Effect of noise on the detectability and fundamental frequency discrimination of complex tones

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Percent correct performance for discrimination of the fundamental frequency (F0) of a complex tone was measured as a function of the level of a background pink noise (using fixed values of the difference in F0, ΔF0) and compared with percent correct performance for detection of the complex tone in noise, again as a function of noise level. The tone included some low, resolvable components, but not the fundamental component. The results were used to test the hypothesis that the worsening in F0 discrimination with increasing noise level was caused by the reduced detectability of the tone rather than by reduced precision of the internal representation of F0. For small values of ΔF0, the hypothesis was rejected because measured performance fell below that predicted by the hypothesis. However, this was true only for high noise levels, within 2–4.5 dB of the level required for masked threshold. The results indicate that the mechanism for extracting the F0 of a complex tone with resolved harmonics is remarkably robust. They also indicate that adding a background noise to a complex tone containing resolved harmonics is not a good means for equating its pitch salience with that of a complex tone containing only unresolved harmonics. [DOI: 10.1121/1.2211408]

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I. INTRODUCTION

The perception of the pitch of complex tones plays an important role in melody recognition, extraction of speech intonation, and the segregation of competing sounds. There have been many experimental studies and computational models aimed at elucidating both the underlying mechanisms of pitch perception and the limits of fundamental frequency (F0) discrimination. With some exceptions (Bilsen, 1973; Hoekstra, 1979; Horst *et al.*, 1984; Scheffers, 1984; Moore and Glasberg, 1991), the majority of those studies have focused on the perception of complex tones presented in quiet. The present study addresses instead the limitations on F0 discrimination imposed by the presence of competing noise and focuses on two issues. The first involves a direct comparison between percent correct performance for the detection of a complex tone and the discrimination of its F0, both as a function of background noise level. By measuring performance on both tasks in the same listeners, and by developing a simple quantitative model of the relationship between the two, we determine the extent to which discrimination performance is limited by detectability. The second issue concerns the question of whether it is possible to equate the salience of the pitches of two tones by adding noise to the one that is initially more salient.

Several researchers have addressed the effect of noise on frequency discrimination for pure tones (Harris, 1966; Henning, 1967; Cardozo, 1974; Hoekstra, 1979; Dye and Hafter, 1980; Sinnott and Brown, 1993; Scheffers, 1984). In most of these studies, thresholds for frequency discrimination, FDLs, have been measured over a range of signal-to-noise ratios, and sometimes, but not always, the masked threshold of the tone in noise has also been measured. The study of Cardozo (1974) is of particular interest, since he measured percent correct performance for both detection and frequency discrimination of a 1000-Hz tone in noise, as a function of the signal-to-noise ratio. A four-alternative forced-choice task was used in both tasks. The detection task was somewhat unusual in that the subject had to indicate in which of the four intervals the tone was *not* present. In the frequency-discrimination task, the subject had to indicate in which of the four intervals the tone was higher in frequency (above 1000 Hz by an amount Δf). Cardozo defined the detection "threshold" as the signal level required for 62.5% correct (corresponding to a detectability index, $d'=1.19$). In the frequency-discrimination task, about 50% correct was achieved for $\Delta f=16$ Hz when the tone was *at* the detection

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threshold. Frequency discrimination for that value of Δf improved rapidly with increasing signal level, up to about 83% correct when the signal was 3 dB above the detection threshold. Performance was poorer for smaller values of Δf and also increased less rapidly with increasing signal level. Remarkably, for relatively large values of Δf (above about 50 Hz), the signal level required for 62.5% correct in the frequency discrimination task was almost the same as the level required for 62.5% correct in the detection task. Also, for large values of Δf, the psychometric function for detection of the tone had the same slope as the functions for discrimination of the frequency of the tone. In other words, subjects could discriminate the difference in frequency as well as they could detect the tone.

Although there are some data on the F0 discrimination of complex tones in noise (Bilsen, 1973; Hoekstra, 1979; Horst *et al.*, 1984; Scheffers, 1984; Moore and Glasberg, 1991), we know of no experiment analogous to Cardozo's (1974), in which discrimination performance has been directly compared with detection performance for complex tones. Moore and Glasberg (1991) measured thresholds for detecting a change in F0 of complex tones containing low (resolvable) harmonics, as a function of the level of a pink noise background. They found that the resulting F0DLs were almost unaffected by the background noise except when the noise level was so high that the tones were "barely audible." However, the noise level was changed in rather large steps (4 dB) and detection thresholds for the tones in the noise were not measured.

Hoekstra (1979) measured thresholds (75% correct in a two-alternative forced-choice, 2AFC, task) for discrimination of the F0 of a pulse train that was passed through a $\frac{1}{3}$-oct filter centered at 2000 Hz. A background noise was passed through the same filter, and F0DLs were measured as a function of the level of the tone relative to its masked threshold in the noise; the masked threshold (75% correct in a 2AFC task) was determined separately for each F0 used, and the value of F0 varied from 200 to 20 Hz. When F0 was 100 Hz or less, so that the tone contained only rather high harmonics, it was not possible to measure F0DLs when the tone was less than about 8–10 dB above masked threshold. For the F0 of 200 Hz, F0DLs could be measured for levels at, or only slightly above, the masked threshold. For this F0, F0DLs decreased progressively with increasing signal level until the tone was 15 to 20 dB above masked threshold. For a given level relative to masked threshold, the F0DLs for the filtered pulse trains were always higher than the FDL for a pure tone centered at 2000 Hz, although the difference was small for the pulse train with F0=200 Hz. For most of Hoekstra's tones, the harmonics would have been too high to be resolved in the auditory system. It is generally assumed that only harmonics up to the fifth to eighth are resolvable (Plomp, 1964; Plomp and Mimpen, 1968; Moore and Ohgushi, 1993; Moore *et al.*, 2006). Bernstein and Oxenham (2003) suggested a somewhat higher limit, based on an experiment where the "target" harmonic was pulsed on and off, but the validity of their procedure has been questioned (Moore *et al.*, 2006). Even for the highest F0 used by Hoekstra, the lowest audible harmonic would have been the ninth, which would have been marginally, if at all, resolvable.

Scheffers (1984) measured the ratio of signal to pink noise level at which changes in F0 of fixed magnitude, ΔF0, could be detected with 75% accuracy in a 2AFC task (defined as threshold), for values of ΔF0 from 0.5% to 10%. The stimuli were vowel sounds, pulse trains (low-pass filtered at 4 kHz), and pure tones. Masked thresholds of the sounds in the pink noise were also measured; again, threshold was defined as the level corresponding to 75% correct in a 2AFC task. Changes of 5% or more in F0 could be detected with 75% accuracy for signal levels close to masked threshold, for all three types of stimuli. Again, the results suggest that, when the change in F0 is reasonably large, the F0 of the tones can be discriminated as well as the tones are detected. For smaller changes in F0, for example 1%, the signal level had to be 5–10 dB above masked threshold to allow 75% correct performance.

In summary, a few studies have assessed F0 discrimination in noise for various levels relative to the masked threshold and have demonstrated remarkably good F0 discrimination for tones containing resolved harmonics, even when the tones were at levels close to the masked threshold. However, we are not aware of any studies in which both signal detectability and F0 discrimination were measured as a function of signal-to-noise ratio.

In the present experiments, percent correct performance for detecting a complex tone in noise was measured as a function of noise level (with the signal level fixed) and compared with percent correct performance for the discrimination of the F0 of the same complex tone, again as a function of noise level. The tone included some low, resolvable components, but not the fundamental component. The results were used to test the hypothesis that the worsening in F0 discrimination with increasing noise level was caused by the reduced probability of the tone being detected rather than by reduced precision of the internal representation of F0 on trials where both tones in a 2AFC trial were detected. F0 discrimination for the complex tone in noise was also compared with that for a complex tone with unresolved harmonics presented in a low level of noise (designed only to mask combination tones, but not to interfere with discrimination or detection).

II. STIMULI AND GENERAL PROCEDURE

Stimuli were complex tones with a nominal F0 of 88 or 250 Hz. All tones were bandpass filtered between 1375 and 1875 Hz (3-dB down points, slopes of 48 dB/oct). For complex tones with equal-amplitude harmonics, harmonics with numbers up to about five to eight are resolved by the auditory system (Plomp, 1964; Plomp and Mimpen, 1968; Moore and Ohgushi, 1993; Bernstein and Oxenham, 2003; Moore *et al.*, 2006). Therefore, within the passband, the tones with the 88-Hz F0 contained only unresolved components (numbers 16–21), while the tones with the 250-Hz F0 contained mainly resolved components (numbers 6 and 7). All components were added in sine phase (starting phase of 0°) and had a level of 45 dB SPL. This low level was chosen to ensure that possible distortion products would be at a low level. A continuous pink noise was presented. This either had a spectrum level of 15 dB (*re* 20 μPa) at 1 kHz (referred to as the baseline level) or a higher level. The background noise was low-pass filtered with a nominal cutoff frequency of 3900 Hz (slope 96 dB/oct). For the tones with a nominal F0 of 88 Hz, the noise was at the baseline level and was intended to mask possible distortion products, particularly combination tones occurring at F0 and low harmonics of F0 (Buunen *et al.*, 1974; Pressnitzer and Patterson, 2001). For the tones with a nominal F0 of 250 Hz, the level of the noise was increased by various amounts above baseline level, so as to manipulate the signal-to-noise ratio. Pink noise was used rather than white noise because the masking produced by pink noise varies less with frequency than for a white noise.

The complex tones were generated and bandpass filtered digitally. They were played out using a 16-bit digital-to-analog converter (CED 1401 plus), with a sampling rate that was varied between trials over the range 40 kHz±10%. This had the effect of randomly varying the F0 over the range ±10% (also producing a variation of ±10% in the duration and in the filter cutoff frequencies). This F0 randomization discouraged subjects from basing their decision on a long-term memory representation of the sound. The randomization was used in both experiments. In what follows, the random variation between trials is not explicitly discussed, and we describe only the nominal F0. The nominal stimulus duration was 400 ms, including 5-ms raised-cosine onset and offset ramps.

Stimuli were passed through an anti-aliasing filter (Kemo 21C30) with a cutoff frequency of 17.2 kHz (slope of 96 dB/oct) and presented monaurally, using Sennheiser HD250 headphones. Subjects were seated individually in an IAC double-walled sound-attenuating booth.

A two-interval two-alternative forced choice (2I-2AFC) task was used. The interval between the two stimuli within a trial was fixed at 500 ms. Each interval was marked by a light and visual feedback was provided following each response. The total duration of a single session was about 2 h, including rest times.

III. EXPERIMENT 1: EFFECT OF NOISE ON F0 DISCRIMINATION

A. Stimuli and procedure

Listeners had to discriminate between the F0s of two sequentially presented complex tones, which had a nominal F0 of either 88 or 250 Hz. For the tones with a nominal F0 of 250 Hz, the level of the noise was increased by various amounts above the baseline level (8, 10, 12, 14, and 16 dB). The value of ΔF0 was fixed at various amounts, chosen individually for each subject. They were selected on the basis of pilot runs, so that performance for F0 discrimination of the complex with a nominal F0 of 88 Hz (which, for noise levels at baseline, led to poorer performance than for the complex with a nominal F0 of 250 Hz) fulfilled the following criteria: (1) for the largest ΔF0, performance was relatively high but not perfect, and (2) for the smallest ΔF0, performance was relatively low but above chance level. Two subjects, who were available for a longer time, were tested using more than two ΔF0 values. The following values of ΔF0 were used: 2% and 4% for subject 1; 1%, 2%, and 3% for subject 2; 2% and 6% for subject 3; 2% and 5% for subject 4; 1% and 4% for subject 5; and 1%, 2%, 4%, and 6% for subject 6. Five blocks of 105 trials were run for each condition and subject. The first five trials in each block were considered as practice and results from these were discarded. Within a block of 105 trials, the condition (determined by the values of F0, ΔF0, and the noise level) was kept constant. The order of the conditions was counterbalanced within and across subjects. One block was run for each condition in turn, before additional blocks were run. The results reported are the mean of 500 trials for each condition and subject.

B. Subjects

Six subjects participated; all had some musical experience. All had taken part in previous experiments involving discrimination of the F0 of complex tones, so they were highly practiced. They ranged in age from 22 to 34 years. Their quiet thresholds at octave frequencies between 250 and 8000 Hz were below 15 dB HL (ANSI, 2004). Stimuli were presented to the left ear for four subjects and to the right ear for the other two.

C. Results and discussion

Figure 1 shows the results. Performance for the tones containing only unresolved components (solid symbols) lies between 60% and 93%. As expected, for the tone with resolved harmonics (open symbols connected by solid lines) performance declined with increasing noise level. However, for a given noise level, increases in ΔF0 did not always lead to improved performance. This was especially apparent for subject 6 (panel f), who was tested for more values of ΔF0 than the other subjects; for her, performance improved when ΔF0 was increased from 1% to 2%, but did not improve with further increases in ΔF0. One interpretation of this result is that, once the value of ΔF0 was sufficiently large, performance depended mainly on whether the tone was audible on both halves of each trial; if the tone was heard in both intervals, then the difference in F0 could be heard. The very poor F0 discrimination for the highest noise levels tested may reflect the fact that the tones were close to their masked threshold at this noise level. This interpretation was tested in experiment 2.

Table I shows the increase in noise level needed for each subject to achieve equal performance for F0 discrimination of complex tones with resolved and unresolved harmonics, for each ΔF0 used; this was estimated by interpolation. For all subjects, the increase in noise level needed to achieve equal performance decreases with increasing ΔF0. Thus, there is no *single* increment in noise level for each subject that leads to equal F0 discrimination of complexes with resolved harmonics (with increased noise) and complexes with unresolved harmonics (with baseline noise). Typically, the noise level required to equate discrimination performance across the two types of complex was 2–3 dB higher when ΔF0 was small (1% or 2%) than when it was larger (3%–

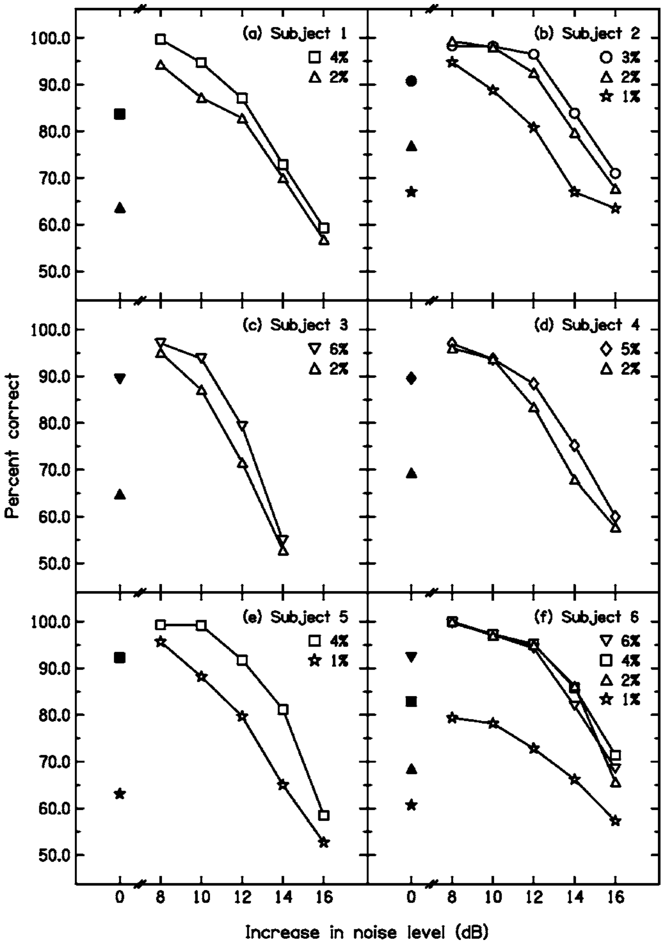

FIG. 1. Performance for F0 discrimination of complex tones filtered between 1375 and 1875 Hz (experiment 1). The parameter is the difference in F0 between the two halves of a trial, ΔF0. The solid symbols at the left-hand side of each panel show performance when the nominal F0 was 88 Hz (unresolved harmonics only). These tones were presented in the presence of a continuous pink background noise with a spectrum level of 15 dB at 1 kHz (the baseline level) that was low-pass filtered at 3900 Hz. The open symbols connected by solid lines show performance when the nominal F0 was 250 Hz (resolved components); performance is plotted as a function of the level of the background noise relative to the baseline level. Each panel gives results for one subject.

6%). A paired-samples t test, based on the noise level required to equate F0 discrimination for the largest and smallest values of ΔF0 used for each subject, showed that the difference was highly significant $[t(5)=11.3, p<0.001]$.

One might expect to be able to gradually reduce the pitch salience of a tone with resolved harmonics by adding increasing amounts of noise, so that this salience would eventually drop to that of a tone with unresolved harmonics. If F0 discrimination provides a direct measure of pitch salience, as is often assumed, then one might expect it to be possible to equate F0 discrimination for complex tones with resolved and unresolved harmonics by adding noise to the former, regardless of the value of ΔF0 used. In fact, it was not possible to choose a noise level which equated performance for resolved and unresolved harmonics for all ΔF0s. This could indicate that F0 discrimination does not provide a direct measure of pitch salience. However, it may also be the case that some other factor is involved.

One possible "other factor" is that F0 discrimination of the tone with resolved harmonics was determined not only by the salience of its pitch but also by its detectability. If the tone was not detected in one or both intervals of a given trial, then this would clearly lead to poorer performance. When ΔF0 was relatively large, the percentage correct F0 discrimination of the tone with resolved harmonics at low noise levels was typically 10%–15% better than for the tone with unresolved harmonics (and the same ΔF0 value). Hence, as the noise level was increased, only a small decrease in detectability would be required to lead to F0 discrimination the same as for the tone with unresolved harmonics. In contrast, when ΔF0 was relatively small (1% or 2%), the percentage correct F0 discrimination of the tone with resolved harmonics at low noise levels was typically 20%–30% better than for the tone with unresolved harmonics. In this case a larger decrease in detectability (corresponding to a higher noise level) would be required to equate F0 discrimination for the tones with resolved and unresolved harmonics. This could account for why the noise level required to equate performance for the tones with resolved and unresolved harmonics was higher for the smaller values of ΔF0. The effect of the noise on detectability of the tone with resolved harmonics was assessed in experiment 2.

TABLE I. Increase in noise level needed for each subject in order to produce F0 discrimination performance for the complex tone with resolved harmonics, RES, equal to that for the complex tone with unresolved harmonics, UNRES (with the baseline noise level), for various ΔF0's.

Subject	ΔF0 (%)	$P(c)$ UNRES (%)	Increase in noise level for RES (dB)
1	4	83.7	12.5
	2	63.7	15
2	3	90.8	13
	2	76.9	14.5
	1	67.0	14.5
3	3	89.4	10.6
	1	65.8	12.7
4	5	89.6	11.5
	2	69.3	13.7
5	2	92.3	11.9
	0.5	63.1	14.3
6	6	92.4	12.5
	4	84.2	14.5
	2	68.5	15.5
	1	60.7	15.5

IV. EXPERIMENT 2: EFFECT OF NOISE LEVEL ON DETECTION OF THE TONE

A. Stimuli, procedure, and subjects

The signal to be detected was the same tone with resolved harmonics as used in experiment 1. The nominal F0 was 250 Hz. Subjects had to indicate which of the two intervals in the 2-AFC task contained the tone. Detection performance was measured as a function of the level of the noise background. The noise used was the same as in experiment 1. Seven different noise levels (increased above baseline level by 8 to 20 dB, in steps of 2 dB) were tested.

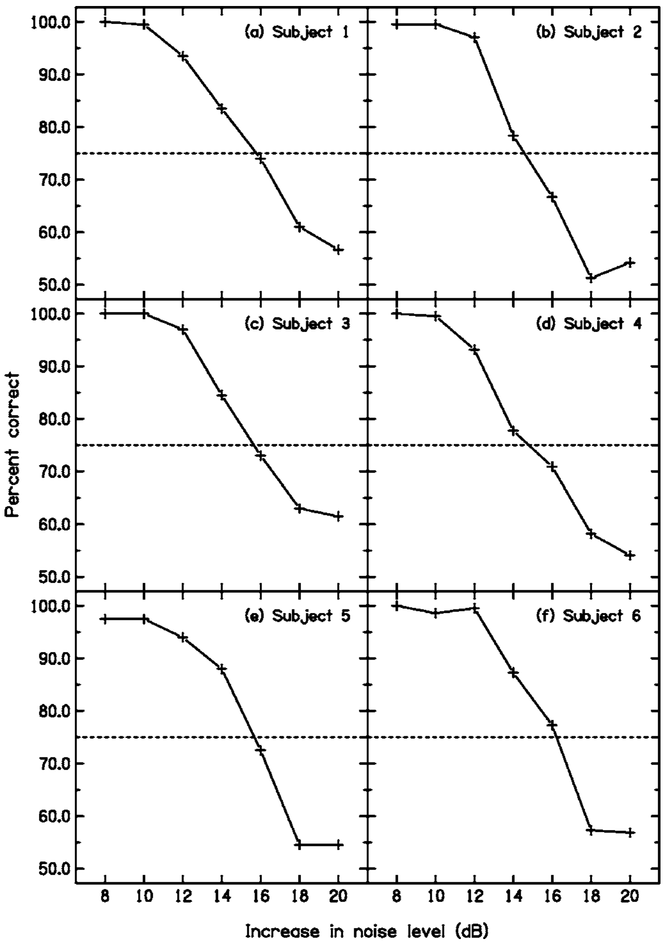

FIG. 2. Performance in a 2AFC task for detection of a complex tone with a nominal F0 of 250 Hz filtered between 1375 and 1875 Hz (experiment 2). Performance is plotted as a function of the level of the background noise relative to the baseline level.

Within a block of 140 trials, the order of the conditions was always from easy (lowest noise level) to hard (highest noise level). There were 20 repetitions of this cycle within a block. Between trials, the noise level was changed from its old to the desired value by changing the setting of the programmable attenuator in steps of 0.1 dB. This resulted in a smooth rather than sudden transition. The noise background was presented for 1 s at the new level before the next trial started. Ten blocks of 140 trials were run for each subject. The results shown are the mean of the 200 trials per condition. The six subjects were the same as for experiment 1.

B. Results and discussion

Each panel in Fig. 2 shows the results for one subject. The percent correct detection is at or close to 100% for the lower noise levels and decreases progressively with increasing noise level, as expected. Performance is generally just above the chance level of 50% for the highest noise level used. It is clear that, over the upper part of the range of noise levels used in experiment 1, one or both of the tones in a forced-choice trial would not have been detected on some trials.

We consider next the hypothesis that, in experiment 1, the decrease in F0 discrimination performance with increasing level was caused solely by the reduced probability that the tone would be detected, rather than by reduced precision in the internal estimate of F0. According to this hypothesis, when both tones in a trial were detected, discrimination of F0 was unaffected by the noise level and was as good as for the lowest noise level used.

To calculate the level of performance predicted on the basis of this hypothesis we assume first that, if the subject detects the tone in both intervals, the probability of discriminating F0 correctly corresponds to that observed in the 2AFC F0-discrimination task for a relative noise level of 8 dB (the lowest level used) for the ΔF0 under consideration. It is necessary also to make an assumption about what happens on trials for which one or both of the tones are not detected. One possibility is that subjects simply guess, in which case the probability of a correct response is 0.5. This represents a lower limit to the performance that can be expected based on the above hypothesis. Another possibility is that, on trials where the tone is detected in only one interval, subjects adopt the optimal strategy of labeling that interval as the one containing the higher F0 whenever the F0 is above 250 Hz and of labeling the interval as the one containing the lower F0 whenever the F0 is below 250 Hz. This optimal strategy assumes that subjects develop a long-term memory representation of the pitch corresponding to the mean of the range of stimuli presented, i.e., the range of F0s presented. This represents an upper limit to the performance that can be expected based on the above hypothesis. We focus here on derivation of the lower limit, since if the measured F0 discrimination performance falls below this lower limit, this would contradict the hypothesis. The use of the "optimal" strategy would lead to only a small improvement in predicted performance, and then mainly for the larger ΔF0 values at high noise levels, due to the randomization of F0 between trials.

As a first stage in the derivation, we converted the percent correct values for the detection data, obtained in the 2AFC task, to values of the detectability index, d' (Macmillan and Creelman, 1991). To reduce the effect of errors of measurement associated with individual data points, for each subject the data relating d' to the signal-to-noise ratio, R (expressed in linear power units), were fitted with a function of the form:

$$d' = kR, \tag{1}$$

where k is a fitting constant (Green and Swets, 1974). The function was fitted to the data for relative noise levels from 12 to 20 dB; the data for the two lowest noise levels were excluded, as d' is difficult to estimate accurately when performance is perfect, or nearly so. The root mean square (rms) difference between the measured d' values and the fitted values ranged from 0.083 to 0.405 across subjects, with a mean of 0.228, indicating that the fits were generally good. The fitted function was used to derive values of d' for each noise level used and these were converted to the probability of detecting the complex tone in a *one-interval task* (Macmillan and Creelman, 1991). We denote this probability, for a background noise level x dB above baseline, as $q(x)$.

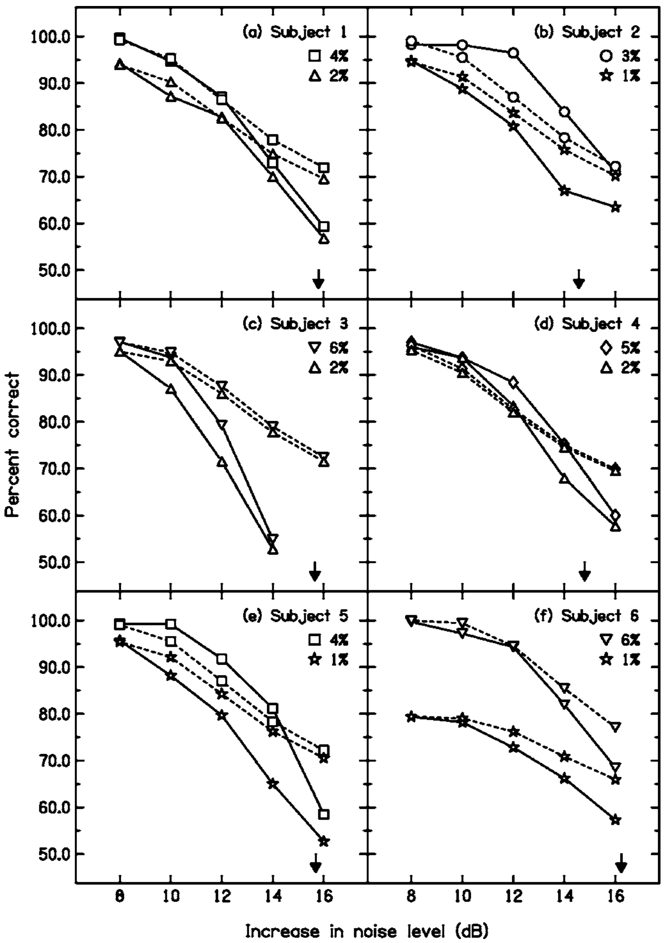

FIG. 3. Predictions of lower limit of performance for F0 discrimination of complex tones filtered between 1375 and 1875 Hz. The solid lines replot performance observed in experiment 1 for a nominal F0 of 250 Hz for the largest and smallest values of ΔF0 used for each subject. The dashed lines show the predicted lower limit of performance based on the assumption that F0 discrimination was limited by the detectability of the tones (see text for details). The down-pointing arrows indicate the noise level leading to 75% correct detection in a 2AFC task, as measured in experiment 2. Performance is plotted as a function of the level of the background noise relative to the baseline level.

In the F0-discrimination task, the probability of detecting both tones in a trial is $q^2(x)$. For trials where this occurs, the probability of correct F0 discrimination is assumed to be equal to that measured for a background noise that is 8 dB above the baseline level, $p(8)$. For trials where one or both tones are not detected, the probability of correct F0 discrimination is assumed to be 0.5. Therefore, the lower limit of proportion correct in the 2AFC F0-discrimination task for a background noise level x dB above the baseline level, $p(x)$, is given by the following expression:

$$p(x) = q^2(x) \cdot p(8) + 0.5[1 - q^2(x)]. \qquad (2)$$

The dashed lines in Fig. 3 show the performance in the 2AFC F0-discrimination task predicted from Eq. (2); to avoid clutter, in cases where subjects were tested using more than two values of ΔF0, predictions are shown only for the smallest and largest values used. Recall that Eq. (2) gives the predicted lower limit to performance based on the above hypothesis. If actual performance falls below predicted performance, this implies that the above hypothesis is false, i.e., that the noise has an effect on F0 discrimination over and above its effect on the detection of the tone.

For the largest value of ΔF0 tested, measured performance fell close to or slightly above predicted performance for relative noise levels up to 12–14 dB, for all subjects except subject 3. For subject 3, measured performance matched predicted performance only for relative noise levels up to 10 dB. For all subjects except subject 2, measured performance for the largest value of ΔF0 fell below predicted performance for the relative noise level of 16 dB, indicating a deleterious effect of the noise on F0 discrimination *per se*. For the smallest value of ΔF0, measured performance fell below predicted performance for relative noise levels of 14 dB or higher for all subjects. For some subjects (3, 5, and 6) this first happened for relative noise levels of 10 or 12 dB. Overall, the results suggest that the noise had a deleterious effect on F0 discrimination *per se*, but only for relatively high noise levels, i.e., the hypothesis is rejected.

The finding of measured performance slightly better than predicted for some noise levels and values of ΔF0 may be accounted for by subjects making use of information from F0-discrimination trials in which only one of the two tones was detected. As noted earlier, on such trials the optimal strategy would be to label the interval in which the tone was detected as the one containing the higher F0 whenever the F0 was above 250 Hz, and to label that interval as the one containing the lower F0 whenever the F0 was below 250 Hz. Calculations of predicted performance based on the optimal strategy indicate that this would lead to only a small improvement in performance, as could be anticipated from the randomization of the mean F0 across trials. The improvement occurs mainly for relatively large values of ΔF0 and for high noise levels. The results of these calculations do not change our basic conclusion that the discrimination of F0 *per se* can be affected by the presence of noise, but only for noise levels within 2–4.5 dB of the level required to reach masked threshold (see below).

V. GENERAL DISCUSSION

The detection "threshold" can be defined as the noise level at which performance reached 75% (illustrated by the dashed horizontal lines in Fig. 2). This level was between 14.6 and 16.2 dB above the baseline level for all subjects. The threshold levels for individual subjects are shown by the down-pointing arrows at the bottom of each panel in Fig. 3. The noise level at which F0 discrimination performance fell below that predicted by Eq. (2) varied somewhat across subjects and across ΔF0 values, from about 10 dB (subject 3, ΔF0=2%) to 16 dB (subject 6, ΔF0=6%). For the larger ΔF0 values used, for three out of the six subjects (subjects 2, 4, and 5) F0 discrimination performance fell below that predicted only when the relative noise level was so high that detection performance was at or below threshold. For subject 2 with ΔF0=3%, measured performance did not fall clearly below predicted performance for any noise level. For those subjects and for large ΔF0s, discrimination performance was equal for a tone containing resolved harmonics and a tone containing only unresolved components when the increase in noise level reduced the detectability of the former but presumably did not reduce the precision of the internal representation of its F0. Typically, for the smaller ΔF0 values used, measured performance first fell below predicted performance for relative noise levels of 12 to 14 dB. The noise only appeared to impair the precision of the internal representation of F0 when the noise level was within 2–4.5 dB of the level required to reach masked threshold. This indicates a remarkable degree of robustness in the mechanism for extracting the F0.

It is instructive to consider whether the results are consistent with models of frequency discrimination based on changes in the excitation pattern (Zwicker, 1956; Moore and Sek, 1994). According to Zwicker's model (Zwicker, 1956, 1970; Zwicker and Fastl, 1999) a change in frequency can just be detected if the excitation level at any point on the pattern changes by 1 dB. Moore and Sek (1994) proposed a model for the detection of frequency and/or amplitude modulation in which information could be combined from different points on the excitation pattern (see also Florentine and Buus, 1981); in this model the change in excitation level required for "threshold" ($d'=1$) is typically about 2–3 dB when the change is restricted to a small region of the excitation pattern (similar values were suggested by Buus and Florentine, 1995); somewhat smaller changes can be detected when the changes occur over a large region. To assess whether such models could account for our data, we calculated excitation patterns following the procedure described by Glasberg and Moore (1990), but using the transfer functions for the outer and middle ear described by Moore *et al.* (1997). The conditions of listening were specified as "diffuse field," as the Sennheiser headphones used here have a diffuse field response.

We started by calculating excitation patterns for two complex tones in noise with a difference in F0 of 4%; the two F0s were 245 and 255 Hz. The spectra of the tones specified as input to the excitation-pattern program took into account the effect of the bandpass filter used in the experiment. The excitation patterns obtained for a relative noise level of 8 dB (the lowest level used) are shown in Fig. 4. The patterns are shown only for center frequencies where the pattern is not dominated by the background pink noise. The largest difference in excitation level between the two patterns was 1.3 dB. This occurred over a very restricted range of center frequencies around 1416 Hz. The difference of 1.3 dB is only slightly larger than the criterion of 1 dB proposed by Zwicker and is markedly smaller than the criterion change required in the model of Moore and Sek (1994) for changes in excitation level in a restricted frequency region. However, performance was close to perfect for this value of ΔF0 and noise level. For the same ΔF0, but with a relative noise level of 14 dB, the maximum difference in excitation level between the two excitation patterns was only 0.5 dB; again this occurred over a restricted part of the pattern around 1416 Hz. Yet, several subjects (subjects 1, 2, 5, and 6) achieved scores over 70% for this value of ΔF0 or a smaller value. It seems implausible that such high scores could be achieved on the basis of such a small difference in the excitation pattern.

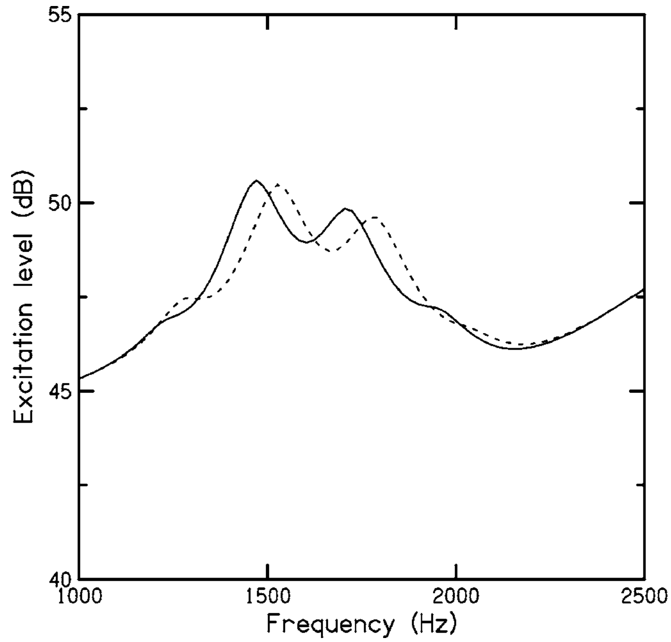

FIG. 4. Excitation patterns for two complex tones with F0=245 Hz (solid line) and 255 Hz (dashed line). The tones were presented in a background of pink noise with a level of 8 dB relative to the baseline level. The patterns are plotted only over the frequency range where they were not dominated by the noise.

Next, excitation patterns were calculated with ΔF0 =2%; the two F0s were 247.5 and 252.5 Hz. For a relative noise level of 8 dB, the largest difference in excitation level between the two was only 0.4 dB. This occurred over a restricted range of center frequencies around 1416 Hz. Yet, all subjects achieved scores over 90% for this value of ΔF0 and noise level. For a relative noise level of 14 dB, the largest difference decreased to only 0.25 dB. Yet, some subjects (subjects 1, 2, 4, and 6) achieved scores in the range 67%–86% under these conditions. Again, it seems implausible that such high scores could be achieved on the basis of such a small difference in the excitation pattern.

Note that the model does not even correctly predict the patterns of performance across conditions. For example, the excitation-level difference for ΔF0=4% and a relative noise level of 14 dB was slightly larger than the difference for ΔF0=2% and a relative noise level of 8 dB, yet performance was markedly worse for the former condition than for the latter.

We conclude that it is unlikely that F0 discrimination performance at the higher noise levels was based on changes in excitation level. It seems more likely that temporal information derived from phase locking was used. A similar conclusion was reached by Moore *et al.* (1984) on the basis of data on the frequency discrimination of individual components within complex tones. In principle, temporal information, if efficiently used, can provide much more precise information about the frequencies of individual components than place information (Siebert, 1970; Heinz *et al.*, 2001a). This applies also to conditions where background noise is present (Heinz *et al.*, 2001a, b).

We described earlier the idea that it might be possible to manipulate the pitch salience of a complex tone with resolved harmonics by varying the level of a background noise. The results presented here indicate that the addition of noise is not a good way to manipulate pitch salience, since the noise level required to reduce the precision of the internal representation of F0 is sufficiently high to markedly reduce the detectability of the tone. The observed effects of noise on F0 discrimination reflect the reduced detectability of the tone as much as, if not more than, the reduced pitch salience of the tone.

VI. SUMMARY AND CONCLUSIONS

Percent correct performance for detecting a complex tone in noise was measured as a function of noise level and compared with percent correct performance for discrimination of the F0 of the same complex tone, again as a function of noise level. The tone included some low, resolvable components, but not the fundamental component. The results were used to test the hypothesis that the worsening in F0 discrimination with increasing noise level was caused by the reduced detectability of the tone rather than by reduced precision of the internal representation of F0. For small values of ΔF0, it was shown that performance fell below that predicted by the hypothesis, but only for high noise levels, within 2–4.5 dB of the level required for masked threshold; at lower levels, the results were consistent with noise reducing performance by virtue of the reduced detectability of the tone. For large values of ΔF0, for some subjects, performance fell below that predicted only when the noise level was so high that it was at or above the level required for masked threshold. For one subject (for a large value of ΔF0) performance never fell below that predicted. The results indicate that the mechanism for extracting the F0 of a complex tone with resolved harmonics is remarkably robust, and operates with high precision even for noise levels sufficient to reduce detectability considerably. The results also indicate that the addition of noise is not a good way to manipulate the pitch salience of a tone with resolved components, since the noise level required to reduce the precision of the internal representation of F0 is sufficiently high to markedly reduce the detectability of the tone. In fact, the results indicate that, at high to medium levels of performance, addition of noise to a tone with resolved components can equate F0 discrimination of that tone to that for a complex tone with unresolved components purely by reducing the detectability of the former.

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ANSI (**2004**). *ANSI S3.6-2004 Specification for audiometers* (American National Standards Institute, New York).

Bernstein, J. G., and Oxenham, A. J. (**2003**). "Pitch discrimination of diotic and dichotic tone complexes: harmonic resolvability or harmonic number?" J. Acoust. Soc. Am. **113**, 3323–3334.

Bilsen, F. A. (**1973**). "On the influence of the number and phase of harmonics on the perceptibility of the pitch of complex signals,"Acustica **28**, 60–65.

Buunen, T. J. F., Festen, J. M., Bilsen, F. A., and van den Brink, G. (**1974**). "Phase effects in a three-component signal," J. Acoust. Soc. Am. **55**, 297–303.

Buus, S., and Florentine, M. (**1995**). "Sensitivity to excitation-level differences within a fixed number of channels as a function of level and frequency," in *Advances in Hearing Research*, edited by G. A. Manley, G. M. Klump, C. Köppl, H. Fastl, and H. Oekinghaus (World Scientific, Singapore).

Cardozo, B. L. (**1974**). "Some notes on frequency discrimination and masking," Acustica **31**, 330–336.

Dye, R. H., and Hafter, E. R. (**1980**). "Just-noticeable differences of frequency for masked tones," J. Acoust. Soc. Am. **67**, 1746–1753.

Florentine, M., and Buus, S. (**1981**). "An excitation-pattern model for intensity discrimination," J. Acoust. Soc. Am. **70**, 1646–1654.

Glasberg, B. R., and Moore, B. C. J. (**1990**). "Derivation of auditory filter shapes from notched-noise data," Hear. Res. **47**, 103–138.

Green, D. M., and Swets, J. A. (**1974**).*Signal Detection Theory and Psychophysics* (Krieger, New York).

Harris, J. D. (**1966**). "Masked DL for pitch memory," J. Acoust. Soc. Am. **40**, 43–46.

Heinz, M. G.,Colburn, H. S., and Carney, L. H. (**2001a**). "Evaluating auditory performance limits: I. One-parameter discrimination using a computational model for the auditory nerve," Neural Comput. **13**, 2273–2316.

Heinz, M. G., Colburn, H. S., and Carney, L. H. (**2001b**). "Evaluating auditory performance limits:II. One-parameter discrimination with random level variation," Neural Comput. **13**, 2317–2339.

Henning, G. B. (**1967**). "Frequency discrimination in noise," J. Acoust. Soc. Am. **41**, 774–777.

Hoekstra, A. (**1979**). "Frequency discrimination and frequency analysis in hearing," Ph.D. thesis, Institute of Audiology, University Hospital, Groningen, Netherlands.

Horst, J. W., Ritsma, R. J., and Wit, H. P. (**1984**). "Frequency discrimination in quiet and in noise for signals with triangular spectral envelopes," J. Acoust. Soc. Am. **76**, 1067–1075.

Macmillan, N. A., and Creelman, C. D. (**1991**). *Detection Theory: A User's Guide* (Cambridge U.P., Cambridge, England).

Moore, B. C. J., and Glasberg, B. R. (**1991**). "Effects of signal-to-noise ratio on the frequency discrimination of complex tones with overlapping or nonoverlapping harmonics," J. Acoust. Soc. Am. **89**, 2858–2865.

Moore, B. C. J., and Ohgushi, K. (**1993**). "Audibility of partials in inharmonic complex tones," J. Acoust. Soc. Am. **93**, 452–461.

Moore, B. C. J., and Sek, A. (**1994**). "Effects of carrier frequency and background noise on the detection of mixed modulation," J. Acoust. Soc. Am. **96**,741–751.

Moore, B. C. J., Glasberg, B. R., and Baer, T. (**1997**). "A model for the prediction of thresholds, loudness and partial loudness," J. Audio Eng. Soc. **45**, 224–240.

Moore, B. C. J.,Glasberg, B. R., and Shailer, M. J. (**1984**). "Frequency and intensity difference limens for harmonics within complex tones," J. Acoust. Soc. Am. **75**, 550–561.

Moore, B. C. J., Glasberg, B. R., Flanagan, H. J., and Adams, J. (**2006**). "Frequency discrimination of complex tones; assessing the role of component resolvability and temporal fine structure," J. Acoust. Soc. Am. **119**, 480–490.

Plomp, R. (**1964**). "The ear as a frequency analyzer," J. Acoust. Soc. Am. **36**, 1628–1636.

Plomp, R., and Mimpen, A. M. (**1968**). "The ear as a frequency analyzer II," J. Acoust. Soc. Am. **43**, 764–767.

Pressnitzer, D., and Patterson, R. D. (**2001**). "Distortion products and the pitch of harmonic complex tones," in *Physiological and Psychophysical Bases of Auditory Function*, edited by D. J. Breebaart, A. J. M. Houtsma, A. Kohlrausch, V. F. Prijs, and R. Schoonhoven (Shaker, Maastricht).

Scheffers, M. T. (**1984**). "Discrimination of fundamental frequency of synthesized vowel sounds in a noise background," J. Acoust. Soc. Am. **76**, 428–434.

Siebert, W. M. (**1970**). "Frequency discrimination in the auditory system: place or periodicity mechanisms," Proc. IEEE **58**, 723–730.

Sinnott, J. M., and Brown, C. H. (**1993**). "Effects of varying signal and noise levels on pure-tone frequency discrimination in humans and monkeys," J. Acoust. Soc. Am. **93**, 1535–1540.

Zwicker, E. (**1956**). "Die elementaren Grundlagen zur Bestimmung der In-

formationskapazität des Gehörs (The foundations for determining the information capacity of the auditory system)," Acustica **6**, 356–381.
Zwicker, E. (**1970**). "Masking and psychological excitation as consequences of the ear's frequency analysis," in *Frequency Analysis and Periodicity Detection in Hearing*, edited by R. Plomp and G. F. Smoorenburg (Sijthoff, Leiden).
Zwicker, E., and Fastl, H. (**1999**). *Psychoacoustics—Facts and Models, Second Edition* (Springer-Verlag, Berlin).