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Thresholds for hearing mistuned partials as separate tones in harmonic complexes

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When a low harmonic in a harmonic complex tone is mistuned from its harmonic value by a sufficient amount it is heard as a separate tone, standing out from the complex as a whole. This experiment estimated the degree of mistuning required for this phenomenon to occur, for complex tones with 10 or 12 equal-amplitude components (60 dB SPL per component). On each trial the subject was presented with a complex tone which either had all its partials at harmonic frequencies or had one partial mistuned from its harmonic frequency. The subject had to indicate whether he heard a single complex tone with one pitch or a complex tone plus a pure tone which did not "belong" to the complex. An adaptive procedure was used to track the degree of mistuning required to achieve a d' value of 1. Threshold was determined for each of the first six harmonics of each complex tone. In one set of conditions stimulus duration was held constant at 410 ms, and the fundamental frequency was either 100, 200, or 400 Hz. For most conditions the thresholds fell between 1% and 3% of the harmonic frequency, depending on the subject. However, thresholds tended to be greater for the first two harmonics of the 100-Hz fundamental and, for some subjects, thresholds increased for the fifth and sixth harmonics. In a second set of conditions fundamental frequency was held constant at 200 Hz, and the duration was either 50, 110, 410, or 1610 ms. Thresholds increased by a factor of 3–5 as duration was decreased from 1610 ms to 50 ms. The results are discussed in terms of a hypothetical harmonic sieve and mechanisms for the formation of perceptual streams.

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INTRODUCTION

Moore *et al.* (1985a) showed that the frequencies of the lower harmonics of a complex tone can be shifted by $\pm 2\%$ – 3% before they begin to lose weight as contributors to the overall pitch of the complex. This result suggests that the mesh size of the hypothetical "harmonic sieve" for pitch (Duifhuis *et al.*, 1982; Scheffers, 1983; Grandori, 1984) is about $\pm 2\%$ – 3% , although the exact size may depend upon the individual subject, and possibly on the harmonic number and stimulus duration.

Although the concept of the harmonic sieve has mainly been used to account for the pitch values of complex tones, Moore *et al.* (1985b) considered the possibility that it might also be a mechanism for the formation of perceptual streams (Bregman, 1978; Moore, 1982, Chap. 6). Partially passed by the sieve might be heard as emanating from a single source, while a partial rejected by the sieve might be heard as a separate tone not "belonging" to the complex as a whole. If this were true, then as a partial was progressively mistuned from its harmonic frequency it should first be heard as a separate tone when its mistuning equalled the mesh size of the harmonic sieve.

Moore *et al.* (1985b) measured thresholds for detecting that a harmonic in a complex tone was mistuned. For the lower harmonics, the subjects reported that the mistuned

harmonic appeared to "stand out" from the complex, whereas for the higher harmonics beats and roughness were heard. For a signal duration of 410 ms, thresholds for detecting that a harmonic was mistuned were 1.1% on average for the first four harmonics. This appears to suggest that the harmonic sieve is not involved in the formation of perceptual streams, since a partial can be heard as mistuned from a complex, but still contribute significantly to its pitch. However, in the task used by Moore *et al.* (1985b) subjects had to detect the mistuning using *any* available cue. It is possible that for the lower harmonics the mistuning can be detected before the mistuned partial is heard as a separate tone. In the present experiment we attempted to measure more directly the degree of mistuning required to make a partial audible as a separate tone.

I. METHOD

A. General procedure

On each trial the subject was presented with a single complex tone. The partials in the complex tone were at harmonic frequencies on 50% of the trials. On the other 50% one partial was mistuned from its harmonic value. The subject was required to indicate whether he heard a single sound with one pitch or two sounds—a complex tone and a component with a pure-tone quality not belonging to the complex.

We wished to determine the extent to which mistuning a partial increases the tendency for it to be heard out in comparison with the case where all partials are at harmonic frequencies. To achieve this we used an adaptive procedure which tracked the degree of mistuning required for the inharmonic complex to be discriminated from the harmonic complex with a d' of 1 according to signal detection theory (Green and Swets, 1974). Trials on which the subject responded "2" when the inharmonic complex was presented were treated as "hits," and trials on which the subject responded "2" when the harmonic complex was presented were treated as "false alarms."

Trials were presented in blocks of eight, each block containing four harmonic complexes and four inharmonic complexes. For the inharmonic complexes the degree of mistuning within a block was held constant. Wherever possible, a run was started with a mistuning sufficient to make the mistuned partial clearly audible as a separate tone (this could not always be done for short-duration stimuli and/or harmonic numbers above 4). The direction of mistuning (upwards or downwards) was always the same within a run. If (hits-false alarms) was ≥ 2 for a given block, then the mistuning of the partial was decreased by a factor of 1.4 for the next block. If (hits-false alarms) was ≤ 1 the mistuning of the partial was increased by a factor of 1.4. A change from decreasing to increasing mistuning and vice versa defined a turnaround. Testing continued until eight turnarounds had occurred, and threshold was taken as the geometric mean of the values of the mistuning at the last six turnarounds. The subject was allowed an indefinite time to respond on each trial. No feedback was given. At least two threshold estimates were obtained for each subject and each condition.

B. Stimuli

The complex tone had a fundamental frequency of either 100, 200, or 400 Hz. For the lower two frequencies, the first 12 harmonics were present at equal amplitude. For the 400-Hz fundamental the first ten harmonics were present. All harmonics had a level of 60 dB SPL. The stimuli were generated exactly as described in Moore *et al.* (1985b). The degree of shift of the mistuned partial was restricted to one-half of the fundamental frequency. When the adaptive procedure would have led to a shift greater than this the run was aborted. This happened frequently for harmonic numbers greater than 6, but only rarely for harmonic numbers less than 6. Hence, thresholds were only estimated for the first 6 harmonics.

Each tone had 10-ms onsets and offsets, with envelopes shaped according to a raised-cosine function. For the 100-Hz and 400-Hz fundamentals the steady-state duration was 400 ms. For the 200-Hz fundamental the steady-state duration was either 40, 100, 400, or 1600 ms, giving overall durations at the 6-dB down points of 50, 110, 410, and 1610 ms.

C. Subjects

Four subjects were tested, all with absolute thresholds within 10 dB of the ISO-1964 standard over the frequency range tested. All were highly practiced in psychoacoustical

tasks, including frequency discrimination and pitch matching. All had taken part in previous experiments on detecting inharmonicity in complex tones (Moore *et al.*, 1985a,b). Three of the subjects were the authors; the fourth was a volunteer.

II. RESULTS

All subjects reported that, for the majority of conditions, the mistuned partial could be clearly heard as separate from the complex at the beginning of a run, when the mistuning was large. The exceptions occurred mainly for the 50-ms duration, where three of the subjects (BM, MS, and RP) had difficulty for harmonics above the third. Subject RP also had difficulty when the fundamental component of the complex with a fundamental of 100 Hz was shifted downwards in frequency. Conditions where a threshold could not be determined within the constraint that the shift should not exceed one-half of the fundamental frequency are indicated in the figures by upward-pointing arrows.

In most conditions the thresholds for upward shifts were similar to those for downward shifts. Hence results were averaged for positive and negative shifts in the frequency of the mistuned partial. Results for the three fundamental frequencies at a duration of 410 ms are shown separately for each subject in Fig. 1. For the third to the sixth harmonics the results for the different fundamentals overlap, and are roughly constant across harmonic number, for three of the four subjects. For subject RP thresholds could not be determined for the fifth harmonic of 400 Hz and the sixth harmonic of 200 and 400 Hz. Overall, the results are consistent with the idea that, provided a partial is resolvable, it is heard as separate when it is rejected by a harmonic sieve whose mesh size is a constant percentage of the harmonic frequency. However, for the first two harmonics thresholds increase progressively as fundamental frequency decreases, for all four subjects. The effect is particularly marked for the 100-Hz fundamental, and may have resulted from the fact that absolute thresholds increase at low frequencies; the sensation level of the lower harmonics would have decreased as fundamental frequency decreased.

Table I compares the present results with those of our earlier experiment measuring thresholds for detecting inharmonicity, in which three of the subjects of the present experiment (BG, BM, and MS) were used (Moore *et al.*, 1985b). The thresholds for the present experiment are consistently higher, and the difference is greater for higher harmonic numbers.

For the higher harmonics the difference can be ascribed to the subjects using beats or roughness as a cue in the earlier experiment; they were specifically asked to ignore these in the present experiment. However, beats and roughness were not audible for the first three harmonics, yet thresholds are still slightly higher in the present experiment. The results suggest that inharmonicity can be detected for degrees of mistuning slightly smaller than required for a partial to be heard as a separate tone, even for the lower harmonics where beats and roughness are not audible. It is not entirely clear how subjects achieve this. It appears that our earlier experiment (Moore *et al.*, 1985b) did not estimate the degree of

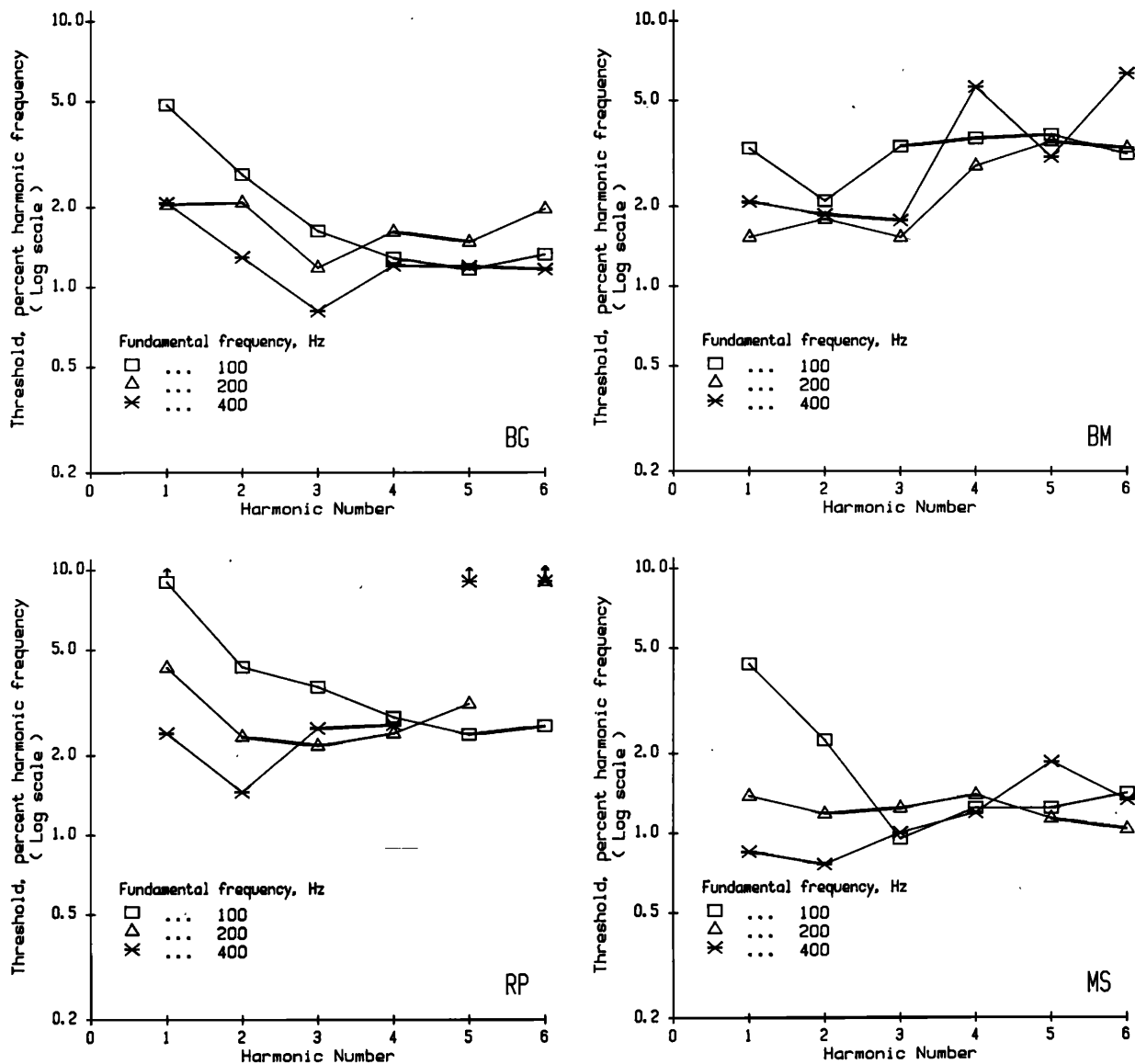


FIG. 1. Individual results for four subjects showing the amount of mistuning required for a partial in a complex tone to be heard as a separate tone. Thresholds are plotted as percentages as a function of harmonic number for three fundamental frequencies: 100 Hz (squares), 200 Hz (triangles), and 400 Hz (asterisks). Stimulus duration was 410 ms.

mistuning required for a partial to be heard as a separate tone.

The results for a fundamental frequency of 200 Hz and durations of 50, 110, 410, and 1610 ms are shown separately for each subject in Fig. 2. Overall, RP shows the highest thresholds and MS the lowest thresholds. For all subjects thresholds increase as duration decreases, although for BM this effect only becomes apparent at the shorter durations. These results are not consistent with the idea that hearing a mistuned partial as a separate tone depends upon the operation of a harmonic sieve with a fixed mesh size. If we wish to retain the idea that a harmonic sieve is involved, then we must postulate that the mesh size is large for short-duration tones, and becomes progressively smaller with increasing duration.

TABLE I. Comparison of the results of the present experiment with those of Moore *et al.* (1985b; their experiment II). The earlier experiment measured the degree of mistuning of a partial in a complex tone required for the mistuning to be detectable, using any available cue. The present experiment measured the degree of mistuning required for a partial to be heard as a separate tone. Thresholds are averaged for subjects BG, BM, and MS, and are expressed as percentages for each harmonic number. The fundamental frequency was 200 Hz, and the duration was 410 ms.

Harmonic number	Threshold, percent harmonic frequency	
	Moore <i>et al.</i> (1985b)	Present experiment
1	1.2	1.7
2	1.3	1.7
3	1.0	1.3
4	0.94	1.8
5	0.89	2.0
6	0.29	2.1

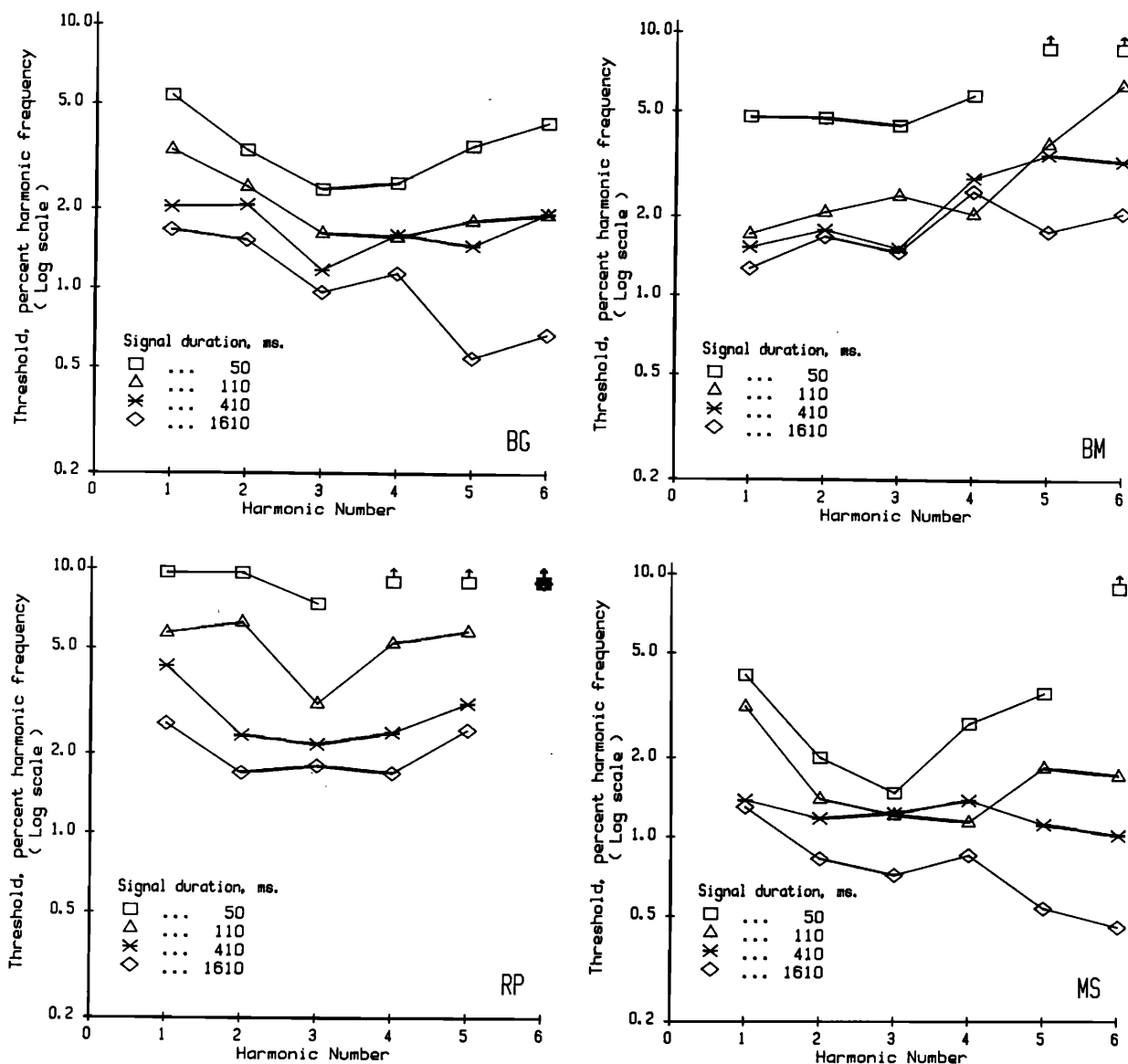


FIG. 2. As Fig. 1, but showing the results at a fundamental frequency of 200 Hz for four durations: 50 ms (squares), 110 ms (triangles), 410 ms (asterisks), and 1610 ms (diamonds).

III. GENERAL DISCUSSION

It seems to be a general phenomenon that complex tones with harmonic components fuse more readily than those with inharmonic components. However, our results show that a component which is sufficiently mistuned to be heard as a separate tone (mistuning about 1.3%–2%) can still contribute significantly to the pitch of the complex as a whole (pitch shifts for mistunings up to 3%–4%). If the mechanism determining the pitch of complex tones does make use of a harmonic sieve, and if that sieve has an all-or-none character (a component is either passed or rejected by the sieve), then our results suggest that the sieve does not play a central role in determining whether a given component is heard as a separate tone. However, it is possible that the sieve does *not* have an all-or-none character. Rather, a component may be weighted less and less in the pitch-determining process as it becomes more and more mistuned. At

the same time the component would become progressively more clearly audible as a separate tone.

The changes in threshold as a function of duration can be interpreted in terms of the processes involved in the formation of perceptual streams. In general, components of sounds which start and stop together, or which are amplitude modulated in a coherent way, tend to fuse together and form a single perceptual stream, whereas components of sounds with a long steady-state portion show a tendency to split into separate perceptual streams (Bregman, 1978; Rasch, 1978; Moore, 1982; McAdams, 1984). Thus, for bursts of a complex tone, the tendency of the components of the tone to fuse will be greater at short durations. We can view the results of our experiment as resulting from a competition between this principle of perceptual organization and the principle that mistuning a component tends to make that component be heard as a separate tone. This interpretation is supported by the finding of Cohen (1980) that a complex of

inharmonic partials, which sounds like a multiple source in steady-state form, can be made to fuse perceptually by imposing a common synchronous exponential amplitude envelope on the partials.

It is not known whether the mesh size of the hypothetical harmonic sieve for pitch also changes with duration. Unfortunately our experiment measuring the pitch shift in a complex tone produced by shifting the frequency of a single partial was carried out using only one duration (410 ms) (Moore *et al.*, 1985a). In that experiment we found that the pitch shift of the complex was approximately a linear function of the shift in frequency of the partial, for shifts up to 2%–3%. It remains to be determined if this limit changes with changes in stimulus duration.

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