The perception of a change in the relative phase of two harmonically related sinusoids .

UNIVERSITY OF CAMBRIDGE

D. Timothy Ives[1], H. Martin Reimann[2], Ralph van Dinther[1] and Roy D. Patterson[1]

tim.ives@mrc-cbu.cam.ac.uk martin.reimann@math-stat.unibe.ch ralph.van-dinther@mrc-cbu.cam.ac.uk roy.patterson@mrc-cbu.cam.ac.uk

[1] Centre for the Neural Basis of Hearing, Physiology Department, University of Cambridge, Downing Street, Cambridge, CB2 3EG United Kingdom.
[2] Mathematics Institute, University of Berne, Sidlerstrasse 5, 3012 Berne, Switzerland.

Centre for the Neural Basis of Hearing

1. Introduction

Current models of basilar membrane motion such as the Gammatone filterbank (de Boer, 1975; de Boer and de Jongh, 1978) overestimate the sharpness of auditory filters. Such models predict that low number harmonics in a harmonic complex are resolved. See left panel of Fig. 1.

A recently developed functional model of the cochlea (Reimann, 2005) proposes much shallower auditory filters.

This model makes specific predictions concerning the phase response of the basilar membrane. In particular that low number harmonics greater than 1 are unresolved and their interaction causes a perception of the basic frequency F1. See right panel of Fig. 1.

The perception of F1 is caused by a modulation of the basilar membrane at a rate of F1. The strength (or level) of F1 is dependent on the relative phase of the components.

We provide experimental validation of the Reimann model by measuring the threshold for a change in the level of the basic frequency.

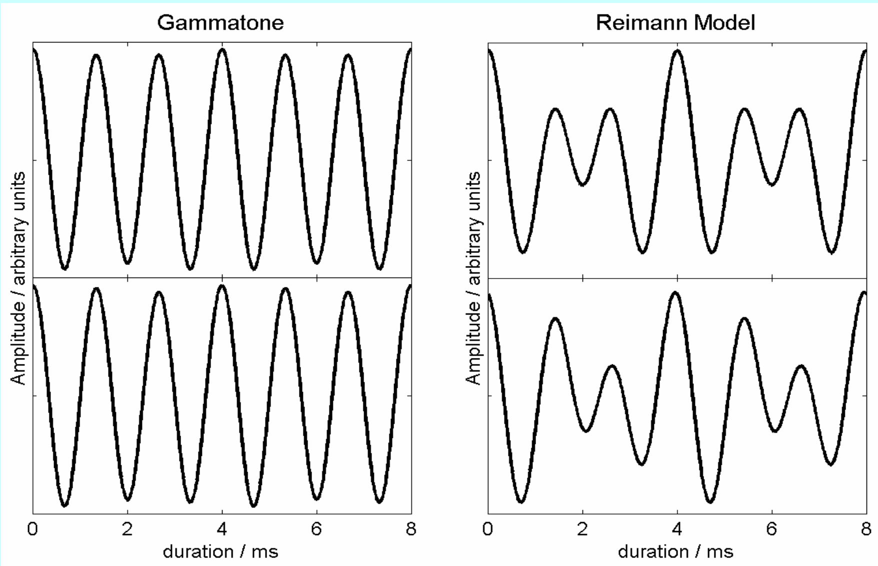

Figure 1. Responses of Gammatone model and Reimann model at centre frequencies of 750 Hz to a composite signal of a 500 Hz tone and a 750 Hz tone attenuated by 6 dB. In the top panels the two components of the input signal are in phase, in the lower panels there is a 90° phase difference.

2. Experimental procedure

In **experiment I**, we measured the threshold for a change in the level of the basic frequency, and consequently the threshold for a change in the relative phase of the components.
The stimulus consisted of two tones, 500 Hz and 750 Hz presented simultaneously for 3 seconds. During the central section of the presentation the phase of F3 was changed gradually. Listeners responded to whether the perception varied or remained constant. The amplitude of the 750 Hz tone was 6 dB lower than the 500 Hz tone, the overall stimulus level was 80 dB.

During the first 1.2 s of the stimulus, the phase was constant. Over the next 600 ms, the phase changed continuously from its starting value to a final test value which was varied over the course of the run to determine threshold. During the last 1.2 s, the phase was held constant (see Fig. 2). In an increasing phase condition, the initial relative phase was 0 radians, in a decreasing phase condition, the final relative phase was 0 radians.

Threshold was estimated using a three-down, one-up adaptive procedure. Eight normal-hearing listeners were tested (3 female and 5 male) with ages from 21 to 39 years. The experiment was repeated for three other pairs of harmonics: namely, F3 and F4, F4 and F5, and F3 and F5.

The purpose of **experiment II** was to confirm that it was the relative phase difference between the two components that produced the audible change in perception and not the absolute phase change. The procedure was the same as in experiment I apart from the following: (i) The phase of F2 followed a similar profile to that of F3, In one condition, the phase of F2 followed the same profile as F3; in the other conditions the cumulative phase change for F3 was a proportion of the phase change applied to F2 and it changed by one of 5 scalars: 0.5, 1, $\sqrt{2}$, 1.5 and 2. The conditions are shown schematically in Fig. 3. (ii) Only positive phase changes were measured. (iii) Only the F2 with F3 condition was measured.

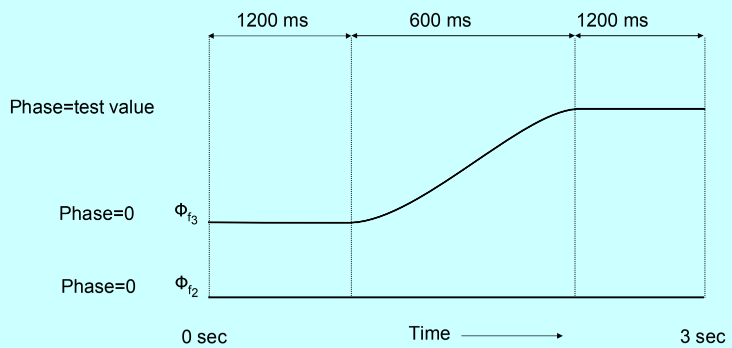

Figure 2. Phase profiles of second and third harmonics over stimulus duration.

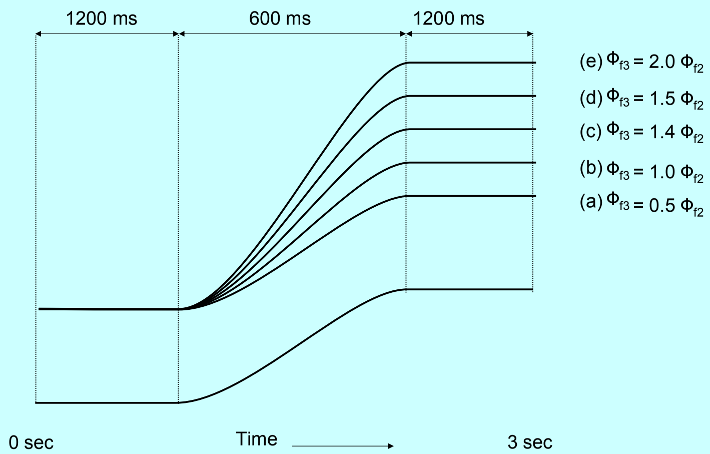

Figure 3. The five conditions of phase change used in experiment II. The cumulative phase of F2 was the independent variable and it determined the phase of F3 according to its specific scalar.

3. Results

The top and bottom panels of Fig. 4 show the results from experiments I and II, respectively; the baseline result (in which the threshold for a phase change of a single component is measured) is shown in both panels (labeled F3 for experiment I and BL for experiment II).

The eight bars in each histogram show the results for the eight subjects, ordered from left to right in terms of their mean threshold in the six conditions where most could perform the task.

The results show that all of the listeners can detect a small change in the relative phase of the components in five conditions: F2+F3 and F3+F4 from Experiment I and 0.5, 1.0 and 2.0 from Experiment II.
The average value for the five conditions is 0.43 radians in 600 ms, this is below the average in the single-component baseline condition of 5.91 radians in 600 ms.

In experiment II the independent variable was the relative rate of phase change as shown on the abscissa. For a relative phase change of 2.0 threshold is low at about 0.7 radians. Decreasing the phase change to 1.5 and 1.4 increases the threshold to values between around 2 and 4 radians. Decreasing the phase change further to 1.0 and 0.5 actually decreases the threshold to below 1 radian.

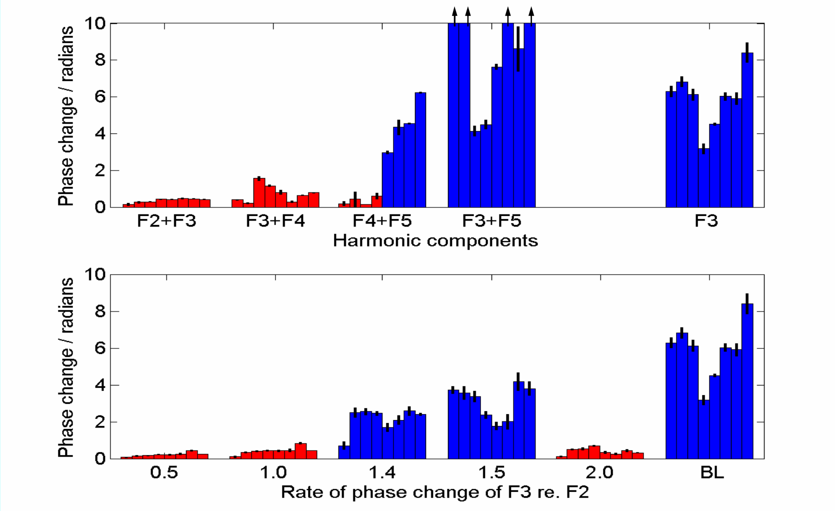

Figure 4. Top graph shows thresholds for detecting a phase change for four different pairs of harmonics. The threshold for detecting a phase change with one component F3 (baseline) is also shown. Bottom graph shows thresholds for detecting a phase change with harmonics F2 and F3 as a function of the rate at which the phase of F3 is changed relative to F2. The baseline condition of detecting the phase change for a single component F3 is also shown (BL). Red bars indicate subject used modulation cue, blue bars indicate instantaneous frequency cue.

4. Analysis

Experiments have shown that changes made to the relative phase of a pair of low number harmonics are audible.

The results fall into two groups:
1. Threshold below values of 1 radian. Subject has used modulation cue, as shown by red bars on Fig. 4.
2. Threshold values above 3 radians. Subject has used instantaneous frequency cue, as shown by **blue bars** on Fig. 4.

Basilar membrane motion simulation shows that the modulation cue is preserved at higher frequencies along the length of the basilar membrane. This is shown in Fig. 5 by the ridges occurring every 4 ms.

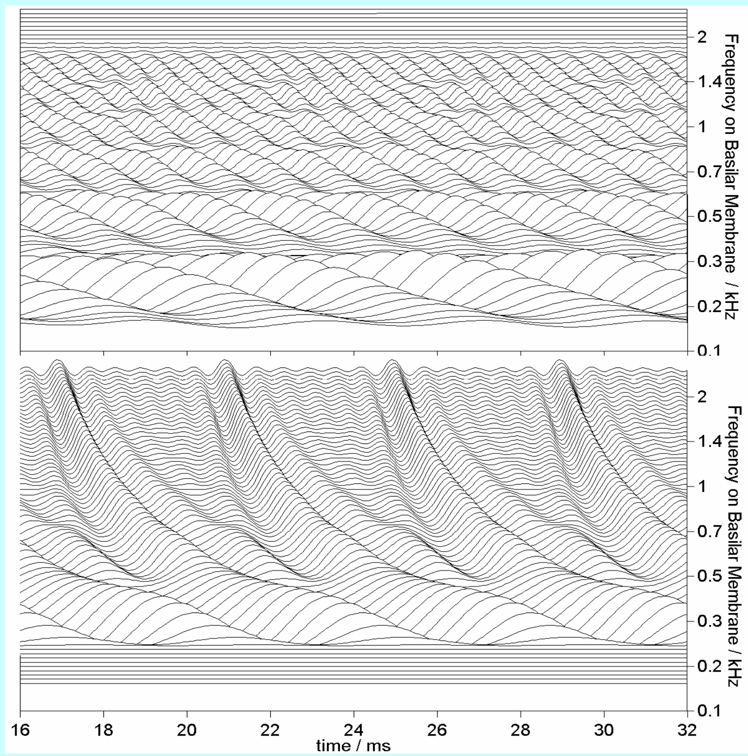

Figure 5. Basilar membrane motion from gammatone filterbank (top panel) and Reimann model (bottom panel). Stimuli is first six harmonics of 250 Hz fundamental, attenuated at 6 dB / octave. Gammatone model shows resolved harmonics. Reimann model shows both unresolved harmonics and also that the timing information of the waveform is preserved further down the basilar membrane.

5. Conclusions

Detection of a change in the relative phase of low number harmonics shows they are unresolved.

The unresolved harmonics provides evidence for broader auditory filters

Timing information of signal is preserved at higher frequencies along basilar membrane

References

de Boer, E. (1975). "Synthetic whole-nerve action potentials for the cat," J. Acoust. Soc. Am. 58, 1030-1045.
de Boer, E., and de Jongh, H.R. (1978). "On cochlea encoding: Potentialities and limitations of the reverse-correlation technique," J. Acoust. Soc. Am. 63, 115-135.
Reimann, H.M., (2005). "The tuning of the cochlea," (review process, submitted J. Acoust. Soc. Am).

Acknowledgements

Research supported by the U.K. Medical Research Council (G9901257).