Enhancing and unmasking the harmonics of a complex tone

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Alternately eliminating and reintroducing a particular harmonic of a complex tone can cause that harmonic to stand out as a pure tone—separately audible from the rest of the complex-tone background. In the psychoacoustical literature the effect is known as "enhancement." Pitch matching experiments presented in this article show that although harmonics above the 10th are not spectrally resolved, harmonics up to at least the 20th can be enhanced. Therefore, resolution is not required for enhancement. Further, during those experimental intervals in which a harmonic is eliminated, excitation pattern models suggest that listeners should be able to hear out a neighboring harmonic—separately audible from the background. The latter effect has been called "unmasking." In the present article we provide the first experimental evidence for unmasking. Harmonics of 200 Hz, with harmonic numbers between about 5 and 16, are readily unmasked. Their pitches are usually matched by sine tones with frequencies that are not exactly those of the unmasked harmonics but are shifted in a direction away from the frequency of the pulsed harmonic. Phase relationships among the harmonics that produce temporally compact cochlear excitation lead to reduced enhancement but greater unmasking. © *2006 Acoustical Society of America.*
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I. INTRODUCTION

Demonstration number one on the compact disc *Auditory Demonstrations* (Houtsma, Rossing, and Wagenaars, 1987) is called "Cancelled Harmonics." In this demonstration a particular harmonic of a complex tone is alternately turned off (cancelled) and turned on, i.e., pulsed. As a result, that particular harmonic is heard as an independent entity standing out from the complex-tone background. Rather surprisingly, this harmonic can often be heard for an indefinitely long time after finally being turned back on. The effect is not new. Helmholtz (1877) quotes Seebeck's remark that the duration of the percept depends on the "… liveliness of our recollection of the tones heard separately." In the more modern literature the electronic version of the technique was attributed to Schouten by Cardozo (1967), and the pulsed harmonic is said to be "enhanced" (Viemeister, 1980; Viemeister and Bacon, 1982; Summerfield *et al.*, 1987). By this technique, many harmonics of a complex tone can be made individually audible. By contrast, normal listening to the complex tones of speech or music does not reveal individual harmonics. Instead, the harmonics are collectively absorbed into the global property of tone color or timbre.

The Cancelled Harmonics demonstration found on the *Auditory Demonstrations* disc presents a complex tone with a fundamental frequency of 200 Hz and 20 harmonics of equal amplitude. In order of increasing harmonic number, the first ten harmonics are turned off and on in 7-interval sequences. Thus the maximum harmonic frequency exposed in this way is $10\times 200=2000$ Hz.

The fact that enhancement can expose harmonics up to the tenth can be contrasted with the harmonic identification task of Plomp and Mimpen (1968), which showed that harmonics could be resolved up to a limit between the fifth and seventh harmonics. *A priori*, it seems possible that the cancelled harmonic demonstration is just a less demanding version of the same thing—capable of exposing harmonics as high as the tenth because they are, at least to some extent, resolvable. The tenth harmonic was recently identified as the limit in the resolution and pitch experiments of Bernstein and Oxenham (2003). That view would suggest that the enhanced harmonic effect might not work much beyond the tenth, though pitch matching experiments by Gibson (1971) found an effect for harmonics as high as the 11th or 12th. By contrast, Yes-No detection experiments by Goupell *et al.* (2003) and Goupell and Hartmann (2004) showed that some trace of a pulsed harmonic could be detected for harmonic numbers as high as 69.

Because of the huge difference in experimental results from different experimental methods, we decided to try the pitch matching method. The pitch matching task is demanding because there is no prior constraint on the matching frequency. If a listener can successfully match the pitch of a pulsed harmonic then that is good evidence that the harmonic is audible.

II. EXPERIMENT 1—SEVEN-INTERVAL SEQUENCE—SINE PHASE

Experiment 1 followed the format of the compact disc's Cancelled Harmonics demonstration, making a selected harmonic separately audible by pulsing it off and on in a seven-interval sequence, as shown by the spectrogram in Fig. 1. Listeners were required to match the pitch of the harmonic

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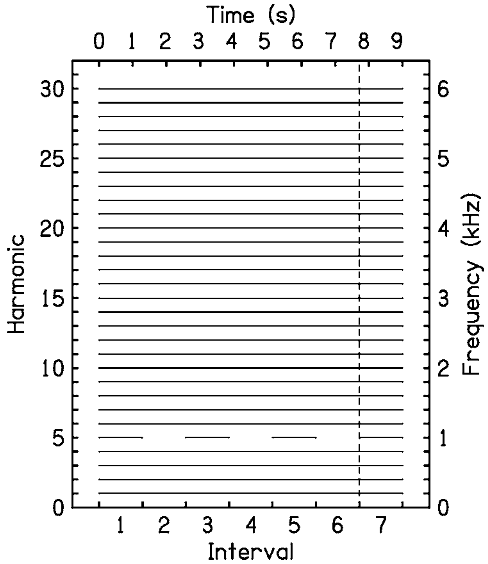

FIG. 1. Spectrogram showing the the seven intervals of the complex stimulus tone when the fifth harmonic was pulsed on and off. The tone was actually continuous for 9.171 s. Only the fifth harmonic was pulsed. The dashed line shows where a six-interval sequence ends.

that was exposed in the sequence. Because the sequence ended with the pulsed harmonic turned on, the sequence naturally cued the enhanced harmonic.

A. Stimulus

As with the compact disc demonstration, the tone, with fundamental frequency f_0, was continuous throughout the sequence. Only the selected harmonic was pulsed. The tone consisted of the first 30 harmonics with equal amplitudes. Fundamental frequency f_0 was nominally 200 Hz, but on different trials it was randomized over a ±5% range with a rectangular distribution as a guard against interaction among successive trials. The harmonics were added in *sine phase*.

The complex-tone sequence was computed in a Tucker-Davis array processor (AP2), converted by a 16-bit DAC (DD1), and given 10-ms raised-cosine edges (SW2). The signal was then lowpass filtered with a corner frequency of 20 kHz and a rolloff of −115 dB/octave. Each of the seven intervals of the sequence had a duration of 1310.72 ms, equivalent to two buffers converted at a sample rate of 50 kHz. Therefore, the duration of the seven-interval sequence was about 9.2 s. The selected harmonic was on or off for the entire duration of an interval, as shown in Fig. 1.

The stimulus was presented diotically at a level of 60 dB SPL (45 dB SPL for each component) through Etymotic ER2 insert earphones. The insert earphones provided an acceptably flat frequency response for the wide range of frequencies of interest in this experiment. Listeners were tested individually in a double-walled sound attenuating room.

B. Procedure

Four male listeners participated in the experiment: B, M, W, and Z. All listeners were between the ages of 21 and 25, except for W, who was 65. Listeners M and W were the authors. An experimental run consisted of 10 trials. On a low-frequency run one harmonic was selected on each trial, chosen randomly from the range 1–10. In a high-frequency run, the range was 11–20. Final data were based on ten runs, i.e., five matches for each harmonic, 1–20.

To begin a trial, the listener pressed the green button on the response box. The computer responded by selecting a harmonic to be pulsed off and on and then playing the seven-interval sequence. Then after a 300-ms silent gap, the computer began a series of matching sine tones (WG2) pulsed on and off (on for 1 s, off for 0.3 s) with 10-ms raised cosine edges (SW2). The series of matching tones continued indefinitely. The listener could vary the frequency of the matching tone by using up/down push buttons to establish a range (two octaves) and a ten-turn potentiometer for fine control within that range. The listener could adjust the level of the matching tone—from inaudible to loud—using a second ten-turn potentiometer, and could mute the matching tone with the blue push button. To hear the seven-interval sequence again, with the same f_0 and same pulsed harmonic number, the listener pressed the red button. Then after a 300-ms gap, the seven-interval sequence was presented once again, followed by a series of matching tones as before. There was no limit to the number of seven-interval sequences or matching tones that could be heard for any trial.

By this procedure the listener converged on a satisfactory matching frequency. When the listener was satisfied with his match, he pressed the green button again to end the trial. The computer then recorded the matching frequency for the trial. Alternatively, the listener could press the white button to abort the trial if he decided that it was impossible to make a match. Such aborted trials were indicated in the data as "no-match." When the green button was pressed again, the next trial began, with a different pulsed harmonic number and a somewhat different f_0. A run of ten trials required as little as six minutes and as much as 30 for completion, depending on the listener.

C. Results

The results of Experiment 1 are shown in Fig. 2 for listeners B, M, and W (listener Z did not participate in this experiment). The figures show the matching error, namely the difference between the matching frequency and the pulsed harmonic frequency as a percentage of the pulsed harmonic frequency. The matching error is shown as a function of the pulsed harmonic number, n, ranging from 1 to 20.

Figure 2 shows each individual match using five different symbols for the different runs. The solid line at zero error shows perfect matching. The dashed lines show the error corresponding to a match at harmonic $n+1$ or $n-1$. Numbers at the top of each plot show the number of failed responses. These are mostly no-match responses (30/33), but there are three matches (listener B) off the chart, i.e., matching attempts outside the range of the graphs. The string of "5"s for harmonic 16 and higher for listener M are all no-matches because M did not hear a harmonic standing out. The lowest numbered matching failure occurred on one match to pulsed harmonic 11 (listener B). Apart from that single failure at harmonic 11, all five matches for all three listeners for every

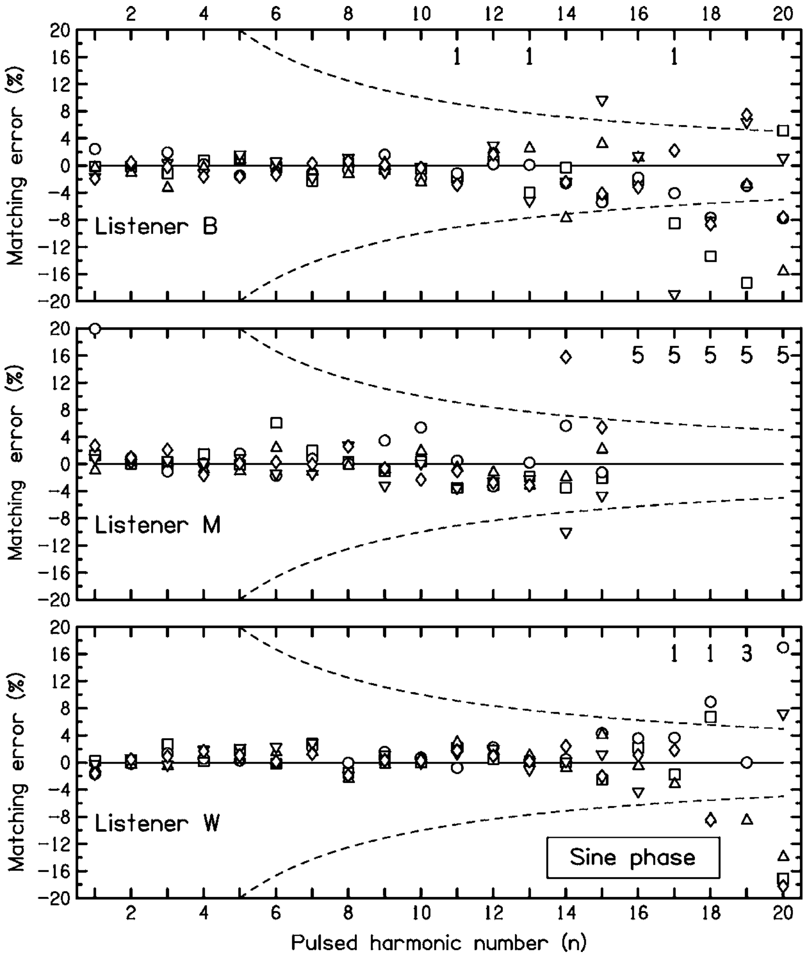

FIG. 2. Experiment 1 pitch matching error in percent showing the discrepancy between the frequency of the matching tone and the frequency of the pulsed (enhanced) harmonic for the seven-interval sequence when all harmonics were presented in sine phase. Each of three listeners, B, M, and W, made five matches. All matches are shown. Matches with common symbols were made in the same experimental run. Dashed lines indicate the frequencies of harmonics $n+1$ and $n-1$, given by the formula $\pm 100/n$. Numbers at the top of the plots indicate unsuccessful matches, either off the chart or no-matches.

pulsed harmonic from 1 to 12, were closer to the pulsed-harmonic frequency than to the frequency of any other harmonic.

D. Discussion

Experiment 1 served to validate the pitch-matching method. Harmonics up to the tenth, and somewhat beyond, could always be successfully matched, in rough agreement with the results of Bernstein and Oxenham (2003). A match closer to the pulsed harmonic than to any other harmonic is shown by a symbol that is closer to the solid line in Fig. 2 than to either dashed line. However, this criterion for the success of matches raises the spectre of spectral pitch shifts, where the pitch of a harmonic in the context of a complex tone is different from the pitch of a sine tone with that frequency (Terhardt, 1971). Except for matches by listener M for harmonics 11, 12, and 13, that run systematically flat, and matches by W for harmonic 7, that run sharp, there is no good evidence for such shifts. Similarly, the pitch-matching and forced-choice experiments of Peters *et al.* (1983) and the zero-mistuning results of Hartmann and Doty (1996) showed no shifts.

Although Experiment 1 did not approach very high harmonic numbers, the results shown in Fig. 2 exhibit large scatter for pulsed harmonics above 16, suggesting that the enhancement effect is limited to harmonics less than about 16, at least for sine phases as used in this experiment. Also, the large number of no-matches above harmonic 16 would seem to be in conflict with the conclusion of Goupell and Hartmann (2004) that pulsed harmonics up to 69 can be detected. However, the latter work was done with harmonics having random phases. The procedure there allowed listeners to take advantage of other phase relationships among harmonics. By contrast, Experiment 1 was restricted to sine phases. To look for the role of relative phases in the enhancement experiment, we performed Experiment 2, which randomized phases. We also expected that comparing the results of Experiments 1 and 2 would lead to relevant insight into the resolution of the harmonics.

III. EXPERIMENT 2—SEVEN-INTERVAL SEQUENCE—RANDOM PHASE

There were four listeners in Experiment 2, B, M, W, and Z—the same as in Experiment 1, plus listener Z.

A. Stimulus

Experiment 2 was identical to Experiment 1 except that every time the listener pressed the red button he was presented with a new randomization of the phases. As phases were rerandomized, the value of f_0 was not changed, though, as in Experiment 1, f_0 was randomized across different trials. For high pulsed-harmonic numbers listeners often took advantage of the randomization by pressing the red button several times to obtain a "good" set of phases for matching.

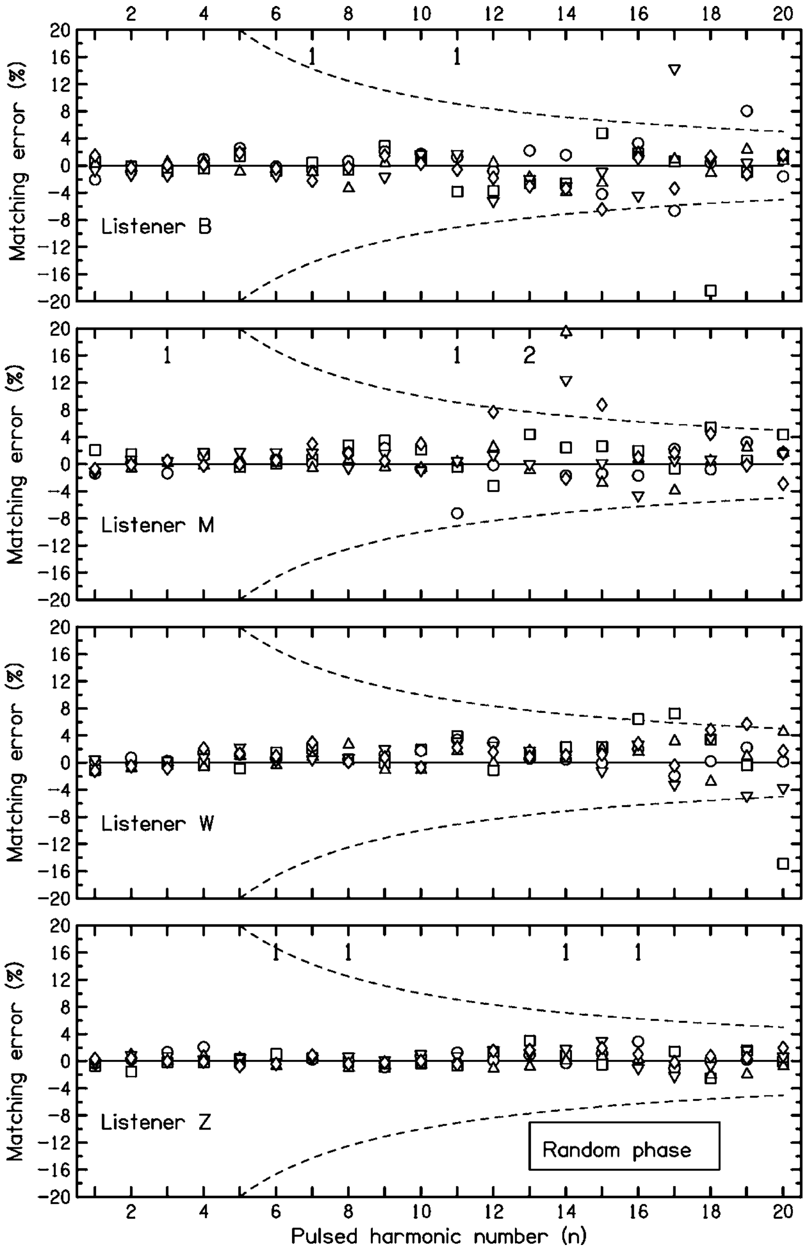

FIG. 3. Experiment 2 pitch matching error, as in Fig. 2. In Experiment 2 listeners could hear as many different random phase relationships as they wanted before making a pitch match. A fourth listener, Z, was added to the group of listeners.

B. Results

The results of Experiment 2 are shown in Fig. 3. Here matching performance was more successful than for Experiment 1 shown in Fig. 2. In contrast to Experiment 1 (sine phases) with 11% of failed matches, Experiment 2 (random phases) led to a failure rate of only 3%, and none of these were no-matches. Listeners B and Z successfully matched the 20th harmonic (ten times out of ten). Matches that are not failures are said to be "on the chart," and they can be compared for listeners B, M, and W, who were in both Experiments 1 and 2. In Experiment 1, 10% of on-the-chart matches fell outside the dashed lines. By contrast, in Experiment 2, only 3% of them fell outside those lines. Listener M, who could not hear pulsed harmonics above 15 for the sine phase, successfully matched out to harmonic 20 when given the chance to choose a phase relationship.

According to informal reports from listeners, randomizing the phases led to important perceptual differences in the high-frequency runs, where harmonics 11–20 were pulsed. The listeners observed that some phase relationships led to enhanced harmonics with a clear tonal character—easy to match. Other phase relationships led to enhanced harmonics (or enhanced spectral regions) that were buzzy in character and hard to match, and still other phases led to no enhanced sensation at all.

Relative phases are expected to be important for high frequencies, where harmonics are poorly resolved. One measure of the minimum harmonic number for which phases play a role can be found in comparing the data for B, M, and W in Fig. 3 (random phases) with their data in Fig. 2 (sine phase). To make the comparison quantitative, we counted the number of matches that fell outside a central band of ±4%. We found no systematic differences between random phase and sine phase for pulsed harmonics less than 14. But for all harmonics from 14 to 20 the number outside the central band was twice as large for sine phase as for random phase. This measure, with its ±4% limits, was chosen because it gives a quantitative value to an effect that is clear to the eye in comparing Figs. 2 and 3. This measure points to harmonic 14 as the onset of *dramatic* phase dependence. As another measure of onset, the authors (listeners M and W) listened to ten different phase relationships in an experiment like Experiment 2, and rated the clarity of enhanced harmonics on a scale of 0 (buzzy) to 5 (tonal). Pulsed harmonics below 8 received scores of 5. Pulsed harmonics 8 and above received variable scores. For example, the scores for harmonic 8 ranged from 2 to 5. This measure points to harmonic 8 as the onset of phase dependence.

C. Discussion

A comparison of the data in Figs. 2 and 3 provides good evidence that randomizing the phases allows listeners to find phase relationships that give better tonal sensations than the sine phase, at least for pulsed-harmonic numbers greater than 13. Records were kept of the number of seven-interval sequences heard by listeners. For Experiment 1, listeners heard an average of 3.3 sequences per trial (i.e., per match). For Experiment 2, where the listeners could find a favorable phase condition, the number of sequences per trial increased to 5.6 for the three listeners common to Experiment 1, and 6.2 when the data from listener Z were added. The number of randomizations, 6.2, is not large. Repeated randomizations were discouraged by the fact that each request for a new randomization produced another stimulus sequence, adding 9.2 s to the trial. Because the number of rerandomizations was small, whatever phase relationship is responsible for strong enhancement cannot be very special in the way that sine phases are special. However, it was clear that even among the few phase relationships actually explored on any trial some were more favorable than others.

The results of Experiment 2, especially the outstanding performance of listener Z, indicate that with nonspecial phases, harmonics up to the 20th can be heard out. Although no matching experiments were done above the 20th harmonic, nothing in the results of Experiment 2 contradicts the randomized-phase results from the Yes-No experiment that showed an audible effect beyond the 60th (Goupell and Hartmann, 2004). However, pulsed harmonics as high as 60 lead to a buzz sensation and not a pure-tone sensation. For that reason, and because pitch perception becomes poor above 5000 Hz, pitch matching much above the 20th harmonic is likely to be inaccurate.

The results of Experiment 2 can be compared with those of Bernstein and Oxenham (2003), who used signal levels similar to ours and also randomized phases. Their experiments found little effective audibility above the tenth harmonic, which they interpreted as indicating that harmonics above the tenth are not resolved. Our experiments tend to agree about resolution, but place the limit between 8 and 14. In our interpretation, that region indicates the upper limit for resolution because that is where important monaural phase effects begin.

The limit between harmonics 8 and 14 can be compared with the onset of phase dependence in fundamental frequency discrimination for 200 Hz complex tones, as measured by Houtsma and Smurzynski (1990), who found a negligible phase dependence when the lowest harmonic was 10, considerable phase dependence when the lowest harmonic was 13, and dramatic phase dependence when the lowest harmonic was greater than 15. Similarly, Shackleton and Carlyon (1994) found a transition to phase dependence in pitch perception when they tested the band including harmonics 11 through 15. Moore *et al.* (2006) found phase effects in fundamental frequency discrimination for harmonics as low as 8, consistent with the onset of phase effects reported here.

The experiments of Bernstein and Oxenham (2003) indicated that the frequencies of pulsed harmonics could be discriminated, to within 3.5–5%, up to about the 10th harmonic, whereas our experiments found successful matching within similar percentage limits up to the 20th, given random phase relationships. The difference between the results is probably related to the experimental techniques. The Bernstein-Oxenham complex tones were brief single shots, one second in duration, but our trials permitted listeners to listen as many times as desired to the 9.2 s sequence. For reasons unrelated to the experiment at hand, Bernstein and Oxenham added a noise background, but our experiments were done in quiet. Their listeners received no feedback, but our listeners were trained over the months of experimenting and received feedback on early runs. On early runs, the ratio of the matching frequency to the pulsed harmonic frequency was displayed on the response box after a match had been made.

Although the differences in results obtained by Bernstein-Oxenham and in our experiments can be attributed to differences in methods, the results lead to different conclusions about the enhancement effect itself. Bernstein and Oxenham regarded an enhancement experiment as a measurement of peripheral resolvability. They found an upper limit at the tenth harmonic and observed that this result is consistent with experiments on the highest numbered harmonics that are useful in producing a strong virtual pitch. Bernstein and Oxenham discounted more central effects whereby an enhanced harmonic behaves as though it were physically more intense, e.g., by the adaptation of suppression as invoked by Viemeister and Bacon (1982). By contrast, the work presented here also suggests that the limit of peripheral resolvability occurs near the 10th harmonic, but the enhancement effect persists at least up to the 20th. Consequently, our experiments suggest a role for a process beyond peripheral resolution that effectively boosts the level of an enhanced harmonic, at least relative to other harmonics. Evidence for such a relative boost, both in firing rate and in synchrony, was found in auditory nerve recordings by Palmer *et al.* (1995).

IV. EXPERIMENT 3—SEVEN-INTERVAL SEQUENCE—SCHROEDER PHASE

The phase effect seen for harmonic numbers 11–20 in Experiments 1 and 2 was intriguing. Clearly some random-phase relationships proved to be more effective than sine-phase in enhancing a harmonic. However, Experiment 2 did not keep track of the successful and unsuccessful phases. Therefore, to try to discover the nature of the phase effects, we performed Experiment 3 in which the relative harmonic phases were controlled.

Experiment 3 used three different phase relationships, sine phase, and two forms of Schroeder phase, $m+$ and $m-$, as defined in Eq. (1). The sine phase leads to a waveform with peaks in tuned channels that contain several harmonics. However, it is expected that dispersion in the inner ear results in cochlear excitation that is less peaked than the waveform itself at the high-frequency place corresponding to those channels. The $m+$ phase compensates for the cochlear dispersion and increases the temporally peaked character at the high-frequency place. The $m-$ phase relationship has properties similar to the $m+$ phase signal in that both tend to be small-peak factor waveforms (Schroeder, 1970), but the curvature of the phase-versus-frequency function is opposite to that of $m+$. The temporally compact character of the $m+$ excitation has been observed in masking experiments that reveal dramatically smaller masking produced by $m+$ compared to $m-$. (Smith *et al.* 1986; Kohlrausch and Sander, 1995; Oxenham and Dau, 2001). A compact masker allows a signal to be detected, or glimpsed, during the "quiet" portions of the masker.

A. Method

Experiment 3 was identical to Experiment 1 in that a fixed phase relationship was used for each experimental run. Listeners did five runs per phase condition. Because phase effects were mainly seen in the high-frequency runs of Experiments 1 and 2, only harmonics 11 through 20 were pulsed on and off in Experiment 3.

The sine-phase runs of Experiment 3 were in every way identical to the high-frequency runs of Experiment 1. The Schroeder-phase runs added a phase shift for harmonic n given by

$$\phi_n = \pm \pi n(n-1)/N, \qquad (1)$$

where N equals 30, the maximum harmonic number in the spectrum. The plus sign corresponds to $m+$ and the minus sign to $m-$. The sine phase has no added phase shift ($\phi_n = 0$) and can be designated "$m0$." Listeners, B, M, W, and Z, participated.

B. Results

The results of Experiment 3 are shown in Fig. 4, where matching data are plotted for all three phase relationships. Open symbols indicate the average of five matches. Filled symbols indicate the average of four or three matches, which occurred when there were one or two no-matches or matches off the chart. If fewer than three matches were on the chart, then no symbol is plotted. Several measures were used to compare results for the different phase relationships.

(1) *No-matches*: The number of no-matches is an indication of the difficulty of hearing the enhanced harmonic. All four listeners indicate the same ordering, with $m+$ leading to the greatest number of no-matches and $m-$ leading to the least. Summed over the listeners, the numbers of no-matches were as follows: For $m+$, 42; for $m0$, 26; and for $m-$, only 1.

(2) *Standard deviations*: The standard deviations (SD) are shown in Fig. 4 by the error bars. A fair assessment of average SD can be obtained from the data for those listeners and those pulsed harmonic numbers for which there are five matches (out of a possible five) for each of the three phase relationships. Over the four listeners, there were 19 such cases (out of a possible 40). Averaged over the four listeners, the SD were as follows: For $m+$, 3.3% (±0.9); for $m0$, 2.7% (±2.4); for $m-$, 1.7% (±0.8). The large error for $m0$ resulted from an anomalously large SD for listener Z. For all listeners, the SD for $m+$ was larger than the SD for $m-$.

(3) *More standard deviations*: More SD data can be included by comparing phase conditions in pairs, where all five matches were made for both phases of a pair, and using a sign test. The SD for $m+$ was greater than the SD for $m0$ on 15 out of 20 such comparisons ($p \leqslant 0.05$). The SD for $m+$ was greater than the SD for $m-$ on 17 out of 21 comparisons ($p \leqslant 0.01$). The SD for $m0$ was greater than the SD for $m-$ on 21 out of 29 comparisons ($p \leqslant 0.05$).

(4) *Absolute deviations*: An absolute deviation is the distance, expressed in percent, between the mean matching frequency and the frequency of the pulsed harmonic, as shown in Fig. 4. Casual inspection shows that the squares (stimulus $m+$) are usually farther from the solid line at 0% than are the other symbols. Averaged over the listeners for the 19 cases with all matches on the chart, the absolute values of the deviations were as follows: For $m+$, 4.1% (±2.3); for $m0$, 2.1% (±0.7); for $m-$, 1.5% (±1.1). Thus, a detailed calculation agrees with casual observation.

C. Discussion

The four measures of pitch matching success presented in Sec. IV B all agree that the $m-$ phase condition leads to the most successful performance, and the $m+$ condition leads to the least successful. Consequently, performance improves monotonically as the phase curvature goes from positive to zero to negative. The positive curvature condition, $m+$, is expected to lead to temporally compact excitation at high-frequency places on the basilar membrane (Smith *et al.*, 1986). The compact time dependence allows a signal to be glimpsed during the fractions of the cycle when the excitation is small. The zero-curvature condition, $m0$, with all sine phases, leads to a compact waveform, as seen on an oscilloscope, but is expected to be less compact at the high-frequency place. The $m-$ phase condition can be expected to produce an even more uniform distribution of excitation throughout the stimulus cycle. In that sense, the $m-$ condition is similar to typical random-phase conditions (Kohlrausch and Sander, 1995). Thus, the results obtained in Experiment 3 agree with what was learned in comparing Experiment 1 (sine phase) with Experiment 2 (random phase). The results support the suspicion from Experiment 2 that what is important about random phase is that it is not special like sine phase. Cochlear dispersion notwithstanding,

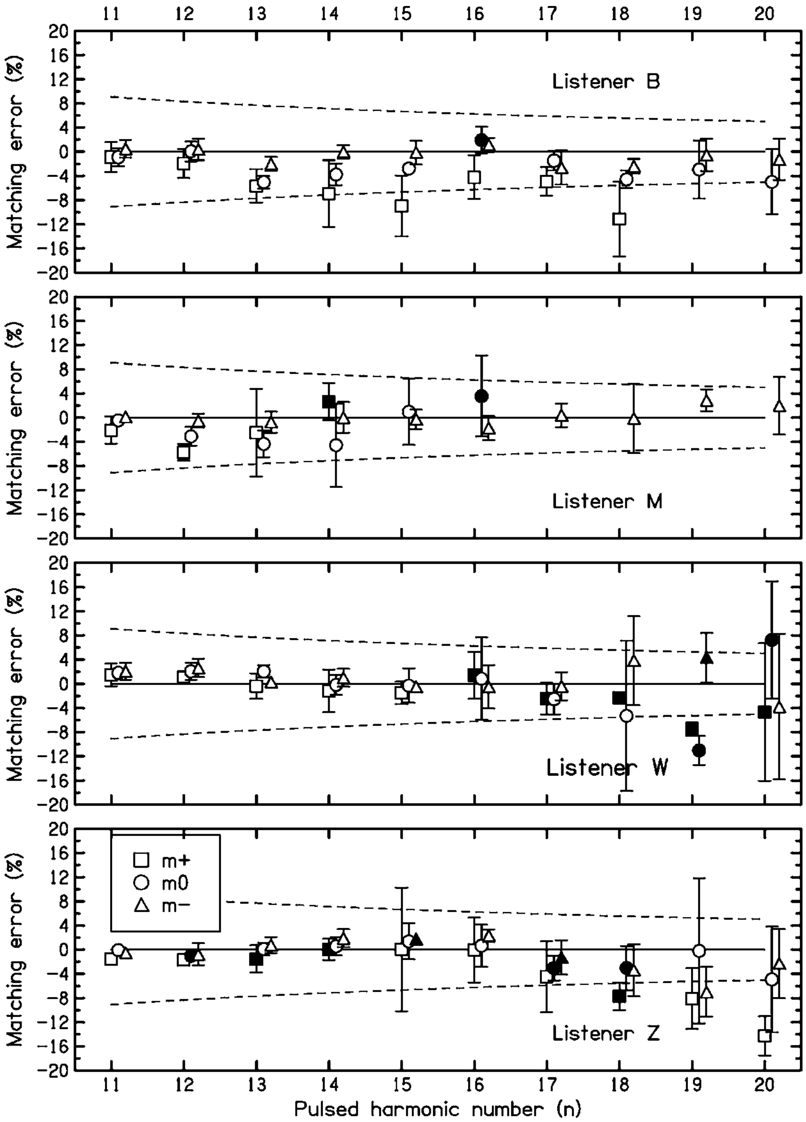

FIG. 4. Experiment 3 pitch matching error in percent, showing the mean discrepancy between the matching tone and the frequency of the pulsed harmonic for the seven-interval sequence with three phase relationships: squares for *m*+ (Schroeder plus), circles for *m*0 (sine phase), and triangles for *m*− (Schroeder minus). Open symbols indicate that all five matches are on the chart. Filled symbols indicate three or four matches. Error bars are two standard deviations in overall length.

the sine phase seems to retain some peaked character at the 2200–4000 Hz places that are probed by pulsing harmonics 11 through 20. The conclusion of this experiment is that enhancement is promoted if the excitation is not peaked in time but is relatively homogeneously distributed over the period of the stimulus. In short, what is good for release from masking (glimpsing) is bad for enhancement, and vice versa.

Because phase effects are important for higher harmonic numbers, a summary of Experiments 1, 2, and 3 for $11 \leqslant n \leqslant 20$ appears in Table I, which shows the number of matches closer to the frequency of n than to the frequency of any other harmonic. Ideally, the entries for the two sine-phase experiments should be the same, and they nearly are. The summary suggests that, overall, the benefits of randomizing the phases in Experiment 2 were all captured by fixing the phase at *m*− in Experiment 3.

V. EXPERIMENT 4—SIX-INTERVAL SEQUENCE—SINE PHASE

Experiments 1, 2, and 3 demonstrated enhancement, an effect that occurs when a harmonic amplitude changes from zero to full on. It is reasonable to expect that the enhancement effect would be similarly present if the harmonic amplitude varied from some small value to full on, or if some other dramatic increase in the amplitude were to occur. A particularly interesting increase in effective amplitude—not *a priori* evident—is suggested by excitation pattern models such as that proposed by Terhardt *et al.* (1982a, b). This excitation pattern model is nonlinear in that the effective strength of each harmonic is reduced by the strengths of

TABLE I. Summary of Experiments 1, 2, and 3—enhancement for unresolved harmonics. For four listeners (B, M, W, and Z) entries in the table show the number of matches that were closer in frequency to the pulsed harmonic (n) than to any other harmonic. The denominator in the Total row indicates the maximum possible total. The table includes only results for $11 \leqslant n \leqslant 20$.

Listener	Expt 1 sine	Expt 2 random	Expt 3 *m*+	Expt 3 sine	Expt 3 *m*−
B	4	7	2	4	9
M	3	4	1	2	6
W	4	6	5	5	6
Z	NA	10	3	4	6
Total	11/30	27/40	11/40	15/40	27/40

neighboring harmonics. This mutual masking, or suppression, is most effective in the upward direction, i.e., the strength of a harmonic is reduced primarily by the harmonic immediately below it. The strength of a harmonic is less affected by the harmonic immediately above it.

A consequence of this nonlinear excitation model is that when a harmonic is turned off, as in a pulsed harmonic experiment, its masking or suppression effect on neighboring harmonics disappears. Therefore, the model predicts an effective boost in the strength of the neighboring harmonics, particularly the harmonic immediately above. Thus turning off harmonic n is predicted to lead to a boost in the effective amplitude of harmonic $n+1$. The boost might be adequate to "pop out" harmonic $n+1$, just as harmonic n pops out when that harmonic is turned on. Exposing harmonic $n+1$ by turning off harmonic n has been called "unmasking" (Hartmann, 1997). The effect has been observed informally, but it has never been experimentally verified. The purpose of Experiment 4 was to try to find clear evidence for the predicted unmasking effect.

Experiment 4 used a six-interval sequence intended to facilitate the matching of an unmasked harmonic. There were four listeners in Experiment 4, the same who participated in Experiments 2 and 3.

A. Stimulus

The six-interval sequence of Experiment 4 was identical to the seven-interval sequence of Experiment 1 except that the final interval was omitted, terminating the sequence at the dashed line shown in Fig. 1. Therefore, the sequence duration was 7.8 s. On the sixth and final interval, the pulsed harmonic was off, leaving the listener with the impression of the unmasked harmonic—if any. The listener's task was to match what he heard standing out on the sixth interval of the sequence.

B. Results

The results of Experiment 4 are shown in Fig. 5, which shows the difference between the matching frequency and the frequency of the pulsed harmonic (harmonic n). The vertical scale limits are ±50% of the pulsed harmonic frequency, in contrast to Figs. 2–4 with limits of ±20%. The solid lines show the frequencies of harmonics $n+1$ and $n-1$. They are solid because they indicate the matches that are expected from the theory of unmasking. Unlike the seven-interval experiments, matches are not expected at 0% difference, i.e., at harmonic n. The dashed lines in Fig. 5 show harmonics n, $n+2$, and $n-2$.

As before, numbers at the top of the graphs indicate no-matches and matches off the chart. The great majority of these responses, including all of them for listeners M and W, were no-matches.

1. Evidence for unmasking

For pulsed harmonics 4, 5, and 6, listeners B, M, and W matched perfectly, in the sense that their matches were always closer to harmonics $n+1$ or $n-1$ than to any other harmonic. Listener Z matched perfectly for pulsed harmonics 5–10, and listener W matched perfectly for pulsed harmonics 1–7.

Pulsing harmonic 1 would be expected to unmask the second harmonic and lead to a matching difference of 100%, off the chart in Fig. 5. Only listeners B and W attempted matches for this harmonic. B's matches were scattered, with a mean matching difference of 123% (±31). W's matches were nearly exact, with a mean matching difference of 99% (±1). Matches at $n-1$ for pulsed harmonic $n=2$ (listener B) have an ambiguous interpretation in that they are at the fundamental frequency corresponding to the pitch of the complex tone as a whole.

The most important result of Experiment 4 is that the hypothesized unmasking effect clearly exists. The experimental matches cluster in the vicinity of the unmasked harmonics as predicted. The odds against such clustering by accident are overwhelming.

2. Relative variability

Unmasking can be compared with enhancement. The variability of the matches to unmasked harmonics in Experiment 4 can be compared to the variability for enhanced harmonics in Experiment 1 for the three listeners common to both experiments. The comparison was made by forming the ratio of the standard deviations in the two experiments for those pulsed harmonics where all five matches were on the chart for both experiments. For Experiment 4, the absolute value of the deviation from f_n was taken to compensate for the bimodal character of the matches. For listener B there were 10 ratios for n between 1 and 18. For M there were 11 ratios for n between 4 and 15, and for W there were 12 ratios for n ranging from 1 to 12. Average ratios for B, M, and W were, respectively, 1.6, 2.2, and 2.4. (Because this statistic is a ratio, it is the same whether calculated as the ratio of frequency standard deviations or as the ratio of frequency standard deviations relative to the pulsed harmonic frequency.) The conclusion of the calculation is that the variability for matches to unmasked harmonics is about twice the variability for matches to enhanced harmonics.

C. Discussion

The data in Fig. 5 clearly demonstrate the unmasking of harmonics. Thus, the question that inspired this experiment is answered in the affirmative: The unmasking effect suggested by the nonlinear excitation pattern model exists. The pitch matches cluster well near the expected frequencies, corresponding to $n+1$ and $n-1$. The standard deviations among the matches to unmasked harmonics in the six-interval experiment are only about twice as large as the standard deviations among the matches to enhanced harmonics in the seven-interval experiment. The standard deviation can be taken as a measure of the relative salience of unmasking and enhancement. Thus, unmasking is found to be about half as salient as enhancement.

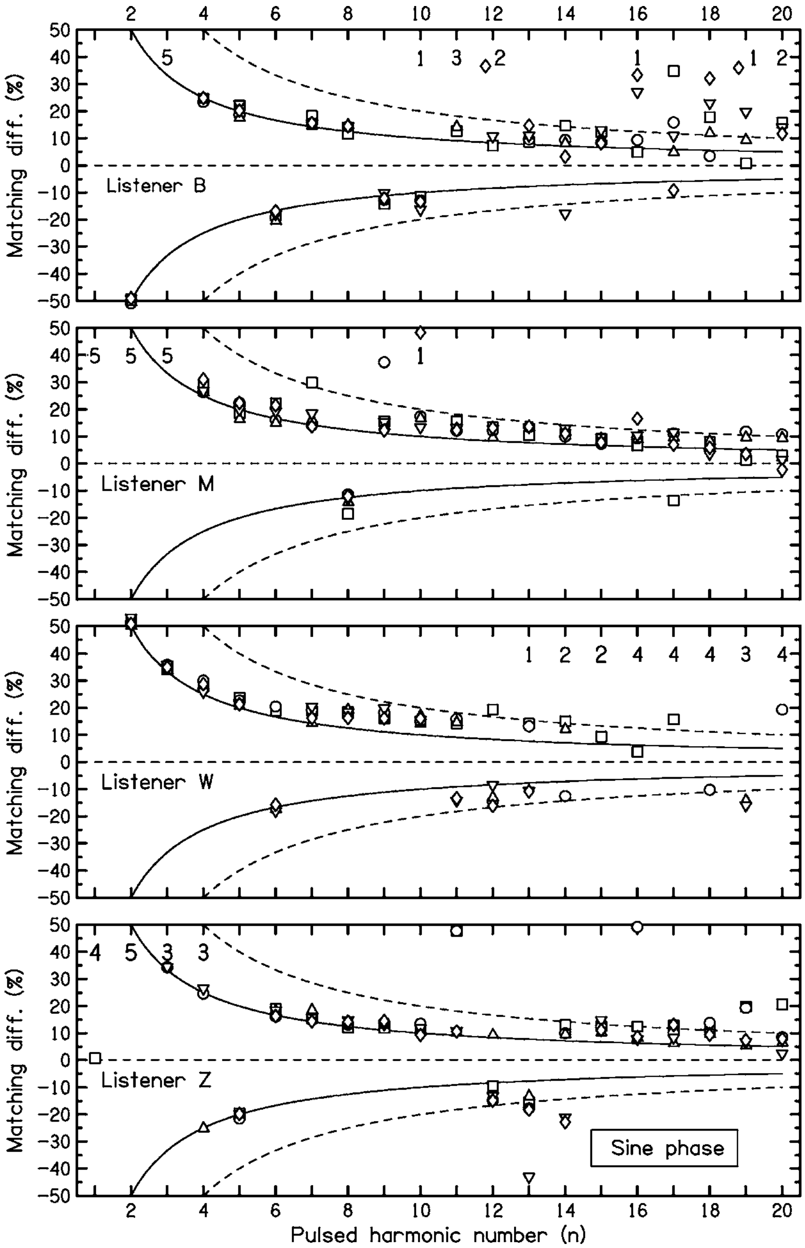

FIG. 5. Experiment 4 results, showing the mean difference between the frequencies of the matching tone and the pulsed harmonic for the six-interval sequence when all the harmonics were presented in sine phase. The solid lines show the frequency differences for expected matches at harmonics $n+1$ and $n-1$. Dashed lines show the frequency differences for $n+2$ and $n-2$ as well as n itself. Numbers at the tops of plots show unsuccessful matches, mostly no-matches but also a few matches off the chart.

1. Upward tendency

According to the unmasking hypothesis, there is mutual masking among the excitation patterns for the harmonics of a complex tone. Each harmonic is partially masked by its neighbors. When harmonic n is removed, the masking of a neighboring harmonic is reduced causing that neighboring harmonic to stand out. Because masking is expected to spread upward in frequency, one would expect that the harmonic made salient by unmasking would be the harmonic that is immediately above the harmonic that is pulsed, i.e., removing harmonic n should unmask harmonic $n+1$. That view is consistent with 82% of the matches for harmonics 3–20 in Fig. 5. Because upward spread of masking is a stronger effect for more intense maskers (Egan and Hake, 1950), the percentage would likely have been even larger if the experiment had been done at a higher intensity level. By contrast, some pulsed harmonics (n) systematically unmasked harmonic $n-1$, and the value of n for which this occurred was different for each listener: $n=2$, 6, 9, and 10 for B; $n=8$ for M; $n=12$ for W; and $n=5$, 12, and 13 for Z. The apparent idiosyncratic unmasking of individual harmonics is reminiscent of other individual differences—otoacoustic emissions and pitch shifts with intensity (Verschuure and van Meeteren, 1975). One is tempted to speculate that the effects are due to differences in the auditory periphery, perhaps in the cochlea. Monaural unmasking experiments that compared the two ears of a given listener would help check that conjecture, as would experiments with odd and even harmonics presented to opposite ears, *per* Bernstein and Oxenham (2003).

Whether the origin is cochlear or more central, it seems unlikely that unmasking results from an effective increase in mere firing rate without regard for timing. The clear pitch of some unmasked harmonics suggests a role for phase locking. Removing a harmonic expands the range of tonotopic axis that can be made synchronous with a neighboring harmonic.

A similar point was made by Moore and Ohgushi (1993) to explain the greater salience of harmonics that occur at spectral boundaries.

2. Pitch shifts

Because of the nature of the unmasking effect, one might expect it to be particularly susceptible to pitch shifts. Figure 5 shows that the great preponderance of shifts are upward—the unmasked harmonics are matched by sine-tone frequencies that are above the frequency of the unmasked harmonic. The exception to that rule occurs when the unmasked harmonic is $n-1$. For the nine cases of systematic $n-1$ matches noted above, the mean match was lower than f_{n-1} for eight.

Because of the positive pitch shifts, matches differ systematically from f_{n+1}. We believe that this is the reason that matches often fall between f_{n+1} and f_{n+2}, and often fall closer to the latter for pulsed harmonics 9–18. Above pulsed harmonic 18 the variation among the matches becomes large, even for the most reliable listeners M and Z.

3. Relationship to the Duifhuis pitch effect

The unmasking effect bears a superficial similarity to the Duifhuis pitch effect (DPE) in that turning off a harmonic causes a perceived tone to emerge (Duifhuis, 1970, 1971; Lin and Hartmann, 1997). However, the two effects are really very different. First, the DPE makes strong demands on the density of the harmonics. It has been studied for fundamental frequencies of 100 Hz and below, which leads to dense spectra at higher frequencies. Our informal attempts to hear the DPE with a fundamental of 200 Hz failed. Similarly, the DPE occurs only if the pulsed harmonic number is rather high. Depending on the listener, Duifhuis (1970) found a minimum harmonic number between 16 and 20. Lin and Hartmann found a minimum between 12 and 20. In contrast to these observations with the DPE, unmasking can be observed with a 200-Hz fundamental and with lower numbered pulsed harmonics. For example, all the listeners in Experiment 4 made 100-percent-successful matches when harmonic 5 was pulsed.

Second, the Duifhuis pitch corresponds to the frequency of the harmonic that is removed, harmonic n, but the unmasked pitch occurs at $n+1$ or $n-1$. Figure 5 makes it clear that the pitch is not at harmonic n.

A third feature of the DPE is that it requires a phase relationship that leads to a small-amplitude portion in the waveform. Duifhuis (1972) discovered that the pitch effect disappeared when phases were randomized. Lin and Hartmann agreed, though the DPE did occur for a sawtooth waveform (zero curvature). The disappearance of the DPE when phases are randomized presented another opportunity to draw a distinction between the DPE and the unmasked pitch. Experiment 5 studied unmasking with random phases.

VI. EXPERIMENT 5—SIX-INTERVAL SEQUENCE—RANDOM PHASES

Based on our experience with the enhancement effect, it seemed possible that exposing listeners to random phases would lead to a stronger unmasking effect and an even tighter distribution of matches than seen in Experiment 4. Alternatively, as suggested above, randomizing the phases might eliminate the effect, as it does for the DPE. There were three listeners in Experiment 5, B, M, and W—the same who participated in Experiment 1.

A. Stimulus

Experiment 5 was identical to Experiment 4, except that the phases of the harmonics were rerandomized, as in Experiment 2, every time the listener pressed the red button to request another six-interval sequence. Thus, Experiment 5 was different from Experiment 4 in the same way that Experiment 2 was different from Experiment 1.

B. Results

The results of Experiment 5 are shown in Fig. 6, which is identical in form to Fig. 5. Not shown are matches by B and W when the first harmonic was pulsed, leading to mean deviations of 118% (±25) for B and 98% (±1) for W. The expected matching deviation is 100%, and the results for B and W are similar to those in Experiment 4.

It is interesting to compare matches for sine phase and random phase for the three listeners who were common to Experiments 4 and 5. A comparison of Figs. 5 and 6 shows that listener B produced nine clusters of five matches for sine phase but only two such clusters for random phase. For listener M there are ten clusters for sine phase and none for random phase. For listener W there are nine clusters (including matches to the pulsed fundamental) for both sine and random phase conditions. All listeners reported that different phase relationships unmasked different harmonics, either above the pulsed harmonic or below it. The fact that W tended to match $n+1$ for random phases, as for sine phase, reflects this listener's choice to wait for a phase condition for which a harmonic above the pulsed harmonic was unmasked. Further, listeners reported that for some phase relationships no harmonic at all was unmasked when n was pulsed for n greater than 10.

C. Discussion

The results of Experiment 5 show that the unmasking effect occurs when the phases are random. Therefore, the results support the contention from the previous main section that the unmasking effect is different from the DPE. However, although the unmasking effect can be seen when the phases are randomized, a comparison of Experiments 4 and 5 shows that changing from the sine phase to the random phase caused matches to become less consistent. Some of the random phase conditions preferentially unmasked the harmonic above the pulsed harmonic while other phase conditions unmasked the harmonic below. Perhaps because of this confusion, each match required more complex tone sequences for the random phase than for the sine phase, on average, 6.0 and 3.5, respectively. Figure 6 shows that the matches to $n+1$ and the matches to $n-1$ were often in separate tight clusters, but the division of a small total number of matches (five) into two clusters made the random phase data less

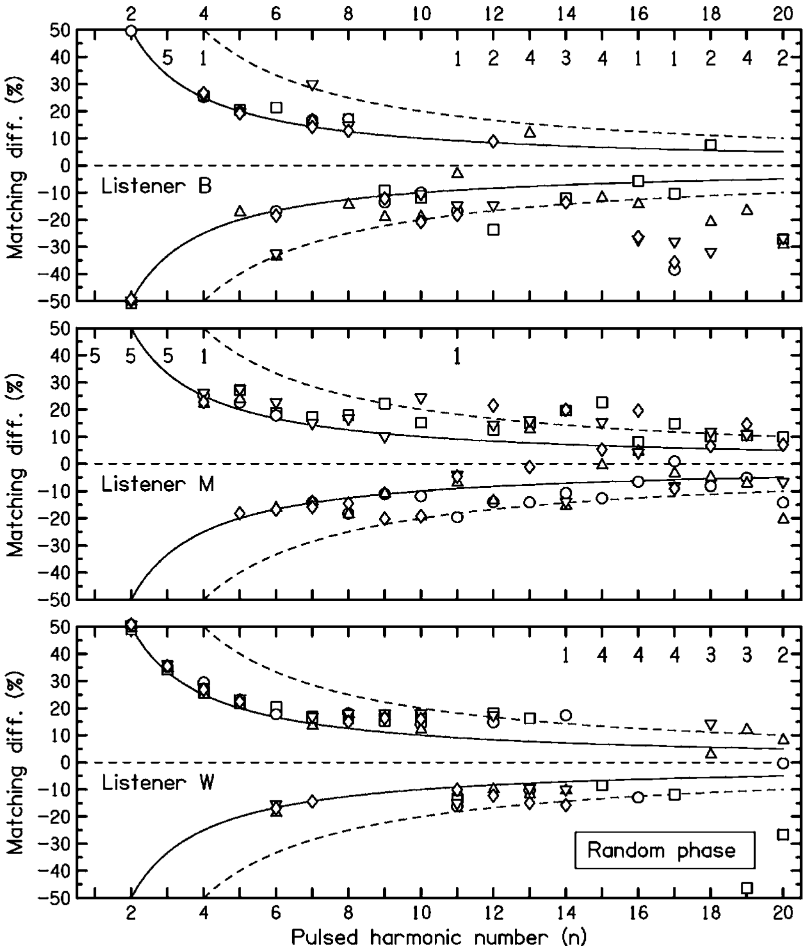

FIG. 6. Experiment 5 results, as in Fig. 6, except that in Experiment 5 listeners could hear as many different random phase relationships as they wanted before making a pitch match.

useful than the sine-phase data.

VII. EXPERIMENT 6—SIX-INTERVAL SEQUENCE—SCHROEDER PHASE

By comparing pitch matches for different phase-versus-frequency curvatures, Experiment 3 arrived at some insight concerning enhancement. Experiment 6 was performed with the hope that employing different curvatures would also lead to some insight concerning unmasking. Especially, it was hoped to discover why some phase relationships in Experiment 5 apparently caused listeners to match harmonic $n+1$ but others caused them to match harmonic $n-1$.

A. Method

Experiment 6 was like Experiment 4 in that the relative phases among harmonics were fixed for each run. Whereas Experiment 4 used only sine phase, Experiment 6 used the sine phase ($m0$) as well as Schroeder phase relationships $m+$ and $m-$, as in Experiment 3. Because phase relationships were expected to be important only for high harmonic numbers, only harmonics 11 through 20 were pulsed in Experiment 6. However, listener W had difficulty hearing unmasking for pulsed harmonics greater than 14 (see Figs. 5 and 6), and, consequently, W was given pulsed harmonics 5 through 15.

B. Results

The pitch matching results of Experiment 6 are plotted in Fig. 7 for the three phase relationships, as in Fig. 4. Because Fig. 7 plots mean and standard deviation, and because listeners matched either up or down (expected to be $n+1$ or $n-1$), this figure led to the unique problem of plotting means in two groups. In practice, it was normally not difficult to decide whether to include any given match in the positive deviation group or the negative group because deviations near zero were rather rare. Consequently, the decisions were made automatically, based only on the sign of the deviation.

For each listener, Fig. 7 shows patterns of matching that resemble those in Figs. 5 and 6, except that listener B had apparently learned to make more consistent matches at high values of n. The patterns were similar for all phase relationships. There was no evidence linking phase curvature with a tendency to match up or to match down. The only consistent trend visible in the figure is that the matching frequencies for listeners B and M for pulsed harmonics 13 through 18 increase monotonically as the curvature decreases from positive to zero to negative. Matches for listener Z did not exhibit that dependence.

A systematic trend did appear in the number of no–matches. As the phase curvature decreased from positive to zero to negative, the number of no-matches summed over

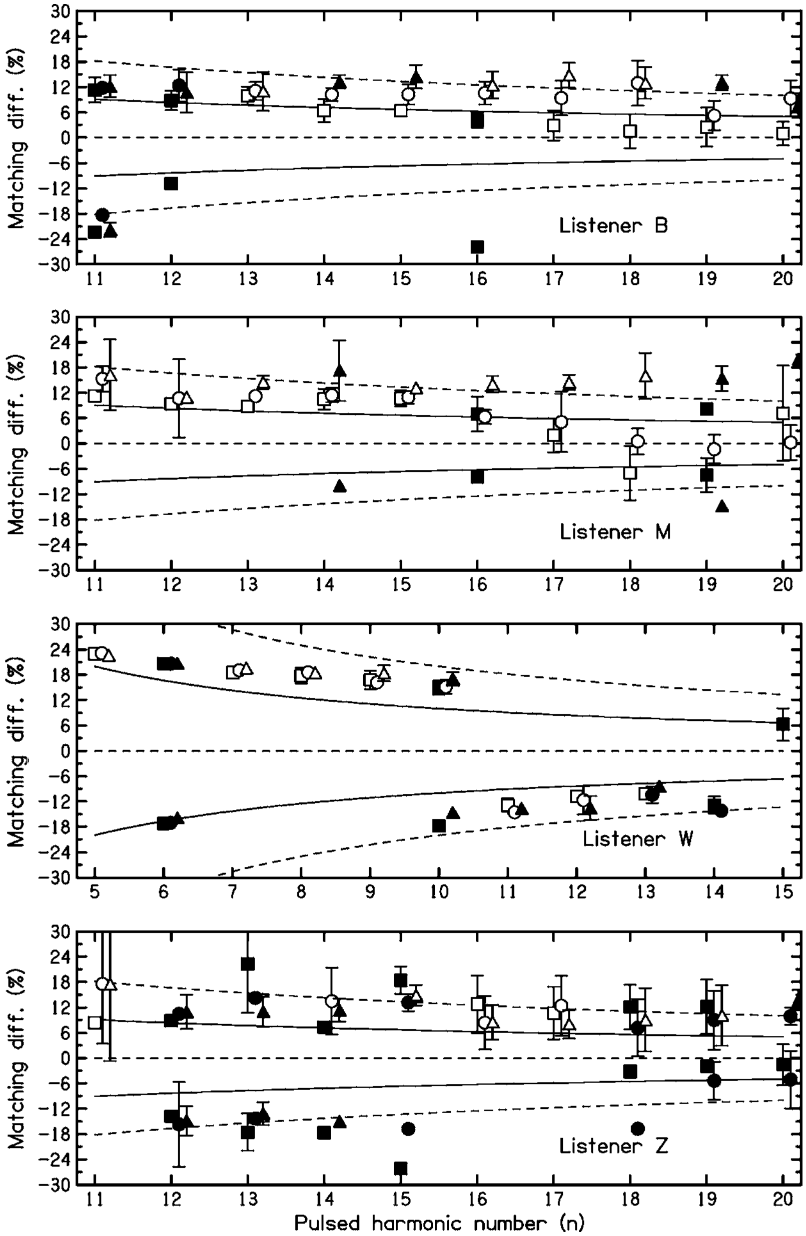

FIG. 7. Experiment 6 results, showing the mean difference between the frequencies of the matching tone and of the pulsed harmonic for the six-interval sequence with three phase relationships: squares for $m+$ (Schroeder plus), circles for $m0$ (sine phase), and triangles for $m-$ (Schroeder minus). Open symbols indicate that all five matches are averaged. Filled symbols indicate 1–4 matches. Error bars are two standard deviations in overall length.

listeners increased from 2 to 15 to 26. For every listener, the number of no-matches for $m+$ was less than the number for $m-$.

C. Discussion

Experiment 6 discovered little, if any, systematic dependence of the pitch of an unmasked harmonic on phase curvature. In particular, it did not make it possible to manipulate a listener's tendency to match $n-1$ instead of $n+1$, or vice versa. Some other form of phase variation, beyond our simple curvature dimension, must be responsible for the effects seen with random phase.

Experiment 6 did discover a suggestive curvature effect in unmasked harmonic detection. The no-match data indicated that detecting an unmasked harmonic is easier for increasing positive curvature. In this sense, the data from the unmasking experiment resemble the data from the detection experiments of Kohlrausch and Sander (1995) and Oxenham and Dau (2001). Apparently, the unmasking effect is aided by a small-amplitude portion during a stimulus cycle, as is the case for the DPE.

VIII. A PLACE MODEL FOR UNMASKING

As noted in the introduction to unmasking, the unmasking effect is suggested by excitation pattern models, including that of Terhardt *et al.* (1982a, b). This model crystallized concepts of excitation patterns, partial masking, and spectral pitch shifts that had been developed in Munich over several decades. The goal of the algorithm is to compute a virtual pitch of a complex tone, based on the strengths and spectral pitches of individual harmonics. It is the strengths and spectral pitch aspects that are applicable in the present article—especially the strengths. To our knowledge, this model is unique in assigning strengths and pitches to individual harmonics of a tone. The strengths of the harmonics, originally called “SPL excess” by Terhardt *et al.* are here called “spectral strengths.” They are measured in dB.

A. Spectral strength

A calculation of the spectral strength begins with the level of the harmonic in dB, compared to a standard absolute threshold for a sine tone of that frequency. Next, the effective level is reduced by accounting for partial masking by neighboring harmonics. The masking pattern caused by a harmonic is assumed to be triangular on a coordinate system of decibels versus the tonotopic scale in bark. Neighboring harmonics *above* the harmonic of interest produce a partial masking that is attenuated at a rate of 27 dB/bark. Neighboring harmonics *below* the harmonic of interest produce additional partial masking with a variable slope—shallower (more effective masking) for lower frequencies and for higher levels of the neighbor.

As noted above, the algorithm applies to the unmasking effect because, as a harmonic is removed from the spectrum, its masking effect on its neighbors is reduced. That reduction in partial masking leads to an effective boost in the strength of a neighbor, especially the neighbor immediately above the removed harmonic. The sudden boost in strength is imagined to cause the neighbor to stand out perceptually so that its pitch can be matched. Because the algorithm ignores phase information, it is evident from the outset that it will not be able to reproduce all the features seen experimentally in the unmasking effect. However, the algorithm applies so naturally that it cannot be ignored, and it does make some interesting predictions.

Figure 8 shows the predictions of the model. The horizontal axis, “Pulsed harmonic number” ranges from $n=1$ to $n=20$, as in our experiments. Above and below that axis are plots that show the effect of pulsing the nth harmonic on the strengths of harmonics $n+1$ and $n-1$, respectively. An open bar shows the strength before harmonic n is removed. The adjacent filled bar shows the strength after n is removed. The difference in height between filled and open bars is a measure of the sudden boost in strength that unmasks a harmonic.

When the spectral strength is negative in Fig. 8, the harmonic is predicted to be inaudible according to the model. This prediction is consistent with the general tendency for matches to fail for pulsed harmonics greater than 15, as observed for listeners B and W for sine phase, but not for M and Z. Thus, the prediction does not hold in general. The spectral strength of high-frequency components is primarily limited by masking from lower harmonics. Increasing the level of the components leads to a shallower masking slope with the result that the spectral strength of high-frequency components becomes more negative as the stimulus level increases.

Because masking from below is more effective than masking from above, removing harmonic n is predicted to have a much greater effect on harmonic $n+1$ than on harmonic $n-1$. This effect can be seen in Fig. 8, where the difference between filled and open bars is greater in the upper graph than in the lower graph. As the pulsed harmonic number increases beyond 10, this disparity is reduced and the algorithm tends to predict that harmonic $n-1$ would be unmasked almost as effectively as harmonic $n+1$. These predictions partly agree with experiment in that there is a clear tendency for listeners to hear out harmonic $n+1$ and not $n-1$. But, as noted in Sec. V C, idiosyncratic and reproducible tendencies for listeners to hear out $n-1$ do occur for n less than 10, and this is not predicted by the algorithm.

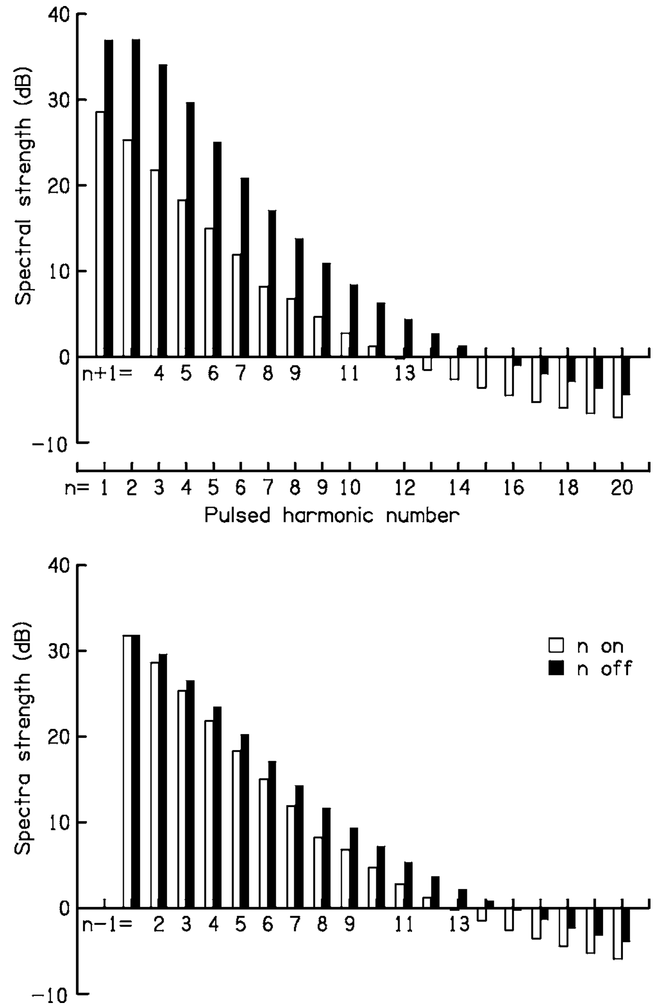

FIG. 8. Spectral strength of unmasked harmonics compared to their normal masked strength as calculated from the algorithm by Terhardt *et al.* The strengths of harmonics $n+1$ and $n-1$ with harmonic n OFF are shown by solid bars. The strengths with harmonic n ON, as normal, are shown by open bars. Negative strengths correspond to harmonics that should not be audible according to the algorithm. A harmonic with a negative strength closer to zero is stronger than one with a negative strength farther from zero.

Figure 8 shows the calculated unmasking only for harmonics $n+1$ and $n-1$. Calculations within the algorithm show that there is some unmasking for harmonics $n+2$ and $n-2$, but the effects are quite small. The predicted unmasking of $n+2$ is always appreciably less than the unmasking of $n-1$. Therefore, the algorithm predicts that the most likely alternative to a match at $n+1$ is not $n+2$ but is $n-1$ instead.

B. Pitch shifts

The algorithm of Terhardt *et al.* computes pitch shifts for each harmonic of a complex tone. The appropriate comparison between the algorithm and our experiment is to compute the difference between the pitch of harmonic $n+1$ (or $n-1$), with harmonic n absent, and the pitch of a sine tone having the level and frequency of the experimental matching tone. As used here a "pitch shift" does not refer to a comparison of the pitch of an unmasked harmonic with the pitch of that harmonic in the context of all harmonics. Instead it refers to the pitch of the unmasked harmonic compared to the pitch of a sine tone in quiet. The differences calculated from the algorithm ought to agree with the shifts of the matches from the solid line in Figs. 5–7.

The algorithm includes pitch shifts of the matching tone per Stevens's rule (Fletcher, 1934) such that pitch p is related to frequency f (Hz) by

$$p = f[1 + (f - 2000)(L - 60) \times 2 \times 10^{-7}],$$

where L is the level in dB SPL. In our experiment, the levels of the matching tone, which listeners adjusted to taste, varied from about 40–70 dB SPL. Over this range the Stevens's rule shifts are less than one percent. Compared to the variability in our data, an uncertainty of this magnitude is not important, and pitch shifts are here computed using matching tone frequencies and not intensity-adjusted matching tone pitches.

Pitch shifts were computed for six-interval runs using only data from those pulsed harmonics for which the listener put all five matches in a cluster. Because Experiment 5 with random phases so often led to matches to both $n+1$ and $n-1$ there were few such clusters. Matches were more consistent in Experiment 4 with the sine phase, leading to 41 clusters for n in the range 2–18 inclusive: 9 for B, 13 for M, 8 for W, and 11 for Z. Of these 41 clusters, there were only 5 at $n-1$. These data, together with the predictions of the algorithm appear in Fig. 9.

The solid lines in Fig. 9 show the predictions of the algorithm. The heavy dashed line shows a shift of harmonic $n+1$ that is so large that the frequency equals that of harmonic $n+2$, i.e., $100[(n+2)/(n+1)-1]$, which sets a terminus for the applicability of the algorithm, somewhat below harmonic 17. Data points show pitch shifts from Experiment 4 for the four listeners, as indicated.

Figure 9 shows that the algorithm successfully predicts the order of pitch shifts for unmasked harmonics $n+1$. It underestimates the shifts for listener W and usually overestimates them for the other listeners. By contrast, the algorithm fails to predict the negative pitch shifts that occur for matches to $n-1$.

The pattern of experimental pitch shifts shown in Fig. 9 is a familiar one indicating contrast enhancement in a matching experiment. Given a target that is above a reference, a listener tends to match high. Given a target that is below a reference, a listener tends to match low. Contrast is enhanced in that a listener's response to a displaced stimulus exaggerates the displacement. Similar results are seen in the pitch shifts caused by a leading tone (Hartmann and Blumenstock, 1976; Rakowski and Hirsh, 1980). These shifts were modeled in a contrast enhancement theory by Kanistanaux and Hartmann in 1979. Similar results occur for a mistuned harmonic (Hartmann and Doty, 1996; Lin and Hartmann, 1998),

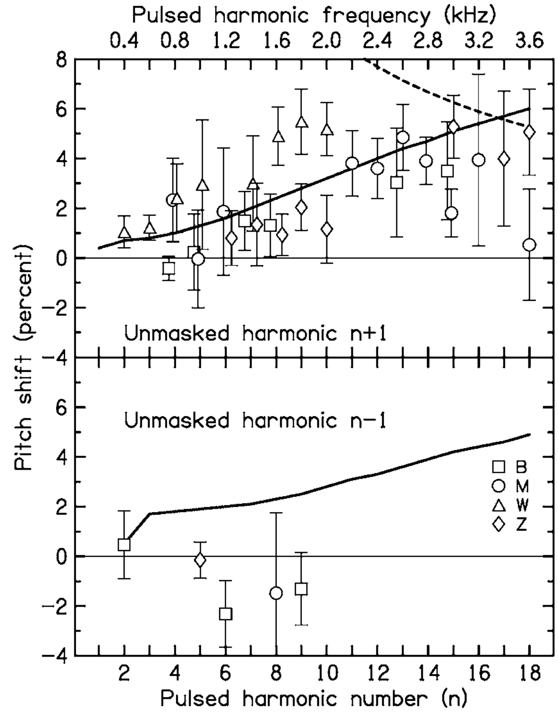

FIG. 9. Pitch shifts calculated from the algorithm of Terhardt *et al.* are shown by solid lines for unmasked harmonics above $(n+1)$ and below $(n-1)$ the pulsed harmonic. The dashed line shows the frequency of harmonic $n+2$. Experimental pitch shifts from Experiment 4 are shown by symbols for four listeners, B, M, W, and Z. Error bars are two standard deviations in overall length.

and a contrast enhancement model was constructed to try to account for these results by de Cheveigné (1997). Roberts and Brunstrom (2003) turned this particular shift into an effective tool for measuring the perceptual fusion of harmonics in a complex tone. As observed in other pitch shift experiments, the unmasking experiment finds that positive pitch shifts in response to a target above a reference tend to be larger and more reliable than negative shifts in response to a target below a reference.

IX. CONCLUSIONS

Alternately omitting and restoring a harmonic in a periodic complex tone creates two salient effects, enhancement and unmasking. In the enhancement effect, the pulsed harmonic itself stands out from the rest of the periodic tone. Enhancement was studied in Experiments 1 through 3 of this article for a 200-Hz complex tone. It was found that the relative phases among harmonics affect the matching data for pulsed harmonics greater than the 14th, though listeners can detect phase effects for pulsed harmonics as low as the 8th. The onset of sensitivity to relative phase indicates a failure of spectral resolution in the auditory periphery. But although harmonics above the 10th (Bernstein and Oxenham, 2003), or 8th–11th (Moore *et al.*, 2006), or 8th–14th (this work) are not well resolved, successful matches can be made to enhanced harmonics up to the 20th for relative phases that are not unfavorable. As shown in Experiment 3, unfavorable phases are those that lead to temporally compact (peaked) excitation. Favorable phases are those that distribute the excitation more uniformly throughout the period of the complex tone. The conclusion of these experiments is that the audibility of an enhanced harmonic is not limited by spectral resolution. Therefore, theories of the enhancement effect that depend on the adaptation or inhibition of tonotopic regions are likely to have difficulty explaining the enhancement of harmonics as high as the 20th. Experiments 1 through 3 also found that the pitches of enhanced harmonics were not shifted significantly.

In the unmasking effect, the pulsed harmonic causes a neighboring harmonic to be audible. Specifically, when harmonics are presented in sine phase and when harmonic n is turned off, harmonic $n+1$ tends to pop out from the complex tone background. However, about 10%–20% of the time it is harmonic $n-1$ that pops out. When harmonics are presented in a random phase, harmonic $n-1$ pops out almost as frequently as harmonic $n+1$, depending on the phase relationship that actually occurs. Phase relationships that produced temporally compact cochlear excitation were most effective in unmasking harmonics.

For favorable phases, unmasking can be reliably heard by some listeners for pulsed harmonics as high as the 18th. Unlike enhanced harmonics, unmasked harmonics are subject to clear pitch shifts. The pitch shifts tend to exaggerate the spacing between the pulsed harmonic and the unmasked harmonic. In other words, matches to $n-1$ tend to be flat and matches to $n+1$ tend to be sharp compared to harmonic frequencies, indicating contrast enhancement.

The preference for unmasking harmonic $n+1$ over harmonic $n-1$ finds a natural explanation in terms of partial masking, as exemplified by the algorithm of Terhardt *et al.* (1982a, b). Because of the upward spread of masking, the removal of harmonic n has the greatest effect on the excitation pattern for a harmonic higher than n. However, the algorithm admits no role for harmonic phases, and so it fails to predict the phase effects observed in Experiment 5, where phases were randomized. Further, the algorithm predicts no unmasking for pulsed harmonics above the 14th, contrary to experiment.

The algorithm also predicts pitch shifts. It is successful for the positive pitch shifts observed for matches to harmonics $n+1$, but it fails for the negative pitch shifts observed for matches to harmonics $n-1$. The existence of negative shifts and the alternative explanation in terms of contrast enhancement raise questions about the role of partial masking in spectral pitch as implemented in the algorithm. However, invoking both partial masking and contrast enhancement allows one to have one's cake and eat it too. The shifts caused by partial masking are always positive; the shifts from contrast enhancement are exaggerations of the difference between target and reference. If the contrast enhancement shifts are the larger, then positive pitch shifts in response to a high target and negative shifts in response to a low target are both predicted. Further, the positive shifts are predicted to be larger and more reliable than the negative shifts, as observed experimentally.

Both the enhancement effect and the unmasking effect offer promising opportunities to study tonotopic and temporal aspects of neural excitation patterns, admittedly at a yet-to-be-determined level of the system. Both effects involve selective attention, though the relative importance of attention *per se* is not clear. In any event, the *unmasking* effect, where the perceived harmonic is different from the pulsed harmonic, reveals a mechanism whereby a harmonic is exposed as the excitation pattern changes. Thus the effect is aptly named "unmasking," though specific roles of pattern masking and suppression are unknown. The unmasking effect provides a way to study excitation patterns experimentally without using powerful masking noises that may change the operating point of the system under study. Unmasking reveals both spectral resolution and phase effects. By studying unmasking with a pitch matching task in the present article, we were able to make use of the extraordinary precision of human pitch perception to reveal details of the effect.

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