MASKING ON THE HIGH-FREQUENCY SIDE OF A MASKING TONE: EFFECTS ON MASKED THRESHOLD OF SELECTIVELY MASKING LOW-FREQUENCY COMBINATION TONES OF DIFFERENT TYPES FORMED BY SIGNAL AND MASKER

by

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ABSTRACT

When signals are presented on the immediate high-frequency side of a pure-tone masker, it is not the signal, but rather combination tones, that are detected at masked threshold (Greenwood, 1971b). At low to moderate masker intensities, the detected combination tone is $2f_1 - f_2$, where $f_1$ is the masker frequency and $f_2$ is the signal frequency. At higher masker levels, the combination tone $f_2 - f_1$ becomes large enough to play a role. To investigate this role, the combination tones $f_2 - f_1$ and $2f_1 - f_2$ were selectively masked in different low-frequency regions, to identify their effects. As has been known, the notch region on the high side of the pure-tone masking pattern creates a secondary peak, which shifts upward in frequency and height as masker intensity is raised. Results indicate that the frequency location of this secondary peak has an upper limit at $1.85f_1$, and that the secondary peak marks the beginning of signal-determined masked thresholds. At masker levels sufficient to shift this secondary peak upward, beyond 1.5 times the masker frequency ($f_1$), both $2f_1 - f_2$ (or $C_1$) and $f_2 - f_1$ (or $D_1$) are detected with about equal likelihood when signals are in the higher-frequency part of the notch region, at frequencies between $1.5f_1$ and the
secondary peak. That is, either $C_1$ or $D_1$, or both, may be detected since their intensities become quite similar at higher levels, as supported by more direct estimates (Greenwood, 1971b, 1972a,b,c; Hall, 1971, 1972a,b).
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INTRODUCTION

The following paper deals with two important concerns in the study of hearing: masking and combination tones. Between these, important interrelationships exist which elucidate both classes of phenomena. For example, certain combination tones influence the masking pattern which is obtained even in the simplest experimental conditions (Greenwood, 1971b; 1972a,b,c).

Definitions and Explanations of Terms

Masking is quantitatively defined as "the amount by which the threshold of audibility of a sound is raised by the presence of another (masking) sound"; and qualitatively defined as "the process by which the threshold of audibility of a sound is raised by the presence of another (masking) sound" (USA Standard, 1960, S1.1). The sound whose threshold is raised is called the signal and the masking sound that produces the increase in threshold is called the masker.

A pure-tone masker, for example, has a peak masking effect on signals close to the frequency of the masker ($f_1$). The masking effect on signals below $f_1$ (the masker frequency) extends over a narrow frequency range and decreases rapidly as signal frequencies decrease immediately below $f_1$. The masking effect on the high-frequency side of the
masker, on the other hand, extends over a greater range of signal frequencies, particularly at higher intensities of the masker. This asymmetry in the masking effect is consistent with the observed asymmetry of the shape of the traveling-wave envelope on the basilar membrane in response to a pure tone. For this, and other, reasons masking has often been used in attempts to infer auditory mechanisms at the periphery of the system.

A combination tone is a tone produced within the auditory system when two or more tones of sufficient intensity are presented simultaneously. There are grounds for explaining the origin of combination tones as a result of nonlinear amplitude distortion in the inner ear (Zwicker, 1955, 1968; Plomp, 1965; Goldstein, 1967; Greenwood, 1971b) rather than as a result of purely neural processes. Although, assuming nonlinearity, the frequency location of innumerable combination tones may be calculated, with respect to the frequencies of primary tones, evidence for the existence of only a small number of these combination tones has been produced (Plomp, 1965). Existing combination tones are classified and described, and their frequencies calculated, according to differences of integral multiples of the frequencies of each of the primary tones. No convincing evidence has yet been presented to suggest that combination
tones described by the sum of integral multiples are produced within the auditory system (Plomp, 1965).

A combination band of noise is the result of the same process as that producing combination tones, but the combination band is produced by a tone and a band of noise or by two bands of noise. Its frequency location and band limits are calculated in a similar way as the frequency location of combination tones is calculated. That is, the frequency components of one of the primaries interact with those of the other in the same way as the primaries generating combination tones interact (Greenwood, 1971b; 1972a,b,c).

In short, combination tones are classified under the two main categories, summation tones and difference tones. Summation tones are described by the sum of integral multiples of the frequencies of each of the primary tones; and difference tones are described by the difference of integral multiples of the frequencies of each of the primary tones. Only the latter type of combination tone is of interest here, for the reason given above.

Difference tones may be further sub-classified into those of odd order and those of even order. The more prominent odd-order combination tones \((C_n)\) are those whose frequency is given by the expression \((n+1)f_1-nf_2\), where \(n\) is an integer \((n=1,2,3\ldots)\), \(f_1\) is the frequency
of the lower primary component (e.g. the masker), and \( f_2 \) is the frequency of the upper primary component (e.g. the signal). The more prominent even-order difference tones (\( D_n \)) are those whose frequency is given by the expression \( n(f_2 - f_1) \), \( n = 1 \) or \( 2 \). The two most readily audible combination tones are those described by the preceding formulas when \( n = 1 \). They are the cubic difference tone, \( 2f_1 - f_2 \), or \( C_1 \), so called because its frequency is predicted by third-order, or cubic, terms in the power series expansion of the nonlinearity; and the quadratic, or second-order, difference tone, \( f_2 - f_1 \), or \( D_1 \), predicted from quadratic terms.

The behavior of the frequency of \( D_1 \) and \( C_1 \) during the manipulation of the frequencies of the primaries is of particular concern here. As the frequency separation between the primaries is increased, from nil to octave separation, the frequency of \( D_1 \) increases from zero to that of the lower primary, and the frequency of \( C_1 \) decreases from that of the lower primary to zero. The two distortion products coincide in frequency at \( .5f_1 \) when the frequency of the higher primary \( (f_2) \) is 1.5 times that of the lower \( (f_1) \). For smaller frequency separations of the primaries (i.e. \( f_2/f_1 \) smaller than 1.5), the frequency of \( D_1 \) is, obviously, lower than that of \( C_1 \), and for greater frequency ratios than 1.5,
the frequency of $C_1$ is lower than that of $D_1$. For example, if the frequency of the lower primary or masker is $2\text{kHz}$ ($f_1 = 2\text{kHz}$), and the frequency of the upper primary or signal is $2.5\text{kHz}$ ($f_2 = 2.5\text{kHz}$), the frequency of $C_1$ is $1.5\text{kHz}$ and the frequency of $D_1$ is $0.5\text{kHz}$ (see Fig. 11, schematic no. 1).

**Historical Synopsis**

Difference tones are a relatively early concern in the study of hearing. Around the middle of the 18th century, Georg Andreas Sorge, Giuseppe Tartini, and Jean-Baptiste Romieu independently published findings relating to the discovery of difference tones. Each has been credited with the discovery. Tartini, however, in a later publication, claims to have discovered them at the earliest date, 1714 (Jones, 1937). Much work on combination tones had been done in the 19th century, but interest in this phenomenon subsided in the early part of the 20th century, despite the development of more sophisticated techniques which could have been useful in studying them.

Lately, particularly within the last decade, interest in combination tones has been revived, with investigators such as Plomp, Zwicker, Goldstein, Greenwood, and Smoorenburg pursuing intensive studies. Recent evidence shows that at least one of the sources responsible for the
creation of combination tones is located in the inner ear. One combination tone in particular, $C_1$, is of interest since its amplitude decreases sharply with the frequency separation of primary tones (Goldstein, 1967). This amplitude decrease seems to reflect characteristics of the frequency analysis of the inner ear.

The study of masking has been of more recent scientific interest than that of combination tones, in part since it is difficult to study without the aid of electronic instruments. Mayer (1876) was probably the first to make systematic, though unquantified, observations concerning masking. Specifically, he noted that sounds of considerable intensity could be made inaudible (i.e. masked) by sounds of lower frequency but not by sounds of higher frequency.

The first extensive study of masking was performed by Wegel and Lane (1924). They were the first to plot masked audiograms. A masked audiogram is a graphical representation of the masked threshold of a signal in the presence of one or more maskers, consisting of one or more tones, noises, or combinations of them. Masked threshold is usually plotted in decibels sound pressure level (dB SPL)\(^1\) as a function of the frequency of the

\(^1\)Decibels Sound Pressure Level are measured with respect to a reference level of 0.0002 dyne per square centimeter, which is reasonably close to the average threshold of hearing of a 1000-cycle tone.
signal. Wegel and Lane kept the masking tone at a constant frequency and intensity. The intensity of the signal tone at which the latter could just be heard was then plotted at suitably chosen frequencies of the signal, both above and below the masking tone. This method of studying masking is still appropriate to the study of many questions, and is basically the same method used in the studies that are the subject of this paper.

Wegel and Lane (1924) have pointed out that, at high intensities of the masking tone, and at signal frequencies just above that of the masking tone, a difference tone is heard instead of the signal at masked threshold. These investigators also reported the presence of a secondary peak in such masked audiograms. They miscentered it, however, at the second harmonic, probably because they assumed the secondary peak to result from masking by the second harmonic. This error was pointed out by later studies, particularly by Ehmer (1959) and more extensively by Greenwood (1971b). Wegel and Lane failed to observe a secondary peak at lower masker intensities for lack of a sufficiently detailed mapping of the frequency range below the second harmonic. This secondary peak shifts upward in frequency as masker intensity increases and becomes the peak observed by Wegel and Lane at high intensity (see Fig. 1).
Fig. 1. (A) Portions of masked audiograms produced by pure-tone maskers at 2000 Hz for one subject. Each curve is displaced on the ordinate to prevent overlap of curves. (B) The same curves are plotted in a three-dimensional graph, as smooth curves—this time on the same ordinate scale but with masker level indicated on a receding z-axis in order to reduce overlap. The low point of the notch remains at nearly the same frequency from low to moderate levels, and at higher masker levels, for this and some other subjects, a small shelf and then an inflection begins at the same frequency. At masker levels too low to produce a notch, the high-frequency side of the masking pattern intersects the quiet threshold curve at very nearly the same signal frequency. The secondary peak increases in size with masker level and moves upward in frequency, increasing the size of the notch markedly (from Greenwood, 1971b, Fig. 6).
FIGURE 1
Fig. 2. Portions of masked audiograms produced by pure-tone maskers at 85 dB SPL presented at 1.2 or 2.0 kHz (top and bottom, respectively) accompanied by low-pass noises presented at ascending spectrum levels. The inset graphs display the stimuli used. The noise accompanying the tone of 1.2 kHz starts to cut off at 1050 Hz with a slope of 110 dB/oct for the first 25 dB. The noise with the 2.0-kHz tone was the same as in Fig. 10. In each graph, curves through solid circles display masked audiograms produced by the masking tone presented alone. The added low-pass noise progressively eliminates the notch. Included in the upper graph is the masked audiogram produced by the most intense low-pass noise when presented alone. The noise alone produces little masking in the notch region. At a spectrum level 20 dB lower, at which it is still completely effective in eliminating the notch, the noise alone produces no masking in the region of the notch (from Greenwood, 1971b, Fig. 11, p. 515).
FIGURE 2
Masking on the High-Frequency Side of a Masking Tone

The trough between the masking peak and the secondary peak of the masked audiogram has been referred to as a "notch" (Greenwood, 1971b). The low point of the notch is located at approximately one critical bandwidth above the frequency of the masking tone (see Fig. 1, reproduced from Greenwood, 1971b, Fig. 6). Evidence of this notch is also present in the data of Chistovich (1957), Small (1959), Ehmer (1959), and Greenwood (1961). Audiograms obtained by these investigators reveal notch- or shelf-like shapes of the masking pattern on the high-frequency side of pure-tone masked audiograms when the masker is at "low-moderate" to high levels. These features of shape have been investigated in greater detail by Greenwood (1971b). By introducing a low-pass noise with an upper cut-off frequency below that of the pure-tone masker, he was able to eliminate this notch (see Fig. 2, reproduced from Greenwood, 1971b, Fig. 11, p. 515). Lower levels of this noise reduced the size of the notch to a lesser extent than did higher levels. In other words, the noise, which was located below the frequency of the pure-tone masker, increased "signal" masked threshold above the frequency of the masker, particularly in the region in which the notch occurs. In this region of signal frequencies, the noise alone either did not mask at all, or insufficiently
to account for such an effect. From this evidence, Greenwood (1971b) inferred that it is the masking of the combination tones $C_n$ (with frequencies $(n+1)f_1 - nf_2$—particularly $C_1$) by the low-pass noise that is responsible for the threshold elevation on the high-frequency side of the masked audiograms. In other words, it has been concluded that it is $C_1$ (at $2f_1 - f_2$, with masker at $f_1$ and signal at $f_2$), rather than the signal per se which is detected at masked threshold, as measured in the frequency region immediately above the masker, where a notch occurs.

That it is actually the cubic difference tone, $2f_1 - f_2$ (or $C_1$), and not the quadratic difference tone, $f_2 - f_1$ (or $D_1$), that is detected in this case is supported by prior findings of Zwicker (1955) and Goldstein (1967). They demonstrate that only $C_1$ is generated at relatively low levels of the primary tones (providing that the latter are close together) whereas $D_1$ is not generated until much higher levels of the primaries are reached.

As the intensity of the pure-tone masker is increased from moderate to high levels, the notch (i.e. the local minimum of the masked audiogram between its main and secondary peaks) may move to a higher frequency locus as the location of the secondary peak also moves to a higher frequency locus (see Fig.1). At these primary intensities, the possibility exists that $D_1$ as well as, or instead of,
may determine the masked thresholds that are measured when the signal is in some portion of the frequency region between the main and secondary peaks of the masked audiogram. Since, at low to moderate levels of the primaries, the intensity of \( C_1 \) drops quite sharply as the frequency separation between masker and signal is increased (Goldstein, 1967; Greenwood, 1971b, 1972c), it is most probable that, if \( D_1 \) is sometimes the combination tone that is detected at masked threshold, then it will play this role when the frequency of the signal is relatively removed from that of the masker—most probably in the region above the low point of the notch and below the secondary peak (see Fig. 1).

**Purpose of the Study and Strategies Used**

In order to determine which combination tone, \( C_1 \) or \( D_1 \), is actually detected when signal intensity is at masked threshold (in various frequency regions on the high-frequency side of pure-tone masked audiograms produced by high-intensity maskers), the strategy described in the following paragraph has been used. Results of this kind are intended to aid in interpreting the shape of the high-frequency side of the pure-tone masked audiogram.

A band-pass noise, strategically placed **below** the masker, will itself **mask** either \( D_1 \) or \( C_1 \), or both,
depending on the frequency of the signal. That is to say, the noise will do so when the signal frequency is within certain limited ranges of frequencies above the masking tone. If only the stronger of the two combination tones is masked by the noise, when the signal is near threshold, then the combination tone that is masked cannot play the role of the detected tone at masked threshold. Consequently, if the combination tone that is now masked by the band-pass noise is the tone that is normally detected at masked threshold, it is easily seen that the signal, in order to be detectably present, will have to be raised in intensity until either the other combination tone or the signal itself becomes audible, whichever occurs first. On the other hand, if the masked threshold is not raised by the band-pass masking noise, then it can be inferred that either the other combination tone or the signal itself is detected at masked threshold in the signal frequency range in question. To approach this latter question, the band of noise below the masker can then be moved (without changing signal frequency) to a position appropriate for masking the other combination component, in order to seek further information as to its role and to analyze the total range of possibilities.

If noise and signal frequencies are such that both $C_1$ and $D_1$ are masked at the same time by the introduced
noise, i.e. when the signal is within a particular frequency range, an increase in measured "signal" threshold will indicate that either \( C_1 \) or \( D_1 \), or both (with no decision between them possible) are normally heard at masked threshold. The increased masked threshold that results when both \( C_1 \) and \( D_1 \) are masked simultaneously will correspond to a level at which the signal per se is detected instead. Therefore, when signal frequencies are near 1.5 times \( f_1 \), and \( C_1 \) and \( D_1 \) are consequently too close together to be masked separately, it is impossible to decide whether it is \( C_1 \) or \( D_1 \), or both, that are being detected at measured masked threshold. It is, however, possible to determine whether or not it is the signal itself that is detected in this case. When signals are in other frequency regions on the high-frequency side of the pure-tone masked audiogram, thus resulting in more widely spaced \( D_1 \) and \( C_1 \) frequencies, both combination tones can, of course, still be masked simultaneously despite their separation—either (a) by using a wider band of noise or (b) by using two narrow bands of noise appropriately situated.

The plan of this research, then, begins with one of the latter two situations—the one in which a wide (effectively low-pass) noise is situated below an intense pure-tone masker. This is the experimental condition in Greenwood's (1971b, Fig. 11, p. 515) report, that
demonstrated that the signal itself was not normally detected in the entire notch region, but left it as an open question, at high masker levels, as to which combination tone—C₁ or D₁—is actually detected when the signal frequency is in the notch region, or in different regions of the notch.

The situation in which two narrow bands of noise are appropriately placed below the masker to mask D₁ and C₁ simultaneously, provides an especially powerful basis for inference, as the experiments of this paper will describe and as can be outlined briefly below. In this case also, an increase in masked threshold, after masking C₁ and D₁ simultaneously, will correspond to a level at which the signal itself is heard. But if this level is higher than the signal threshold measured when only one of the combination tones is masked by one of the two noises, then it is the unmasked combination tone that is being detected after the selective masking, and the masked threshold obtained in this case will correspond to the level of the signal required to make the unmasked combination tone audible. For example, if masking either D₁ or C₁ selectively causes no increase in masked threshold in the specific signal frequency region under consideration, whereas masking both causes a marked increase in threshold in the same region, then it follows that both
$C_1$ and $D_1$ are of about the same intensity at the masked threshold as it is normally measured.

With the exception of those signal frequencies that are approximately 1.5 times $f_1$ (the masker frequency), in which case masking selectively is precluded, a great deal of information may be obtained by selectively masking $C_1$ and $D_1$. The data will reveal not only whether the $D_1$, $C_1$, or both are detected at masked threshold when the signal lies on the high-frequency side of a high-intensity pure-tone masker, but they will also indicate the individual signal levels for which $C_1$, $D_1$, and the signal itself become audible. Basically, then, the following experiments constitute a further extension of the attempts by Greenwood (1971b) to determine the "events" that are actually detected at masked thresholds in the pure-tone masked audiogram, and the levels at which the signal itself, and $D_1$, become audible.
METHODOLOGICAL AND APPARATUS

General Method

A modified von Békésy tracking method was used. It was modified in that thresholds were obtained at fixed and closely spaced frequencies of the pure-tone signal. This method has advantages over the employment of a continuous sweep of the frequency range. Thresholds may be obtained both rapidly and with reduced variability, since the subject is not required to contend with rapid changes of threshold that accompany changes of frequency. For only one subject and one aspect of the experiment was there a departure from this method. A very slow (20 Hz/min.) linear sweep was used for one especially reliable subject (the experimenter, FK) in the preliminary mapping of masked thresholds in the region of the selective masking noise which was later used to mask combination tones in the experiments proper (see discussion of strategy in the Introduction). Sweeps in the opposite direction, from high to low frequencies, and comparison of thresholds with those obtained from fixed-frequency measurements confirmed the reliability of the measurements obtained in this single case in which this method was used. In the experiment proper, the method of fixed-frequency signals was used exclusively.
Stimuli and Controls

The signal was a series of tone bursts repeated at a rate of 3 times per second. Signal duration was 165 msec, with onset and decay periods of 30 msec, to eliminate detectable transients. Signal pulses began at least 300 msec after the onset of the continuous masker. The signal was continuously monitored by an oscilloscope. The maskers consisted of a band of noise, a pure tone, or a pure tone presented simultaneously with one or two bands of noise. The maskers remained at the same frequency and intensity throughout the experiment. Signal level was varied by the subject in discrete 2-dB steps. Signal frequencies were separated by small discrete intervals, and presented consecutively from low to high frequencies. Both masker and signal were presented monaurally. All stimuli were presented inside an IAC double-walled sound-proof room.

To map the high-intensity, pure-tone masked audiograms of this study, it is particularly important to determine thresholds at successively adjacent frequencies in order to minimize the lapse of time between determinations of threshold in the same part of the masked audiogram. Minimizing the time interval between adjacent frequencies is advisable in order to minimize the likelihood of any small changes in sensation level.
since small changes in the sensation level (dB SL)\(^2\) of
the masker result in large changes in the masked thresh­
old on the high-frequency side of the masking pattern.
To control for any small changes in masker SL\(^2\), "tone
alone" and "tone plus noise" conditions were alternated
at each signal frequency used during the experimental
session. This alternation of conditions was intended
to prevent any change in threshold, over time, from con­
founding the change in threshold due to the introduction
of the noise, which is the critical variable in the
following experiments (see discussion of experimental
strategy in the Introduction).

Reliability of thresholds was ascertained by intro­
ducing, without the subject's knowledge, checks of his
performance. Such checks consisted of raising or lower­
ing the intensity of the signal during a trial, removing
the signal, or repeating the trial; and observing the
subject's corresponding compensatory response.

Subjects

Five subjects, including the author (FK), partici­
pated in the study. All were in their early twenties.

\(^2\)Sensation Level, abbreviated SL, indicates the number of
decibels (dB SL) a sound is above the threshold of
hearing at that frequency (Stevens and Davis, 1938).
Subjects were selected for normal quiet threshold curves without marked irregularities in the frequency range in which thresholds were obtained. They were also chosen for ability to perform stably and reliably throughout an experimental session. Subjects were familiarized with the task of tracking thresholds during at least five, one-hour sessions. At the end of this period of familiarization and assessment of the subject's reliability, either data-gathering began, or the subject was dismissed. Subject RB, from whom the most complete data was obtained, has had about one year's experience in the threshold-tracking task before serving in the present study.

**Apparatus**

The masking tone was generated by a Hewlett-Packard (Model 203-A) oscillator. A General Radio oscillator (Model 1309-A) generated the signal. Signal pulses were produced by an electronic switch and gate. Another switch, controlled by the subject during threshold determinations, was located inside the IAC double-walled sound-proof room. This switch was used to control an attenuator and a Hewlett-Packard (Moseley 7035AM) X-Y recorder (see Fig.3). Pushing the lever on the switch in one direction lowered the signal level by 2 dB, and pushing the lever in the opposite direction raised the signal level by 2 dB. Simultaneously, when the subject
Fig. 3. Block Diagram of the apparatus
lowered the signal level by 2 dB, the pen on the X-Y recorder moved downward and then to the right (about 1 mm.). Similarly, each time the subject raised the signal level 2 dB, the pen moved upward 4 mm. and then again forward.

**Generation of noise bands**

Noise bands were generated so as to produce masking effects that are as localized as possible. Specifically, they were produced with steep skirts and at the minimum level sufficient to the purpose. The levels of the noises were chosen so as to mask tones at levels below 40 dB SPL. This level was arrived at as being the lowest which would ensure masking of any combination tone generated by masker and signal, falling within the noise. Single narrow bands of noise, 50 Hz in width, were obtained from a General Radio wave analyzer (1900-A), used as a filter. Where two 50-Hz bands of noise were used simultaneously, the second was the filtered output of a balanced modulator with a carrier input at the desired center frequency of the output band and a modulating input consisting of a 25-Hz low-pass noise from an electronic filter. Since steep slopes were necessary for the wider (than 50-Hz bandwidth), band-pass noises, the noise fed to the modulating input of the balanced modulator was put through two low-pass filters, jointly
producing a steep, 54 dB/octave slope of the low-pass noise at the input stage. The output was steeper to an extent dependent on frequency location, and was also filtered to remove carrier harmonics. The bandwidths of the wider (than 50 Hz) noises, as given in this paper, are specified at nine, rather than the customary three, decibels down. Customarily, only one filter is used to generate a band of noise. In this case, the cut-off frequency of the filter specifies the edge of the noise at 3 dB down. Since, however, three filters, set at the same cut-off frequencies, were used, and each filter lowered the edge by three decibels, the edges of the wider noises, as specified by the cut-off frequencies of the filters, are nine decibels down. For example, the noise of 350-Hz bandwidth, as specified by the cut-off settings of the three filter, has a bandwidth of 300 Hz according to the conventional 3-dB down cut-off points; the 600-Hz wide band, used here, has a conventional width of 500-550 Hz (becoming narrower at higher frequency); and the 1400-Hz wide band of noise used in this study is conventionally only 1100 Hz wide.

**Calibration**

Response of the earphones (TDH-49) was flat up to 3600 Hz. Measurements of thresholds obtained above 3600 Hz were corrected for the reduced response of the earphones.
Stimuli were calibrated both electrically, by measuring the voltage across the earphones with a Ballentine true-
r.m.s. voltmeter (Model 320), and acoustically, in a 6-cm$^3$ coupler with a General Radio 1590 P5 microphone. Noises produced with the balanced modulator were measured acoustically by substituting an oscillator for the noise generator and measuring the output of the balanced modulator with the wave analyzer.

Certain intermodulation distortion products have the same frequencies as the combination tones studied in this paper. When two tones at levels of 80 to 90 dB SPL were measured acoustically, all intermodulation distortion products were more than 70 dB down. When one of the tones is lowered by as little as 10 dB (as in a masking experiment), the distortion components become unmeasurable.
Chronological Description of an Experimental Session

The experimental sessions were conducted daily and lasted about one hour, one to three minutes being required to measure each threshold. During each session, the signal and maskers were set and monitored, using a true-r.m.s. voltmeter to measure intensities and an electronic counter to measure and adjust the frequencies of the signal, masker, and the carrier or center frequency of the noises. After calibration, the stimuli were adjusted to the desired levels by means of attenuators. The subject was seated in a comfortable, but unpadded, wooden chair inside an IAC double-walled soundproof room. The subject held a switch controlling the recording attenuator. This switch was used to vary the level of the signal in discrete 2-dB steps. The circumaural CZW-6 socket (Zwislocki, 1955) of the earphone was positioned evenly and tightly around the subject's ear. (Only one phone delivered stimuli.) Wires leading from the earphone were suspended behind the subject's head in order to avoid noise caused by their rubbing against the subject's clothing.

The subject was instructed to respond to any sound or event (i.e. to detect "anything") that occurs with the repetition rate of the signal (3 times per second). The subject's response consisted of lowering the level of
the signal when he could hear a repeating sound, and raising the level of the signal when he could not, 2 dB per decision. The subject's cue to begin responding was the onset of a sound repeating at the rate of 3 times per second. His cue to stop responding was either the termination of the masker, or, when quiet thresholds were measured, an increase in the intensity of the signal followed by its termination.

The level of the signal was first adjusted to about 10 dB above quiet threshold and the signal turned on. The subject lowered the level of the signal to threshold and then repeatedly bracketed, or tracked, his threshold over time by adjusting the level of the signal until he could not hear it, then raising its level until he could hear it, etc. When the automatically recorded levels were stable, the signal level was raised by the experimenter and the signal turned off.

The range of the subject's adjustments is about 4 dB on the average, and only rarely greater than 6 dB. After each trial, a visual average of the record is immediately recorded on a graph. Such visual averages are very reliable, determinations of such averages by different experimenters being within $\frac{1}{2}$ dB.

After each trial, the frequency of the signal was changed and adjusted to the desired frequency with an
accuracy of ±1 Hz. After one or more thresholds (including that of a tone at the masker frequency) are obtained in the quiet, thresholds in the presence of one or more maskers are determined. When determining thresholds in the presence of a masker, the masker is turned on first, before the signal. After a threshold is obtained, the signal is turned off first, before the masker.
RESULTS

The results of this study will be considered under two main headings: (a) masking of \( C_1 \) and \( D_1 \) selectively, and (b) masking of \( C_1 \) and \( D_1 \) simultaneously. Greenwood (1971b, Fig. 11), when masking \( C_1 \) and \( D_1 \) simultaneously (and over almost the whole frequency range in which they exist), showed that the dip in the masking pattern between the main and secondary peak of the pure-tone masked audiogram is consequently completely eliminated (see Fig. 2). That is, when detection of \( C_1 \) and \( D_1 \) is precluded and the masked thresholds one measures are consequently those at which the signal itself is detected, no notch is evident in the masked audiogram, the transition from main to secondary peaks being smooth. Since this experimental fact has been demonstrated quite clearly, it was not considered necessary to replicate it for every subject in the present study. Nevertheless, it is important to keep this finding in mind during an examination of the following findings on selective masking, since the band-pass noise introduced below the masker often has only a small effect in terms of elevating signal thresholds above the pure-tone masker. A small increase in threshold with the introduction of the noise does not necessarily indicate that the particular combination tone which is masked by the noise is any the less
critical in determining masked threshold on the high-frequency side of the masking tone. A small effect on thresholds after the addition of a selective-masking noise simply indicates that the intensities of \( D_1 \) and \( C_1 \) are more nearly comparable than in a case where the threshold increase after selective masking is large. In other words, any one finding cannot be considered in isolation, but must be considered in conjunction with results of other, complementary experimental situations.

In considering the following findings, another experimental fact must be kept in mind; namely, the variation in the shape of the high-frequency side of the pure-tone masked audiogram with small changes in masker intensity (see Fig. 1; and Wegel and Lane, 1924, Fig. 2). From this experimental fact we know that small changes from session to session, in the "effective" intensity of the tone masker at the ear will result in relatively large changes in the shape of the high-frequency side of the masked audiogram. Such changes in "effective" intensity are likely those due to random variations of the quiet threshold from day to day due to small conductive changes in the middle ear and other factors such as variation, on different occasions, in the position of the headphones with respect to the ear (which alters intensity levels at the tympanic membrane). Although the
electrically measured intensity of the tone as delivered to the earphone remained constant in each experiment, small random variations in the "effective" intensity of the tone may have a marked effect on masked threshold at higher signal frequencies of high-intensity pure-tone masked audiograms. This variation in "effective" (actual) levels, and hence shape, reduces the exactitude of direct comparisons of audiograms obtained during different experimental sessions. Also, even more marked differences in the shape of the high-frequency side of the masked audiogram can occur between subjects, because of differences in quiet threshold and levels of the combination tones, among other factors. During the same experimental session, however, any confounding effects of changes in the "effective" intensity of the pure-tone masker with respect to the critical variable under observation, were minimized as far as possible. To do so, "tone alone" and "tone plus noise" conditions were presented on consecutive trials for each signal frequency.

Masking C₁ and D₁ Selectively

The data on selective masking is considered in two sections: (1) moderately intense maskers—the case in which the secondary peak of the masked audiogram is near or below 1.5 times the masker frequency (f₁); this peak
shifts toward higher frequencies as masker intensity increases; (2) more intense maskers—the case in which the secondary peak of the masked audiogram has progressed above 1.5 times $f_1$ sufficiently to permit selective masking of $C_1$ or $D_1$ when signal frequencies are presented that lie in the interval between 1.5 times $f_1$ and the secondary peak. $C_1$ and $D_1$ cannot be selectively masked when signals are near 1.5 times $f_1$, since the two combination tones coincide when signal and masker are at this frequency ratio (If $f_2=1.5f_1$, $C_1=2f_1-1.5f_1=1.5f_1-f_1=D_1$).

Moderately intense maskers (secondary peak near or below 1.5$f_1$)

At moderately high intensities (about 70 to 80 dB SL) of a pure-tone masker, the secondary peak of the masked audiogram is located near or below 1.5 times $f_1$. When $C_1$ is selectively masked for signal frequencies between the main and secondary peak of the masking pattern, the masked threshold at these signal frequencies increases considerably (see Fig. 4). The level of the new masked threshold is that at which either the signal, or another combination tone (most likely $D_1$), becomes audible. The increase in masked threshold, after the addition of the noise, occurs at signal frequencies between the main and secondary peak of the masked audiogram. Also, because of the magnitude of the obtained threshold elevation, one may infer that the levels of $D_1$ and any other combination
Fig. 4. Masked thresholds above the pure-tone masker ($f_1 = 1.3$ kHz, top and middle; $f_1 = 2$ kHz, bottom) before (solid circles) and after (open circles) addition of a band of noise just below the tone masker ($f_1$). Squares represent thresholds in the noise alone. As can be seen from the schematic at the top left of the Figure, the frequency loci of both $C_1$ and $D_1$ change systematically as the frequency of the signal ($f_2$) is changed. For example, in the top graph, signals at frequency (1) place $C_1$ on the skirt of the noise, and signals at (2) generate a $C_1$ falling in the center of the noise. In both cases $D_1$ falls outside the influence of the noise. The same information is more completely determined from the curves at the bottom right-hand corner of each graph. These curves display the masked thresholds (squares) in the noise, which is located below $f_1$. Hence they show the masking effect of the noise at those frequencies where $C_1$ (solid line) or $D_1$ (dashed line) will fall when signals are presented in the frequency range of the notch to which these curves have been shifted. Thus, for a given signal frequency, the shifted curves show to what extent $C_1$, $D_1$, or both will be subject to the masking effect of the noise below the masker. (The apparent narrowing in the shape of these curves is due solely to the logarithmic contraction on the frequency axis). The noise is placed so that signal
frequencies between the main and secondary peaks of the masked audiogram produce a $C_1$ which falls in the noise. Signals in this same frequency range produce a $D_1$ falling outside the influence of the noise. The masked thresholds of signals presented in the "tone plus noise" condition (open circles) show that the notch is eliminated by the noise, which masks $C_1$, but not $D_1$, when signal frequencies are below $1.5f_1$.

The low-frequency slope of the masked audiogram (-----) is measured in the presence of the tone alone. Level of the noise is indicated on each graph in terms of its total SPL (sound pressure level). The level of the tone masker is indicated in both decibels sound pressure level (dB SPL) and decibels sensation level (dB SL). Decibels sensation level are the number of decibels the tone is above its quiet threshold.
FIGURE 4
Fig. 5. Masked thresholds above the tone masker ($f_1 = 1.3$ kHz, top; $f_1 = 2$ kHz, bottom)—before (solid circles) and after (open circles) addition of a band of noise just below a frequency half that of the masker (i.e. $0.5f_1$). In these audiograms, the location of the secondary peak is at $1.5f_1$. The audiograms, when compared to those associated with a differently situated noise in Figure 4, do not show such elevated thresholds on the high-frequency side of the masker. The audiograms indicate that $D_1$ is not relevant in determining masked threshold on the high-frequency side of the pure-tone masked audiogram.

The levels of the tone masker are indicated in both dB SPL (decibels sound-pressure level) and dB SL (decibels sensation level). For an explanation of the curves and symbols, see Figure 4.
FIGURE 5
tones, are considerably below that of $C_1$. Results similar to those in Fig. 4 are revealed in audiograms (not shown here) obtained from three other subjects, when the stimulus parameters were the same as those illustrated at the bottom of Figure 4.

Conversely, when a noise is placed within the frequency region surrounding the frequency of the $D_1$ which is simultaneously generated by the same signals that generate the $C_1$ which is masked in Figure 4, no comparable threshold elevation is obtained. Instances of this result are shown in Figure 5. Similar results (not shown) were obtained from three other subjects.

More intense maskers (secondary peak above $1.5 f_1$)

At levels of the pure-tone masker greater than about 75 dB SL, the secondary peak of the masking pattern occurs above $1.5$ times $f_1$. At these higher intensities of the pure-tone masker, the meaning of the term "secondary peak", as it is used here, is not as obvious as it is at lower levels of the masker, since other peaks may be seen in the masking pattern at frequency loci lower than that of the secondary peak, and, at times, even at higher frequencies. Therefore, the "secondary peak" must be more specifically defined as the nearest peak below $2$ times $f_1$. The data indicate that the secondary peak, so defined, marks the frequency at and above
which the signal itself constitutes the "event" detected at masked threshold.

At these higher masker intensities, signal frequencies just below the secondary peak but sufficiently above 1.5f₁, produce C₁ and D₁ components that are sufficiently separated to allow their selective masking, and an examination of their respective roles.

Masked thresholds between f₁ and 1.5f₁

Differences in the effect of the selective masking noise, as compared to its effect on pure-tone masked audiograms obtained at lower intensities, are seen in the signal frequency region between f₁ and 1.5 times f₁. That is to say, with the exception of the data from subject TT (Fig. 6), which was obtained at a lower masker frequency (1.3 kHz), Figures 7 through 12 illustrate that the selective masking of C₁ produces smaller threshold elevations, relative to the depth of the notch, at the higher levels, than at the lower levels, of the tone masker. That is, selective masking of C₁ raises measured threshold by a smaller amount since, as signal level is raised, the unmasked D₁ reaches threshold before the threshold of the signal per se is reached. At lower masker levels, the reverse was true. Such lesser threshold elevations, then, represent the levels of the signal for which D₁ is at threshold below the tone masker. When the noise is placed in the region
**Fig. 6.** Masked thresholds above the tone masker \((f_1=1.3\text{ kHz})\)—before (solid circles) and after (open circles) addition of a band of noise, either just below \(f_1\) (top), or just below \(0.5f_1\) (bottom) for subject TT. **Top:** This noise masks \(C_1\) when signal frequencies are below 1950 Hz \((1.5f_1)\), and it masks \(D_1\) when signal frequencies are above 1950 Hz. **Bottom:** This noise masks \(D_1\) when signal frequencies are below 1950 Hz \((1.5f_1)\), and it masks \(C_1\) when signal frequencies are above 1950 Hz. Masked thresholds are elevated at signal frequencies that place \(C_1\) in the noise. That is, the notch is eliminated when \(C_1\) is selectively masked.

The level of the tone masker is indicated in both decibels—sound pressure level (dB-SPL) and decibels—sensation level (dB SL). For an explanation of the curves and symbols, see Fig. 4.
Fig. 7. Masked thresholds above the tone masker ($f_1 = 2$ kHz) —before (solid circles) and after (open circles) addition of a band of noise, either just below $f_1$ (top), or just below $0.5f_1$ (bottom) for subject KL. **Top:** This noise masks $C_1$ when signal frequencies are below 3 kHz ($1.5f_1$), and it masks $D_1$ when signal frequencies are above 3 kHz. **Bottom:** This noise masks $D_1$ when signal frequencies are below 3 kHz, and it masks $C_1$ when signal frequencies are above 3 kHz. Thresholds are elevated at signal frequencies below 3 kHz ($1.5f_1$) that place $C_1$ in the noise.

The level of the tone masker is indicated in both dB SPL and dB SL. For an explanation of the curves and symbols, see Fig. 4.
FIGURE 7

Masking by noise in frequency region where C and D fall in dB SPL.

Masking threshold in dB SPL.
Fig. 8. Masked thresholds above the tone masker ($f_1 = 2$ kHz) —before (solid circles) and after (open circles) addition of a band of noise, either just below $f_1$ (top), or just below $.5f_1$ (bottom) for subject FK. **Top:** This noise masks $C_1$ when signal frequencies are below 3 kHz (1.5$f_1$), and it masks $D_1$ when signal frequencies are above 3 kHz. **Bottom:** This noise masks $D_1$ when signal frequencies are below 3 kHz, and it masks $C_1$ when signal frequencies are above 3 kHz. Masked thresholds are elevated at signal frequencies below 3 kHz (1.5$f_1$) that place $C_1$ in the noise, and at signal frequencies above 3 kHz that place $D_1$ in the noise.

Masked thresholds in the noise alone (---+) were measured using a very slow sweep method (see Methods). This method was used only for this subject, FK, and only for the "noise alone" condition. The level of the 90 dB SPL tone masker is also indicated in dB SL. For an explanation of the curves and symbols, see Fig. 4.
FIGURE 8
where $D_1$ falls when signal frequencies are below $1.5f_1$ (see bottom of Figs. 6 to 12), no threshold elevation is observed. Therefore, as is the case for the less intense maskers, it is $C_1$, and not $D_1$, that determines the measured masked threshold when signals lie in the frequency region below $1.5f_1$ and above $f_1$.

Masked thresholds between $1.5f_1$ and the secondary peak

From Figures 6 to 12 it can be seen that, as one of the combination tones, $C_1$ or $D_1$, is subject to masking by a given band of noise when signal frequencies are greater than $1.5f_1$, it is necessarily the other of these two combination tones that is masked selectively by the same noise when signal frequencies are below $1.5f_1$. That is to say, the $C_1$ and $D_1$ interchange places when the signal is shifted as described.

When signal frequencies are greater than $1.5f_1$, and either $C_1$ or $D_1$ (depending on the frequency location of the noise) is selectively masked, it can be seen from Figures 6 to 12 that masked threshold elevations of these signals are generally small and comparable, or absent under both experimental conditions.

That small threshold elevations are evident in the same signal frequency region, when $C_1$, as well as when $D_1$, is selectively masked, may be accounted for as follows. Less than perfectly selective masking of the
intended difference tone is obtained when the medium-width (350- or 600-Hz) bands of noise invade, to some extent, the frequency range in which the other difference tone is located. The intrusion of the skirts of the selective-masking noise on a frequency range in which the other "unmasked" combination tone is located, will tend to produce small increases in "signal" threshold, due to the masking of the other combination tone. This is the case when signal frequencies are near 1.5f₁. Then, D₁, if present, is near C₁ in frequency, and both C₁ and D₁ may fall on the skirt of the noise and be subject to masking at the same time. Consequently, the skirt of the noise may, in addition, interfere with any summation or beating interaction that occurs, and can normally be detected between C₁ and D₁. Summation, for example, has been demonstrated by Gässler (1954), who showed that tones less than a critical bandwidth apart summate to reduce threshold. The perception of beats between C₁ and D₁, when they are close together, may also be hindered by the presence of the noise and consequently lead to threshold elevations when the noise is added.

Reduction in the level of the band of noise (not illustrated) or reduction of the bandwidth of the noise (see Figs. 10 and 12) precluded such effects by the skirts of the noise by respectively lowering the level of the
Fig. 9. Masked thresholds above the tone masker ($f_1 = 2\text{kHz}$) —before (solid circles) and after (open circles) addition of a 600-Hz band of noise, either just below $f_1$ (top), or just below $.5f_1$ (bottom) for subject RB. **Top:** This noise masks $C_1$ when signal frequencies are below 3 kHz ($1.5f_1$), and it masks $D_1$ when signal frequencies are above 3 kHz. **Bottom:** This noise masks $D_1$ when signal frequencies are below 3 kHz, and it masks $C_1$ when signal frequencies are above 3 kHz. Masked thresholds are elevated at signal frequencies below 3 kHz ($1.5f_1$) that place $C_1$ in the noise.

The level of the tone masker, as indicated, is 80 dB SPL and 78 dB SL. For an explanation of the curves and symbols, see Fig. .
FIGURE 9
Fig. 10. Masked thresholds above the tone masker ($f_1 = 2$ kHz) —before (solid circles) and after (open circles) addition of a narrow, 50-Hz, band of noise, either just below $f_1$ (top), or just below $.5f_1$ (bottom) for subject RB. Masked thresholds are elevated at signal frequencies below 3 kHz ($1.5f_1$) that place $f_1$ in the noise.

The level of the tone masker, as indicated, is 80 dB SPL and 80 dB SL. For an explanation of the curves and symbols, see Fig. 3.
FIGURE 10
Fig. 11. Masked thresholds above the tone masker ($f_1 = 2$ kHz) —before (solid circles) and after (open circles) addition of a 600-Hz band of noise, either just below $f_1$ (top), or just below $.5f_1$ (bottom) for subject RB. Masked thresholds are elevated at signal frequencies below 3 kHz ($1.5f_1$) that place $C_1$ in the noise.

The level of the 85-dB SPL masker is also indicated in dB SL. For an explanation of the curves and symbols, see Fig. 3.
FIGURE 11
Fig. 12. Masked thresholds above the tone masker \( (f_1 = 2 \text{ kHz}) \) —before (solid circles) and after (open circles) addition of a narrow, 50-Hz, band of noise, either just below \( f_1 \) (top), or just below \( .5f_1 \) (bottom) for subject RB. Masked thresholds are elevated at signal frequencies below 3 kHz \( (1.5f_1) \) that place \( f_1 \) in the noise.

The level of the tone masker, as indicated is 85 dB SPL and 83 dB SL. For an explanation of the curves and symbols, see Fig. 3.
FIGURE 12
skirts, or removing them from the area in which they have these effects. Results of reducing noise level were obtained, at various widths and locations of the noise, from three subjects. The effect of narrowing the selective masking noise was observed in two subjects. In both cases, the small threshold elevations of signals near and above 1.5f₁ were either considerably reduced or eliminated (see Figs. 10 and 12).

The question, in any individual case, of whether it is C₁ or D₁ that determines masked threshold of signals greater than 1.5 times f₁ (the masker frequency) is difficult to answer, since the threshold elevations at these signal frequencies are nearly comparable whether the noise selectively masks C₁ or D₁. The results shown in Figure 6 suggest that subject TT detects C₁ when signal frequencies are above 1.5 times f₁ since the level of D₁ is far below that of C₁ in the case when signal frequencies are less than 1.5f₁.

Additional experiments with this subject and the same tone masker confirmed this conclusion. For example, narrow masking noise did not produce the small threshold elevation obtained when wider noise bands (e.g. Fig. 6, top) selectively masked D₁ components generated by signal frequencies greater than 1.5f₁. Narrow-band noise did, however, produce a masked threshold elevation when it selectively masked C₁ components generated by signals
presented in the same frequency region above $1.5f_1$.

That it is, in fact, $C_1$ that is actually detected in this case, when signals are at masked threshold, was also confirmed by more direct measurement of $C_1$ and $D_1$ levels. This was accomplished by substituting a narrow (50-Hz) band of noise at an intensity slightly greater than measured masked threshold for a signal near 1.6 times the frequency of the masker ($f_1$). Masking by $C_1$ and $D_1$ combination bands of noise components revealed that $C_1$ distortion was at a higher level in this case.

Therefore, for this particular subject (TT) and for the masker frequency of 1.3 kHz presented at the levels here employed, $C_1$ is most likely the only combination tone to be detected at masked threshold as measured when the signal frequency lies between the main and secondary peaks (see Fig. 6). As will be shown in subsequent paragraphs, for other subjects the relative levels of $C_1$ and $D_1$, and hence the conclusion drawn in this experimental situation, can differ. It can, for example, implicate $D_1$ instead.

As mentioned earlier, narrow (50-Hz) selective masking noises were used with subject RB. From Figures 10 and 12, it may be seen that the use of narrow selective masking bands does not produce threshold elevations for signals in the frequency range between $1.5f_1$ (3 kHz) and the secondary peak. This finding suggests that $C_1$ and
D₁ levels are equal, or very nearly so, when the level of the signal is at masked threshold. Also, measurements of masking by C₁ and D₁ combination bands of noise provide independent evidence of this conclusion for the subject RB (Greenwood, 1972c; see Discussion).

The same conclusion may be drawn from the audiograms of subject KL, which show comparable threshold elevations at signal frequencies just below the secondary peak, and above 1.5f₁, whether it is C₁ or D₁ that is selectively masked (see Fig. 7). For subject FK, however, (see Fig. 8) threshold elevations obtained by selective masking of D₁ are somewhat greater than those obtained by selective masking of C₁. This result indicates that, here again, C₁ and D₁ levels are comparable for signals above 1.5f₁, since threshold elevations are small, but it also suggests that D₁ is the combination tone that determines "signal" masked threshold in this frequency region and for this subject.

Masking C₁ and D₁ Simultaneously

As discussed in the previous section, the selective masking of only one of the two suspected combination tones, C₁ or D₁, often produces either undramatically small increases of signal thresholds, or none at all, especially when the pure-tone masker is of high intensity.
Fig. 13. Masked thresholds above the pure-tone masker (f₀ = 2 kHz)—before (solid circles) and after (open circles) addition of a wide (1400-Hz bandwidth), effectively low-pass, band of noise below f₀. This noise masks both C₁ and D₁ simultaneously when signal frequencies are between the main and secondary peaks. After addition of the noise, masked thresholds are considerably elevated at signal frequencies between the main and secondary peaks.

The level of the tone masker is indicated in both dB SPL and dB SL. For an explanation of the curves and symbols, see Fig. 4.
FIGURE 13
The consistently supported reason given for the small size of this elevation is that, as signal intensity increases, both combination tones become more intense and more comparable in level. Whichever combination tone is left unmasked, is the one that becomes audible before the signal itself can reach an audible intensity on the high-frequency side of the masker.

When both of the most prominent combination tones, \( C_1 \) and \( D_1 \), are masked simultaneously, it follows that the much greater signal thresholds on the high-frequency side of the masker indicate the levels at which the signal itself (or, conceivably, yet another combination tone) becomes audible.

**Wide band of noise**

This threshold elevation certainly occurs with the introduction of a wide band of noise below the masker (see. Fig. 13). This noise, however, must also mask combination tones other than \( C_1 \) and \( D_1 \), that may be present. As discussed in consequent sections, the use of narrower bands of noise which mask \( C_1 \) and \( D_1 \) simultaneously circumvents this problem.

As previously mentioned, a dip in the masking pattern between the main and secondary peaks was progressively eliminated with increasing levels of a low-pass noise located below the masker (Greenwood, 1971b, Fig. 11, p. 515).
as shown in Figure 2 of this paper. Such a noise masks both $C_1$ and $D_1$ throughout the frequency range of their existence. The same result has been confirmed for high-intensity masked audiograms of two subjects used in the present study (see Fig. 13), using a wide band of noise.

The purpose of masking $D_1$ and $C_1$ simultaneously and confirming that the effect of the wide or low-pass noise does not have another explanation may be accomplished by using narrow bands of noise that will mask within more restricted frequency ranges. Then, only those signal frequencies that generate $C_1$ and $D_1$ components, both of which fall simultaneously within the masking influence of the noise, should be elevated. The elevation, moreover, should be comparable to that obtained when the wide band of noise is used. This latter level of elevation is the level at which it will then be most reasonable to conclude that the signal itself is heard.

**Medium-width bands of noise**

Masking $C_1$ and $D_1$ simultaneously with medium-width (350- or 600-Hz) bands of noise may be accomplished by centering the noise at a frequency half that of the masker (0.5 times $f_1$). There, the noise will consequently mask both $C_1$ and $D_1$ since they coincide or are close together when they fall within this region near $0.5f_1$. Since signals near $1.5f_1$ place $C_1$ and $D_1$ in this noise,
masking the difference tones near \( .5f_1 \) is expected to affect the thresholds of signals near \( 1.5f_1 \). As may be seen from Figures 14 to 17, and 19, measured thresholds are elevated in the frequency region in which the signal, together with the masker, is responsible for the generation of \( C_1 \) and \( D_1 \) components which both fall within the noise. As evident from the Figures, the threshold elevation is restricted to signal frequencies which place both \( C_1 \) and \( D_1 \) in the noise. The restriction of the effect to the thresholds of a limited range of signal frequencies demonstrates that only \( D_1 \) and \( C_1 \), and no other type of combination tone, are detected in the frequency range over which the introduction of the noise led to threshold increases.

**Effect of noise bandwidth**

By using still narrower widths of noise, the restriction of threshold increases to signal frequencies whose \( C_1 \) and \( D_1 \) are simultaneously masked may be somewhat more dramatically demonstrated. Figure 17 compares the effects of three noises of different width. The respective narrowing of the region of elevated thresholds is clearly demonstrated. The Figure shows that threshold elevations are comparable for the different widths of noise used, while the extent of the frequency region over which masked thresholds are elevated is reduced as noise bandwidth is reduced.
Fig. 14. Masked thresholds above the pure-tone masker ($f_1 = 1.3$ kHz)—before (solid circles) and after (open circles) addition of a band of noise (350-Hz bandwidth) centered at $0.5f_1$, for subject TT. This noise masks both $C_1$ and $D_1$ simultaneously when signal frequencies are near 1950 Hz ($1.5f_1$). After addition of the noise, masked thresholds are considerably elevated at signal frequencies near 1950 Hz.

Masked thresholds obtained in the presence of the tone plus the noise (diamonds) demonstrate an additive effect of the noise on the thresholds of signals just below the tone. The level of the tone masker is indicated in both dB SPL and dB SL. For an explanation of the curves and the symbols, see Fig. 4.
FIGURE 14

MASKED THRESHOLD IN DB SPL

0.3
0.5
0.7
1.0
1.5
2.0

SIGNAL FREQUENCY IN KHZ

Masking by noise in frequency region where C, D fall in DB SPL

Masked threshold in DB SPL

42 DB
0.7 DB
95 DB

FIGURE 14

MASKED THRESHOLD IN DB SPL

0.3
0.5
0.7
1.0
1.5
2.0

SIGNAL FREQUENCY IN KHZ

Masking by noise in frequency region where C, D fall in DB SPL

Masked threshold in DB SPL

42 DB
0.7 DB
95 DB
Fig. 15. Masked thresholds above the pure-tone masker ($f_1 = 2$ kHz)—before (solid circles) and after (open circles) addition of a band of noise (600-Hz bandwidth) centered at 1 kHz ($0.5f_1$), for subject TC. This noise masks both $C_1$ and $D_1$ simultaneously when signal frequencies are near 3 kHz ($1.5f_1$). After addition of the noise, masked thresholds are elevated at signal frequencies near 3 kHz.

The level of the tone masker is indicated in both dB SPL and dB SL. For an explanation of the curves and symbols, see Fig. 4.
FIGURE 15
Fig. 16. Masked thresholds above the pure-tone masker (\(f_1 = 2\) kHz)—before (solid circles) and after (open circles) addition of a band of noise (600-Hz bandwidth) centered at 1 kHz (\(0.5f_1\)), for subject RB. This noise masks both \(C_1\) and \(D_1\) simultaneously when signal frequencies are near 3 kHz (\(1.5f_1\)). After addition of the noise, masked thresholds are elevated at signal frequencies near 3 kHz.

The level of the tone masker is indicated in both dB SPL and dB SL. For an explanation of the curves and the symbols, see Fig. 4.
Fig. 17. Masked thresholds above a pure-tone masker ($f_1 = 2$ kHz) before (solid circles) and after (open circles) addition of noise-bands of different width (1400 Hz, top; 600 Hz, middle; 50 Hz, bottom), for subject RB. All bands are centered at 1 kHz ($0.5f_1$). These noises mask both $C_1$ and $D_1$ simultaneously when signals are within various intervals about 3 kHz ($1.5f_1$), the extent of the interval depending on the width of the noise. After addition of the noise, masked thresholds are elevated at those signal frequencies which place both $C_1$ and $D_1$ in the noise.

The level of the tone masker is indicated in both dB SPL and dB SL. For an explanation of the curves and the symbols, see Fig. 4.
FIGURE 17
Fig. 18. Masked thresholds above a pure-tone masker \( f_1 = 2 \text{ kHz} \)—before (solid circles) and after (open circles) addition of two narrow (50-Hz) bands of noise below the tone masker. These noises mask both \( C_1 \) and \( D_1 \) simultaneously when signal frequencies are in the region indicated in the bottom right-hand corner of each graph. Again, thresholds are elevated at signal frequencies which place both \( C_1 \) and \( D_1 \) in the noise.

The level of the tone masker is indicated in both dB SPL and dB SL. For an explanation of the curves and symbols, see Fig. 4.
FIGURE 18
Two narrow bands of noise

Two narrow bands of noise may also be used to mask $D_1$ and $C_1$ simultaneously in restricted frequency regions other than those centered around $0.5f_1$. The effect of simultaneously masking $C_1$ and $D_1$ may, consequently, be observed in restricted segments of the high-frequency side of the masked audiogram other than those centered at $1.5f_1$. To accomplish this purpose, two narrow bands of noise are used and placed so that when the signal is in the frequency range of the audiogram under scrutiny (i.e., a chosen range in the notch area), the $D_1$ will fall within one narrow band of noise and the $C_1$ within the other band of noise. Figure 18 shows the results of this experiment. Marked elevations in the measured masked threshold occur only at those signal frequencies generating $D_1$ and $C_1$ components both of which fall in the noise and are masked. When either of the two noises is used by itself, threshold elevations in the same "signal" ranges are smaller or absent (see Figs. 10 and 12) since a single band of noise masks only one combination tone in one of these regions, leaving the other unmasked. In this case, as pointed out earlier, masked threshold elevations correspond to a level at which the unmasked combination tone generated by signal and masker becomes audible. When both $C_1$ and $D_1$ are masked by the two narrow bands of noise,
masked threshold elevations correspond to a level at which the signal itself becomes audible. We know this since masked threshold elevations correspond to a level obtained when the wide band of noise was used (see Fig. 13).

This large difference of threshold elevations between selective and simultaneous masking of $C_1$ and $D_1$ demonstrates conclusively that $C_1$ and $D_1$ are of comparable intensity near threshold when masker and signal parameters are those represented in high-level pure-tone masked audiograms, particularly when signal frequencies are between $1.5f_1$ and the secondary peak. In other words, $C_1$ and $D_1$ singly or jointly produce the detected "events" at masked threshold values of the pure-tone masked audiogram, as measured in the notch or trough region of the audiogram.

**Effects of Noise Level**

As the intensity of the noise below the masker is lowered, the elevation of masked threshold on the high-frequency side of the masker is not expected to show a corresponding decrease until the intensity of the noise is lowered below a level at which either one or both combination tones are no longer masked. Then the lower masked threshold on the high frequency side of the tone masked reflects the signal intensity at which the most
Fig. 19. Masked thresholds above a pure-tone masker ($f_1 = 2$ kHz)—before (solid circles) and after (open circles) addition of a 50-Hz band of noise at different levels. This noise, which is centered at 1 kHz ($0.5f_1$), masks both $C_1$ and $D_1$ simultaneously when the frequency of the signal is near 3 kHz ($1.5f_1$). As the level of the noise is lowered, the amount by which signal thresholds are elevated does not show a corresponding reduction until the level of the noise is lowered below 35 dB SPL.

The level of the tone masker, as indicated, is 85 dB SPL and 86 dB SL. For an explanation of the curves and symbols, see Fig. 4.
FIGURE 19
prominent combination tone in the noise is just detectable at its masked threshold value.

Figure 19 shows the effect of lowering the intensity of a narrow band of noise which masks $C_1$ and $D_1$ simultaneously. It is readily evident that the level of the combination tones falling within the masking influence of the noise is well below that of the masking noise used in the remainder of the experiments reported here. Specifically, the most intense combination tone is at least 5 dB, but less than 15 dB below the 40 dB masking noise of Figure 19, since lowering the level of the noise 5 dB did not lower masked threshold elevations, whereas lowering it 15 dB did lower the amount by which thresholds were raised. This result was confirmed in another experiment (not shown), similar to that illustrated in Figure 19, except that a wider (600-Hz) noise (as in Fig. 16, bottom), centered at the same frequency, was lowered 10 dB from 45 dB to 35 dB total SPL. The lower-level noise produced comparable threshold elevations as the one at 45 dB so long as $C_1$ and $D_1$ fell in the center of the noise, implying they were still masked and that the subject was detecting the signal per se. The lower-level noise, however, produced smaller threshold elevations at those signal frequencies which placed both difference tones on the skirts of the noise, implying that
the subject was then detecting the combination tones before the signal became audible. Since the lower-level noise was 10 dB below the 45-dB SPL noise, one may infer that combination tones produced by signals near $1.5f_1$ are about 10 dB below the masking influence of the 45-dB noise, at these masker and signal levels, which, as the highest used for this subject (RB), produce the largest combination tones. From the foregoing, one can conclude that the elevated masked thresholds near $1.5f_1$ are those of the signal itself.

In other experiments (not shown), using TT and TC as well as RB as subjects, the level of a noise located near the foot of the pure-tone masked audiogram was lowered 10 dB below the levels used in the experiments reported here. This noise masks $C_1$ when signal frequencies are below 1.5 times $f_1$. Lowering the level of the noise lowered the elevated masked thresholds, which were observed when the higher-level noise was used, but only at signal frequencies which placed a combination tone on the skirt of the noise. Thus, combination tones near the center of the higher-level noise must have been more than 10 dB below their thresholds. Specifically, for intense tone maskers, lesser threshold elevations, in the presence of the lower-level noise, occur at signal frequencies near and above $1.5f_1$, which had placed $C_1$ and $D_1$ on the skirts
of the higher-level noise.

In addition, lesser masked thresholds, accompanying the reduction in noise level, occurred at signal frequencies just above the masker, i.e. on the steeply declining part of the audiogram. These threshold elevations are smaller since the upper skirt of the higher-level noise can have an additive effect on thresholds just below the tone masker. This reduction in elevations just above the masker indicates that $C_1$ determines masked threshold even when the signal is quite close to the masking tone.

This additive masking effect of the noise, below the tone masker, on masked thresholds at or near the tone was previously reported by Greenwood (1972a), and is illustrated in Figure 2 and the top of Figure 14. The top of Figure 14 shows the additive effect of the skirt of the noise on thresholds below the tone masker and the consequent small threshold elevations just above the masker in relation to the masking produced by the tone alone.
DISCUSSION

Significance of Masked Thresholds in the Notch

In previous research (Greenwood, 1971b), the notch observed on the high-frequency side of the pure-tone masker was eliminated after the introduction of a low-pass noise, which masked all combination tones below the masker. Greenwood, therefore, attributed masked thresholds measured at signal frequencies within the notch region to the detection of the combination tones below the masker, specifically to the detection of $C_1$ at low to moderate masker levels and possibly also to $D_1$ at higher masker levels when $D_1$ was also generated. The results, reported here, of selectively masking different combination tones, or masking two combination tones simultaneously over short frequency ranges below the masker, confirm and extend Greenwood's findings. That is, results from the present study, conducted at higher masker levels, also indicate that, over the entire notch region (the frequency interval between the main and secondary peaks of the masked audiogram), measured masked thresholds actually represent signal intensities at which the combination tones produced by the signal and the masker, rather than the signal itself, are detected. Also, as Greenwood (1971b) demonstrated in the case of low to moderate masker levels, it is the detection of $C_1$, that,
in most cases, determines masked threshold at signal frequencies in the notch region. Although, for one subject and over a short frequency range (Greenwood, unpublished results, personal communication), \( C_2 \) was most probably detected at masked threshold at low masker levels, \( C_2 \) or \( C_3 \) were not so implicated at the higher masker levels used in the present study, the results of which suggest that \( C_1 \) constitutes the detected "event" even when the frequency of the signal is just above that of the masker. And, it is only at high intensities of the masker that the detection of \( D_1 \) can, in some cases, determine masked threshold.

Instances in which \( D_1 \) is sometimes implicated occur when the frequency of the signal is in the high-frequency portion of the notch, i.e. below the secondary peak but above \( 1.5f_1 \). That is, detection of \( D_1 \) can sometimes determine masked thresholds, as normally measured at frequencies in the high-frequency portion of the notch above \( 1.5f_1 \).

The secondary peak of the masked audiogram occurs at a frequency locus of \( 1.5f_1 \) or higher only when the masker is at a high intensity, greater than about 75 dB SL. Then, the selective masking of \( C_1 \) or \( D_1 \) elevates thresholds measured at higher frequencies in the notch only slightly, or not at all, since \( C_1 \) and \( D_1 \) are of approximately equal
amplitude. In this circumstance, it may be either $C_1$ or $D_1$, or both, that are detected at measured masked threshold at these frequencies, depending on the individual subject.

The finding that $C_1$ and $D_1$ are approximately equal in level when parameters of the masker and signal are those of the situation just described, is consistent with more direct determinations of the levels of $C_1$ and $D_1$ obtained by Greenwood (1972c) and Hall (1971, 1972a,b). More strictly speaking, Greenwood estimated the levels of $C_1$ and $D_1$ bands of noise from the amount of masking produced by combination bands of the two corresponding types. Hall, on the other hand, used the levels of cancellation tones as estimates of $C_1$ and $D_1$ intensities. At primary intensity levels sufficiently high to allow measurement of $D_1$, both investigators report nearly equal levels of $C_1$ and $D_1$. Such is particularly the case when frequency and intensity parameters of the primaries approximate those of the masker and signal in the audiograms reported here. With respect to the stimulus parameters as they obtain in the audiograms reported in this paper, one can add that the level of $C_1$ is slightly greater than that of $D_1$ when the frequency of the signal is in the lower-frequency portion of the notch region (signal frequency less than $1.5f_1$), while $C_1$ and $D_1$ are nearly the
same level when the frequency of the signal is in the higher-frequency part of the notch. That the level of the D\textsubscript{1} is only slightly below that of C\textsubscript{1} is determined from measurements of signal levels in those situations in which it is D\textsubscript{1} that is detected at masked threshold, as described in the following section.

**Signal Intensities at which C\textsubscript{1}, D\textsubscript{1}, or the Signal Itself are Detected at Threshold**

When only one of the two difference tones, C\textsubscript{1} or D\textsubscript{1}, is masked and the other is not, measured threshold above the masker is elevated to a level at which it is either the signal, or the unmasked combination tone, that first reaches detection at masked threshold. When both C\textsubscript{1} and D\textsubscript{1} are masked simultaneously, the new, elevated masked threshold is that of the signal itself. It follows, then, that if the masked threshold measured after selective masking is lower than that obtained after simultaneous masking, then this lower threshold level represents the signal level at which the unmasked combination tone reaches threshold outside the selective masking noise.

In that these data display levels at which C\textsubscript{1}, D\textsubscript{1}, and the signal itself are heard, the Figures, together, constitute a more complete and correct representation than Wegel and Lane's (1924, Fig. 5) schematic of a
pure-tone masked audiogram which illustrates signal levels at which a "difference tone" and the signal become audible. Their schematic shows that the primary and a "difference tone" are heard when signals are at, and somewhat above, masked thresholds measured between main and secondary peaks. At still higher signal levels, the primary, a "difference tone", and the signal itself are shown to be heard. The experiments reported here extend these findings in that they identify two difference tones, and directly measure the signal levels at which, respectively, each of the difference tones and the signal itself become audible.

The signal level at which $C_1$ becomes audible is generally that of the measured masked threshold between the main and secondary peak of the masked audiogram. In some cases, when the masker is intense, $C_1$ may become audible at levels slightly higher than masked threshold in the higher-frequency part of the notch.

When the level of the masker is less than approximately 70 to 75 dB SL, and the secondary peak is at or below $1.5f_1$, $D_1$ is not generated at sufficient intensity to appear above threshold before the signal itself reaches its masked threshold. In other words, the level of the signal, in this case, must exceed the level at which the signal itself is detected, before $D_1$ can become audible.
This latter level is not illustrated in the Figures. Unless the masker, and also the signal, are at high levels, D₁ does not exist. Therefore, the D₁ becomes relevant only when masking by high-level stimuli is measured. In this case, when the secondary peak is above 1.5f₁, D₁ is likely to become audible and, after selective masking of C₁, to determine a measured threshold. This level of the signal at which D₁ becomes audible is greater than masked threshold as normally measured, when signal frequencies are below 1.5f₁. The greater the masker intensity, the sooner D₁ becomes audible as signal levels are raised above masked threshold. When signal frequencies are in the upper part of the notch, i.e. above 1.5f₁ but below the secondary peak, either D₁ alone is detected at masked threshold, as normally measured, or, if not, D₁ becomes audible at a level only slightly higher than that of masked threshold.

Dips in the Masking Pattern

Dips, or abrupt changes, are sometimes observed in the masking pattern. These are the result of the beating between two distortion components, or the beating between a distortion component and the signal.

A dip, due to beating between the distortion components C₁ and D₁, is often seen at 1.5 times f₁, particularly for subjects KL and FK (e.g. Figs. 7 and 8).
At this frequency ratio of the primaries \((f_2/f_1 = 1.5)\), \(C_1\) and \(D_1\) both fall at \(0.5f_1\). Since the signal is not usually set exactly at \(1.5f_1\), the resulting slow beats between \(C_1\) and \(D_1\) allow their detection at lower signal levels. That this monaural phase effect is due to the interaction of \(C_1\) and \(D_1\) has been amply demonstrated by Hall (1972b), and its occurrence at masked threshold has been reported by Clack et. al. (1972).

A dip in the masking pattern is also evident at the second harmonic \((2f_1)\) in some high-level pure-tone masked audiograms. This dip is the result of beating between the signal and the second harmonic. It was first reported by Wegel and Lane (1924). They placed the secondary peak of the masked audiogram at this locus of beating with the second harmonic, since they assumed the secondary peak to be due to masking by the aural harmonic. Although the secondary peak of Wegel and Lane's audiograms was, in general, mis-centered at the second harmonic, it may occur there for the highest masker levels used (see Figures 8 and 13). Evidence of the presence of the second harmonic is also seen in some of the audiograms of Greenwood (1971b) as a dip in masked threshold at the second harmonic. In the present paper, also, a dip at the second harmonic is seen in Figures 8 and 13 (bottom) for the subject FK. It also appears in other audiograms of this
subject which are not illustrated here. In addition, the same subject heard the signal beat when it was near the frequency of the second harmonic.

That the aural harmonic is normally not far below masked threshold was demonstrated by Clack et. al. (1972) who estimated the amplitude of the aural harmonic from data showing a monaural phase effect when a threshold-level signal was presented at the second harmonic of the masker and varied in phase.

**Limiting Position of the Secondary Peak**

The shift in location of the secondary peak of the masked audiogram to a frequency near the aural harmonic, however, seems to be an upper limit. That is, the secondary peak of the masked audiogram does not progress beyond a frequency twice that of the masker (i.e. \( 2f_1 \)). The upper end of the notch region, and hence the beginning of signal-determined masked thresholds at and beyond the secondary peak, is reached at a signal frequency equal to approximately 1.8 to 1.85 times \( f_1 \). This frequency ratio of signal to masker (\( f_1/f_1 \)) corresponds to the same ratio, in a Figure of Greenwood's (1972c, Figure 1), at which the masking effect of a \( D_1 \) combination band of noise merges, and disappears into, the low-frequency foot of the masking pattern produced by the lower, pure-tone
component of the primary masker. At the same time, $C_1$, whose amplitude decreases with increasing frequency separation between masker and signal, recedes into inaudibility in the low-frequency region. $C_1$, of course, ceases to be defined when $f_2$ reaches $2f_1$ ($C_1 = 2f_1 - f_2$).

Generality and Implications of the Results

The results of the present study demonstrate that masked thresholds measured above a tone of moderate to high intensity are actually those of combination tones ($C_1$, $D_1$, or both) below the masker. Thus, an inaudible, masked signal above the masker, can generate, by interacting with the masker, audible, unmasked combination tones below the masker. Measurements of masking by complex stimuli such as noises also are influenced by the presence of combination tones of the same type in a manner to be described below.

For certain purposes, also detailed below, it is important to determine the masked threshold of the signal itself. Therefore it is of value to know which combination tones appear above threshold, and at which frequencies of the signal they can appear above threshold while the signal itself is at a level below that of its own threshold. Then, such aural distortion can be localized, and consequently eliminated so that the threshold of the
signal itself can be determined. Determination of the threshold of the signal itself is of great importance to the task of relating psychoacoustic and neurophysiological data.

**Masking by complex stimuli**

When measuring the masking by complex stimuli, such as noises, the presence of combination components of the type $C_n$ and $D_\perp$ is relevant, as discussed at length by Greenwood (1971b). His conclusions are briefly restated here. As mentioned in the Introduction, Greenwood (1971b, 1972a,b,c) pointed out that the constituent frequency components of one or more bands of noise, or of tone-noise combinations, generate combination tone components in the same way that two or more tones do. The resulting combination bands of noise, produced by noise or noise-tone primaries, are at levels corresponding to those of combination tones, produced by tone primaries at similar levels to those of the noise-tone primaries (Greenwood, 1972b,c). Also, combination bands (and combination tones) produce masking as do bands of noise of external origin (Greenwood, 1972a). Therefore, combination bands of noise will also have effects on measurements of masking, the specific effects being determined by the characteristics of the combination components produced by the complex stimuli, and by the parameters of the latter.
Narrow bands of noise, for example, produce a notched form of the masking pattern similar to that of pure-tone masked audiograms. The results of the present study apply also to the notch observed in the masking pattern above a narrow band of noise, except that combination bands of noise, rather than combination tones, are detected instead of the signal when signals are at frequencies in the notch. For somewhat wider bands of noise, the notched form disappears, but the slope of decreasing thresholds above the noise is still determined by the detection of combination components. At still wider widths of the noise, the signal itself is detected at masked threshold above the noise (Greenwood, 1971b).

In addition to the combination components generated by a band of noise and a signal, a band of noise by itself produces combination components which are the result of the interaction of frequency components within the noise. Therefore, if the skirts of the noise are sufficiently steep, the combinational aggregate will be present at greater amplitude than the skirt and will produce masking just below the band of noise and hence determine masked threshold at signal frequencies just below the band of noise. For a more complete description, see Greenwood (1971b).
Masked threshold of the signal itself

As mentioned earlier, it is sometimes important to determine the masked threshold of the signal itself. For example, the threshold levels of the signal itself are needed to relate psychoacoustic measures of masking to auditory mechanisms at the periphery of the system, specifically near the locus on the basilar membrane at which the signal produces its maximum effect.

Zwicker (1955, 1968, 1969), for example, bases his determination of the "psychoacoustical excitation" of a sound on masked thresholds of the signal itself. He presents evidence to suggest that this "excitation", and hence also masked thresholds of the signal itself, reflect primarily a hydromechanical filtering process, within the cochlea, that occurs before transduction to neural spikes. Furthermore, he demonstrates that the "excitation level" (comparable to masked threshold level of the signal itself), as a function of frequency (in critical-band units), is important to the understanding of JND's (just noticeable differences), loudness, pitch and timbre (Zwicker, 1969).

Masked thresholds of the signal itself may also be utilized in making comparisons with measurements of masking derived from the recording of the responses of single nerve cells near the periphery of the auditory system.
Masking, in the context of the discharge of a single unit, is defined by Greenwood and Maruyama (1965) as: "the action of one stimulus in partially or completely preventing an otherwise effective stimulus from activating the unit in question." The single unit derives its major input from one locus on the basilar membrane, which is indicated by the nerve cell's best frequency. The masking of a neuron's response to a signal at its best frequency, by introduction of a second stimulus, may then be compared to the psychophysically measured masked threshold at a frequency analogous to that of the best frequency of the neuron. To relate such neurophysiological data, for example, to psychophysical results, it is important to understand the meaning of masked thresholds as measured psychophysically (i.e. what is detected and at what level), before other fundamental inferences can be drawn from the data obtained in this way.
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