SCANDINAVIAN AUDIOLOGY
SUPPLEMENTUM 25

COCHLEAR MECHANICS AND OTOACOUSTIC EMISSIONS

Edited by
G. Cianfrone and F. Grandori

Distributed by
THE ALMQVIST & WIKSELL PERIODICAL COMPANY
STOCKHOLM, SWEDEN

Scand Audiol Suppl 25, 1986

PITCH DISCRIMINATION FOR COMPLEX SOUNDS IN NORMAL AND HEARING IMPAIRED EARS

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ABSTRACT

On the grounds of previous researches on periodicity and virtual pitch, the present paper describes the results of some experiments on pitch extraction in normal ears and in subjects with sensorineural hearing loss of cochlear origin, with harmonic and inharmonic stimuli. The latter stimuli are constituted by complex tones with constant ratios between the frequency of adjacent components; for this reason the term *geometric* spectrum is used. These stimuli can be considered as an alternative to harmonic stimuli, since inharmonic components play an important role in sound analysis and therefore in the perception of sound. Comparison between the data obtained in experimental measurements from normal and hearing impaired subjects (also in relation to the estimates predicted by a mathematical model for pitch), revealed that pitch extracted by hearing impaired subjects tends to be shifted towards the high frequencies.

INTRODUCTION

Pitch perception is one of the most controversial problems related to the understanding of the mechanisms involved in the analysis and integration of sound. Several aspects of this process have been explained by recent research in cochlear physiology.

It is well known that peripheral frequency analysis is based on a spatial mechanism; furthermore, several studies have shown that the tonotopic organization is found throughout the whole auditory system. However, many psychoacoustic phenomena cannot be explained uniquely on the base of the spatial theory and one of these is the residue phenomenon.

It is generally accepted that this phenomenon, that is the reconstruction by the auditory system of the (missing) fundamental of a harmonic signal, is based on temporal rather than spatial analysis. Physiological basis for this analysis are found in the frequency selectivity of the eighth-nerve fibers (see e.g., Kiang, 1965; Evans, 1974).

The percept of a complex sound, as a whole, is based both on analytical listening, or *spectral pitch* (as with pure tone stimuli), and on synthetic listening or *virtual* pitch (as in the residue phenomenon) (Terhardt, 1974).

The notion of virtual pitch is applicable to frequencies below about 900 Hz. Above this frequency, the perception is due to spectral analysis, although pitch perception occurs throughout the whole frequency range as a continuous phenomenon. The virtual pitch (coincident with the fundamental frequency in the case of harmonic signals) is dominant over any other pitch. Approximately above 900 Hz the most salient pitch is perceived as the dominant pitch (Terhardt et al., 1982a, 1982b).

Thus spectral dominance is an important factor since, due to the energy distribution of a complex sound, one of its components can determine the pitch without this necessarily being the fundamental (see, e.g., de Boer, 1976; Moore et al., 1985a, 1985b).

However, like for the virtual pitch, the residue phenomenon also occurs within a well defined frequency range (Schouten et al., 1962).

In the present study we compared these two modes of perception using stimuli with different spectral pattern (harmonic and inharmonic) for various frequency ranges.

As stressed by the present authors in some previous works (Cananzi, 1982; Filipo et al., 1985; Orlando, 1985), inharmonic stimuli are rarely used in audiology, despite their relevance in the perception of everyday sounds; it is for this reason that these stimuli have been included into the present experimental study.

MATERIALS AND METHODS

Our study is based on the evaluation of pitch perception in normal ears and in subjects with sensorineural hearing loss of cochlear origin - characterized by a high frequency loss - both with harmonic and inharmonic stimuli.

Several studies have been published on the picth produced by inharmonic stimuli, for normal hearing subjects (see, e.g., Terhardt et al., 1982b; Grandori, 1984; Moore et al., 1985b), but no data are available to the authors knowledge on subjects with sensorineural hearing loss.

Stimuli used in the present experiments covered various conditions and frequency ranges: sinusoidal stimuli, complex harmonic stimuli with and without the fundamental (see Table I), inharmonic stimuli (Table II). All these stimuli were digitally synthetized.

With reference to the inharmonic spectra, we chose a signal with a constant ratio between the components, thus producing stimuli which are easily comparable to harmonic sounds. These inharmonic or *geometric* spectra were obtained with the following formula:

$$f_n = K^{\pm n} F_o$$

where

n = number of the partial

K = constant factor

f_n = frequency of the n-th partial

F_o = frequency of the central partial

In the experiment reported here, these stimuli have been synthetized with $K = 1.33$ and $n = 0, 1$ and 2, with center frequencies $F_o = 250, 500, 1000, 2000$ and 4000 Hz, respectively.

Table I.
Frequencies of the harmonic stimuli (in Hz); the value on the left of each panel is the frequency of the (missing) fundamental

	375		750		1500		3000		6000
	312		625		1250		2500		5000
62.5	250	125	500	250	1000	500	2000	1000	4000
	187		375		750		1500		3000
	125		250		500		1000		2000

Table II.
Frequencies of the inharmonic stimuli (in Hz); the frequency of the central stimulus (F_o, see text) is italicized

443	888	1777	3555	7111
333	666	1333	2666	5333
250	*500*	*1000*	*2000*	*4000*
187	375	750	1500	3000
140	281	562	1125	2250

Thirty subjects participated in the experiments (their ages ranged from 16 to 30 years); 15 were normal hearing subjects and 15 had a sensorineural hearing loss of cochlear origin, with a dip at 4 and 8 kHz.

The experimental apparatus is schematically illustrated in Fig. 1. The subjects were asked to make a comparison between stimuli with various spectral content and in particular to compare pairs of signals which normal hearing subjects judge to have the same pitch, even when presented with stimuli where pitch extraction is both spectral and virtual.

For the inharmonic spectra, we used a mathematical model for the pitch extraction derived from Goldstein's model (Grandori, 1984); model results were used to predict the reference pitch values for the experimental data.

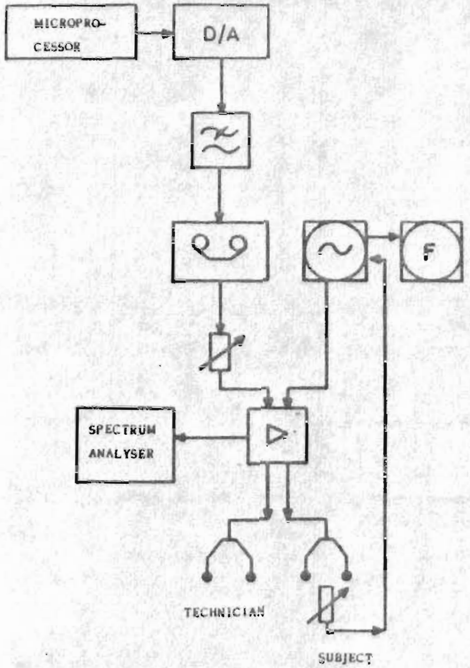

Fig. 1. Schematic representation of the equipment. Stimuli have been digitally synthetized and stored on a magnetic tape.

Two different trials were carried out:

i) In the first series of comparisons (see Table III), stimulus durations were 2.4 seconds, with intensity of 70 phon. Two successive stimuli (A-B1 and A-B2, respectively) were presented six times through the headphones, to make the task easier; pitch was estimated with a 2-AFC procedure. Therefore, the task was to compare a harmonic complex signal (without the fundamental, signal A of Table III) with its corresponding complete harmonic spectrum (i.e. including the fundamental, condition B1 of Table III), or, alternatively, to compare A with a single sinusoidal stimulus at the frequency of the missing fundamental (B2 of Table III).

Table III.
The three stimulus patterns used in the first experiment

A harmonic stimulus (without the fundamental)	B1	complete harmonic spectrum
	B2	pure tone at the frequency of the fundamental

Table IV.
Stimulus pattern used in the experiment with inharmonic stimuli

C «geometric» inharmonic stimulus	D1	harmonic stimulus with the fundamental at the frequency of the predicted pitch
	D2	pure tone at the frequency of the predicted pitch

ii) The second series of comparisons is resumed in Table IV. Duration for all the stimuli was 1.2 seconds, at intensities of 70 phon. Under the same testing procedures, the task was to compare the pitch of the five inharmonic stimuli of Table II with the pitch produced by a harmonic signal with fundamental frequencies of 222, 333, 444, 500 and 777 Hz, respectively (condition C-D1 of Table IV) or, alternatively, with a pure tone at the same frequencies of 222, 333, 444, 500 and 777 Hz (condition C-D2 of Table IV). These frequency values were the results of pitch estimates for the five stimuli of Table II, for the group of normal subjects; these estimates were confirmed also by a model for pitch extraction (Grandori, 1984).

RESULTS

Data are presented as deviations of the subjective evaluations from the estimated pich values (the reference values), in terms of X^2.

Fig. 2 illustrated the data obtained from the first experiment. It is clearly seen that the discrepancies between the two groups, normal and hearing impaired subjects, are remarkable and increase considerably with frequency; pitch estimates from the pathological ears were always higher than normal.

The last datum point of Fig. 2 deserves some comments. In this frequency range (1000-6000 Hz) the notion of *synthetic* pitch is no more applicable. To verify whether in this case also the above trend was confirmed, the reference frequency of this last trial for the pathological subjects was increased to 1200 Hz (instead of 1000 Hz, see Table I).

As it can be seen in the last bar of Fig. 2, deviations are smaller.

Results from the second experiment are summarized in Fig. 3. Pitch estimates from the subjects with cochlear hearing loss, for stimuli under 1500 Hz, were comparable to the data obtained in normals; above this value, pathological subjects showed a clear tendency to report pitch values higher than normal. As a control, the last datum of Fig. 3, corresponding to the frequency range 2250-7111 Hz, was obtained with a reference frequency of 1000 instead of 777 Hz; it is again verified that in this case the discrepancies are smaller, thus confirming that the pitch perceived by pathological ears is higher than normal.

DISCUSSION

It is perhaps premature to draw some conclusions on the basis of these preliminary experiments; one consistent result does however merge, that is an increase of the picth value for sensorineural hearing loss, both for harmonic and inharmonic signals.

As far as harmonic signals are concerned, pathological ears tend to locate the missing fundamental one octave above its actual value: this seems to confirm the presence of an integrating mechanism for the extraction of the virtual pitch.

In the case of inharmonic signals, it is interesting to observe that the results differ noticeably from those obtained from the normal group (and confirmed by the model predictions); subjects with hearing loss do not give coherent answers for this type of stimuli. The pitch identified by these subjects was localized within the frequency range of stimuli itself, without actually beeing neither one of the components nor a multiple thereof.

These results are not easily explained on the basis of the available mathematical models for pitch extraction (Terhardt, 1979; Terhardt et al. 1982a; Goldstein, 1973; Duifhuis et al., 1982; Scheffers, 1983; Grandori, 1984). The overall structure of these models is basically constituted by two stages, a peripheral analyzer followed by a central processor. It is the peripheral stage that:

i) computes the frequency of the stimulus components, at least for the components that can be aurally resolved (see, e.g. Goldstein, 1973; Moore, 1973);

ii) introduces the combination tones, if any, and computes their amplitudes;

iii) transmits all these cues to the following stage corrupted with some noise (Goldstein, 1973).

It is therefore easily undestood that any alteration of the functional state of the cochlea will affect one or more of these processes.

For the results reported in the present paper, it is reasonable to assume that all the points above are affected by a sensorineural hearing loss. In fact, if the frequency selectivity is altered, the response of the peripheral «frequency analyzer» will be far less accurate. In addition, it is expected that the growth of the combination tones (a manifestation of cochlear nonlinearities) should be altered (decreased) since cochlear responses seem to behave more linearly with pathology.

Also the information regarding the amplitudes is altered.

This is particularly true for the case of inharmonic stimuli in that the task is much more challenging for the whole system (an additional «sieving» process is at work in this case (Duifhuis et al., 1982; Scheffers, 1983; Grandori, 1984).

Combination of all these factors can well produce large deviations from the results obtained with normal subjects.

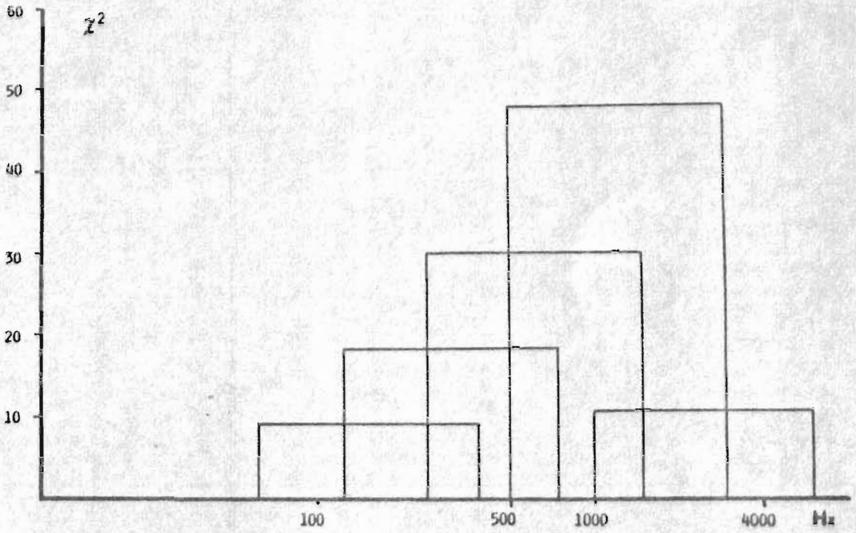

Fig. 2. Harmonic stimuli and the residue. The plot represents the values of X^2 obtained for the different frequency bands; each band is identified by the minimum and the maximum value of the component frequencies (see Table I).

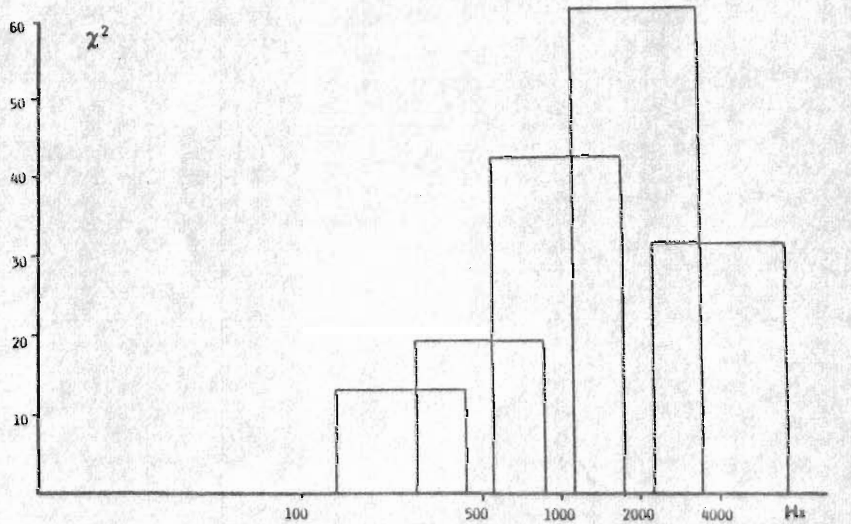

Fig. 3. Inharmonic stimuli. As in previous Fig. 2, values of X^2 are given for each frequency band of Table II.

AKNOWLEDGEMENTS

This work was supported in part by grants from the National Research Council (Project on Technologies of Information - Expert Systems).

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