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Note

Left ear advantage in pitch perception of complex tones without energy at the fundamental frequency

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Abstract—Normal right-handed subjects were required to make pitch comparisons of complex tones in which the fundamental frequency was either present or absent. In both conditions, tones were presented monaurally. An increase in left-ear superiority was observed in the response time measurements when the fundamental was absent. These findings support the notion that the right hemisphere possesses a special mechanism for pitch computation.

Key Words: pitch perception; residue pitch; laterality; monaural ear effect; missing fundamental.

Introduction

Pitch may be defined as that attribute of auditory sensation in terms of which sounds may be ordered on a musical scale [1]. Pitch perception is related to the repetition rate of the waveform; for a pure tone, this corresponds to its unique frequency and for a complex tone, to the fundamental (f0) frequency. Pitch extraction in pure and complex tones can apparently take place at different levels in the neural system.

The relative pitch of two pure tones can be perceived after unilateral [14] as well as bilateral temporal lobe lesions [13]. In contrast, pitch discrimination of complex tones is impaired after such lesions, particularly if they are located in the right hemisphere [19, 25]. This suggests that the pitch perception of complex tone pitch may involve cortical processing in the right hemisphere, whereas perception of pure tone may involve subcortical processing.

This hypothesis is supported by several dichotic listening studies in normal subjects. The study of Sidtis [23] is particularly enlightening in this respect. His task took the form of an AB-X choice reaction time procedure where A and B were presented dichotically and were followed by X presented binaurally. Subjects were required to indicate whether or not the binaural probe was a member of the dichotic pair. Depending on condition, the presented tones increased in complexity—i.e. in number of harmonics—from pure tones to square waves (which corresponds to the f0 plus its odd harmonics). The results showed an increase in left-ear advantage (LEA) when more harmonics were added to the tones, consistent with a right hemisphere advantage. No ear effect for pure tones was observed, as reported in other studies [3, 22, 23]. Positron emission tomographic studies have largely confirmed these results by demonstrating right-hemisphere dominance for processing the pitch of complex tones [29, 30] and no hemispheric asymmetry for pure tones [11].

Although overall there is strong evidence for right hemisphere involvement in the perception of complex tone pitch, the ear effects reported in dichotic listening studies have shown some variability. For instance, in a previous study using the same AB-X paradigm but with naturally complex piano tones, Sidtis and Bryden [26] observed a shift in ear superiority with practice: a right-ear advantage (REA) was observed in the first half of the experiment and a LEA in the second half. The same shift in laterality pattern with practice was reported by Greenberg and Graham [7] in an evoked potential study of pitch discrimination. These results suggest that the left hemisphere may also contribute to the perception of complex tone pitch.

The problem with attempting to specify the neural locus of pitch perception is that tonotopic organization, whereby neurons responding to different frequencies are laid out topographically from low to high frequencies, is evident at all levels of the central auditory system [11, 12]. Thus, a "place" mechanism may underlie simple frequency discrimination. One way to circumvent a straightforward place mechanism for frequency analysis, and perhaps more cogently assess cortical mechanisms of pitch processing, is to render pitch computation more elaborate. One such

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situation can be found in the phenomenon of missing fundamental, whereby the pitch of a complex tone corresponds to its fundamental even when there is no energy at f0 [20, 21]. Such computation cannot be solved solely by frequency analysis but requires a more complex mechanism that infers f0 from the harmonic combination in the signal [6, 15, 27].

While it has recently been shown that information about the missing f0 is present in the temporal discharge pattern of the auditory nerve [4, 5], dichotic studies have indicated that the abstraction process is central [10]. Zatorre [28] has demonstrated in temporal lobectomy patients that right-sided excisions extending into Heschl's gyri impair the abstraction of the missing f0. A more recent study [2] indicated that bilateral auditory cortex lesions may cause a greater deficit than unilateral right lesions. Thus, it appears that while both auditory cortices contribute to the abstraction of the missing f0, the right auditory cortex is probably endowed with a special mechanism that computes the missing f0, and hence is specialized for pitch computation.

Given that studies of the neural basis of the missing fundamental have been carried out, to our knowledge, exclusively with neurologically impaired patients, and that the ability to abstract the missing fundamental of complex tones is more likely to involve cortical mechanisms than pitch discrimination of complex tones with energy at f0, we thought it would be worthwhile to seek convergent evidence in normal subjects using a monaural presentation.

In the present study, we modeled the stimuli and task requirements after those of Zatorre [28]. The major exception is that stimuli here were presented monaurally, since it is known that under these circumstances the primary projection is the contralateral hemisphere [11, 12]. This procedure avoids undesirable effects of dichotic presentation (such as fusion of the stimuli or attentional bias to one ear) and has been shown to produce reliable laterality effects ([8], and in our laboratory, see [17, 18]). Subjects were required to indicate whether the pitch of two successive tones rose or fell. In one condition, the f0 was present in the stimuli (Pf0) and in another condition, it was missing (Mf0). We predicted a left-ear/right hemisphere advantage would be greater and/or more reliable when f0 was absent than when it was present.

Method

Subjects

Thirty-two subjects between the ages of 19 and 37 participated in the study. There were 16 females and 16 males; all were right-handed according to Oldfield's handedness questionnaire [16] and nonmusicians (i.e. having less than 5 years of musical practice). All had normal pure tone audiograms at 125–8000 Hz. Two subjects were excluded because they were unable to perform the practice trials.

Stimuli

There were two conditions: the missing f0 condition (Mf0) and the present f0 condition (Pf0). Stimuli differed only by the absence vs presence of energy at f0. Each complex tone consisted of successive harmonics corresponding to a given f0. Seven pairs of stimuli that differed by their f0 were selected. The f0 pairs were 200 Hz vs 300 Hz, 250 Hz vs 375 Hz, 350 Hz vs 525 Hz, 400 Hz vs 600 Hz, 450 Hz vs 675 Hz, 550 Hz vs 825 Hz, and 600 Hz vs 900 Hz. Each of these tone pairs appeared with two different spectral compositions, for a total of 14 different pairs. In the low-spectrum condition, the member of a pair that had the lower f0 contained the second through to the fourth harmonics, while the other tone (the one with the higher f0) contained the third through to the sixth harmonics. In the high-spectrum condition, the lower tone contained the fourth to the sixth harmonics, and had to be compared to a sound containing the sixth through to the ninth harmonics.

Two pairs of stimuli are presented in Fig. 1. The sounds were built so that the mean and frequency range of the harmonics was the same for each member of a pair, while the f0 was different (the f0 being absent or present). Any given pair, when perceived correctly, was heard as containing a change in pitch from one tone to the other.

The 14 different pairs were either in a low–high (rising in pitch) or high–low (falling in pitch) order with respect to the f0. This yielded 28 different pairs. The experiment consisted of

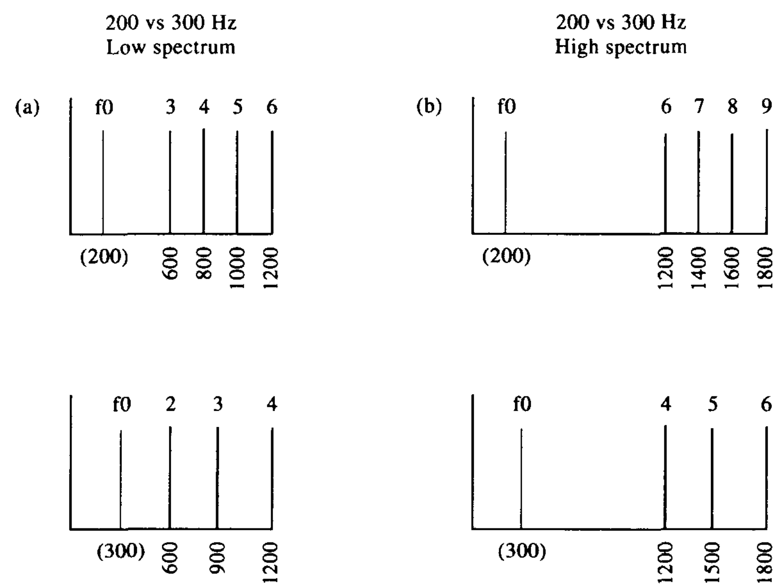


Fig. 1. Example of stimulus spectra used in the pitch judgement task. The numbers in parentheses correspond to the frequency of the fundamental (present or absent). The solid lines represent the different components present in the stimulus, with the corresponding harmonic number above each. (a) Represents the low-spectrum condition, (b) represents the high-spectrum condition (after [28]).

112 trials (4 blocks of 28 pairs). Each trial started with a warning signal (a beep), which was followed by a pair of successive tones. Each tone was 500 msec long with a 500 msec intertone interval. Each trial was separated by a 4 sec interval. The tones were digitally synthesized using an IBM 386 computer and MITSYN software [8]. Tones were digitally synthesized and recorded on to tape using a 12-bit digital-to-analog converter with a 20 kHz sampling and low-pass filtering at 7.8 kHz. The overall intensity of each complex tone was equated to within 3 dB before recording.

Procedure

The experimental session started with the handedness questionnaire, followed by the musical education questionnaire and the audiometric test. The subject then read instructions for the pitch judgement task. On presentation of two successive tones, participants were asked to indicate as quickly as possible whether the pitch rose or fell, with a toggle switch. Only the right hand was used. The toggle had to be moved up for a rising pitch and down for a falling pitch. The subject sat in a sound-attenuated room and wore headphones (Uher W770). The toggle switch was connected to an IBM 386 computer that recorded responses and their latencies. The computer also controlled a tape recorder (REVOX B77), which delivered both successive tones to either the right or the left ear. Stimuli were presented monaurally at 50 dB A-weighted sound pressure level (measured with a 2 cc coupler and a sound level meter at the headphones output). The ear of presentation was alternated for each block. The first ear of presentation was counterbalanced across subjects. Each subject was presented with the two conditions (Mf0 and Pf0), separated by a pause. Before each condition, participants familiarized themselves with the task with 10 practice trials. Half of the subjects started with the Pf0 condition and the other half started with the Mf0 condition.

Results

A preliminary analysis of variance (ANOVA) was conducted on correct mean response times and on correct raw scores. In these analyses, the potential effect of the sex of the subjects and of the order of presentation of the two conditions were examined. No sex effect was found but both analyses revealed an interaction between order of presentation and condition (F (1, 30) = 9.37, $P < 0.005$ for response times and F (1, 30) = 6.49, $P < 0.05$ for accuracy). Subjects were both slower (F (1, 30) = 7.6, $P < 0.05$) and made more errors (F (1, 30) = 7.7, $P < 0.05$) in the Mf0 condition when it was their first task than when it was their second. When they started with the Pf0 condition, there was no significant difference in response times nor in accuracy between the two conditions ($F < 1$ in both cases). Since order of presentation and sex did not interact with ear of input, results were combined over these two factors in subsequent analyses.

In order to evaluate laterality effects, an ANOVA was computed on mean correct raw scores with conditions (Mf0 vs Pf0), harmonic spectrum (low vs high) and ear of input (right vs left) as within-subjects variables. No significant effect was found. Both conditions were performed at a high level of accuracy, with 91.5 and 93% of correct responses in the Mf0 and the Pf0 condition, respectively. This high level of performance does not favor the emergence of laterality effects. Indeed, there was no significant difference with respect to response accuracy for left ear (91.9%) vs right ear (93.3%) trials (Fig. 2). Response times were therefore considered the most important dependent variable.

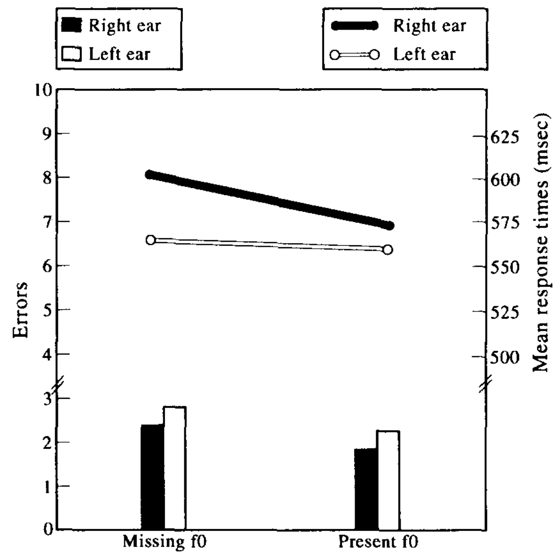


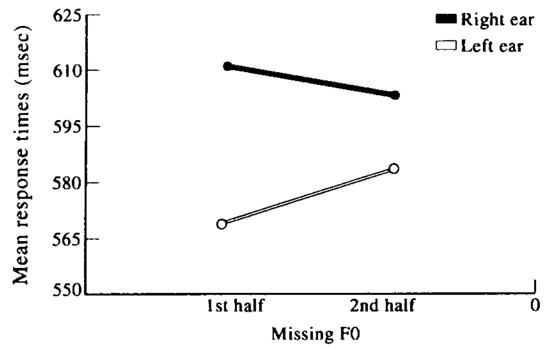
Fig. 2. Accuracy (histogram) and response times (lines) for each ear in both pitch judgement conditions.

For each subject, the response times for correct responses differing from the subject's mean by at least 3 standard deviations were considered as outliers. The mean rejection rate was 1.8% across all subjects. An ANOVA computed on the mean response times with conditions, harmonic spectrum and ear of input as within-subjects factors, revealed a main ear effect (F (1, 31) = 11.03, $P < 0.005$), indicating a significant LEA. The ANOVA also revealed an interaction between condition and ear of input that was nearly significant (F (1, 31) = 4.06, $P = 0.053$). Figure 2 shows that response times were faster when stimuli were presented to the left ear rather than to the right ear and that this ear effect was larger in the Mf0 condition. This difference in ear asymmetry between conditions was supported statistically: a significant LEA emerged in the Mf0 condition ($t_{31} = 3.2$, $P < 0.005$), but not in the Pf0 condition ($t_{31} = 1.25$, $P > 0.10$). This discrepancy between conditions is primarily due to a difference in the magnitude of ear advantages since in both conditions 21 out of the 32 subjects exhibited a LEA.

In order to assess the number of trials that were necessary to obtain the observed ear effect, we compared the laterality pattern observed in the first half (two first blocks) and in the second half (two final blocks) of the trials in each condition. An ANOVA was computed on mean response times as a function of condition, ear of input and half of trials. A LEA was observed for the first half in both conditions (F (1, 31) = 9.7, $P < 0.005$). On the second half, the ear effect interacted with condition (F (1, 31) = 5.8, $P < 0.05$), indicating the presence of a REA in the Pf0 condition and a LEA in the Mf0 condition; however, neither of these ear advantages reached significance. This interaction is represented in Fig. 3.

Discussion

Response time measurements revealed an ear advantage in the predicted direction (left ear/right hemisphere) for the perception of complex tone pitch when f0 was absent. These results are in agreement with the hypothesis that the right hemisphere is dominant for abstract pitch computation while both hemispheres are capable of pitch perception when f0 is present. Therefore, the present results extend Zatorre's [28]



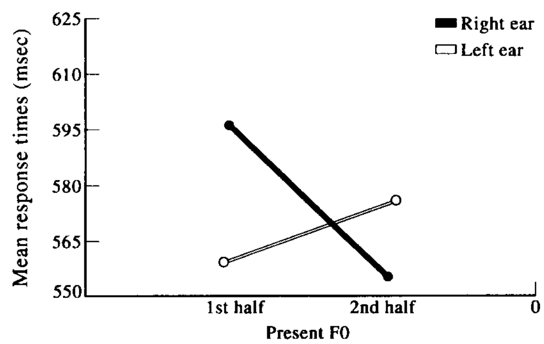


Fig. 3. Ear superiority in response times for the first and second half in each pitch judgement condition.

findings with brain-damaged subjects to the normal population.

The present results are, however, not entirely consistent with previous laterality studies. Unlike Sidtis' work [24], a robust LEA did not emerge in the Pf0 condition where tones were complex, comprising 4–5 harmonics (including f0). Moreover, the evolution of the laterality pattern as a function of practice, which shifted here from an initial LEA to a REA, was opposite to that previously observed by Sidtis [26].

As explained in the Introduction, variable outcomes in laterality findings for the perception of complex tone pitch when energy at f0 is present might be expected because place representations of f0 can be found at several levels of the central auditory nervous system. Factors that promote the processing of complex tone pitch at a particular neural locus are currently little understood. This renders problematic the identification of the relevant aspects in Sidtis' situation that promoted a left ear advantage as well as a particular evolution of laterality with practice. The fact that the present evidence of a left ear/right hemisphere advantage in normal subjects converges with evidence from brain-damaged subjects is encouraging in this respect. It also provides an impetus for future systematic studies of task factors that are likely to involve differentially subcortical and cortical neural structures in pitch computation.

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