PURE-TONE OCTAVE MASKING IN LISTENERS WITH SENSORINEURAL HEARING LOSS

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Pure-tone octave masking was investigated in 14 listeners with sensorineural hearing loss to examine the hypothesis that the sensorineural ear introduces abnormal harmonic distortion. Thresholds for a test signal at f_2, masked by a masking signal at f_1, (where $f_2 = 2f_1$) were obtained as a function of the level of the f_1 masker for four different f_1 frequencies (250, 500, 1000, and 2000 Hz) and two different phase relations between the f_1 and f_2 signals (90° and 270°). Analysis of the data in terms of the absolute level of the f_2 test signal at masked threshold vs the absolute level of the f_1 masking signal leads to the conclusion that these pathological ears do not perform differently from normal ears, except along the dimension of hearing loss. That is, their hearing losses do not add significant distortion to the acoustic signal. Analysis of the data in terms of the sensation level of the f_2 test signal at masked threshold leads to the specious conclusion that the sensorineural ear introduces abnormal distortion.

The primary impetus behind this investigation of octave masking involves the issue of aural distortion among listeners with sensorineural hearing loss. Interpretations of results from three types of experiments have led to the inference that listeners with sensorineural hearing loss exhibit more aural distortion and have lower aural overload thresholds than do listeners with normal hearing. Masking experiments have shown more upward spread of masking from sensorineural ears than from normal ears (Jerger, Tillman, and Peterson, 1960). Best-beat experiments have shown lower thresholds of aural overload in sensorineural ears (Opheim and Flottorp, 1955; Lawrence and Yantis, 1956b), and mistuned octave-masking experiments have shown lower thresholds of octave masking in sensorineural ears than in normal ears (Clack and Bess, 1969). Careful consideration of the results reported in those papers has led us to conclude that all the evidence leading to an interpretation that sensorineural ears produce more aural distortion than normal ears can be traced to inappropriate considerations of sensation level in that interpretation.

In the case of increased upward spread of masking, the results can be explained by the fact that a higher-level masking noise was used with sensorineural ears than with the comparative normal ears. In the case of aural overload thresholds, either with best-beat or mistuned octave-masking experiments, the data appear to simply reflect sensorineural losses of sensitivity. More pertinent evidence of aural distortion, we contend, can be obtained by examining how the sensorineural ear performs at moderate and at high signal levels, that is, once the problem of sensitivity loss has been overcome. For example, if listeners with sensorineural hearing loss exhibit more octave masking at suprathreshold levels of a primary tone than listeners with normal hearing, one might infer that those sensorineural ears produce more second-harmonic distortion than normal ears. This investigation employs phase-locked octave masking (Clack, 1967, 1968), a modification of the steady-tone technique of measuring aural distortion (Trimmer and Firestone, 1937; Lewis, 1940), as a technique for estimating second-harmonic (octave) distortion products.

Using a simplified version of the pure-tone masking experiment, in which the test signal is twice the frequency of the masker, several investigators have shown nonlinear masking functions which they have explained in terms of the growth of an "aural harmonic," presumably reflecting overload distortion in the cochlea (Newman, Stevens, and Davis, 1937; Egan and Klumpp, 1951; Lawrence and Yantis, 1956a; Clack, 1967, 1968; Clack and Bess, 1969). Other investigators (Opheim and Flottorp, 1955; Lawrence and Yantis, 1956b; Clack and Bess, 1969) have used this octave-tone paradigm to study the threshold of "aural overload" in listeners with impaired as well as normal hearing. They found that the sensation level of a masking signal (f_1) necessary for that signal to just interact with a test signal at the octave ($2f_1$) was significantly lower for listeners with sensorineural hearing loss than for listeners with normal hearing or with conductive loss. The fact that Lawrence and Yantis' procedure was called a test of aural overload, coupled with the result that listeners with sensorineural hearing loss showed lower thresholds for aural overload, has led to the inference that the sensorineural ear generates more harmonic distortion than does the normal sense organ.

Lawrence and Yantis (1956b, p. 76) were careful to point out that the absolute level of the masking signal necessary to produce a noticeable effect on a test signal at the frequency of the second harmonic was 18-20 dB greater, on the average, for sensorineural ears than for normal ears. Therefore, they suggested that the impaired sense organ was probably less susceptible to distortion than the normal ear. Even so, subsequent results on the upward spread of masking in sensorineural ears (Jerger, Tillman, and Peterson, 1960) and on the threshold of octave masking in sensorineural ears (Clack and Bess, 1969) have perpetuated the notion that sensorineural ears exhibit more aural distortion than do normal ears.

All of the evidence concerning thresholds of aural distortion in sensorineural ears points only to the ability of sensorineural ears to detect beats at lower sensation levels than normal ears and may be no more than a reflection of the amount of sensorineural hearing loss. How the sensorineural ear performs once the problem of threshold sensitivity is overcome (at suprathreshold levels of stimulation) would seem to provide more pertinent evidence of distortion in the sensorineural ear. Since aural distortion products have been shown to be capable of masking acoustic signals at the same frequency, exhibiting nonlinear masking functions with slopes greater than 1 dB/dB (Newman, Stevens, and Davis, 1937; Clack and Bess, 1969), those octave-masking functions offer an appropriate way of obtaining evidence to resolve the question of harmonic distortion in sensorineural ears. If listeners with sensorineural hearing loss exhibit more octave masking at suprathreshold levels of a masking signal than listeners with normal hearing, then one might infer that their ears produce more harmonic distortion than normal ears. An experiment is reported here in which octave-masking functions were obtained from a group of listeners exhibiting sensorineural hearing loss. Absolute masked thresholds and amount of masking were then compared with similar octave-masking functions obtained from a group of normal-hearing listeners.

METHOD

Equipment

The frequencies (f_1) of the masking signals (S_m) employed as maskers in this experiment (250, 500, 1000, or 2000 Hz) were generated by a programmable oscillator (Krohn-Hite Model 453-2). Phase-locked, octave test signals (S_t) at 500, 1000, 2000, or 4000 Hz (f_2) were generated by doubling the S_m frequencies with a wave-form generator (Wavetek Model 116). The phase relation between the S_t and S_m was varied by means of a phase shifter (Grason-Stadler Model 3520B). Masking signals and phase-locked octave test signals were gated with separate electronic switches (Grason-Stadler Model 829), attenuated separately, and then added together in a resistive mixing circuit. The combined wave form was then fed to a TDH-49 earphone mounted in an MX-41/AR cushion.

Psychophysical Procedures

An adaptive four-interval forced-choice (4IFC) procedure was used to obtain quiet and masked thresholds. The listener was seated in front of a console that contained a warning light, an observe light, and an answer light, in addition to four lighted response buttons corresponding to the four temporal intervals. At the termination of the warning light (red), the observe light (white) was flashed four times in synchrony with four tone presentations. Concurrently, the light in each response button flashed in sequence with its corresponding tone, so that, for example, the third response button was lighted simultaneously with the lighting of the observe light and the presentation of the third tone. During three of the intervals, an S_m at a frequency of f_1 was presented alone. During the remaining interval, a signal complex was presented which consisted of S_t at a frequency of $f_2 = 2f_1$ added to S_m. The interval that contained both signals was randomly determined from trial to trial. Each signal was gated on and off with a 25-msec rise and decay time and remained above 90% of its maximum amplitude for 450 msec. Silent intervals of 250 msec separated the signals. Oscilloscopic calibration was maintained throughout the experiment to insure simultaneous onset and offset when both signals were gated together during a single interval.

The listener's task was to determine which of the four consecutive intervals contained a signal that was different from the signals in the other three intervals and to press the response button corresponding to that interval during an answer interval. Visual feedback was presented as soon as the listener responded during an answer interval. The intensity ratio between S_m and S_t was adjusted so that at the beginning of a threshold determination, discrimination between S_m alone and $S_m + S_t$ was made easily. As the listener correctly discriminated the different signals in two consecutive 4IFC trials, the task was made more difficult by attenuating the level of S_t in 2-dB steps until an estimate of 50% correct performance could be obtained. The estimate of 50% correct performance and the decisions to change the level of S_t were made by a computer program that controlled the experiment.

During a single test session, quiet thresholds were determined first at the frequencies of the masking signal (f_1) and the test signal ($f_2 = 2f_1$). Then masked thresholds for S_t were obtained at levels of S_m from 40 to 100 db SPL in ascending 10-dB steps (called an octave-masking function). After each octave-masking function had been measured, quiet thresholds for signals at f_1 and f_2 were determined again.

Phase Relations of Signals

The phase relations between S_m and S_t were held constant at 90° ($\pi/2$) or 270° ($3\ \pi/2$) during the determination of an octave-masking function (phase specified in terms of the phase angle of f_2). The masking function for the 90° phase was always obtained before that for the 270° phase.

Normal-Hearing Listeners

Normal-hearing listeners were two highly experienced and 10 inexperienced listeners, who had normal hearing in the test ear. Six of the 10 inexperienced listeners were outpatients who had been referred to the laboratory for study. The data on normal ears is reported in detail in a companion paper (Nelson and Bilger, 1974). Only the mean octave-masking curves from those normal ears are presented here.

Listeners with Sensorineural Hearing Loss

Listeners with sensorineural hearing loss also were outpatients, who had been referred to the laboratory for study. Their hearing impairments were diagnosed as sensorineural on the basis of audiological and medical findings.

Most exhibited audiological results indicating primarily a cochlear impairment. In some cases, however, an air-bone gap, indicating a mixed conductive and cochlear hearing loss, was present.

RESULTS

Octave Masking in Normal-Hearing Listeners

Mean masking functions (defined as the amount of masking of S_t as a function of the sensation level of S_m) for listeners with normal hearing (Nelson and Bilger, 1974) are shown in Figure 1 for masking signals with f_1 frequencies of 250, 500, 1000, and 2000 Hz, respectively, for the 90°-phase condition. Amount of masking at f_2 is shown on the ordinate in sensation level (f_2 dB SL) as a function of the sensation level of the f_1 masker on the abscissa (f_1 dB SL). The masking functions in Figure 1 are nonlinear. At low S_m levels, little or no masking occurs. At moderate S_m levels, masking grows rapidly. At high S_m levels, the masking functions flatten out, that is, with increases in the S_m level above about 70-80 dB SL only small increases in S_t masked thresholds are seen.

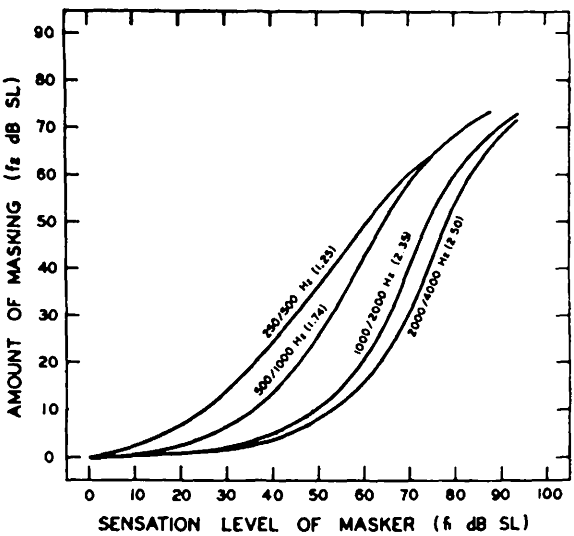

FIGURE 1. Mean octave-masking functions for normal-hearing listeners (from Nelson and Bilger, 1974). Amount of masking of a test signal at f_2 is plotted on the ordinate as a function of the sensation level of the masking signal at f_1. The parameter is frequency of the masking signal and test signal. The phase of the test signal relative to the masking signal is 90° ($\pi/2$). Each function is labeled with f_1 and f_2 frequency and with the slope of the steep portion of each mean masking function. The slopes are given in dB of change in masking per dB of change in the level of the masking signal.

These nonlinear octave-masking functions are similar to those obtained by Newman et al. (1937) for octave tones, by Wegel and Lane (1924) for tones above the masker, and by Chapin and Firestone (1934) and Trimmer and Firestone (1937) for phase-locked octave tones. It appears that earlier results obtained with different psychophysical methods can, in general, be compared with results obtained using a forced-choice procedure.

In normal-hearing listeners tested with 90°- and 270°-phase-locked octave tones (Nelson and Bilger, 1974), the 90° condition produced more masking than the 270° condition, especially at low S_m levels. The 270°-octave-masking functions were steeper than the 90° functions. Both phase conditions produced similar S_t masked thresholds at high S_m levels. These results are consistent with Clack's (1968) findings. However, no direct comparison was made here, because the exact phase corresponding to maximum masking was not obtained from each listener in the present experiments but was approximated by the 90° condition that produced maximum masking at moderate levels of S_m in the normal study (Nelson and Bilger, 1974).

In Figure 1, the slopes of the mean octave-masking functions increase with the frequency of the fundamental. At low S_m sensation levels, more masking was produced by low-frequency masking signals (250 and 500 Hz) than by the higher-frequency masking signals (1000 and 2000 Hz). The slopes of the steep portions of the masking functions are about 1.3, 1.7, 2.4, and 2.5 dB/dB, respectively, for the 250, 500, 1000, and 2000 Hz masking signals.

The functions in Figure 1 provide estimates of typical octave-masking functions from normal-hearing listeners. Since the "normal" masking functions were obtained with the identical procedures used to obtain the "abnormal" masking functions described below, these normal data will be used as a reference to determine if listeners with sensorineural hearing loss exhibit more octave masking than listeners with normal hearing.

Masked Thresholds at f_2 in Sensorineural Ears

The masking functions obtained from listeners with sensorineural hearing loss are shown in Figure 2 for masking signals with frequencies of 250, 500, 1000, and 2000 Hz. As in Figure 1, these data are for the 90°-phase condition. Fourteen different listeners were tested. Two were tested in both ears, so a total of 16 sensorineural ears are included in the graphs. Each is coded by a different symbol. Where the same ear was tested with more than one S_m frequency, the symbol used is the same for all frequencies. In Figure 2, masked threshold test signals at f_2 are plotted in dB SPL as a function of the SPL of masking signals at f_1. The heavy solid curves in each graph represent normal masking functions for each S_m frequency and the dashed lines represent the expected range of normal masked thresholds shown in Figure 1.

In addition, quiet thresholds for each listener are shown in Figure 2. A symbol for each ear has a listener's code number and an arrow next to it. Those symbols are plotted on coordinates corresponding to a listener's quiet thresholds for signals at f_1 and f_2. The two digits of a code number specify a listener's number, and the letter specifies which ear the symbol represents. For example, in Figure 2B, the lower-half-filled circle with the number of 16R and an arrow next to it shows that listener 16's right ear had a quiet threshold at f_1 (500 Hz) of 14 dB SPL and a quiet threshold at f_2 (1000 Hz) of 11 dB SPL. Although 16R has essentially normal hearing, his quiet threshold at f_2 was 10 dB higher than that of any other normal-hearing listener. His data, therefore, are in-

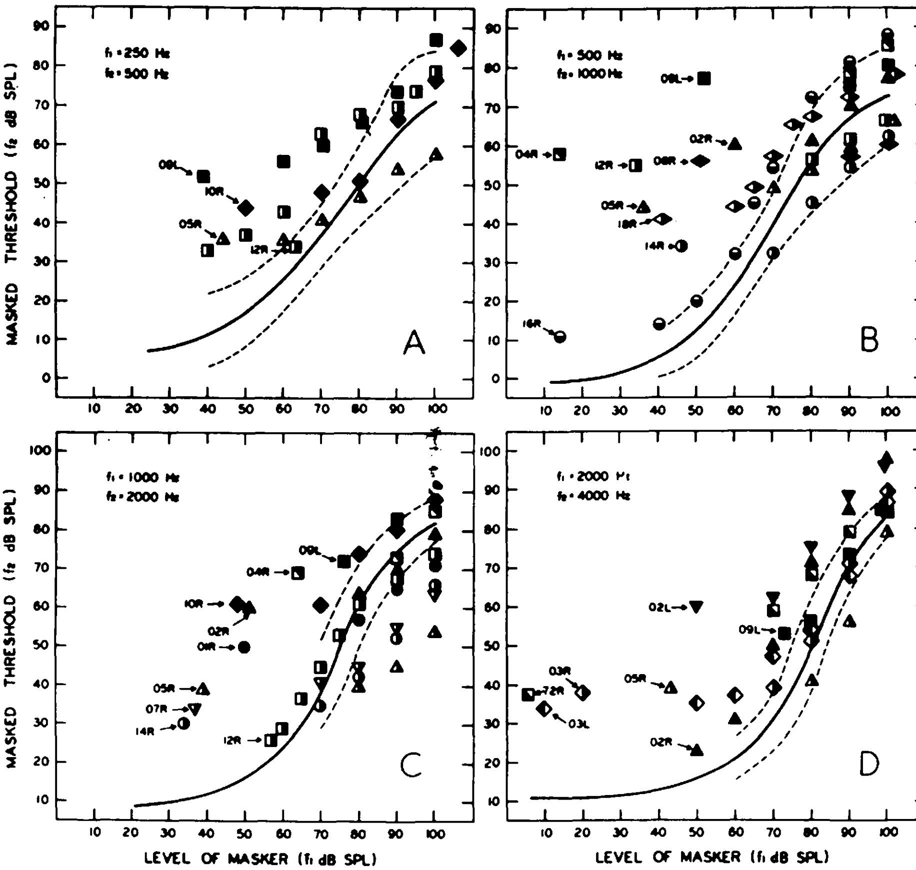

FIGURE 2. Masked thresholds for test signals at f_2 from listeners with sensorineural hearing loss. Masked thresholds for test signals at f_2 are plotted on the ordinate as a function of the sound pressure level of the masking signals at f_1. The phase of the test signal relative to the masking signal is 90° ($\pi/2$). Each graph contains data for different f_1 and f_2 frequencies. Each outpatient listener is coded with a number and a letter to indicate which ear was tested. An arrow next to each ear's code number indicates its f_1 and f_2 quiet-threshold coordinates. Mean masked thresholds for test signals at f_2 from normal-hearing listeners are shown by the solid curves (Nelson and Bilger, 1974). The dashed lines show the 85% confidence limits for masked thresholds at f_2 from those normal-hearing listeners.

cluded in Figure 2B with the data from the listeners who exhibited considerable hearing loss.

It can be seen from Figure 2 that the sensorineural ears exhibited a wide range of hearing loss, from the near normal thresholds of 16R to the profound hearing loss exhibited by 09L (filled squares), whose thresholds at 250, 500, 1000, and 2000 Hz were 39, 52, 77, and 72 dB SPL, respectively.

The most obvious characteristic of the sensorineural masking data shown in Figure 2 is that the sensorineural octave-masking functions do not cluster around a typical masking function as do normal masking functions. Sensorineural hearing loss obviously affects the amount of octave masking. In general, however, the sensorineural octave-masking functions were similar, across frequency, to normal octave-masking functions. The slopes of the sensorineural masking functions tended to be steeper for high-frequency masking signals than for low-frequency masking signals, just as in subjects with normal hearing. But the masking functions for sensorineural ears also tended to be flatter than for normal ears. The sensorineural masking functions often did not show the characteristic steep rise in masking followed by the saturation effect that is seen in normal functions.

Close examination of Figure 2 shows that S_t masked thresholds for high S_m levels (above 80 dB SPL) tended to fall within or below the range of normal. Few of the sensorineural ears exhibit S_t masked thresholds for high S_m levels that could be described as being consistently higher than normal masked thresholds. These data suggest that listeners with sensorineural hearing loss cannot discriminate as well between S_m alone and $S_m + S_t$ when S_t is close to its own threshold. Once S_m was sufficiently intense, sensorineural listeners performed about the same as normal listeners in discriminating between S_m alone and $S_m + S_t$. If anything, the sensorineural ears tended to show less masking than normal ears. These results might be interpreted as supporting the hypothesis that listeners with sensorineural hearing loss exhibit the same or less, rather than more, aural-harmonic distortion than normal listeners (Martin and Pickett, 1970). If hearing losses are due to either damaged hair cells or damaged neural units at f_2, then it is reasonable to expect poorer than normal performance from those ears. As the f_2 test signal becomes more intense, however, more and more of the basilar membrane is involved, allowing more undamaged hair cells or neural units to contribute to the total discrimination. When f_2 test signal becomes intense enough to involve enough undamaged hair cells or undamaged neural units, it is reasonable to expect sensorineural ears to perform as well as normal ears.

Amount of Masking at f_2 in Sensorineural Ears

The masking functions for listeners with sensorineural hearing loss shown in Figure 2 were plotted in terms of absolute levels, that is, S_t masked thresholds at f_2 in dB SPL as a function of S_m SPL at f_1. From those displays, we suggested that once the absolute S_m level is intense enough to overcome their sensorineural loss of sensitivity, those listeners show the same or lower S_t masked thresholds than normals. It behooves us, however, to replot these data in terms of the amount of masking at f_2 (f_2 dB SL) as a function of the sensation level (SL) of S_m at f_1, that is, on coordinates used by earlier investigators (Clack and Bess, 1969). Thus, the data from Figure 2 have been replotted in SL-like terms in Figure 3. The solid line represents the mean for normal-hearing listeners on these SL coordinates.

As a matter of principle, one would expect a good transformation of the data to reduce the variability among subjects. The SL transformation data

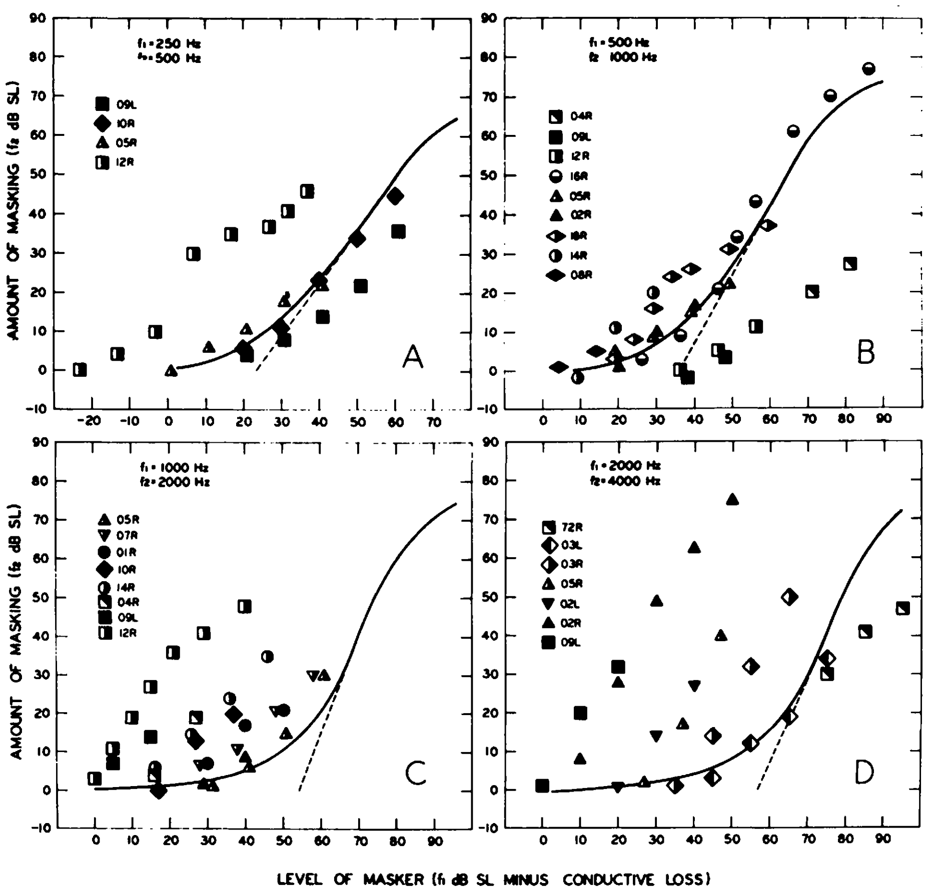

FIGURE 3. Octave-masking functions from sensorineural ears plotted on sensation-level coordinates. The data from Figure 2 have been replotted with the amount of masking (or threshold shift) of test signals at f_2 on the ordinate (f_2 dB SL) as a function of the sensation level of the f_1 masking signals on the abscissa. Any conductive component that existed in a listener's sensorineural hearing loss at f_1 has been corrected to yield a more realistic representation of the effective level of the f_1 masking signal on the basilar membrane. Normal masking functions, plotted on sensation-level coordinates, are shown by the solid curves. The dashed lines are extrapolations from the steep portion of each normal function to a "threshold of octave masking" (TOM) at 0 dB SL the test signal.

in Figure 3, if appropriate, should make the data cluster more closely than they did in Figure 2. Casual inspection of Figure 3 shows this is not the case. The data in Figure 3 are much more variable than those in Figure 2. In spite of this variation, there are aspects of these data that require explanation.

Estimates of the threshold of aural distortion, similar to best-beat estimates of aural overload (Lawrence and Yantis, 1956a, b), can be calculated from the present data simply by extrapolating downward from the steep portion of the masking functions until the quiet threshold at f_2 is reached. This has been done for the normal curves in Figure 3 and is shown by dashed lines.

The sensation level of S_m (f_1), at which the extrapolated masking function intersects with the S_t (f_2) quiet threshold, is a measure similar to Clack and Bess' (1969) threshold of octave masking, which they demonstrated to be highly correlated with the best-beat threshold of aural overload. A comparison of estimates of the normal threshold of aural distortion obtained in the present study, with estimates of the normal threshold of aural distortion obtained by previous investigators, is shown in Figure 4.

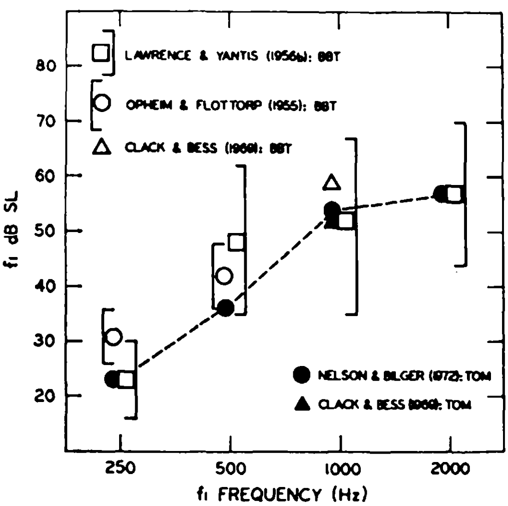

FIGURE 4. A comparison of various estimates of thresholds of aural distortion from normal-hearing listeners. Estimates obtained with the best-beat technique (BBT) are shown by open symbols. Estimates of the threshold of aural overload reported by Lawrence and Yantis (1956b) are shown with the open squares. Estimates of aural overload reported by Opheim and Flottorp (1955) are shown by open circles. The brackets indicate one standard deviation above and below each mean. The mean threshold of aural overload at 1000 Hz reported by Clack and Bess (1969) is shown by the open triangle. Estimates of aural distortion obtained with extrapolated thresholds of octave masking (TOM) are shown by the filled symbols. The filled circles are the extrapolated thresholds of octave masking from the normal curves in Figure 3 of the present study. The filled triangle is the mean normal threshold of octave masking at 1000 Hz reported by Clack and Bess (1969).

Figure 4 shows that the extrapolated thresholds of octave masking for normals are in good agreement with earlier estimates of thresholds for aural distortion that were based on a variety of different experimental techniques. For example, the extrapolated threshold of octave masking for S_m at $f_1 = 1000$ Hz is 54 dB SL in the present study. Lawrence and Yantis (1956b) reported the mean normal threshold of aural overload at 1000 Hz to be 52 dB SL for the method of best beats. Clack and Bess (1969) obtained a value of 59 dB SL with the method of best beats, and a value of 53 dB SL with octave masking. This difference between methods can be explained as a bias due to masking associated with the method of best beats at low S_m levels (Egan and Klumpp, 1951).

Consistent with the earlier literature, which reported lower than normal thresholds of aural distortion in listeners with sensorineural hearing loss (Lawrence and Yantis, 1956b; Clack and Bess, 1969), is that estimates of thresholds of aural distortion, based upon extrapolations from the data of the sensorineural ears in Figure 3, would in nearly all cases tend to be lower than normal. Notice, however, that in many instances, it would be necessary to use what appears to be the "saturated" portion of a masking function rather than the steep portion in order to make that extrapolation (see data for 01R and 10R in Figure 3C). If thresholds of aural distortion from normal-hearing listeners were based upon this upper saturated segment, then those extrapolations would give correspondingly low thresholds of aural distortion for normal-hearing listeners. In other words, the absence of the steep portion from the octave-masking function for listeners with sensorineural hearing loss compromises the validity of aural-distortion estimates based upon extrapolated thresholds of octave masking.

Conductive Hearing Loss and Octave Masking

A factor which confounds any interpretation of these data (and is often overlooked during the interpretation of other masking data) is the possible existence of conductive hearing loss for signals at either f_1 or f_2. A conductive hearing loss, selective to either f_1 or f_2, would act like a simple attenuator in the signal channel for either f_1 or f_2. The octave-masking functions obtained

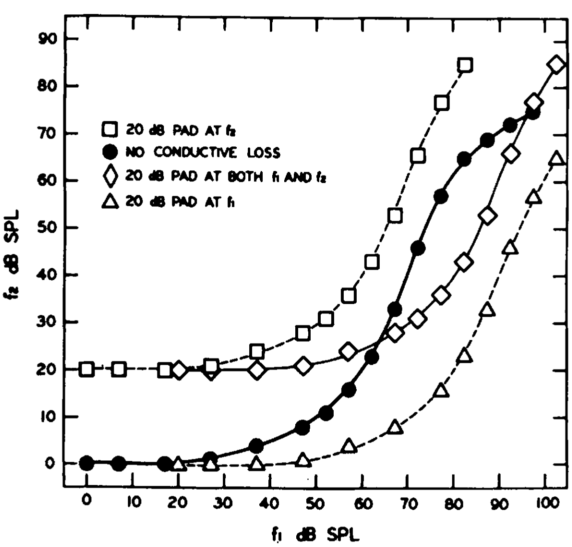

FIGURE 5. An example of the effects of frequency-selective conductive-hearing loss on an octave-masking function. In this example, the effects of frequency-selective conductive-hearing losses are assumed to be analogous to the effects of frequency selective attenuator pads.

with a conductive loss would be predictably shifted by the amount of the conductive loss.

Figure 5 illustrates this problem. The solid circles show an octave-masking function from a normal ear without conductive hearing loss. A 20-dB conductive loss, selective to f_1 alone, would shift the obtained masking function to the right, as illustrated by the unfilled triangles. A 20-dB conductive loss, selective to f_2 alone, would shift the resulting masking function upward, as illustrated by the unfilled squares. Comparable 20-dB conductive losses at both frequencies would shift the resulting masking function both upward and to the right, as illustrated by the unfilled diamonds in Figure 5. To correct a masking function for the effects of a conductive hearing loss, the obtained masking function would have to be shifted downward, to the left, or both, depending upon the conductive component at either f_1 or f_2 or both.

In the present experiment, no laboratory measurements were made of the listeners' bone-conduction thresholds. Clinically determined bone-conduction thresholds, however, were available for each sensorineural ear at frequencies of 500 Hz and above. Corrections for the air-bone gaps, or conductive components at both f_1 and f_2 were made. The data were replotted and then examined. Those conductive corrections placed most of the masked S_t thresholds obtained from sensorineural ears for high S_m levels within or below the range of normal masking data. The results of a consideration of such corrections for conductive losses (not shown) lends support to the hypothesis that listeners with sensorineural hearing loss exhibit the same or less nonlinear distortion than normal-hearing listeners.

The concept of conductive hearing loss can be invoked further to aid in the interpretation of the sensation-level plot of the octave-masking data in Figure 3. A listener with a purely conductive hearing loss at both f_1 and f_2 would be expected to exhibit a masking function similar to a normal masking function, that is, once S_m and S_t become loud enough to overcome the conductive loss. That masking function should then overlay the normal curve when plotted in terms of the sensation level of S_m and S_t. Masking of S_t at f_2 would not begin until the S_m at f_1 was just above 50 dB SL, just as in normal ears. If, however, the hearing loss were purely sensorineural, then it is reasonable to expect masking to occur as soon as the f_2 test signal is heard and as soon as, or before, the f_1 masking signal is heard.

If this reasoning is valid, then those listeners in Figure 3 whose masking functions fall on top of or near the normal masking curve (for example, 05R and 07R in Figure 3C) probably had a sizeable conductive hearing loss that was larger than indicated by clinical bone-conduction measurements. Similarly, those listeners in Figure 3, whose masking functions fell far to the left of the normal masking curves and rose steeply when S_m and S_t were only slightly above threshold (for example, 12R, 09L, 10R, 04R, and 01R in Figure 3C), probably had a true sensorineural hearing loss that was relatively uncontaminated by a large conductive hearing loss. Indeed, those listeners whose data fall on top of or near the normal masking curve (05R, 07R, and 14R in Figure 3C) did have sizeable conductive components at either or both frequencies. Since they had mild hearing losses, their 10-20 dB conductive components were large relative to their hearing losses. The value of SL-like plots of octave masking, such as in Figure 3, may be to simply reflect the amount of pure sensorineural hearing loss, uncontaminated by a conductive component.

Type of Sensorineural Hearing Loss and Amount of Masking

Consideration of the etiology of sensorineural hearing loss leads to further inferences from the octave-masking data. Interestingly, there were marked differences between the probable pathologies of those sensorineural ears that displayed steep masking functions displaced to the left of the normal curves, and those sensorineural ears that displayed flatter masking functions nearer to the normal curves in Figure 3.

Both 05R and 07R in Figure 3C showed strong "cochlear" indications in their audiological results. Their hearing losses were diagnosed (with the aid of otological, neurological, ENG, and audiological examinations) to be caused primarily by noise trauma. Similarly, 14R showed strong cochlear indications in his audiological results. His hearing loss was diagnosed to have been caused by cochlear otosclerosis. Listener 02R, who exhibited considerable hearing loss, also showed strong cochlear indications in his audiological results. The probable locus of pathology for all four listeners is peripheral in the auditory system, that is, before or at the hair-cell level. The octave-masking functions exhibited by these four listeners tended to fall closest to the normal masking curve and grow slowly with S_m intensity.

In contrast to those four masking functions, the masking function of 12R in Figure 3C is radically different. It falls far to the left of the normal curve, shows considerable masking at low S_m sensation levels, exhibited a steep masking slope, and showed a saturation effect at high S_m levels. Audiological results from 12R indicated retrocochlear auditory pathology (Type III discrete Bekesy tracings, severe tone decay at audiometric frequencies between 500 and 8000 Hz, 0% SISI scores even at high levels of the carrier tone, a 0% discrimination score for W-22 recorded words, and a 23% discrimination score for VC nonsense syllables). Audiological results from the opposite ear, 12L, were completely normal. Exhaustive neurological and otological examinations excluded the possibility of a tumor. However, overwhelming evidence points to a pathology more neural than sensory.

These results suggest that different types of hearing pathology may exhibit radically different masking functions when plotted in terms of the amount of masking of S_t at f_2 and the sensation level of S_m at f_1. The same data, plotted in terms of absolute masked thresholds for S_t at f_2 and absolute level of S_m at f_1, lead to the conclusion that sensorineural ears perform much alike (except at low S_m sensation levels) and do not exhibit abnormal distortion at high S_m levels. For example, the masking function of 12R, plotted in terms of absolute masked thresholds for S_t at 2000 Hz in Figure 2C, closely resembles a normal masking function. In Figure 3C, plotted in terms of the amount of masking of S_t, the same masking function for 12R looks very different from a normal function, and also looks different from the other sensorineural functions.

Phase Effects and Hearing Loss

The effect of varying the phase angle between S_m and S_t on masked S_t thres-

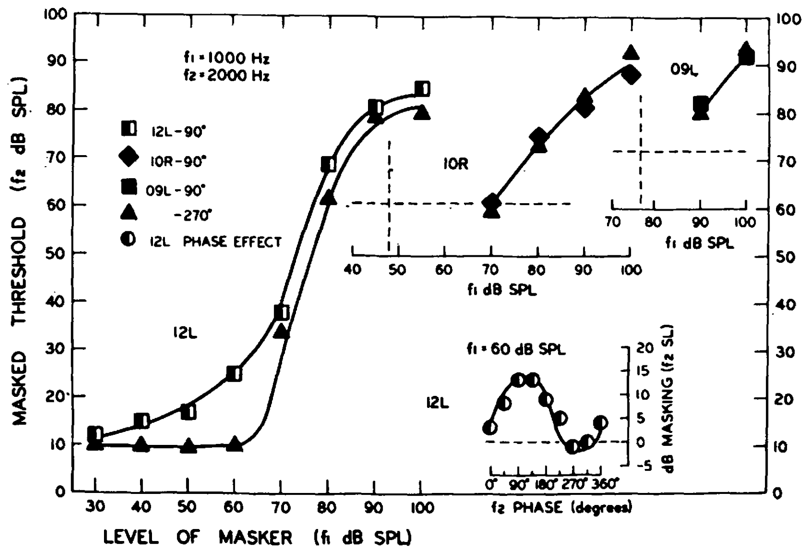

FIGURE 6. Demonstrations of monaural phase effects from a normal-hearing ear and from two sensorineural ears. Masked thresholds for test signals at f_2 ($f_2 = 2000$ Hz) for a 90° ($\pi/2$) f_2 phase and a 270° ($3\pi/2$) f_2 phase are plotted in dB SPL as a function of the level of the masking signal in dB SPL ($f_1 = 1000$ Hz) for three different sensorineural ears: 12L, 10R, and 09L. Quiet thresholds for signals at f_1 and f_2 are shown by dashed lines. Quiet threshold at f_1 for 12L was 0 dB SPL. Masked thresholds for test signals at f_2, as a function of f_2 phase, for sensorineural ear 12L are shown in the lower right. Level of the f_1 masking signal was 60 dB SPL in this case.

holds at f_2 is shown in Figure 6. Two octave-masking functions are shown on the left from an outpatient (12L), who had normal hearing in her left ear. Half-filled squares show the masking function for the 90°-phase angle, and filled triangles show the masking function for the opposite 270°-phase angle. These two functions are typical of the phase data obtained from normal-hearing listeners (Nelson and Bilger, 1974). The maximum effect of phase angle for this listener occurred when S_m was at 60 dB SPL. A detailed representation of that phase effect is shown in the lower right inset of Figure 6. Sinusoidal variation in the masked S_t threshold at f_2 occurs through 360°. These results are also consistent with those reported by Trimmer and Firestone (1937) and Clack (1967, 1968). Maximum masking was obtained at a phase angle of 90° and minimum masking was obtained at a phase angle of 270°. These two phase angles for maximum and minimum octave masking, respectively, were typical for nearly all the phase data that were collected on normals. These phase effects are strongly level dependent. At high S_m levels, the phase effect decreased markedly. In normal-hearing listeners, the phase effect was completely absent or was extremely small at high S_m levels (Nelson and Bilger, 1974).

Since phase effects in normal-hearing listeners occur only at low to moderate

S_m levels, phase effects in listeners with sensorineural hearing loss could be expected to depend upon the amount of hearing loss at S_m and S_t. Indeed, that was the case in those sensorineural ears tested for a phase effect. When quiet thresholds at f_1 and f_2 were high enough to prohibit measurement of masked thresholds below S_m levels at about 70-80 dB SPL, no phase effect was observed. Examples of this are shown by the 90°- and 270°-masking functions for two listeners with considerable hearing loss (10R and 09L) in the upper two insets on the right of Figure 6. Again, filled triangles represent the 270°-masked thresholds. The filled diamonds are for 90°-masked thresholds from 10R and the filled squares are for masked thresholds from 09L. Quiet thresholds at f_1 and f_2 are shown by dashed lines.

The amount of hearing loss at f_2 may not be the only factor which precludes measuring a phase effect. That the phase effect may depend upon the amount of hearing loss at f_1, the type of hearing loss, or both, is demonstrated in the masking functions of Figure 7. Two sets of 90° and 270° octave-masking functions are shown from two listeners with comparable sensitivity losses at f_2. However, the etiologies of their hearing losses differed, as did their sensitivity losses at f_1. Listener 12R (half-filled squares) showed reliable audiological findings that are more indicative of neural than sensory pathology. Listener 14R (half-filled circles) exhibited audiological indications of a mixed cochlear

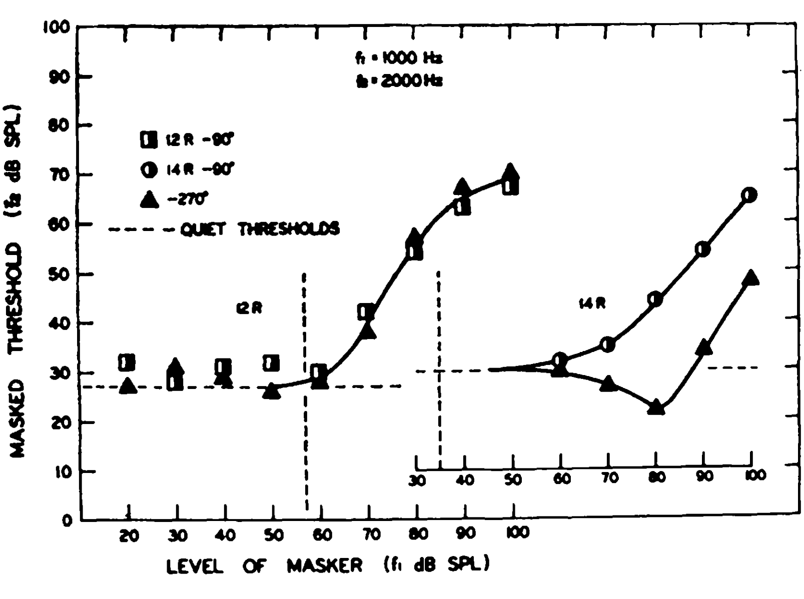

FIGURE 7. Octave-masking functions for a 90° ($\pi/2$) and a 270° ($3\pi/2$) phase angle between test signal and masking signal from the two ears with different types of hearing loss. Listener 12R exhibited audiological results strongly indicating retrocochlear or neural pathology. Listener 14R exhibited audiological results indicative of more peripheral cochlear pathology, along with a 20-dB conductive component in the hearing loss at f_1. Quiet thresholds for test signals at f_1 and f_2 alone are shown by the dashed lines.

and conductive loss, more sensory than neural. Listener 12R had a quiet threshold at f_1 of 58 dB SPL and listener 14R had a quiet threshold at f_1 of 34 dB SPL. A large phase effect can be seen in Figure 7 for listener 14R. Relatively little phase effect can be seen for listener 12R, even though their loss in sensitivity is about the same at f_2. These results demonstrate the complexity of octave masking data. Is the absence of a phase effect from 12R due to her higher threshold at f_1, or is it due to the neural nature of her hearing loss? We only venture to speculate at this time.

Since 12R exhibited considerable difficulty in discriminating among speech sounds that contained a wealth of temporally coded information, it is tempting to attribute the lack of a phase effect from listener 12R to the inability of her neural system, from the cochlea to the brain stem (since the opposite ear, 12L, was normal), to transmit adequately temporal information about the $S_m + S_t$ waveform. This speculation is consistent with a neural pattern recognition model of octave masking offered by Nelson and Bilger (1974).

The fact that 14R showed a maximum phase effect at an S_m level of 80 dB SPL (20 dB higher than for most normals) is easier to explain. A 20-dB conductive component existed in 14R's hearing loss at f_1. Therefore, the assumption was made that effective stimulation by S_m at f_1 on his basilar membrane was 20 dB less than for normals, and that an 80-dB-SPL-f_1 masker was needed to produce the maximum phase effect usually seen at about 60 dB SPL in normals.

DISCUSSION

Comparisons of masked thresholds at the octave from sensorineural ears, with similar data from normal ears, demonstrated that once intense enough signals are used to overcome the sensorineural loss of sensitivity, listeners with sensorineural hearing loss perform as well as normals in discriminating S_m alone from $S_m + S_t$. From these results we conclude, in terms consistent with traditional notions of harmonic distortion in the ear, that the sensorineural ear does not generate more second-harmonic distortion than the normal ear.

The nonlinearity of octave-masking functions in sensorineural ears and the confounding effects of frequency-selective conductive-hearing losses on those octave-masking functions has led us to regard the examination of pure-tone octave-masking data in sensation-level coordinates as a precarious procedure that can lead to spurious conclusions about the amount of aural distortion in sensorineural ears. However, careful examination of octave-masking functions on sensation-level coordinates may offer some promise of separating sensorineural ears by type of hearing pathology.

Monaural phase-effects at f_2 in sensorineural ears were shown to be dependent upon the absolute level of S_m at f_1, as is the case in normal ears. Therefore, if the amount of sensorineural hearing loss at f_1 and f_2 in a particular sensorineural ear is sufficient to preclude utilization of moderate sound pressure level signals, then no significant phase effects will be observed from that sensorineural ear. If large phase effects are observed at high S_m levels, it is probable that a large conductive component exists in that sensorineural hearing loss.

Most of the interpretations of these octave-masking data up to this point have assumed that the auditory system introduces harmonic distortion in the ear. Those interpretations imply a model that depicts the spectral products of harmonic distortion within the ear as traveling waves at the place on the basilar membrane corresponding to the frequency of those distortion components. The phase-dependent interactions that take place on the basilar membrane, between the internally generated distortion product at f_2 and the externally generated test signal at f_2, have been traditionally explained with the concept of harmonic distortion and a vector-summation model that implies traveling waves at the frequency region of the distortion product (Clack, 1967, 1968). Recent physiological data (Dallos and Sweetman, 1969) have raised serious questions about the existence of those traveling waves.

Nelson and Bilger (1974) have pointed out several properties of octave-masking data in normal-hearing listeners that cannot be explained adequately by traditional concepts of aural-harmonic distortion. In that paper, alternative explanations have been offered which account for those properties of octave masking that are inconsistent with traditional distortion concepts and which take recent neurophysiological data into account (Dallos and Sweetman, 1969; Brugge, Anderson, Hind, and Rose, 1969). Those alternative explanations rely heavily upon a temporal pattern recognition model which assumes nonlinearity in the auditory system as do traditional models. However, instead of an energy detector that is insensitive to temporal coding, a temporal-pattern recognizer similar to that proposed by Craig and Jeffress (1962), at the neural level following some nonlinear stage in the auditory system, is suggested.

In terms consistent with temporal pattern recognition concepts, the behavior of the sensorineural ear during octave masking would not be interpreted much differently than with traditional distortion concepts. The fact that sensorineural ears show masked thresholds at f_2, the same or below those of normal ears, would be interpreted as indicating the sensorineural ears can perform temporal pattern recognition at high S_m levels just as well as normals. Because nonlinearity in the auditory system is translated into waveform distortion in the temporal pattern recognition model, it is implied with the temporal model that sensorineural ears do not produce more waveform distortion than normal ears. Similarly, at low S_m levels, sensorineural ears do not perform temporal pattern recognition as well as normal ears since they show more masking. However, this result can be adequately explained by the sensitivity loss. Both classical distortion models and the temporal pattern model lead to the same conclusion that sensorineural ears do not add significant distortion to acoustic signals.

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