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Effects of signal envelope on the pitch of short sinusoidal tones

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The pitch of short sinusoidal tones with exponentially rising or decaying envelopes is judged higher than the pitch of a gated tone of the same frequency, duration, and energy. The upward pitch shift depends on the rise or decay rate, the intensity, and the frequency. The effect, which requires a nonlinearity in the auditory system, cannot be adequately explained by existing models of hearing. Control experiments on pitch matching for short tones of varying duration and varying intensity are described. These suggest that envelope-induced pitch effects are linked to changes in average intensity, so that they are essentially the same as intensity-induced pitch changes. A model based on these considerations is proposed.

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INTRODUCTION

Although the pitch of a sinusoidal tone is mainly determined by its frequency, it may depend on other parameters as well, such as intensity (Stevens, 1935; Cohen, 1961; Terhardt, 1974; Verschuure and van Meeteren, 1975), duration (Doughty and Garner, 1948; Hartmann *et al.*, 1985), envelope shape (Hartmann, 1978), masking tones or masking noise (Terhardt and Fastl, 1971), or a preceding or following tone (Békésy, 1960; Rakowski and Hirsh, 1980; Ebata *et al.*, 1984). Pitch shifts brought about by changes in these parameters can sometimes be as large as a semitone, but can also vary considerably among subjects. This may be one of the reasons why there are no satisfactory physiological or even black-box models that can account for these phenomena.

The aim of this investigation was to study the influence of envelope shape on the pitch of short sine tones and harmonic two-tone complexes. In this paper, pitch differences between short sinusoidal tones of the same frequency, one with an exponentially falling or rising amplitude envelope, the other with a constant envelope, are systematically studied. In a future paper, we will discuss the effect of amplitude envelope on the fundamental pitch and on the pitches of partials of complex tones.

Hartmann (1978) showed that the perceived pitch of a short exponentially decaying sinusoidal tone is consistently higher than the pitch of a simply gated sine tone of the same frequency and energy. His experiment was carried out over a 3-oct frequency range, at one sound-pressure level (89 dB SPL for the comparison tone) and at one exponential test tone decay rate (1 dB/ms). Cohen (1982), on the other hand, found that slowly decaying exponential envelopes imposed on "buzz" tones (periodic pulses with a 9 dB/oct spectral rolloff) caused their pitch to decline, while rising exponential envelopes caused an upward pitch shift. His envelope climb and decay rates ranged from 0.03–0.2 dB/ms, and his buzz tones had fundamentals of 140 Hz.

In the experiments reported in this paper, pitch matches were made between short sine tones with exponentially falling, rising, and constant amplitudes at several intensity levels. Some control experiments are presented that allow comparison of envelope-induced pitch changes with effects of simple variations in tone intensity or duration. Throughout the experiments the same subjects were used and experimental procedures were kept mostly the same, to make the results as comparable as possible. An attempt is made to explain all measured envelope-induced pitch effects in terms of a primary intensity effect and a secondary duration effect.

Four experiments are discussed in this paper. The first one deals with measured pitch differences between short sinusoidal test tones with exponentially decaying amplitudes and comparison tones with constant amplitudes. Pitch changes are measured as a function of exponential envelope decay rate and overall intensity of the experiment. The second experiment is identical with the first, except that rising instead of falling exponential envelopes are used. In the third experiment, the effect of stimulus duration on the pitch of constant-amplitude pure tones is investigated, and, in the fourth experiment, pitch changes induced by intensity variations are studied. In the final section of the paper, a model is proposed that attempts to connect the different measured phenomena.

I. EXPERIMENT 1

A. Method

In this experiment, the pitch of a 40-ms sinusoidal test tone pulse with an amplitude that started to decay exponentially at the onset of the tone was compared with the pitch of a 40-ms sinusoidal comparison tone pulse of constant amplitude. Both pulses alternated regularly with 860-ms inter-pulse silent intervals. The exponential decay rate of the test tone (0.5, 1, 2, 4, or 8 dB/ms) and the intensity of the comparison tone (70, 80, 90, or 100 dB SPL) were the experimental variables. Test and comparison tones were gated on in sine phase and were truncated after 40 ms. Initial amplitudes of the test tones were computed such that the stimulus energy in test and comparison tones was always the same.

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Measurements on the electrical signals delivered to the headphones showed that even in the worst cases (8-dB/ms decay, low frequency), initial test tone amplitudes were correct within 1 dB. This equal-energy condition made test and comparison tones roughly of equal subjective loudness. Stimuli were computed between trials by a Philips P857 computer, converted through a two-channel 12-bit D/A converter, and were presented binaurally through TDH-49 headphones with MX41/AR cushions. This system has sufficient bandwidth to provide an accurate acoustic representation of all signals used, which was verified by visual inspection of the signal from a Bruel & Kjaer artificial ear and $\frac{1}{2}$ -in. microphone. The subject, who was seated in an IAC double-wall chamber, was instructed to turn the unmarked dial of a ten-turn potentiometer which controlled the frequency of the comparison tone, using a bracketing procedure, until test tone and comparison tone sounded matched in pitch. At the push of a button, the frequency of the comparison tone was recorded and a new stimulus sequence presented. Four runs of 20 match trials each were taken with four different subjects at all five test tone decay rates and a comparison tone level of 100 dB SPL, and at four overall intensity levels and a test tone decay rate of 2 dB/ms. Each run of 20 trials, typically lasting 10 min, covered a test tone frequency range of 1 oct, so that from each of the four subjects 80 match trials were collected over a 4-oct frequency range from 200 to 3200 Hz. Test tone frequencies were chosen randomly within each octave band. The final frequency difference recorded at each pitch match was interpreted as an indicator of pitch difference between test and comparison tones when these have equal frequencies.

Three of the four subjects had previous musical training and were familiar with psychoacoustical experimentation. These included both authors. The fourth subject had no musical training or previous experience with systematic listening experiments.

B. Results

The pitch shift data were first processed individually for each subject. The similarity in behavior was such that averaging across subjects seemed justified. Data points of all four subjects were therefore pooled within each of the 4-oct bands of test tone frequencies, for every combination of envelope decay rate and intensity, and the means and standard deviations of the means were computed.

The results are shown in Fig. 1, where the frequency difference between comparison tone and test tone is plotted as a function of test tone frequency. A positive frequency difference on the ordinate means that the comparison tone frequency was greater than the test tone frequency at equal subjective pitch, and that, conversely, the test tone would sound that much higher in pitch if both frequencies were equal. The abscissa shows the test tone frequency f_t on a logarithmic scale divided into octave bands. The mean pitch shift for each octave band is plotted at the (geometric) center frequency of that band, together with the limits of one standard deviation of the mean.

Figure 1(a) shows pitch shifts for a comparison tone intensity of 100 dB SPL and for five different exponential

FIG. 1. Pitch shift Δf as a function of test tone frequency f_t for various exponential signal decay rates (a), and for different intensities (b). Test tone frequencies along the abscissa are plotted in octave bands. Averages and averages $\pm$ one standard deviation of the mean (SD_m) of data from four subjects. Symbols top figure: 0.5 dB/ms ($\circ$), 1 dB/ms ($\triangle$), 2 dB/ms ($+$), 4 dB/ms ($\times$), and 8 dB/ms ($\diamond$). Symbols bottom figure: 70 dB ($\circ$), 80 dB ($\triangle$), 90 dB ($+$), and 100 dB ($\times$) SPL.

decay rates of the test tone. Figure 1(b) shows similar results for four different intensities at which the experiment was performed with a test tone decay rate of 2 dB/ms. Besides the dashed curves, which simply connect the pitch shift means of each octave band, sets of linear approximations of the data are shown as solid lines. These were obtained by fitting straight lines by eye between the limits of the standard deviations of the means. This simple linear description of the data allows comprehensive data description in terms of a product of three functions, one of sound-pressure level, one of decay rate, and one of test tone frequency, respectively. This expression is

$$\Delta f = 0.0221 e^{0.07 L_p} (\log x + 0.4508) (\log f_t - 2), \quad (1)$$

where Δf is the frequency difference between comparison and test tone (or pitch shift) in Hz, L_p is the sound-pressure level of the comparison tone in decibels, x is the exponential decay rate of the test tone in dB/ms, and f_t is the test tone frequency in Hz. This formula is only meant as a description of the data, and does not provide any insight into causal relations between pitch, intensity, and envelope decay rate.

The variance in the data taken at test tone decay rates of 8 dB/ms is quite large. This is a direct result of spectral "splatter" for tones that may have only two or three audible cycles. These test tones sound like clicks with a very faint tonality. Also, sound-pressure levels of 100 dB for the comparison tone, and sometimes near 120 dB SPL for the initial level of the test tone, may seem very high. Those levels are actually quite safe, however, because of the short durations, lying well below TTS-inducing levels (Smoorenburg, 1982).

No complaints of discomfort were heard from subjects during the experiment.

C. Discussion

The results of experiment 1 firmly establish the envelope-induced pitch shift effect first reported by Hartmann (1978). They also show that this rather robust effect holds across subjects and is found at different tone decay rates and intensities. The data obtained by Hartmann at 89 dB SPL and 1-dB/ms test tone envelope decay, which showed average pitch shifts of 10 Hz at 400, 12 Hz at 800, 16 Hz at 1600, and 28 Hz at 3200 Hz are quite comparable with our results at 100 dB SPL and 2 dB/ms. Given the possible difference in absolute calibration of the sound level at two laboratories, differences in truncation of the test tone, duration differences of the comparison tone, and also the differences between Hartmann's forced-choice and our matching procedure, we see no basic discrepancy between Hartmann's results and ours.

The important new information provided by our data is the systematic dependence of envelope-induced pitch shift on overall intensity. This intensity dependence is significant because it shows that the phenomenon under study is essentially nonlinear. The short-term spectral model or the Huggins phase difference model proposed by Hartmann (1978) as possible explanations of the pitch shift effect are, therefore, insufficient because they are linear models, and must at least be modified with some nonlinear amplitude dependence.

Our results are quite different from those of Cohen (1982) who used complex test tones with much slower envelope decay rates, between 0.03 and 0.2 dB/ms, and also complex tones compared to the sinusoidal tones of our experiments. Cohen found negative pitch shifts whereas we found, almost exclusively, positive shifts. Our data are also inconsistent with Cohen's neural coding theory, which says that neural spike signals evoked by intense sounds travel faster along the auditory pathways than spikes evoked by acoustically weaker signals. Such a neural mechanism implies that a tone whose intensity decreases with time evokes a train of progressively further delayed spikes, i.e., a spike train with a stretched interspike interval. Such a train should perceptually evoke a lowered pitch sensation. A rising tone envelope, on the other hand, should evoke a sensation of increased pitch. Our data show that the measured pitch shifts consistently go in a direction opposite to what Cohen's theory predicts, and also that these shifts become larger when the test tone decay rate increases.

Cohen's model does raise a very important question, however. If the rate of change of the test tone envelope is made positive, i.e., if exponentially rising test tones are used, and all other parameters of our present experiment are left unchanged, will the direction of pitch shift reverse? If this happened, it would indicate that the observed pitch shift depends directly on the rate of change of the test tone envelope, including its sign. Alternatively, the results of experiment 1 could be an artifact of a change in effective duration of the test tone. Or, perhaps, they could reflect a change in average intensity, because despite the equal amounts of ener-

gy in test and comparison tone, there were systematic differences in average amplitude or sound-pressure level. These possibilities were explored in three other experiments that employed the same general procedure as experiment 1, and used three of its four subjects.

II. EXPERIMENT 2

A. Method

The procedure of the second experiment was exactly the same as the procedure of experiment 1, except that the test tones were reversed in time. This means that the exponentially rising test tone was gated on in some random phase such that, exactly 40 ms later, it was switched off at a negative zero crossing. The three subjects with musical experience from experiment 1 were used.

Pitch matching data were taken at a comparison tone level of 100 dB SPL, and at exponential climbing rates of 0.5, 1, 2, and 4 dB/ms for the test tone. Measurements were taken over the same 4-oct test tone frequency range as in the first experiment.

B. Results

Although the behavior of one of the subjects at the steeper envelope climbing rates deviated somewhat from the other two subjects' behavior, the data still seemed sufficiently similar to justify averaging. The results, shown in Fig. 2, are plotted in the same format as the data of the first experiment. One sees that, despite the temporal reversal of the test tone envelope, the measured pitch shift is still clearly positive. In fact, the data are quite similar to those shown in Fig. 1(a), except that the curves for envelope climbing rates of 2 and 4 dB/ms show less rise at the higher frequencies. This is largely due to the behavior of one subject who, in contrast to the other two, showed a sharp decline in pitch shift for combinations of steep envelopes and high frequencies.

C. Discussion

Despite minor differences between the results of experiments 1 and 2, it seems reasonable to conclude that they are essentially the same. The conclusion from the two experiments is that a positive pitch shift is obtained when a short gated sine tone is changed into a sine tone burst with exponential envelope, and that the magnitude of the pitch shift

FIG. 2. Pitch shift as a function of frequency for various exponential signal climbing rates. Averages $\pm$ one SD_m from three subjects. Symbols: 0.5 (○), 1 (△), 2 (+), and 4 (×) dB/ms.

depends systematically on intensity and envelope rate of change, regardless of its sign. This finding limits the range of explanations of the pitch shift phenomenon still further. It specifically rules out the Huggins phase difference model as a possible explanation of the pitch shift effect, because such a model necessarily implies a pitch lowering for a tone with an exponentially rising envelope. Furthermore, models which assume some kind of causal relation between instantaneous signal amplitude and periodicity in neural firings also predict opposite pitch shifts for rising and falling signal envelopes. The present data suggest that pitch shift may not be directly related to signal envelope as such, but to some artifact of signal envelope such as the effective duration. This idea will be pursued in the next experiment.

III. EXPERIMENT 3

A. Method

The purpose of this experiment was to investigate the dependence of the pitch of a short sine tone on its duration. The procedure was again the same as the one used in experiments 1 and 2, but this time the test signal was also a gated sine tone turned on in sine phase and turned off after exactly 10 or 20 ms. The experiment was done in two parts. In the first part, the test tone amplitude was chosen such that it had the same energy as the 40-ms, 100-dB SPL comparison tone, whereas during the second part of the experiment the test tone had the same amplitude as the comparison tone. Runs of 20 pitch match trials, one for each test tone octave band from 200 to 3200 Hz, were made by the same three subjects who had participated in experiment 2.

B. Results

The results, averaged over subjects and over frequencies within each test tone octave band, are shown in Fig. 3. Figure 3(a) shows the data for test tone pulses of the same energy as comparison pulses, and Fig. 3(b) shows similar data for test tone pulses of the same amplitude as the comparison tones. In both cases, it is evident that shortening a tone pulse from 40 to 20 ms does not alter its pitch significantly. The data for the 10-ms test tone pulses show considerably more variance than the 20-ms test tone data. This seems at first not too surprising because the shorter the tones, the more difficult it should be to match the pitches because of spectral splatter. Inspection of the unaveraged data, however, shows that the noise in the 10-ms test tone data is mostly due to differences in matching behavior of the three subjects, and not so much to varying pitch matches of each subject.

C. Discussion

The fact that only two test tone durations were used in this experiment, and the apparent fact that matching behavior is quite different under these two conditions, makes it necessary to view the present results in the context of other comparable experiments reported in the literature. Unfortunately, there seem to be only two studies that are relevant. One is a study by Doughty and Garner (1948) in which 90-dB SPL, 500-ms comparison tones were matched in pitch to test tone pulses of 250, 1000, and 4000 Hz with various

FIG. 3. Pitch shift as a function of frequency between 10-ms ($\circ$) or 20-ms ($\triangle$) test tone pulses and 40-ms comparison tone pulses. (a) Test tone pulses were amplitude compensated for same energy as comparison tone. (b) Test tones had same amplitude as comparison tones. Averages $\pm$ one SD_m from three subjects. Crosses are data points taken from Doughty and Garner (1948).

(short) durations. The other is a recent study by Hartmann *et al.* (1985) in which, primarily, the variance of pitch matches for short sinusoidal tones was studied, but tendencies in mean pitch shift were also reported.

Doughty and Garner found no measurable pitch shift with test tone durations of 20 and 50 ms. Hartmann *et al.*, however, reported that in pitch matches between 25-ms and 50-ms tone pulses of the same frequency, the shorter tones appear to have the higher pitch most of the time, but they do not indicate how much higher. Their results also show that mean pitch matches vary from one subject to another, and that sometimes the mean match systematically depends on which of the two tones is being adjusted. When we consider all three experiments with 20-ms tone pulses together, ignoring the 5-ms duration difference in the experiment by Hartmann *et al.*, one might say that the slightly negative shift observed in the present experiment is qualitatively offset by Hartmann's average positive shifts, so that, consistent with the Doughty and Garner results, no measurable average pitch shift occurs for an arbitrary group of subjects.

For 12-ms test tones, Doughty and Garner reported an average negative pitch shift of two percent at 250 Hz, 1% at 1000 Hz, and no shift at 4000 Hz, all in comparison with a

500-ms adjustable tone. Because they had not found any shift between a 50-ms test tone and a 500-ms comparison tone, their results imply that the same shifts should have been found with a 12-ms test tone and a 50-ms comparison tone, a condition comparable to our experiment. Doughty and Garner's results, which are plotted in Fig. 3(b) as crosses, agree qualitatively with ours in the sense that the resulting shift versus frequency function shows a "down and up" trend. Our positive pitch shift at high frequencies, however, is much larger than theirs. When Hartmann *et al.* compared tones of 25- and 50-ms duration, they found that for tones of 1000 Hz and below, the shorter tone had a lower average pitch in 10 out of 15 test conditions, a higher pitch in one condition, with no consistent relationship between match and duration in the other four conditions. At test tone frequencies of 2000, 4000, and 7000 Hz, they report that the shorter tone appeared to have the higher pitch in 21 of 30 test conditions. Although no information is given on the magnitude of the observed shifts, the tendency of their data agrees well with our results shown in Fig. 3. When we put the results of all three studies together, one could conservatively argue that at least the slope of the pitch shift versus frequency function must be positive when the test tone has a duration of about 10 ms and the comparison tone is several times longer.

Duration-dependent pitch shift studied in this experiment does not seem to provide a sufficient basis to explain the effects that were demonstrated and measured in the first two experiments. Test tone pulses of 20 ms do not exhibit any significant pitch shift compared with longer tones of the same frequency, whereas exponentially decaying or rising tones of similar effective duration show a rather robust pitch shift, even when effective duration is conservatively defined as one exponential time constant. The pitch-duration effect which was found at very short test tone durations (10 ms) varies considerably from one experiment to another, and also from one subject to another within the same experiment. This is incompatible with the robust nature of pitch shifts induced by exponential shaping of the amplitude envelope. There must be another, more fundamental cause for the consistent shifts found in the first two experiments. At the most one could say that, as a secondary effect, tones with very steep rates of envelope change may cause an extra pitch rise at high frequencies, and a pitch drop at low frequencies. This would introduce a tilt function of pitch shift versus test tone frequency, increasing its slope. The cause of a primary effect, however, must be found elsewhere.

IV. EXPERIMENT 4

A. Method

The purpose of this experiment was to study the influence of intensity on the pitch of 40-ms sine tone bursts. The reason for doing this experiment in the light of the rather abundant data on pitch-intensity relations available in the literature is that most of these data deal with sine tones of much longer duration than the tones we used in this study (Stevens, 1935; Cohen, 1961; Terhardt, 1974; Verschuure and van Meeteren, 1975). The Doughty and Garner (1948)

experiment is the only one we found that had conditions directly comparable to ours. In addition, of course, we wanted to perform the pitch-intensity experiment on the same subjects and under the same general laboratory conditions as the previous experiments.

The experimental procedure was again the same as the one described before, except that this time both test and comparison tones were 40 ms long, gated on in sine phase, and had a constant amplitude. The comparison tone was kept at 100 dB SPL, and the test tone took values of 110, 90, 80, 70, or 60 dB SPL. Runs of 20 pitch-matching trials were taken for each of the four test tone frequency octave bands between 200 and 3200 Hz. Three subjects participated in the runs taken at test tone intensities of 110 and 80 dB, the other runs were done with only two subjects.

B. Results

The results, averaged over subjects and test tone frequencies of each octave band, are shown in Fig. 4(a). The data show a rather uniform and monotonic dependence of pitch on intensity. Test tones, stronger than the comparison tone of 100 dB SPL, sound lower, whereas test tones of lower intensity, sound progressively higher in pitch. The positive pitch shift seems to saturate at a test tone level of about 70 dB SPL.

FIG. 4. Intensity-induced pitch shifts for 40-ms tone pulses as a function of frequency. Test tones were at 110 dB (○), 90 dB (△), 80 dB (+), 70 dB (×), and 60 dB (◇) SPL. The comparison tone was at 100 dB SPL. (a) Means $\pm$ one SD_m of data from three (or two) subjects. (b) Simplified straight-line description of the subject-averaged data.

Figure 4(b) shows an approximate description of the same data by straight lines. This simplification of the data, which was done by eye, turns out useful in explaining the results of experiments 1 and 2 in terms of the present data.

C. Discussion

The rather regular and uniform behavior of pitch as a function of intensity, found in this experiment, contrasts with results of several pitch-intensity studies for pure tones found in the literature. Stevens (1935) found that the pitch of sine tones above 2000 Hz, increased with increasing intensity, and below 1000 Hz, decreased. In the present experiment, a general decline of pitch with increasing intensity is found all the way up to a test tone frequency of 3200 Hz, the highest tested. Cohen (1961), Terhardt (1974), and Verschuure and van Meeteren (1975) all found that pitch-intensity relations vary considerably among subjects. We did not find too much variance in our data, but, of course, three of the runs were done with only two subjects. All these comparisons, however, are only of limited relevance because the test tone durations used in most of these literature studies were much greater than the ones we used.

In fact, the only comparable study we encountered (Doughty and Garner, 1948) had results that are in excellent agreement with ours. Using 12-ms sine tone bursts and a comparison tone level of 110 dB SPL, they found pitch rises of about 1% for every 10-dB decrease in test tone intensity. This held true for test tone frequencies of 250, 500, 1000, 2000, 4000, and 8000 Hz. The pitch increase stopped at a test tone level of 70 dB SPL. The agreement between our data, measured with two or three subjects over a 4-oct frequency and a 50-dB intensity range, and their data measured with ten subjects over a 5-oct and a 80-dB range, is further support for the general validity of the linear data simplification shown in Fig. 4(b).

From the effects of duration and intensity on the pitch of short pure-tone pulses, the intensity effect appears by far the more robust and systematic. The next section will present an attempt to explain the observed envelope-induced pitch effects in terms of a primary intensity effect and a secondary duration effect.

V. TOWARDS A MODEL

The results of experiments 1, 2, and 4 suggest that envelope-induced pitch shift may not be caused by signal envelope as such, but rather by some quantity that is influenced by signal envelope, such as average intensity or average amplitude. Although in the first two experiments test and comparison tones always had the same energy, and, therefore, also the same average power, one still can find several amplitude-related averages that are not equal. One of such quantities is illustrated in Fig. 5. For each of the test signal envelopes of experiments 1 and 2, the sound-pressure level is shown on a linear time scale, resulting in a family of straight lines since envelopes were exponential. For each of these contours, the arithmetic average (in dB) is computed. A threshold at 50 dB SPL has been introduced below which no averaging takes place, so that tails of steeply decaying (or climbing) exponential signals are discarded. This threshold

FIG. 5. Sound-pressure levels of signals from experiment 1 as a function of time, for (a) a 100-dB-SPL comparison tone and (b) a 70-dB comparison tone.

is the main nonlinear element in the model and is crucial for the model's ability to account for the intensity dependence of pitch shift effects found in the first two experiments. Figure 5(a) shows test and comparison tone contours for a comparison tone of 100 dB SPL, and Fig. 5(b) for a level of 70 dB. A list of averaged levels relative to comparison tone level is found in Table I.

Figure 6 represents a plot obtained from vertical slices of Fig. 4(b). It shows pitch shift dependence on test tone intensity (relative to the 100-dB comparison tone), with the octave band of the test tone frequency as parameter. With the aid of this set of curves, every average log-amplitude value from Table I is converted into an expected pitch shift Δf (in Hz). A plot of these shift values against frequency yields a set of predicted pitch shift curves for experiments 1 and 2. The model makes identical predictions for these two experiments because of the averaging of signal amplitude.

Two sets of model-generated predictions are shown in Fig. 7. Figure 7(a) shows results for high comparison-tone levels (100 dB), and Fig. 7(b) for low comparison-tone levels (70 dB). Comparing these figures with Figs. 1 and 2, one

TABLE I. Envelope slopes, initial sound-pressure levels, and average log-amplitude levels relative to comparison tone levels for 100- and 70-dB comparison tones. Values hold for signals used in experiments 1 and 2.

	Env. slope (dB/ms)	In. level (dB)	Av. level-Comp. level (dB)
100 dB	0.5	107.1	- 2.9
Comp. tone	1.0	109.7	- 10.3
	2.0	112.6	- 18.7
	4.0	115.7	- 17.2
	8.0	118.7	- 15.7
70 dB	0.5	77.1	- 2.9
Comp. tone	1.0	79.7	- 5.1
	2.0	82.6	- 3.7
	4.0	85.7	- 2.2
	8.0	88.7	- 0.7

FIG. 6. Average pitch shifts as a function of intensity difference between test tone and a comparison tone of 100 dB SPL. Functions are obtained from the simplified data of Fig. 4(b). Curve parameters are the octave band numbers of the test tone frequencies [(1) 200–400 Hz, (2) 400–800 Hz, etc.].

sees, on the one hand, that the model makes qualitatively correct predictions. On the other hand, however, comparison of Figs. 7(a) and 1(a) shows that the model does not predict a sufficiently large pitch shift for large exponent values, especially at the higher frequencies, when the overall intensity is large. This is a direct result of the model's threshold, which controls the maximum difference between test tone and comparison tone amplitude averages. Lowering this threshold to, say, 30 or 20 dB SPL will improve the similarity between Figs. 7(a) and 1(a), but will also significantly increase pitch shifts in Fig. 7(b). At intensities of 70 dB SPL such pitch shifts are not found empirically, as the data of Fig. 1(b) clearly show.

The model we propose resembles in some respects the model used by Ronken (1971) to account for equal discriminability in pitches of short sinusoidal tones having different amplitude envelopes. Ronken found that pitch discriminability for short tones does not depend much on bandwidth or duration as such, but rather on effective dura-

FIG. 7. Model-generated predictions of expected results for experiment 1 [Fig. 1(a) and (b)], from data of experiment 4 (Fig. 4). (a) Predictions for 100 dB SPL; (b) predictions for 70 dB SPL.

tion defined as the time that the signal is above a certain threshold. He was able to account for his discrimination data using a threshold value of 50 dB above the noise floor, which is in excellent agreement with our threshold of 50 dB SPL for measurements in a very quiet environment. The apparent fact that results of two entirely different experiments can be accounted for with similar models that have the same threshold value may indicate that the proposed model is not merely an *ad hoc* construction, but may have general significance.

Another nonlinear element of the model, besides the threshold, is the logarithmic amplitude transformation. The choice of a logarithmic transformation is to a large extent arbitrary, although such transformations are very commonly used in the literature on intensity perception. It is possible, however, that some other nonlinear transformation could result in a greater spread between the functions of Fig. 7(a) without spreading those of Fig. 7(b). On the other hand, one can show that a quantity such as effective intensity, i.e., the signal power integrated over and divided by the above-threshold time interval, does not lead to a correct prediction of pitch matching behavior. Because all signals used in experiments 1 and 2 had the same amount of energy, one finds that, for all signals that remained above the 50-dB threshold, the effective intensities are identical so that their pitches should be the same. This holds for the test signals with a rise or decay of 0.5 and 1.0 dB/ms, as well as for the comparison tones. Figures 1(a) and 2 clearly show that there is a significant pitch shift for those signals. A similar argument can be made when one tries to use the effective rms value of the test signal.

Another possible way to solve the quantitative discrepancy between the data of experiment 1, shown in Fig. 1, and the predictions of the proposed model shown in Fig. 7 is to view envelope-induced pitch shifts as the result of two cumulative effects. The primary effect is one of intensity difference and is described by the above model. A secondary effect of duration may play a role when exponentially changing tone bursts become very short, i.e., at high decay or climbing rates. That secondary effect, although not well understood or modeled, tends to tilt the pitch shift curves toward a higher slope value, as one can see in the 10-ms tone pulse data of Fig. 3(a) and (b). Such an extra "tilt" in the 4- and 8-dB/ms curves of Fig. 7(a) improves their similarity to comparable empirical curves of Fig. 1(a).

The pitch shift effects described in this study can be used conveniently as a tool to study other problems in hearing. To this end, one does not need to understand the effect entirely, nor have a good model for it. An example where this tool is used to investigate the dependence of complex-tone (virtual) pitch on pure-tone (spectral) pitch will be discussed in a future paper.

Finally, the proposed model has rather obvious limitations. The model does not really explain why observed pitch shifts happen, but merely explains envelope-induced pitch shifts in terms of intensity-induced shifts. Intensity-induced pitch shifts have been studied extensively in the literature, but have never really been explained. The results of this study may provide an incentive for a renewed interest in this pitch shift phenomenon.

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- Békésy, G. von (1960). *Experiments in Hearing* (McGraw-Hill, New York), pp. 364–368.
- Cohen, A. (1961). "Further investigation of the effects of intensity upon the pitch of pure tones," *J. Acoust. Soc. Am.* **33**, 1363–1376.
- Cohen, J. R. (1982). "A theory of neural coding of pitch," Working paper No. 705, Institute for Defense Analyses, Princeton, NJ.
- Doughty, J. M., and Garner, W. M. (1948). "Pitch characteristics of short tones II: pitch as a function of duration," *J. Exp. Psychol.* **38**, 478–494.
- Ebata, M., Tsumura, N., and Okuda, J. (1984). "Pitch shift of tone burst in

the presence of preceding or trailing tone," *J. Acoust. Soc. Jpn.* **5**, 149–155.

- Hartmann, W. M. (1978). "The effect of amplitude envelope on the pitch of sinewave tones," *J. Acoust. Soc. Am.* **63**, 1105–1113.
- Hartmann, W. M., Rakerd, B., and Packard, T. N. (1985). "On measuring the frequency difference limen for short tones," *Percept. Psychophys.* **38**, 199–207.
- Rakowski, A., and Hirsh, I. J. (1980). "Poststimulatory pitch shifts for pure tones," *J. Acoust. Soc. Am.* **68**, 467–474.
- Ronken, D. A. (1971). "Some effects of bandwidth-duration constraints on frequency discrimination," *J. Acoust. Soc. Am.* **49**, 1232–1242.
- Smootenburg, G. F. (1982). "Damage risk criteria for impulse noise," in *New Perspectives on Noise Induced Hearing Loss*, edited by R. P. Hamernik, D. Henderson, and R. Salvi (Raven, New York), pp. 471–490.
- Stevens, S. S. (1935). "The relation of pitch to intensity," *J. Acoust. Soc. Am.* **6**, 150–154.
- Terhardt, E. (1974). "Pitch of pure tones: its relation to intensity," in *Facts and Models in Hearing*, edited by E. Zwicker and E. Terhardt (Springer, New York), pp. 353–360.
- Terhardt, E., and Fastl, H. (1971). "Zum Einfluss von Störtönen und Störgeräuschen auf die Tonhöhe von Sinustönen," *Acustica* **25**, 53–61.
- Verschuure, J., and van Meeteren, A. A. (1975). "The effect of intensity on pitch," *Acustica* **32**, 33–44.