Ear dominance and sequential interactions

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When two tones of different frequency are simultaneously presented, one to each ear, a single pitch may be heard that corresponds to the frequency delivered to one ear rather than to the other. That is, the frequency information delivered to one ear may be followed and to the other ear suppressed. The present study explored the sequential conditions under which this effect occurs. Clear ear dominance was obtained in sequences where the two ears received the same frequency in succession. However, ear dominance was absent in sequences where successive dichotic chords were composed of different frequencies. From these and other findings a basis for ear dominance is proposed.

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INTRODUCTION

Several recent studies have demonstrated an effect which has come to be known as ear dominance. This occurs when two tones of different frequency are simultaneously delivered, one to each ear. The studies have found that the pitch which is heard tends to correspond to the frequency delivered to one ear rather than to the other; that is, the frequency information delivered to one ear is perceived and the information delivered to the other ear is suppressed.

In one such study, Deutsch (1974a,1974b) used a sequence consisting of two tones, which were spaced an octave apart (400 and 800 Hz) and repeatedly presented in alternation. The identical sequence was presented to both ears simultaneously, except that when the right ear received the high tone the left ear received the low tone and vice versa. Thus 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 several different illusory percepts. The percept most commonly obtained was that of a single tone that switched from ear to ear, and 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. Further investigation showed that this rather bizarre illusion has two basic components: The following of the sequence of frequencies presented to one ear rather than to the other, and the localization of each tone toward the ear receiving the higher-frequency signal regardless of whether the higher or the lower frequency is in fact perceived (Deutsch and Roll, 1976).

Another paradigm demonstrating ear dominance was employed by Efron and Yund (1974,1975) and Yund and Efron (1975,1976). Here each trial consisted of two presentations of the identical dichotic chord and these presentations were separated by a 1-sec delay. On one presentation the right ear received the high tone and the left ear the low tone, and on the other presentation this configuration was reversed. The identical frequencies were used throughout an experimental session. Under these conditions, subjects tended to follow the sequence of frequencies presented to one ear rather than to the other. In many cases this was true even when the signal delivered to the nondominant ear was substantially higher in amplitude. In contrast to the paradigm used by Deutsch (1974a,1974b), and by Deutsch and Roll (1976), the components of the dichotic chords were not in octave relation. Typically the two frequencies were quite close in pitch and in a higher-frequency range (for instance, 1650 and 1750 Hz).

In each of these experiments, the sequences were such that each ear always received a frequency that was identical either to the frequency it had just received, or to the frequency just received by the opposite ear. However, using a different dichotic tonal sequence, Deutsch (1975a) found no ear dominance. Listeners were presented with a C-major scale, with successive tones alternating from ear to ear. This scale was played simultaneously in both ascending and descending form, and switching from ear to ear such that when a component of the ascending scale was in the right ear, a component of the descending scale was in the left ear and vice versa. The majority of listeners perceived 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. Other listeners perceived instead only a single melody, which corresponded to the higher sequence of tones, and they heard little or nothing of the lower sequence. Thus in contrast to the results described earlier, no ear dominance was produced here. When only one melody was heard this corresponded to the higher frequencies and not the lower, regardless of ear of input. Moreover, for most listeners, both members of each simultaneous tone pair were perceived and neither was suppressed. This experiment therefore indicates that ear dominance cannot be regarded simply in terms of simultaneously interactions, but depends on sequential relationships also. The present experiments were performed to obtain a better understanding of the sequential conditions for producing ear dominance. On the basis of these experiments a model for ear dominance is proposed.

I. EXPERIMENT I

A. Method

Tones were generated as sine waves by two Wavetek function generators (model No. 155) controlled by a PDP-8 computer. The output was passed through a

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Crown amplifier and presented to subjects in sound-insulated booths through matched headphones (Grason-Stadler model No. TDH-49). Each function generator produced the sequence that was presented to one ear. When sequences were presented with no gaps between tones, there were no voltage jumps at the frequency transitions, neither did the voltage slope change sign at the transitions. This was so as to minimize transients.

The experiment consisted of two conditions. In each condition subjects were presented with sequences consisting of 20 dichotic chords, each 250 msec in duration, with no gaps between chords.

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 high and low tones were always 800 and 400 Hz. This is essentially the same sequence as that of Deutsch (1974a, 1974b), and it can be seen that here the two ears received the same frequencies in succession [Fig. 1(a)]. On half of the trials the sequence presented 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 employed in condition 2 consisted of the repetitive presentation of two dichotic chords in alternation; the first forming an octave and the second a minor third, so that the entire four-tone combination constituted a major triad. It can be seen that here the two ears did not receive the same frequencies in succession [Fig. 1(b)]. The frequencies composing the 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 octave and ended with the minor third, and on the other half the sequence began with the minor third and ended with the octave. Further, for each of these subconditions on half of the trials the right ear received the upper component of the first chord and the lower component of the last chord, and on the other half this order was reversed.

In both conditions, subjects judged for each sequence whether it began with the high tone and ended with the low tone, or whether it began with the low tone and ended with the high tone; and from these judgments it was inferred which ear was being followed for pitch. The subjects responded by writing "high–low" (indicating a sequence that began with the high tone and ended with the low tone) or "low–high" (indicating a sequence that began with the low tone and ended with the high tone) on paper.

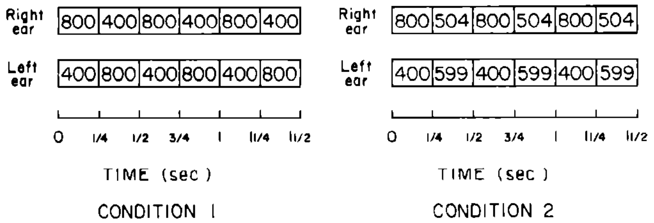

FIG. 1. Examples of stimulus configurations used in the two conditions of experiment I. Numbers in boxes indicate tonal frequencies.

In order to evaluate the strength of ear dominance under these two conditions, the amplitude relationships between the tones presented to the two ears were systematically varied, and the extent to which each ear was followed was plotted as a function of these amplitude relationships. [This procedure is similar to that used by Efron and his colleagues (e.g., Efron and Yund, 1974).] Thus in both conditions, for each type of sequence, a left-ear sequence consisting of tones at 70 dB SPL was paired equally often with a right-ear sequence consisting of tones at 70, 73, 76, 79, 82, and 85 dB. Similarly a right-ear sequence consisting of tones at 70 dB was paired equally often with a left-ear sequence of tones at 70, 73, 76, 79, 82, and 85 dB.

Each condition was presented for three sessions, with 72 trials per session in condition 1, and 48 trials per session in condition 2. The two conditions were presented alternately in successive sessions, and the presentation order was counterbalanced across subjects. Sequences within a session were presented in random order 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.

Four subjects were selected for the experiment, on the basis of consistently hearing a single high tone alternating with a single low tone in sequences designed as in condition 1 but with all tones at equal amplitude. Two of the subjects were right-ear dominant and two were left-ear dominant. All had normal audiograms. The subjects were selected from a group who had participated in experiments on memory for pitch, where the information had been presented binaurally through loudspeakers. This group has been heavily selected for high performance on the pitch memory task, the selection ratio being about 1:6. The selection ratio for the present experiment from this group was about 1:3. All subjects were undergraduates at the University of California at San Diego, and were naive as to the purpose of the experiment.[1] The selection session for this experiment lasted for half an hour. Apart from this, the subjects were not practiced on the task before the experiment.

B. Results

The results of the experiment, averaged over all subjects, are shown in Fig. 2. The results for the individual subjects separately are shown in Fig. 3. It can be seen that in condition 1 the sequence of frequencies presented to the dominant ear was followed until a critical level of amplitude relationship between the ears was reached, and the nondominant ear was followed beyond this level. Thus a clear following on the basis of ear of input occurred, and clear ear dominance was obtained. However, no such following occurred in condition 2. Not only were there no ear dominance effects, but a simple following on the basis of amplitude did not

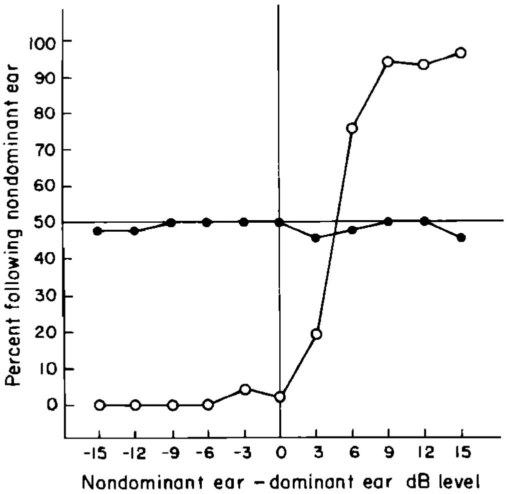

FIG. 2. Percent following of nondominant ear in experiment I as a function of amplitude differences at the two ears. O condition 1; ● condition 2.

occur either.[2] If, however, we hypothesize that subjects were following this sequence on the basis of frequency proximity (Dowling, 1973; Deutsch, 1975a; Bregman, 1978) a very consistent pattern emerges. All subjects produced a pattern of responses that showed consistent following of either the higher frequencies or the lower frequencies, regardless of ear of input or of relative amplitude. Three of the subjects consistently followed the lower frequencies, and one consistently followed the higher frequencies (Fig. 4).[3]

This experiment therefore provides further evidence that ear dominance effects occur in sequences where the two ears receive the same frequencies in succession. When this condition was fulfilled, clear-cut ear dominance was obtained. But when this condition was not fulfilled there was a complete absence of ear dominance, and following on the basis of frequency range occurred instead.

II. EXPERIMENT II

A. Method

In this experiment, two conditions were again employed. In both conditions, subjects were presented with a pair of dichotic chords, each 250 msec in duration, with no gaps between chords within a pair.

The basic sequence employed in condition 1 consisted of two presentations of the identical dichotic chord, whose components formed an octave, such that one ear received first the high tone and then the low tone, while simultaneously the other ear received first the low tone

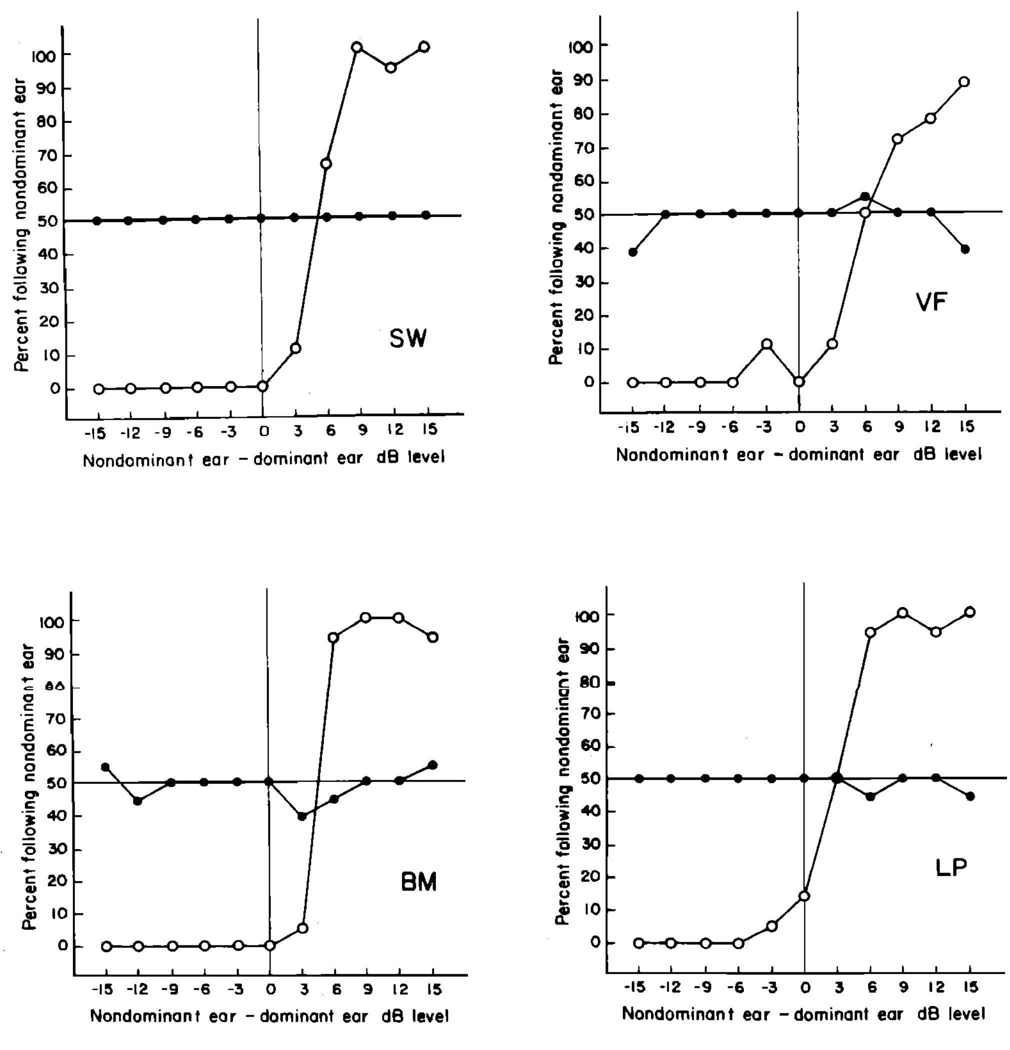

FIG. 3. Percent following of nondominant ear in experiment I, plotted separately for each subject. O condition 1; ● condition 2.

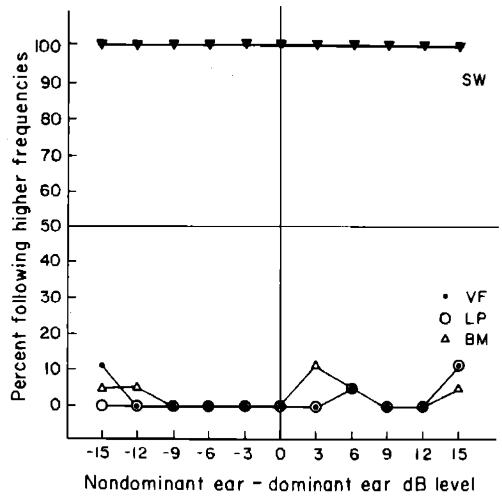

FIG. 4. Percent following of higher frequencies in condition 2 of experiment I, as a function of amplitude differences at the two ears.

and then the high tone. The frequencies employed were always 400 and 800 Hz [Fig. 5(a)]. On half of the trials the right ear received first the high tone and then the low tone, and on the other half this order was reversed.

The basic sequence employed in condition 2 consisted of two dichotic chords, each of which formed an octave, but which were composed of different frequencies. Each trial consisted of the chords formed either by 366 and 732 Hz, and by 259 and 518 Hz; or of the chords formed by 308 and 616 Hz, and by 435 and 870 Hz [Fig. 5(b)]. These combinations were presented in strict alternation. Thus any given frequency combination was repeated only after a substantial time period during which several other frequency combinations were interpolated. For each of the above combinations, on half of the trials the sequence began with the higher of the two chords and ended with the lower; and on the other half this order was reversed. Further, within each of these combinations, on half of the trials the right ear received the upper component of the first chord and the lower component of the second 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 in exactly the same way as in experiment I. Subjects were required to judge for each sequence whether it was of the "high–low" type or the "low–high" type.

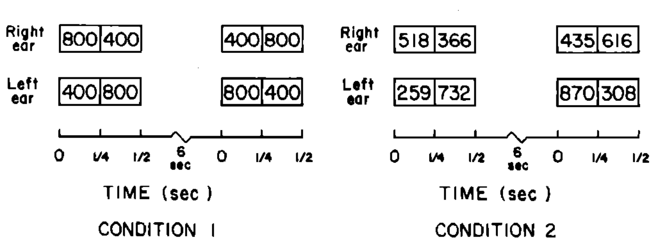

FIG. 5. Examples of stimulus configurations used in the two conditions of experiment II. Numbers in boxes indicate tonal frequencies.

Each condition was presented for three sessions, with 72 judgments per session in condition 1 and 96 judgments in condition 2. The two conditions were presented alternately in separate sessions, and the order of presentation was counterbalanced across subjects. Sequences within a session were presented in random order in groups of 12, with 6-sec pauses between sequences within a group, and 1-min pauses between groups. The same warning signal as in experiment I preceded each group of sequences by 15 sec.

Four subjects were selected for this experiment, on the basis of showing a clear following of the dominant ear, even in sequences where the information presented to the nondominant ear was higher in amplitude. Thus the selection criterion for experiment II was more stringent than for experiment I. Three of the subjects were undergraduates at the University of California at San Diego and were naive as to the purpose of the experiment. The author served as the fourth subject. Two of the subjects were right-ear dominant and two were left-ear dominant. All had normal audiograms. The three naive subjects had participated first in a half-hour session in which they listened to equal-amplitude sequences such as used in subject selection for experiment I. They then participated in a second selection session in which the sequences presented to the two ears varied in amplitude, as in condition 1 of experiment I. This session lasted for 45 min. They were given no further practice before the experiment. The author had had considerable experience with this general type of task, but did not practice on the specific task before the experiment.

B. Results

The results of the experiment, averaged over all four subjects, are shown in Fig. 6. The results for the individual subjects separately are shown in Fig. 7. It can be seen that, as expected, clear-cut ear dominance effects occurred in condition 1. However, as also expected from the proposed hypothesis, there was a total absence of ear dominance in condition 2. And just as in experiment I, following by amplitude did not occur

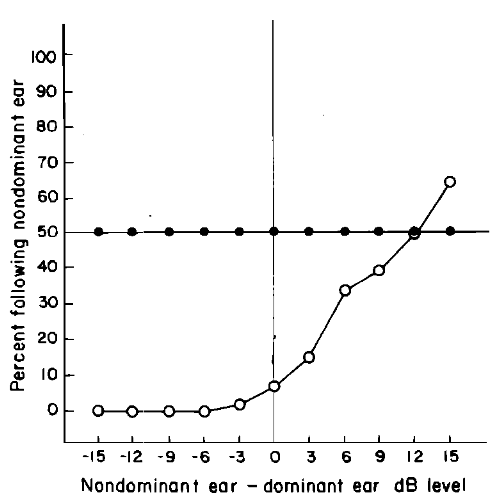

FIG. 6. Percent following of nondominant ear in experiment II as a function of amplitude differences at the two ears. ○, condition 1; ●, condition 2.

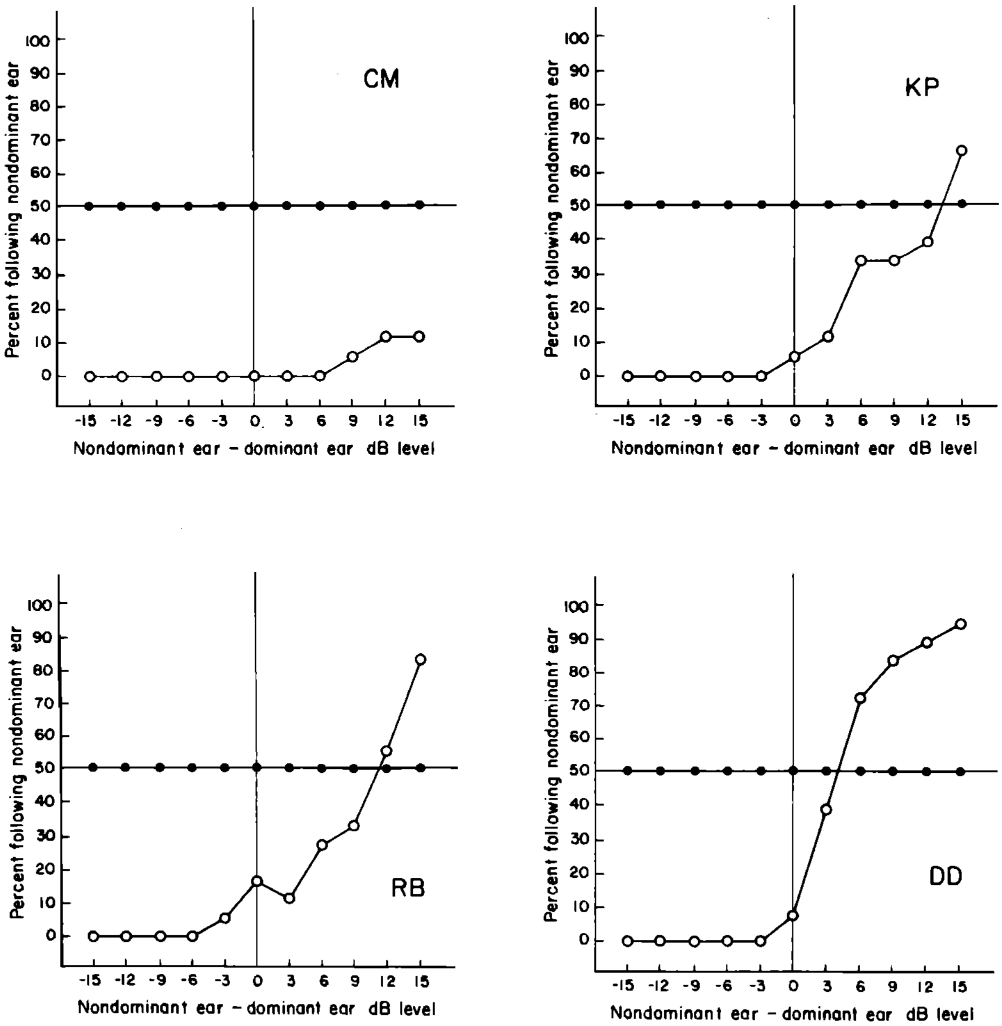

FIG. 7. Percent following of nondominant ear in experiment II, plotted separately for subject. O condition 1; ● condition 2.

either.[4] If we assume, however, that the subjects were responding in this condition on the basis of overall contour; i.e., that they were following either the higher frequencies or the lower frequencies, we obtain a very consistent result. As shown in Fig. 8, following on this principle occurred throughout. This experiment therefore reinforces the hypothesis that ear dominance effects occur when the two ears receive the same frequencies in succession.

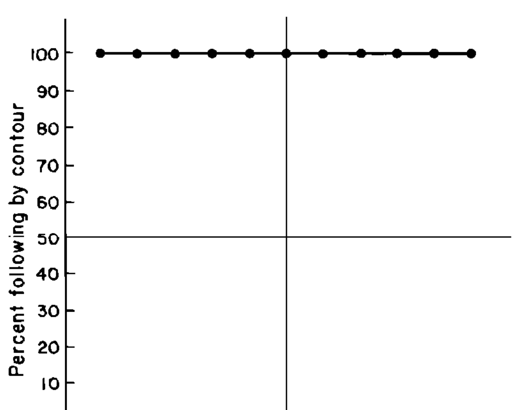

FIG. 8. Percent following by contour in condition 2 of experment II, as a function of amplitude differences at the two ears.

III. EXPERIMENT III

We now turn to the question of whether the absence of ear dominance found in conditions 2 of experiments I and II was due simply to the time delay between successive presentations of the same frequencies to the two ears, or whether this was due to the interpolation of tones of different frequencies. The experiment studied the effect on ear dominance of interpolating a tone of different frequency between the dichotic chord pairs; holding the delay between members of these chord pairs constant.

A. Method

This experiment employed two conditions, which are shown in diagram form in Fig. 9. In condition 1, two dichotic chords were presented, at 400 and 800 Hz, such that one ear received first the high tone and then the low tone, whilst simultaneously the other ear received first the low tone and then the high tone. All chords were 250 msec in duration, and the members of each chord pair were separated by 750-msec pauses. Condition 2 was identical to condition 1, except that a single tone was interpolated during the interval between the dichotic chord pairs. The frequency of this tone was

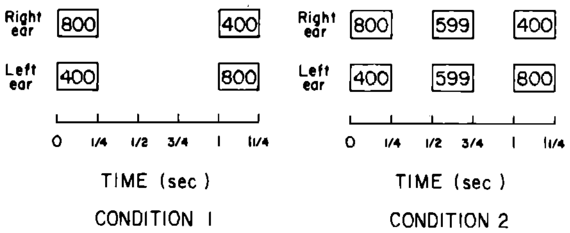

FIG. 9. Examples of stimulus configurations used in the two conditions of experiment III. Numbers in boxes indicate tonal frequencies.

always 599 Hz, and the tone was presented simultaneously to both ears. The interpolated tone was also 250 msec in duration, and it was preceded and followed by 250-msec pauses. In each condition, on half of the trials the right ear received the high tone of the first dichotic chord and the low tone of the second; and on the other half this order was reversed. Subjects judged for each dichotic chord pair whether it was of the "high–low" type or the "low–high" type. In condition 2 they were instructed to ignore the interpolated tone.

In both conditions, the amplitude relationships between the tones at the two ears varied systematically across sequences, in the same way as in experiment I. Each condition was presented for four sessions, with 72 judgments per session. The two conditions were presented in alternation, and the order of presentation was counterbalanced across subjects. Other aspects of the procedure were the same as in experiment I. The same subjects were employed as for experiment II. There were no practice sessions on the specific task of this experiment, though all subjects were experienced with the general type of task, as described above.

B. Results

The results of the experiment averaged over all four subjects are shown in Fig. 10. It can be seen that a single interpolated tone did indeed reduce the size of the ear dominance effect. As shown in Fig. 11, this reduction was very clear in the three naive subjects,

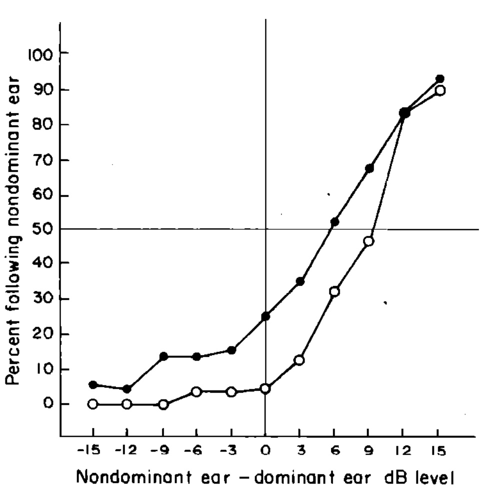

FIG. 10. Percent following of nondominant ear in experiment III as a function of amplitude differences at the two ears. ○, condition 1; ●, condition 2.

and the fourth (the author) showed only a marginal effect in this direction.[5]

IV. DISCUSSION

In considerating the basis for this ear dominance effect, two other findings should be taken into account. First, the effect can also be obtained when the stimuli are presented through two spatially separated loudspeakers rather than earphones (Deutsch, 1974a, 1975b). Thus the interactions producing this effect must take place between pathways which convey information from different regions of auditory space, rather than between pathways conveying information from the two ears. That highly specific regions of auditory space are involved here is evidenced by the finding that the illusion can be obtained even when the speakers are situated side by side, both facing the listener. The following informal experiment makes a good demonstration of this effect. The listener initially hears the alternating octave sequence through earphones placed correctly, and then slowly removes them, bringing them out in front of him. In the case of a listener who obtains a clear and unambiguous illusion with dichotic presentation, the earphones can be removed a considerable distance before the illusion disappears. (It is interesting to note that a hysteresis effect operates here: The illusion is maintained with the earphones positioned at a greater distance than that required for its initiation.[6])

A second finding to be taken into account is that the behavior of this illusion correlates with handedness. Right handers tend significantly to follow the pattern of frequencies presented to their right ear rather than to their left; however left handers do not show this tendency (Deutsch, 1974b; Deutsch and Roll, 1976).

On the basis of these and the present findings, it is proposed that ear dominance results from interactions within an array whose elements are sensitive both to specific values of frequency and also to specific values of spatial location. Evidence for such elements has been obtained at various levels in the auditory system; for instance by Moushegian, Rupert, and Langford (1967) and Goldberg and Brown (1969) at the superior olivary complex; by Rose *et al.* (1966) and Geisler, Rhode, and Hazelton (1969) at the inferior colliculus; and by Brugge *et al.* (1969) at the auditory cortex. Such studies describe units which have characteristic frequencies, and whose responses are also sensitive to the precise value of interaural amplitude difference or interaural time difference presented. It is assumed that although elements on this array respond to specific combinations of frequency × location, the outputs from this array signal pitch alone. It is further assumed that units with the same (or closely overlapping) frequency response areas, but which convey information from different regions of auditory space, are linked in mutual inhibitory interaction. From the handedness correlates it is further assumed that units which convey information from the dominant side of auditory space, i.e., the side that is contralateral to the dominant hemisphere, exert the strongest influence. The inhibition exerted by one such unit on another acts forward over time. Further, disinhibition occurs when units re-

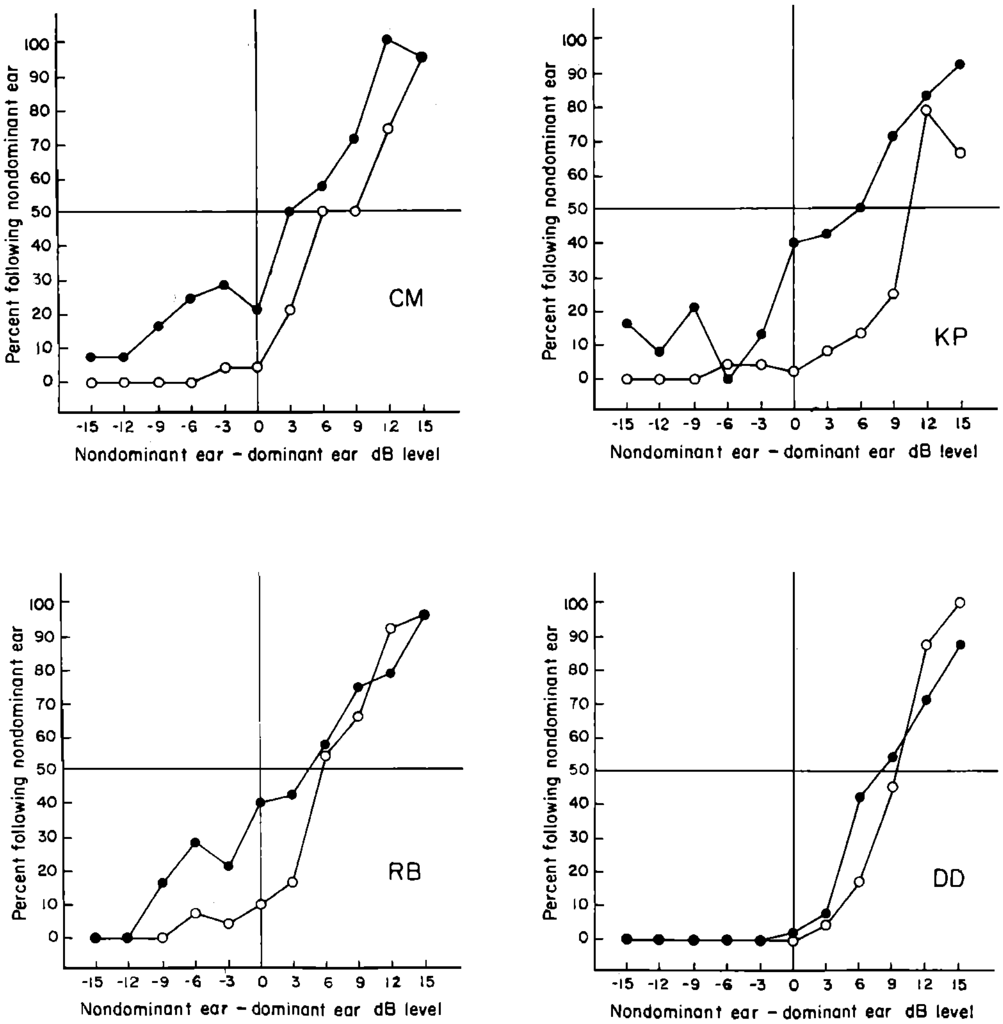

FIG. 11. Percent following of nondominant ear in experiment III, plotted separately for each subject. O, condition 1; ●, condition 2.

sponding to different frequencies are activated.

It should be noted that an array of frequency × location units has been hypothesized by Jeffress (1948, 1972) as mediating both pitch and localization decisions. The outputs from the present array are assumed to mediate pitch decisions alone, with localization being mediated by a second parallel array. The reason for hypothesizing two separate arrays here is that the influences acting on localization decisions in the present paradigm differ from those acting on pitch decisions (Deutsch, 1974b; Deutsch and Roll, 1976; Deutsch, 1978). If both types of influence occurred on the same array they would cancel each other out. One might, however, hypothesize that the arrays mediating pitch and localization arise as parallel outputs from a single array, such as that proposed by Jeffress (1948, 1972). It should be noted that the triplex theory of pitch perception, proposed by Licklider (1956, 1959) also assumes an array of such conjunction units.

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. The present effect may therefore fall into the class of phenomena (of which the precedence effect is another example) which act to counteract misleading effects due to echoes and reverberation (Wallach, Newman, and Rosensweig, 1949; Haas, 1951; Sayers and Cherry, 1957; Tobias and Schubert, 1959; Schubert and Wernick, 1969; McFadden, 1973).

A second possibility, suggested by an anonymous reviewer, is that in listening to sound sequences, we generally form perceptual configurations out of elements that are proximal in frequency (Dowling, 1973; Deutsch, 1975a; Bregman, 1978). However with this unusual type of sequence no such following is possible, since the stimulus configuration consists of the same tones repeatedly presented. The listener might, under these conditions, settle for attending on the basis of spatial location.

The effects investigated here display interesting similarities and differences with the effects reported by Efron and Yund (1974, 1975) and Yund and Efron (1975, 1976). There are two basic similarities. First, in the present situation the frequencies delivered to one ear may be perceived and those delivered to the other ear suppressed; similarly in the Efron–Yund situation the pitch mixture of a dichotic chord may be dominated by the tone presented to one ear rather than to the other. Second, in both sets of studies, each ear received a frequency that was identical either to the frequency it had just received or to the frequency just received by the opposite ear.[7] Given these similarities it is tempting to speculate that the ear dominance effects found by Efron and Yund may depend on sequential relationships in the same way as the present effect.

However, differences between the two sets of studies also exist. One important difference is that the patterns of ear dominance obtained by Efron and Yund did not correlate with handedness. This would imply that the two sets of effects are taking place at different levels in the auditory system.

Yund and Efron (1977) propose a model to explain their findings which assumes 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 could be a difference in sharpness of tuning at the two ears; and the ear with the sharper tuning curve would provide the more salient information. Support for this argument was supplied by Divenyi, Efron, and Yund (1977) who obtained correlations between patterns of ear dominance and differences at 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 could be due to an asymmetrical weighting factor for the excitations arriving simultaneously at the two ears.

The present results cannot be accommodated on this model, since they show that whether or not ear dominance occurs depends critically on the frequency relationships between the tones as they occur in sequence at the two ears. A second problem is that analogous effects can occur when the information is presented through speakers rather than earphones. This shows that the interactions here are based on auditory space rather than monaural channels. However, the present results are not inconsistent with the conclusions reached by Yund and Efron as applied to their own findings. Given that differences between the two types of effect have been found, especially that there is a strong handedness correlate in the one case and none in the other, it is not implausible to assume that both types of interactions occur, and that they take place at different levels in the auditory system

ACKNOWLEDGMENTS

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[1]It should be emphasized that the type of percept obtained by this group of subjects does not hold for all listeners. As described in Deutsch (1974) some listeners obtain complex percepts, such as two low tones alternating from ear to ear, with an intermittent high tone in one ear. A small minority of subjects perceive a sequence of single tones that alternate from ear to ear, but perceive very little difference in the pitches of these tones. The results obtained here, therefore, apply only to those listeners who hear a sequence of single tones with a clear difference in pitch.

[2]A two-way analysis of variance was performed separately on each subject's data, treating condition and amplitude as fixed effects. The only effect of interest here was that of condition, and it was found to be significant for all subjects [for subject VF, $F(1,44) = 145.455$, $p < 0.01$; for subject LP, $F(1,44)$ 135.042, $p < 0.01$; for subject LP, $F(1,44) = 35.042$, $p < 0.01$; for subject BM, $F(1,44) = 39.765$, $p < 0.01$; and for subject SW, $F(1,44) = 39.385$, $p < 0.01$].

[3]The near-horizontal lines in Fig. 2 and 3 simply reflect a following on the basis of frequency proximity, as shown in Fig. 4, given the counterbalancing procedure of the experiment. Similarly the horizontal lines in Figs. 6 and 7 simply reflect a consistent following on the basis of contour, as shown in Fig. 8.

[4]A two-way analysis of variance was performed separately on each subject's data, treating condition and amplitude as fixed effects. The only effect of interest here was that of condition, and it was found to be significant for all subjects [for subject RB, $F(1,44) = 324.9$, $p < 0.01$; for subject KP, $F(1,44) = 704.167$, $p < 0.01$; for subject CM, $(1,44) = 2945.333$, $p < 0.01$; and for subject DD $F(1,44) = 57.066$; $p < 0.01$].

[5]A two-way analysis of variance was performed separately on each subject's data, treating condition and amplitude as fixed effects. The only effect of interest here was that of condition, and it was found to be significant for three of the subjects but not the fourth [for subject RB, $F(1,66) = 8.363$, $p < 0.01$; for subject KP, $F(1,66) = 31.905$, $p < 0.01$; for subject CM, $F(1,66) = 36.300$, $p < 0.01$, and for subject DD, $F(1,66) = 0.473$, $p > 0.05$].

[6]I am indebted to Professor R. L.Gregory for suggesting this procedure.

[7]In a study of Efron and Yund (1976) a dichotic chord followed by a binaural chord was used. In the binaural chord, each ear received both the frequency it had just received and also the frequency just received by the opposite ear.

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