, on half the trials the right ear received 800 and 600 Hz and the left ear received the 400 and 1200 Hz, and on the other half the ears receiving these frequency combinations were reversed.

All subjects were also tested in this condition for three sessions, with 96 trials per session. Specifically, for each of the eight subjects, there were 48 replicates for the equal amplitude subcondition (24 for each temporal order), and there were 24 replicates for each of the other relative amplitude subconditions (12 for each temporal order). Sequences within a session were presented in random order.

Each subject received a different random ordering of the nine experimental sessions. Within each session, sequences were presented in groups of 12, with 10-s pauses between sequences within groups, and 2-min pauses between groups. Subjects indicated their judgments by writing "right–left" or "left–right" during the intertrial intervals. As a warning signal, a 2000-Hz diotic tone at 70 dB preceded each group of sequences by 15 s.

C. Subjects

Eight subjects were selected for the experiment, on the basis of consistently reporting a single high tone in one ear alternating with a single low tone in the other ear, with 12 sequences designed as in condition 1 and 12 designed as in condition 2, but with all tones at equal amplitude. All subjects were undergraduates at the University of California, San Diego, and were naive to the purpose of the experiment. They had all previously performed at a high level on a pitch memory task, in which tones were presented binaurally through loudspeakers. The selection ratio for the present experiment was roughly 1:3. All subjects had normal audiograms, and were paid for their services. Before the experiment began, each subject was given a single practice session, in which sequences were presented as in all three conditions. Otherwise, they received no practice on the task.

II. RESULTS

Figure 2 plots the percentage lateralization to the lower frequency signal in the different conditions of the experiment, averaged over all subjects. It can be seen that, in condition 1, lateralization to the higher frequency signal occurred for all subconditions, except for those in which the lower frequency signal was at least 12 dB or more higher in amplitude. The same effect was present in condition 2, though it was less pronounced, being overcome in those subconditions where the lower frequency signal was 9 dB or more higher than amplitude. The tendency was still present in condition 3, though it was considerably less pronounced, being compensated for when the lower frequency signal was 3 dB higher in amplitude. Figure 3 plots the results for each subject separately. The differences between the conditions are clearly manifest in the individual data, although subjects can be seen to differ in the overall strength of the lateralization effect.

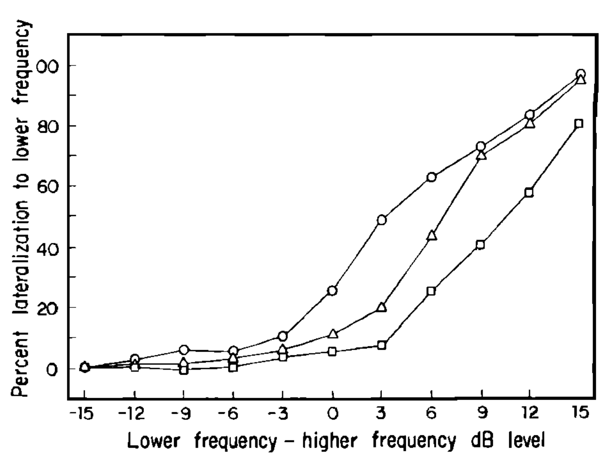

FIG. 2. Percent lateralization to lower frequency signal in the different conditions of the experiment, averaged over subjects: □—condition 1; Δ—condition 2; O—condition 3.

The overall percent lateralization to the higher frequency signal was found to be significantly higher in condition 1 than in condition 3 ($p < 0.01$, two tailed, on a Wilcoxon test), and also significantly higher in condition 2 than in condition 3 ($p < 0.02$, two tailed, on a Wilcoxon test). In addition, it was significantly higher in condition 1 than in condition 2 ($p = 0.02$, two tailed, on a Wilcoxon test).

III. DISCUSSION

The results of the experiment show that the strong tendency to lateralize toward the higher frequency signal in the octave illusion depends, in part, on the two ears receiving the same frequencies in succession: Increasing the amplitude of the lower frequency signal was found to overcome the lateralization effect considerably more readily when this sequential condition did not hold. An analogous dependence on sequential relationships has also been found for the ear dominance component of the illusion (Deutsch, 1980). However, in contrast with ear dominance, the lateralization component is here shown to be present at equal amplitude even when the two ears did not receive the same frequencies in succession.

The results of the experiments also show, as a subsidiary finding, that the lateralization effect is more readily compensated for by enhancing the amplitude of the lower frequency

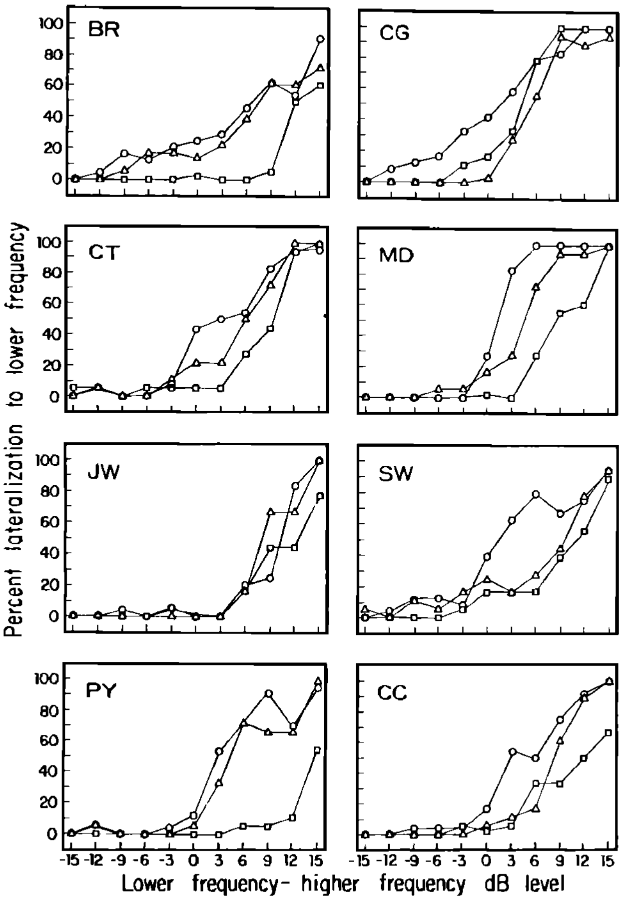

FIG. 3. Percent lateralization to lower frequency signal in the different conditions of the experiment, taking each subject separately: □—condition 1; △—condition 2; ○—condition 3.

signal in sequences consisting of 600- to 1200-Hz chords than in those consisting of 400- to 800-Hz chords. We may hypothesize that this reflects the stronger influence of interaural amplitude disparities on lateralization judgments at higher frequency levels. Although this influence is more pronounced at even higher frequencies, it is still present in the range employed here (Mills, 1972; Durlach and Colburn, 1978).

The lateralization to the higher frequency signal described in this letter may be related to similar effects obtained by others using different paradigms. Deatherage (1961) presented two clicks simultaneously, one to each ear, when these were bandpass filtered at different frequencies. With stimuli below 4000 Hz, a single image was produced, which was lateralized toward the higher frequency signal. Békésy (1963) delivered a tone at 800 Hz to one ear, together with a tone at between 750 and 880 Hz to the other ear. When the simultaneous tones were amplitude modulated in-phase, they fused perceptually to form a unitary image, which was lateralized toward the ear receiving the higher frequency signal. Zerlin (1969) presented simultaneously pulsed tones at different frequencies, one to each ear. Again, a single image was produced, and this image was lateralized toward the higher frequency signal.

The above authors all interpreted their findings in terms of the traveling wave, since the receptors in the basilar membrane responding to the higher frequency signal would be activated before those responding to the lower frequency signal. However, the traveling wave cannot account for the lateralization effect in the octave illusion since the size of this effect has been found not to be influenced by onset and offset disparities between the higher and lower tones of up to 5 ms in either direction (Deutsch, 1981). Further, an explanation in terms of the traveling wave cannot account for the sequential effects described here. We may hypothesize that the present effect results from the action of a specialized central mechanism, which has evolved to take account of spectral differences at the two ears in determining the locations of complex sounds.

ACKNOWLEDGMENT

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[1]It should be noted that not all listeners, when presented with the octave illusion pattern, obtain a clear percept of a single high tone in one ear that alternates with a single low tone in the other ear (though the majority of listeners do so). As described in Deutsch (1974), some listeners obtain complex percepts, such as two low tones alternating from ear to ear, together with an intermittent high tone in one ear. Clearly, the results described in this letter would not be obtained in the case of subjects obtaining complex percepts.

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Vibrational modes of Chinese two-tone bells[a)]

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The vibrational modes of a modern copy of an ancient Chou dynasty bell have been studied by means of holographic interferometry and by scanning the sound field near the bell. The modes are compared to those observed in church bells, carillon bells, and handbells, as well as other ancient Chinese bells. Modes tend to occur in pairs, one with a node at the *xian* or spine, and one with an antinode there; the frequencies of the two doublet members differ by about 3% to 10%. Bells of this type emit two distinctly different notes, depending upon where they are struck.

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For some years, the acoustical behavior of ancient Chinese bells has greatly interested archaeologists and ethnomusicologists.[1–6] This interest was further stimulated by the discovery in 1977 of a rack of 64 bells in the tomb of the Marquis Yi of Zeng. These bells, carefully tuned and richly inscribed, dated from the 5th century B.C.

Unlike most Western bells, ancient Chinese bells are usually oval in shape, which causes them to emit two different pitches when struck at the *sui* and *gu* strike points [locations S and G in Fig. 5(a)].

We have studied the modes of vibration and sound spectra of a modern copy of an ancient Chou dynasty bell in the National Carillon Museum located in Asten in The Netherlands. The copy was cast at the Royal Eijsbouts Bellfoundry in Asten.

The experimental methods used to study this bell are similar to those used previously to study tuned handbells.[7] Time-average holographic interferometry was used to record the vibrational configuration at 24 different resonances between 200 and 3000 Hz. From the reconstructed images, we attempted to deduce the normal modes of vibration and to predict which ones would be more strongly excited at each of the strike points. The modal shapes were confirmed by scanning the sound field near the bell with a small microphone.

The vibrational modes tend to occur in pairs, one with a node at the spine or *xian*, and one with an antinode at that location. The doublet with a node at the spine generally has the higher frequency.

Following the practice used to describe the vibrational modes of church bells and handbells, we label a mode by two indices m and n, with m denoting the number of complete nodal meridians and n denoting the number of nodal circles. In the case of the oval Chinese bells, we label the modes as $(m,n)_a$ or $(m,n)_b$, respectively, where the a mode has an antinode at the *xian*, and the b mode has a node.

Figure 1 compares the $(2,0)_a$ and $(2,0)_b$ modes in our Chinese bell to the (2,0) mode in a handbell. Striking the bell at the *sui* strike point at the center of the long side will excite the $(2,0)_b$ mode which has a node at the center of this side. The *gu* strike point lies near the node of the $(2,0)_a$ mode, however, so striking at this point preferentially excites the $(2,0)_b$ mode.

Figure 2 shows the (3,0) mode in a handbell and a pair of (3,0) modes in the Chinese bell. In this case, neither member of the pair has a node precisely at the *xian*, and thus the modal frequencies differ by only 3%. Normally, striking a bell at the *sui* point emphasizes the a mode when m is odd but the b mode when m is even. No such general rule exists for the *gu* strike point, however.

Figure 3 shows the two (4,1) modes in the Chinese bell. The circular node occurs near the mouth of the bell, and the mode might be compared to either the (4,1) mode [Fig.

a) The experimental results in this letter were first reported at the 112th Meeting of the Acoustical Society of America in Anaheim, California, 8–12 December 1986 [J. Acoust. Soc. Am. Suppl. 1 80, S101 and S102 (1986)].
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