Thresholds for the detection of inharmonicity in complex tones

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Thresholds were measured for the detection of inharmonicity in complex tones. Subjects were required to distinguish a complex tone whose partials were all at exact harmonic frequencies from a similar complex tone with one of the partials slightly mistuned. The mistuning which allowed 71% correct identification in a two-alternative forced-choice task was estimated for each partial in turn. In experiment I the fundamental frequency was either 100, 200, or 400 Hz, and the complex tones contained the first 12 harmonics at equal levels of 60 dB SPL per component. The stimulus duration was 410 ms. For each fundamental the thresholds were roughly constant when expressed in Hz, having a mean value of about 4 Hz (range 2.4–7.3 Hz). In experiment II the fundamental frequency was fixed at 200 Hz, and thresholds for inharmonicity were measured for stimulus durations of 50, 110, 410, and 1610 ms. For harmonics above the fifth the thresholds increased from less than 1 Hz to about 40 Hz as duration was decreased from 1610–50 ms. For the lower harmonics (up to the fourth) threshold changed much less with duration, and for the three shorter durations thresholds for each duration were roughly a constant proportion of the harmonic frequency. The results suggest that inharmonicity is detected in different ways for high and low harmonics. For low harmonics the inharmonic partial appears to "stand out" from the complex tone as a whole. For high harmonics the mistuning is detected as a kind of "beat" or "roughness," presumably reflecting a sensitivity to the changing relative phase of the mistuned harmonic relative to the other harmonics. The results are discussed in relation to theories of pitch perception.

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note:
if (ΔH [illegible]
[illegible] constant
mech = spe[illegible]
(c.f. D[illegible]
for [illegible]

if (ΔH [illegible]
[illegible] vo[illegible]
mech = temporal
i.e. bea[illegible]
when [illegible]

The pitch of inharmonic tones: 2 methods:
1. shift H_i → measure Δ Pitch of Complex
2. shift H_i → detect inharmonicity

INTRODUCTION

Several recent pitch models assume that the perception of the pitch of complex tones is a two-stage process. In the first stage the complex tone is subjected to a frequency analysis which resolves some of the lower partials. In the second stage the pitch of the complex is derived or synthesized from the resolved partials (Terhardt, 1972, 1974; Goldstein, 1973; Wightman, 1973). In essence, the theories assume that a central pattern recognizer tries to find the fundamental frequency whose harmonics provide the best match to the partials which have been analyzed from the complex.

In everyday life we are often presented with two or more complex tones simultaneously. The pitch mechanism must then have some way of partitioning the partials, deciding which harmonics "belong" to one harmonic series and which belong to another. One way in which this might be done is based on the theory of Goldstein (1973) and uses the concept of a "harmonic sieve" (Duifhuis *et al.*, 1982; Scheffers, 1983; Grandori, 1984); a partial will only be accepted as part of a given harmonic series if its estimated frequency falls within a preset range around each harmonic frequency. Some recent results of our own are relevant to the concept of a harmonic sieve. We introduced a new method for estimating the relative dominance of the individual partials in determining the pitch of complex tones (Moore *et al.*, 1985). The method involves shifting the frequency of a single partial in a complex tone upwards or downwards from its "correct" harmonic value. Subjects are required to adjust the repetition rate of a periodic complex tone so that its pitch matches that of the inharmonic complex. The shift in the pitch match, produced by shifting the partial, gives an estimate of the relative dominance of that partial. We found, for complex tones with fundamental frequencies of 100, 200, and 400 Hz, that the lowest six harmonics were generally the most important, a result broadly consistent with earlier work on the "dominant region" (Plomp, 1967a; Ritsma, 1967). We also found that the shift in the pitch of the complex sound produced by shifting the frequency of a single partial was, on average, approximately a linear function of the shift in the partial, for shifts up to 2%–3%. However, the pitch shift, expressed as a proportion of the shift in the partial, decreased for shifts beyond about 3%, and partials shifted by 6%–8% hardly affected the pitch of the complex tones as a whole. This suggests that the hypothetical "harmonic sieve" accepts partials within a range of about ±2%–3% around each harmonic frequency.

1 tone
2 oct
3 [illegible]
4 [illegible]
5 [illegible] 3

One question raised by these studies is whether a partial which has been rejected by the harmonic sieve is actually heard out from the complex as a separate tone. If this were the case then the harmonic sieve could also be regarded as a

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mechanism for the formation of perceptual streams (Bregman, 1978; Moore, 1982, Chap. 6); partials passed by the sieve would be heard as part of one stream, being perceived as emanating from a single source, while partials rejected by the sieve would form one or more separate streams, not "belonging" to the first sound. The experiments in the present paper represent a preliminary attempt to study this problem. We measured thresholds for detecting that a single partial in a complex tone was mistuned from its "correct" harmonic value. We wished to determine whether a partial was only heard as mistuned if it was rejected by the harmonic sieve, i.e., if it was mistuned by more than about 3%, or whether mistunings smaller than this could be detected.

I. GENERAL METHOD

The object of the experiments was to determine the amount by which a partial in a complex tone had to be mistuned from its harmonic value in order for the inharmonicity to be detected. On each trial the subject was presented with two successive complex tones. One was a truly harmonic complex, and the other had one partial shifted slightly upwards or downwards in frequency from its harmonic value. The subject was required to identify which complex tone contained the mistuned partial.

A. Stimuli

It's not [illegible] whether shift up-or-down!

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. Each harmonic had a level of 60 dB SPL (except in a few conditions where the mistuned harmonic was incremented in level by 6 or 9 dB relative to the other components). All components except the one to be shifted were computer generated (Texas Instruments 990/4) using a 12-bit digital-to-analog converter (DAC), and a sampling rate of 10 kHz. The output of the DAC was low-pass filtered at 4 kHz (− 3 dB point) using a Barr and Stroud EF16 filter (100 dB/oct slope). All components were in sine phase. The component to be shifted was obtained from a Farnell DSG1 digital signal generator, under computer control. The frequency of that component could be set with an accuracy of 5 parts in 10^6. Resolution was 0.1 Hz up to 1000 Hz and 1 Hz above that. The component was set to an exact harmonic frequency for one interval of a trial, and was mistuned slightly, either upwards or downwards for the other interval. The phase of this component relative to the other components was uncontrolled. The interval containing the mistuned partial was either the first or the second at random (probability 0.5 for each interval), and the mistuning was either upwards or downwards at random. Thus the task could not be performed by listening to the direction of pitch change of the partial: The subject had to detect which interval contained the "out-of-tune" partial.

The tone in each observation interval had onsets and offsets of 10-ms duration, with envelopes shaped according to a raised-cosine function. In experiment I the steady-state duration was 400 ms. In experiment II the steady-state duration was either 40, 100, 400, or 1600 ms. Overall durations, at the 6-dB down points were 50, 110, 410, and 1610 ms. The silent interval between the two observation intervals comprising a trial was 500 ms. Stimuli were presented via the lef earphone of a Sennheiser HD414 headset. The frequency response, as measured in a Bruel and Kjaer artificial ear type 4153, was flat within ± 3 dB over the range 100–4000 Hz. Stimuli were checked with a Hewlett–Packard 3582A spectrum analyzer.

B. Procedure

Thresholds were determined using a two-interval, two-alternative forced-choice procedure that estimated the 71% point on the psychometric function. At the start of a run the subject was presented with six bursts of the partial which would be mistuned, in order to focus attention on the appropriate frequency region. The duration of each burst was the same as the duration to be used for the complex tone. A sequence of trials started with the partial mistuned by an amount somewhat greater than the expected threshold value (except for some conditions in experiment II, which will be described later). On each trial the subject was presented with two successive complex tones and was required to indicate which contained the mistuned partial by pressing the appropriate button on the response box. Immediate feedback was provided by lights on the response box, and the subject's response initiated the next trial after a delay of 1 s. After two consecutive correct responses the mistuning of the partial (the frequency deviation from its harmonic value) was decreased by a factor of 1.4. After each incorrect response the mistuning was increased by the same factor. The factor 1.4 was found empirically to give stable threshold estimates, and also rapid convergence to the threshold value. The transition from increasing to decreasing mistuning, and *vice versa*, defines a turnaround. Testing continued until 12 turnarounds had occurred, and threshold was estimated as the geometric mean of the mistuning at the last eight turnarounds.

The thresholds reported are based on six estimates per condition in experiment I, and at least three estimates per condition in experiment II. The thresholds for a given subject and condition had roughly a normal distribution on a logarithmic frequency scale. Hence, the final estimates were computed as the geometric mean of the individual estimates. The sample standard deviation of the logarithms of the estimates for a given subject and condition was on average 0.12 (the range was from 0.02–0.36).

C. Subjects

All subjects had absolute thresholds within 10 dB of the ISO-1964 standard over the frequency range tested. The three subjects of experiment I were author RP and two students who were paid for their services. All subjects had taken part in other psychoacoustical experiments, and they were trained for about 14 h each before the data reported here were obtained. The three subjects of experiment II were authors BM and BG, and a third volunteer, MS. All three were highly experienced in psychoacoustical tasks, and they were given practice at each stimulus duration until their performance stabilized. This took between 2 and 4 h. Subjects were tested individually in a double-walled sound-attenuating chamber.

II. EXPERIMENT I

A. Conditions

This experiment had two parts. In the first part the complex tones had components which were all of equal level (60 dB SPL per component), and thresholds for detecting inharmonicity were measured for each component of complex tones with fundamental frequencies of 100, 200, and 400 Hz. In the second part the fundamental frequency was fixed at 200 Hz, and thresholds for detecting inharmonicity were measured when the mistuned component was incremented in level by either 6 or 9 dB relative to the levels of the other components.

B. Results

The results for the three subjects were similar (with one exception, noted below), and Fig. 1 shows the results averaged across subjects for the first part of the experiment. Thresholds for inharmonicity, expressed as percent mistuning of the partial concerned, decrease progressively with increasing harmonic number and with increasing fundamental frequency. The only marked exception to this rule is for the fourth harmonic at a fundamental frequency of 400 Hz. One subject (SY) performed consistently poorly in this condition, even after extensive practice. The pattern of results appears somewhat different if the thresholds are expressed simply as mistuning in Hz. Then thresholds vary little with harmonic number or fundamental frequency, covering a range from 2.4–7.3 Hz (again with the exception of SY for the fourth harmonic of 400 Hz, where the threshold was 46 Hz).

The subjects reported that the nature of the task was very different for low harmonic numbers and for high harmonic numbers. For the low harmonics the mistuned partial was heard as "standing out" from the complex as a whole, and the interval containing the mistuned partial could be identified on that basis. For the high harmonics, the mistuned partial was not heard out from the complex. Instead, the mistuning produced a kind of "beat" which could be used to identify the interval containing the mistuned partial. The transition was reported to occur around the fourth to sixth harmonic, depending on the subject. The particular difficulty experienced by subject SY for the fourth harmonic of 400 Hz appeared to occur because for this particular condition the partial could not be clearly heard out from the complex, but at the same time beats could not be heard.

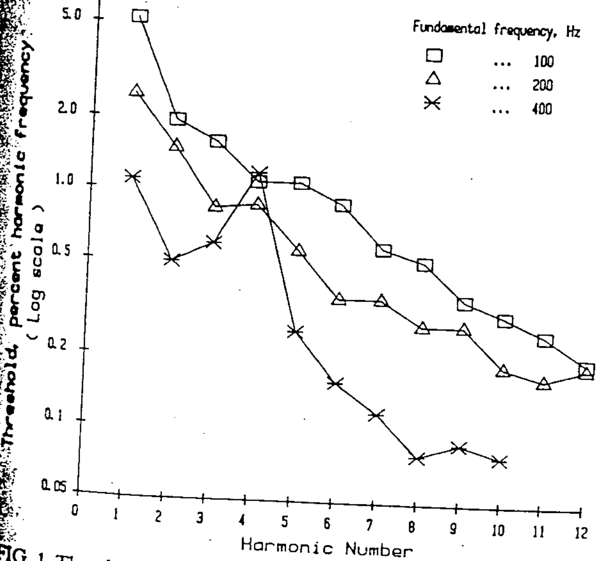

FIG. 1. Thresholds for detecting inharmonicity, averaged across three sub- The threshold mistuning required for detection of that mistuning is ssed as a percentage and plotted for each harmonic in turn. The stimuli were complex tones with equal-amplitude harmonics. The parameter is the fundamental frequency of the complex tones.

The beats heard for the higher partials could occur in two different ways. One possibility is that the mistuned partial interacts with a combination tone introduced by the ear. A combination tone of the type $2f_1-f_2$, produced by the two harmonics above the mistuned harmonic, would lie at the "true" harmonic frequency of the mistuned harmonic. Thus the beats would be similar to those produced by the simple interaction between two tones. An explanation of this type has been put forward to explain phase effects in three-component stimuli (Buunen *et al.*, 1974; see Plomp, 1976, for a review). We feel that it is unlikely that the beats heard in our experiments were mediated by combination tones, for the following reasons: First, the subjective nature of the beats was not that of a simple loudness fluctuation; changes in pitch and timbre could also be heard. Second, combination tones generally have levels at least 15 dB below the levels of the primary tones (Goldstein, 1967; Smoorenburg, 1974). Thus, if the beats arise from interaction of the mistuned partial with a combination tone, the beats should be heard more distinctly if the level of the mistuned component is reduced; the beating components would then be more nearly equal in amplitude. In fact, reducing the level of the mistuned component made the beats *less* distinct, and if the level of the component was reduced by more than 15 dB the beats became completely inaudible. Finally, adding a simulated combination tone at a level relative to the primary components between − 10 and − 20 dB, had no detectable effect on the perception of the beats. Thus we feel that combination tones do not provide an explanation for the perception of beats in our experiments.

The second possibility is that the beats and roughness reflect a sensitivity to changes in waveform at the output of the auditory filter. The mistuning of the partial produces a continuously changing phase relationship between it and the adjacent partials, which results in such waveform changes. Our sensitivity to such waveform fluctuations is already well established (Mathes and Miller, 1947; Terhardt, 1974b; Plomp, 1976), and Terhardt has described in detail how the percept changes from one of hearing the individual fluctuations to one of hearing roughness as the rate of fluctuations increases. Our results seem to be well explained with this concept.

The results of increasing the level of the mistuned partial, by either 6 or 9 dB, are shown in Fig. 2. There was only a very small effect for the first three harmonics, presumably because these harmonics were relatively easy to hear out from the complex even when their level was not incremented. Increasing level decreased the threshold for the fourth and fifth harmonics, which would have been harder to hear out from the complex. However, at higher harmonic numbers the effect of level decreased once more, probably

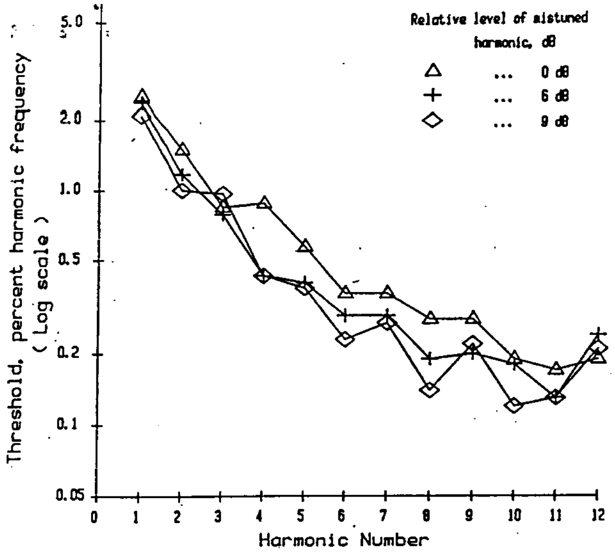

FIG. 2. As in Fig. 1, but showing the effects of varying the level of the mistuned harmonic relative to the levels of the other harmonics. The fundamental frequency was 200 Hz.

because the audibility of the beats was affected only slightly by the relative level of the partials. The fact that increasing the level of the mistuned partial made the beats somewhat easier to detect again indicates that the beats are not mediated by combination tones.

Clearly, the interpretation of the data is made difficult because the subjects appeared to perform the task in different ways for high and low harmonic numbers. Only the data for the low harmonic numbers appear relevant to the issue of the harmonic sieve raised in the Introduction. For the second, third, and fourth harmonics the subjects were able to detect mistunings significantly less than 3%, which suggests that even harmonics which are heard as mistuned may still fall within the harmonic sieve and contribute to the pitch of a complex tone. However, we cannot rule out the possibility that, even for low harmonics, subjects were able to perform the task on the basis of some type of beat detection.

Experiment II was carried out in an attempt to clarify the importance of beat detection as a function of harmonic number. Thresholds for detecting inharmonicity were measured over a wide range of signal durations. We reasoned that at very short durations beats would not provide a very effective cue, since only a small fraction of a beat would occur within the presentation time of the stimulus. Thus, where beats are being used as a cue, performance should vary dramatically with signal duration. On the other hand, if some sort of harmonic sieve is involved, and the mistuned harmonic is simply heard out from the complex, we might expect relatively little effect of signal duration.

III. EXPERIMENT II

A. Conditions

Thresholds for detecting inharmonicity were measured for each of the 12 harmonics of a 200-Hz fundamental. Each component had a level of 60 dB SPL. The signal duration was either 50, 110, 410, or 1610 ms at the 60-dB down points.

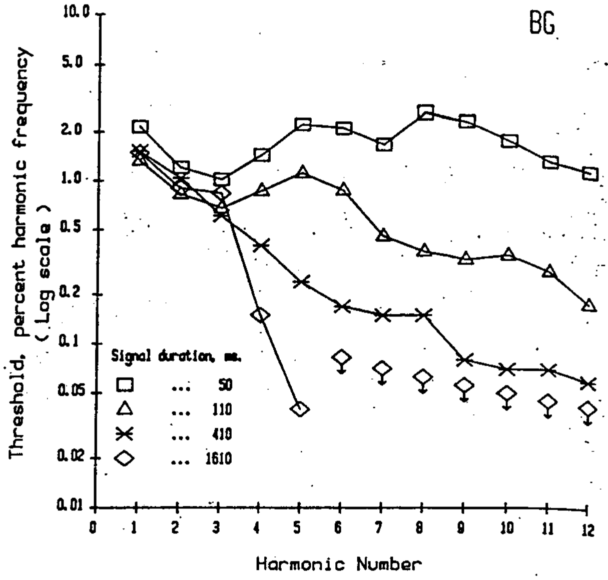

FIG. 3. Results for subject BG, showing thresholds for inharmonicity, expressed as percentages and plotted as a function of harmonic number. The parameter is the duration of the signals in ms. Downward pointing arrows indicate thresholds which were less than 1 Hz, and were below the limit of resolution of the equipment for frequencies above 1 kHz.

B. Results

Initially we found that while results for the lower harmonics were rather stable, there was a high degree of variability for the higher harmonics, particularly for the short signal durations. We found that more stable results could be achieved by starting each run with the mistuning close to or slightly less than the estimated threshold value. In some conditions it appeared that relatively slow beats could be used as a cue, but if the mistuning was too great at the start of a run, then the beats were too rapid to be usable, and much higher thresholds resulted. The data presented here are the "low" thresholds obtained by starting the runs with mistunings close to the lower thresholds obtained in pilot trials. With this procedure, the results were relatively consistent for all harmonic numbers; the sample standard deviation of the logarithms of the estimates for a given subject and condition did not vary significantly with duration or harmonic number, having an average value of 0.12.

The results for the individual subjects did differ somewhat, and so they are presented separately in Figs. 3, 4, and 5. For the longest duration and for harmonics above the fifth all subjects achieved essentially errorless performance when the mistuning was 1 Hz, the limit of resolution of the equipment. They reported listening for a slow fluctuation or beat during the presentation time of the stimulus. For the higher harmonics, shortening duration produced a very large impairment in performance, as would be expected if subjects were using beats as a cue. At the shortest duration (50 ms) thresholds for harmonics above the sixth were between 24 and 68 Hz. Such large thresholds correspond to rather rapid beats, and at this duration subjects reported detecting the inharmonicity as a "roughness," the individual fluctuations being too rapid to follow (as would be expected from previous work, e.g., Terhardt, 1974b). Subject BG appeared to be somewhat more sensitive to beats than the other two sub-

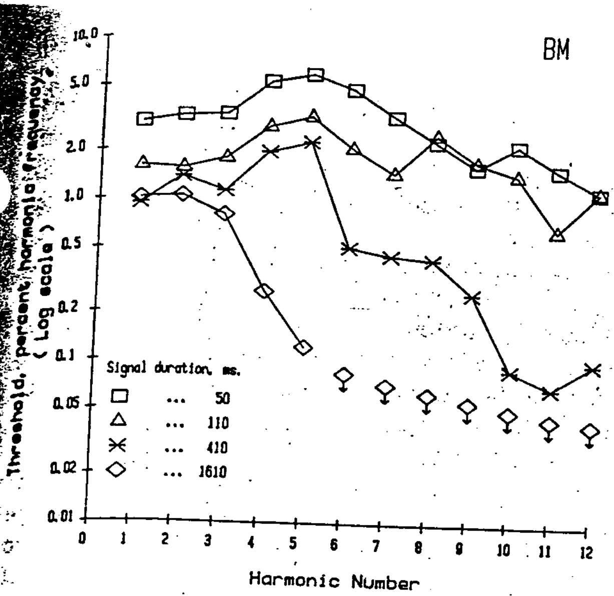

FIG. 4. As in Fig. 3, but showing the results for subject BM.

jects, particularly for the 110-ms duration. BG's thresholds for the higher harmonics at this duration were typically around 6 Hz, which means that less than one "beat" would have occurred during the presentation time of the stimulus. Subject MS approached this level of performance for some harmonics but not for others, but BM was consistently worse, requiring at least one and a half "beats" during the presentation time of the stimulus.

For the first four harmonics performance varies considerably less as a function of duration. This is illustrated in Table I which shows the mean thresholds across subjects for the first four harmonics. For the first three harmonics performance worsens by only a factor of three as duration is decreased by a factor of 32. The variation is somewhat greater for the fourth harmonic, but this is largely produced by the large drop in threshold for the 1610-ms duration. In this condition subjects reported hearing faint beats which could be used as a cue. Beats were not audible for the first four harmonics at shorter durations. Consistent with this, the thresholds for each of the three shorter durations were roughly a constant proportion of the harmonic frequency, rather than being a constant number of Hz, as was the case for the higher harmonics. The average thresholds, expressed as a percentage of the harmonic frequency, were 2.4%, 1.5%, and 1.1% for durations of 50, 110, and 410 ms, respectively.

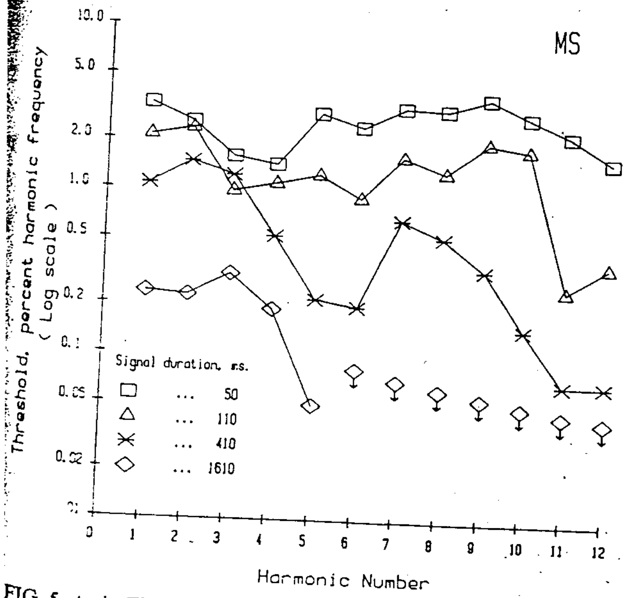

FIG. 5. As in Fig. 3, but showing the results for subject MS.

TABLE I. Results from experiment II showing thresholds for inharmonicity, expressed in Hz, as a function of stimulus duration and harmonic number, for harmonic numbers up to four. Each figure is the average result for three subjects. Figures in parentheses give the thresholds expressed as a percentage of the harmonic frequency.

Hz

Harmonic number	Duration, ms 50	110	410	1610
1	5.6(2.8)	3.4(1.7)	2.4(1.2)	2.1(1.0)
2	9.3(2.3)	6.3(1.6)	5.1(1.3)	2.8(0.7)
3	11.7(2.0)	6.8(1.1)	5.9(1.0)	3.9(0.6)
4	21.5(2.7)	12.6(1.6)	7.5(0.9)	1.6(0.2)

200
400
600
800

The thresholds for subject BM at a duration of 410 ms increase progressively with increasing harmonic number up to the fifth harmonic, and then decrease abruptly. A similar pattern may be seen in the results for BG at 110 ms (and for SY in experiment I for a fundamental frequency of 400 Hz). This is consistent with the idea that different cues are used for low and high harmonics. The decrease in threshold occurs when beats first become usable as a cue.

IV. DISCUSSION

Our results suggest that inharmonicity can be detected in two different ways. For high harmonic numbers subjects appear to be sensitive to the changing relative phase of the components produced by shifting the frequency of a partial from its harmonic value. The periodic fluctuations in waveform produced by the changing phase relationship are heard as beats or roughness. The cyclic variations in pitch and timbre reported by our subjects appear similar to those reported by Craig and Jeffress (1962), Plomp (1967b), and Lamore (1975) for two-tone complexes slightly mistuned from frequency ratios of 1: n, where n is an integer, and $1 < n < 6$. However, in their experiments beats were only heard when the higher frequency tone was considerably lower in level than the lower frequency tone. For equal-amplitude tones, such as used in our experiments, the beats are not audible for widely spaced components (i.e., for the lower harmonics), but are clearly heard when the components are closely spaced in frequency relative to the auditory filter bandwidth. This is consistent with the results of Plomp (1967b) on the beats of mistuned consonances.

Craig
Plomp
Lamore

Beats appear to provide a particularly effective cue at long signal durations, where mistunings less than 1 Hz can be detected for harmonics above the fifth. For short durations beats are much less effective, and performance worsens considerably. For low harmonics, up to about the fourth, beats are not generally audible, particularly at short durations. In this case the inharmonicity is detected by virtue of the mistuned harmonic appearing to "stand out" from the complex as a whole. For the lower harmonics, the degree of mistuning required at a given duration is roughly a constant percentage of the harmonic frequency. Thresholds vary only slowly with duration.

The results of experiment II can be compared with the results of two other experiments using the same subjects. Moore *et al.* (1984) measured frequency difference limens (DLs) for individual harmonics within complex tones, under conditions very similar to those reported here. For a complex tone with a fundamental frequency of 200 Hz, containing the first 12 harmonics at a level of 60 dB SPL per component, the DLs for the first four harmonics averaged 0.5% at a duration of 410 ms. In the present experiment the thresholds averaged 1.1% at the same duration. This suggests that in the present experiment performance was not limited by the ability to detect a change in the frequency of the partial concerned. For the lower harmonics the shift in frequency of the mistuned partial between the two halves of a trial could generally be heard fairly easily. The difficulty was in deciding which interval contained the mistuned partial.

Rel. between PT & pitch detection vs inharmonicity for the 1st 4

For higher harmonics the reverse effect occurs. Moore *et al.* (1984) found frequency DLs for harmonics above the sixth to be about 2%–3%. In the present experiment the DLs were much smaller than this, being as small as 0.1%–0.2% at a duration of 410 ms. In the experiment of Moore *et al.* (1984), the harmonic to be discriminated was mistuned in both halves of a trial, upwards from its harmonic value in one half, and downwards in the other half. Thus, merely detecting beats did not provide a basis for performing the task, and thresholds were much larger than obtained in the present experiment. The comparison of the two experiments supports the idea that in the present experiment the task was performed in different ways for high and low harmonics.

The results for the lower harmonics can be used to answer the question posed in the Introduction: Does the hypothetical harmonic sieve play a role in the formation of perceptual streams? In other words, is a component rejected by the harmonic sieve heard as a tone separate from the complex as a whole? For the lower harmonics subjects did report that they performed the task by listening for a component which appeared to "stand out" from the complex as a whole. These subjective reports are consistent with the results of Martens (1984). He found that if a single partial in a harmonic complex tone was mistuned from its harmonic value by 40 Hz, then that partial was much more easy to "hear out" from the complex than when it was tuned to an exact harmonic frequency. This would appear to indicate that the harmonic sieve does play a role in the perceptual segregation of complex tones. However, a comparison of our results with those of a different experiment using the same subjects (Moore *et al.*, 1985) reveals a difficulty. In that experiment the effect on the pitch of a complex tone of shifting the frequency of a single partial was determined. The results showed that, for the lower harmonics, the shift in pitch of the complex was, on average, approximately a linear function of the shift in the partial, for shifts up to about 2%–3%. If there is such a thing as a harmonic sieve, this implies that the sieve accepts components whose frequencies fall within ± 3% of their nominal values. For the same signal duration (410 ms), thresholds for detecting that a harmonic was mistuned were 1.1% on average for the first four harmonics. Thus a partial can be heard as mistuned but can still contribute significantly to the pitch of a complex tone. Apparently the pitch processor has a wider tolerance range than the mechanism which determines whether a particular component is heard as "belonging" to a harmonic series. Nevertheless, there does seem to be a link between the two.

harmony! different mechs → more structure
mistuning
[illegible]

Finally, the present results have some relevance to the perception of the lower notes produced by stringed instruments, particularly pianos. These notes tend to have slightly inharmonic partials, the lowest two to three partials having frequencies slightly below their nominal values. To measure the extent of the mistuning we recorded samples of the lower notes of pianos using a Bruel and Kjaer microphone type 4134 and a digital recording system (Sony PCM digital audio processor, with Sony F1 video recorder). The frequencies of the partials were measured with a Wavetek 5820A spectrum analyzer, using the "improved accuracy" facility which gave estimates accurate to better than 0.05%. The two lowest partials, and particularly the lowest partial, were typically found to be shifted downwards by about 1% from their nominal values for notes below G1 (fundamental frequency 49 Hz), although the size of the shifts differed from one instrument to another. The shifts for the very lowest notes were sometimes as large as 2%–3%. These values approach, and in many cases exceed the thresholds for inharmonicity measured in the present experiments, especially for the long-duration stimuli. Thus the inharmonicity of the partials would be audible, particularly for the lower notes on pianos. This probably partially accounts for the fact that the lower notes on some pianos have a rather ambiguous and indistinct pitch.

ACKNOWLEDGMENTS

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