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EVIDENCE OF TEMPORAL CODING IN A FORWARD MASKING TASK

by

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Submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

Faculty of Graduate Studies
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Abstract

The use of masking to study the auditory system's frequency selectivity characteristics has been quite extensive. From these studies, a specific model of spectral analysis has been developed that emphasizes the energy distribution across frequency. This perspective is acceptable when describing the processing of simple tones, but certainly lacking when interest is in a description of the processing of more complex stimuli. The following experiments examined the ability of sinusoidal signals to mask single- and double-frequency probes. The paradigm was similar to that used in psychophysical tuning curve studies: the masker level was adapted to just mask a low-level probe of fixed frequency. The results showed that knowledge of masking with single-frequency probes cannot predict performance with the double-frequency probes. Further, it was found that these effects could be demonstrated in the binaural system, where the detection of difference tones could not play a role. A third experiment demonstrated similar effects with a different masking paradigm. It is obvious from these data, that the auditory system encodes more than the power spectrum of the signals; for example, aspects of the time structure of the waveforms are also coded and analyzed. This is hypothesized to explain the observed differences. Therefore, it is incorrect to describe

auditory frequency selectivity as simply a matter of power spectrum analysis.

ACKNOWLEDGEMENTS

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1. Introduction

Although a complete description of the way in which the auditory system encodes frequency requires an understanding of the response to both simple and complex stimuli, many of the conclusions about spectral processing have been drawn from studies using single sinusoidal tones. There is evidence, however, that responses to sinusoids cannot predict responses to tone combinations. In the following sections I shall review three factors that can have important consequences for the frequency coding of sinusoidal pairs in the auditory periphery, that cannot be fully anticipated from knowledge of coding of sinusoids. These factors are: two-tone suppression, combination tone generation and the temporal fine structure of the auditory discharge pattern. Before examining each of these areas, I will present a brief summary of frequency coding of sinusoidal stimuli.

1.1 Coding of sinusoids at the auditory periphery

The mechanical response of the basilar membrane to sinusoidal tones is the initial stage of frequency coding. Depending on the frequency of the stimulus, the travelling-wave envelope will peak near the apical or basal end of the membrane; low frequencies at the apex, high frequencies at the base (Bekesy, 1960; Johnstone and Boyle, 1967; Johnstone et al., 1970; Khanna and Leonard, 1982; Rhode, 1980). Further, the shape of the envelope is usually somewhat asymmetric (except at very low frequencies and intensities), with the slope of the envelope being steeper apically than basally (Bekesy, 1960; Rhode, 1978; 1980). Therefore, the membrane's vibratory response to sinusoids is similar to that of a narrow band-pass filter (Khanna and Leonard, 1982; Leonard and Khanna, 1984).

The hair cells adjacent to the basilar membrane become deflected with membrane movement, and it is this shearing action i.e. thought to initiate neural transduction (Dallos, 1981; Eldredge, 1974). Recordings made from the inner hair cells show tuning characteristics parallel to those found on the basilar membrane (Russell and Sellick, 1978). For example, iso-amplitude functions show that inner hair cells are very sensitive to one frequency, but are much less responsive to other frequencies (Russell and Sellick, 1978).

Measurements of single fibres in the auditory nerve show similar tuning properties. By measuring the firing rate increments for sinusoids of various frequencies these units show a preference for a small range of frequencies (Kiang et al., 1965). The data are most often described by a neural tuning curve, displaying stimulus intensity as a function of frequency for a just detectable increase in the spontaneous firing rate of the fibre (Liberman and Kiang, 1978). Typically, fibres show their best response to a very narrow frequency region, while tones presented at other frequencies require greater intensities to activate the fibre. Further, these sharp tuning properties are constant as stimulus intensity is increased (Evans, 1975; Rose et al., 1971). Therefore, the frequency response characteristics of the auditory periphery seem to be determined mainly by the coding occurring at the cochlea. The vibration pattern of the basilar membrane coded by the neural array of hair cell receptors, transmits the tuned response measured at the basilar membrane to the auditory nerve fibres. This response is most often summarized as being similar to a process of band-pass filtering. Finally, it can be noted that these tuned fibres are organized tonotopically in the eighth nerve (Kiang et al., 1965). Single nerve fibres with high frequency responses are found in the periphery of the nerve bundle, and there is an orderly decrease in the characteristic frequency toward the center of the bundle.

Although the response of the peripheral auditory system is commonly described by the change in the firing rate of the receptors or auditory-nerve fibres, a second characteristic of the neural response to sinusoidal stimuli is the temporal synchrony of the firing response to low frequency tones. The presentation of sinusoidal stimuli less than 5 kHz produces a neural discharge pattern synchronous with the phase of the stimulating waveform. This phenomenon can be best demonstrated by considering the number of spikes that occur within one cycle of the sinusoid with repeated presentations. Often, the greatest number of spikes occur near the peak of the sinusoid, such that a plot of the number of spikes within a given time-frame resembles a sinusoidal pattern. Such behavior from single fibres is likely the result of the coding of the waveform as it occurs along the basilar membrane. Interestingly, this response of a fibre to the phase of the waveform can be detected not only before an increase in the mean firing rate is observed (Rose et al., 1967), but also above the rate of saturation of the neuron (Rose et al., 1971). An examination of this type of neural response makes it evident that "phase-locking" is a more sensitive indicator of stimulus intensity than neural rate responses, (for example, some studies have shown that phase-locking can be up to 20 dB more sensitive; Evans, 1975; Rose et al., 1967).

1.2 Coding of sinusoidal pairs

When examining the response of the auditory system to more complex tonal stimuli, other factors become important. Tonal elements in a complex stimulus can produce either suppression or excitatory interactions at the auditory periphery. Two-tone suppression is a demonstration of one such interaction.

1.2.1 Two-tone suppression

The discharge rate of an auditory-nerve fibre responding to a sinusoid can be reduced when a second tone, that does not excite the fibre when presented in isolation, is introduced at an appropriate frequency and intensity. Sachs and Kiang (1968) first showed that the tuning curve of an auditory-nerve fibre showed regions of suppression when examined in the presence of a second tone. Arthur et al. (1971) found that the firing rate of a fibre responding to a low-level sinusoid of 8 KHz could be reduced by over 20% by a 5 kHz tone at approximately 60 dB SPL.

The phenomenon of two-tone suppression is limited by the relationship of the stimulus parameters, such as frequency and intensity. Only specific frequency and intensity relationships between the stimuli produce robust effects. This can be demonstrated most clearly with measurements of the suppression of the neuron's firing rate. Limitations also exist in the measured range of the suppression effects. For example, a suppressor tone will never reduce the firing rate of a neuron below its characteristic spontaneous rate. Further, high level tones will cease to suppress the firing rate, producing excitatory responses in the neuron.

Suppression is also observable in the discharge patterns of the auditory-nerve fibres, although its measurement involves more detailed analyses. Abbas (1978) and Hind et al. (1967) described suppression effects in neural firing patterns by timing the occurence of the each discharge relative to the periods of the individual tones. More recent measurement techniques involve generating period histograms from the phase-locked patterns, which are then analyzed by methods of Fourier analysis for the relative contribution of each tone (Arthur, 1976). If suppression effects are coded in the neuron's discharge pattern, then clearly more complex mechanisms are necessary for the auditory system to extract this information, than are necessary for coding the suppression of the rate code.

Also, by examining suppression in the neural discharge patterns, a more complete description of the suppression effects can be obtained than when examining rate suppression. For example, discharge rate, as an index of suppression, cannot code the stimulus situations where the suppressor tone itself excites the fibre, or when the discharge rate of the fibre has saturated (Javel, 1981). Studying the effects of suppression from changes in the discharge patterns reveals larger effects than those found by the discharge rate criterion. Arthur (1976), and others, have shown that a suppressor tone can attenuate the neural response pattern of another tone by 30 to 60 dB (Javel, 1981; Rhode et al., 1978; Sachs and Hubbard, 1981). Pattern measures are also able to show suppression effects throughout a nerve fibre's response area, suppression being greatest for the frequencies near the fibre's characteristic (or best) frequency.

The phenomenon of suppression has also been found at levels other than the eighth nerve. Sellick and

Russell (1979) demonstrated rate suppression at the level of the inner hair cells. Others have found two-tone suppression effects in whole-nerve action potentials (Harris and Dallos, 1977), and in the recordings of the cochlear microphonic (Dallos et al., 1974). From these studies, it is the consensus that two-tone suppression is a cochlear phenomenon, not due to neural inhibition. This argument is most clearly supported by Rhode (1977), who found that the basilar membrane displacement patterns displayed two-tone interactions of suppression. Therefore, it is commonly suggested that the travelling wave is the origin of two-tone suppression.

Psychophysical masking studies have demonstrated an effect similar to two-tone suppression. In a forward-masking situation, the amount of masking produced by a sinusoidal tone can be reduced by the addition of a second sinusoid to the masker (Houtgast, 1973; O'Malley and Feth, 1979; Shannon, 1976; Weber, 1978). This phenomenon of "unmasking" is, like neurophysiological suppression, dependent on the frequency and amplitude of the added sinusoid (Abbas, 1978; Duifhuis, 1980; Weber and Green, 1979). Therefore, two-tone suppression can be demonstrated in the neural coding of stimuli, as well as in

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psychophysical tasks, and is certainly an important factor in defining frequency selectivity.

1.2.2 Combination tones

The nonlinear response of the auditory system can also be demonstrated by the amplitude distortion products known as combination tones. These are generated when two or more tones are presented simultaneously to the auditory system, and result in responses at frequencies not present in those tones. Goldstein and Kiang (1968) first showed that auditory nerve fibres would respond (by increases in the firing rate or by measured phase locking responses) to combination tones, even when it could be shown that the initial tones did not, individually, produce any response in that fibre. Such nonlinearities are easily demonstrable with only two sinusoids, therefore this situation is the most commonly studied. Also, although several combination tones are possible in a nonlinear system, the phenomenon may be illustrated by considering only two: the simple difference tone and the cubic difference tone.

The simple difference tone is the response at the frequency corresponding to the difference in the two pure tones or primaries (designated as f1 and f2, where f2 > f1). The cubic difference tone, on the other hand, is the response at the frequency 2f1 - f2. Rose et al. (1969) were able to demonstrate prominent difference tones in the discharge patterns of auditory nerve fibres. This work has been expanded by Kim et al. (1980) and others, to show that the response of a fibre to a generated combination tone is not different from the response to a single sinusoid at the frequency of the combination tone (Greenwood et al., 1976; Pfeiffer and Kim, 1975; Smoorenburg et al., 1976). Kim et al. (1980) argue that these similarities indicate a common base for generating these reponses; i.e., the propagation mechanisms are likely the same.

Again, these responses recorded at the level of the cochlea have psychophysical correlates. Two sinusoids presented simultaneously can result in the perception of additional tones such as the simple and cubic difference tones. A great deal of psychophysical research has specifically examined the stimulus conditions that produce combination tones, as well as estimating the amplitude of the distortion product itself. There are three general methods used in combination tone research. In one procedure, the use of a third (or probe) tone is introduced at the same time as the two primary tones. This probe tone is then either varied in frequency or intensity to produce a beating or cancellation of the combination tone. From the intensity of the probe, the amplitude of the distortion product is estimated (Goldstein, 1967; Goldstein et al., 1978; Hall, 1977).

A second procedure for measuring the amplitude of the combination tone is the masking paradigm. This can be accomplished with a direct masking procedure, where the combination tone is used as a masker for a third probe tone similar in frequency to the combination tone (Smoorenburg, 1972; Zwicker and Fastl, 1973). This method can also be used in a forward masking paradigm (Smoorenburg, 1972; Humes, 1980), again to extrapolate to the level of the distortion product.

A third procedure involves a nonsimultaneous presentation of a probe tone to the ipsilateral or contralateral ear (known as the pulsation threshold method; Smoorenburg, 1974; Zurek and Leshowitz, 1976; Shannon and Houtgast, 1980). The primaries are presented in alternation with the probe (of equal frequency to the combination tone) at a rate of approximately 4 per second. When the probe is presented at a specific level, the perception of the combination tone is continuous; i.e., the actual distortion product and the probe at the same frequency are not perceived as being gated every 250 ms. When the level of the probe is increased a distinct probe is perceived to be alternating with the primaries. The level at which this transition from continuity to pulsation occurs is called the pulsation threshold, which is taken as a measure of the level of the combination tone. Using these methods, the stimulus parameters that generate the combination tone can be summarized.

The simple and cubic difference tones are the two distortion products that are most commonly reported, being perceived with the lowest level primaries. In general, the cubic difference tone is perceived at primary levels lower than those producing the simple difference tone. For example, with f2/f1 less than 1.2, the cubic difference tone is perceived with the levels of the primaries as low as 20 dB SL. Further, with differential levels of the primaries (e.g., L1 ≠ L2; where L1 and L2 are the levels of the primaries f1 and f2 respectively), the cubic difference tone can be perceived when the level of one primary is near threshold. (Smoorenburg (1972) reported perceivable cubic difference tones when L1 was 40 dB SL and L2 between 0 and 4 dB SL.) On the other hand, the perception of simple difference tones requires much higher levels of the primaries. With L1 = L2, the simple difference tone is perceived when primary levels reach 50 to 60 dB SL.

Because of the difficulties in the three procedures for estimating the level of the distortion product, the reliability of these data has been questioned recently. For example, with certain frequency and intensity relationships between the primaries, the combination tone in the simultaneous paradigms may become masked (Egan and Klumpp, 1951), and/or suppressed (Houtgast, 1972; Shannon, 1976), thus leading to an inaccurate measure of the level of the combination tone. The advantage of the nonsimultaneous presentation of the probe is that this procedure will not produce suppression of the probe (Harris and Dallos, 1977). (In fact, Shannon and Houtgast (1980) have shown significantly lower measures of the combination tone with the pulsation threshold measurement over the cancellation method.) There remains, though, the possibility of a masking of the distortion tone by the probe in the nonsimultaneous procedures. Therefore, there is no current method of measuring combination tones i.e. exempt from the confounding influences of suppression or masking. These factors, when present, will result in an overestimation error in the levels required to produce combination tones, and an underestimation of the level of the distortion product itself.

Finally, combination tones seem to be generated in the initial stages of frequency coding by the peripheral auditory system. In agreement with the physiological data, the psychophysical data show that combination tones behave much like externally applied signals. The distortion products produced by two primaries can mask or suppress probes, be masked by probes, or produce further combination tones when an appropriate tone is presented. Greenwood (1971) and Zwicker (1979) have also found that the perception of the combination tone is affected by the frequency resolution of the peripheral auditory system; that is, specific hearing deficits are detrimental to the perception of combination tones. Further, for certain ratios of the primary frequencies, the two combination tones can be made to interact much like two externally produced tones. This is accomplished by changing the phase of the primaries. Hall (1972) demonstrated this with primaries in the frequency ratio (f1:f2) of 2:3. In this situation, both the simple difference tone and the cubic difference tone are equal in frequency (i.e., f1/2). Depending on the phase relation of the primaries, Hall (1972) found that the loudness of the combination tone varied. Presumably, the two combination tones cancelled or reinforced each other, depending on the respective phase and amplitude of each distortion product. Since such interactions (and the other properties of combination tone phenomena) are peripheral, the psychophysical data also suggest that distortion products occur in the initial stages of coding of frequency by the auditory system (Tyler et al., 1979). Despite such arguments that combination tones are the result of a peripheral nonlinearity (presumably the basilar membrane response; Gibran and Kim, 1982), some questions remain as to its specific origins.

1.2.3 The temporal fine structure of the neural discharge pattern to two tone complexes

Although the response of the peripheral auditory system to sinusoids was described earlier, when more than a single sinusoid is present, the neural discharge pattern reflects more than two-tone suppression effects and combination tones. Additional characteristics can also be observed.

The work of Hind et al. (1967) first recorded the neural response to sinusiodal pairs. They showed that fibres in the eighth-nerve in the squirrel monkey responded to sinusoidal pairs locked in various frequency and amplitude ratios in three ways. With large amplitude ratios, the time pattern corresponded only to the lower frequency, or only to the higher frequency tone. With smaller amplitude ratios, the fibre responded to both tones, reflecting the relative amplitude of each component. For example, measures of the syncronization coefficient (a measure of the syncrony of the firing pattern and the phase of the stimuli) would be higher for each tone when presented as a pair than when presented individually.

When the temporal response of the neuron shows evidence of both stimuli, information about other properties of the combination is present also. These include information about the phase relationship of the two tones. For example, systematically changing the phase of one of the tones produces changes in the phase of the temporal response of the neuron (Rose et al., 1974). The response patterns can also be a sensitive indicator of the intensities of the tones. Stimulus levels near threshold can produce marked changes in temporal response to both tones. For example, when both tones are presented at threshold (determined by rate of response), significant phase-locking to both tones can be evident (Rose et al., 1974). Also, when one of the tones is presented at subthreshold levels (e.g., - 15 dB SL), an interaction can still be evident in the temporal response patterns. Rose et al. (1974) also have shown that cells in the anteroventral cochlear nucleus of the cat can display two-tone interaction when one tone is even as low as -25 dB SL. Therefore, the temporal pattern of the neural response to sinusoid pairs is able to accurately reflect interactions with threshold level stimuli, as well as when one tone is presented at levels well below threshold.

Unlike the phenomena of two-tone suppression and combination tones, there is little evidence concerning the role of temporal coding of phase or intensity in psychophysical tasks. There seem to be two reasons for this. First, the most simple manner of representing spectral information in the eighth nerve has been the place code, where frequency information is determined by the profile of discharge rate versus the neuron's best frequency. Second, the temporal code has been seen as either redundant or irrelevant in the spectral processing of simple stimuli. With the recent research into the temporal fine structure of neural response to complex stimuli (e.g., Horst et al., 1986), and the arguments that complex sounds are processed in a different way from simple sounds (Moller, 1980), the temporal code has been reconsidered for its importance in spectral processing, especially the processing of complex stimuli whose waveform envelope, phase, frequency or intensity may be changing over time.

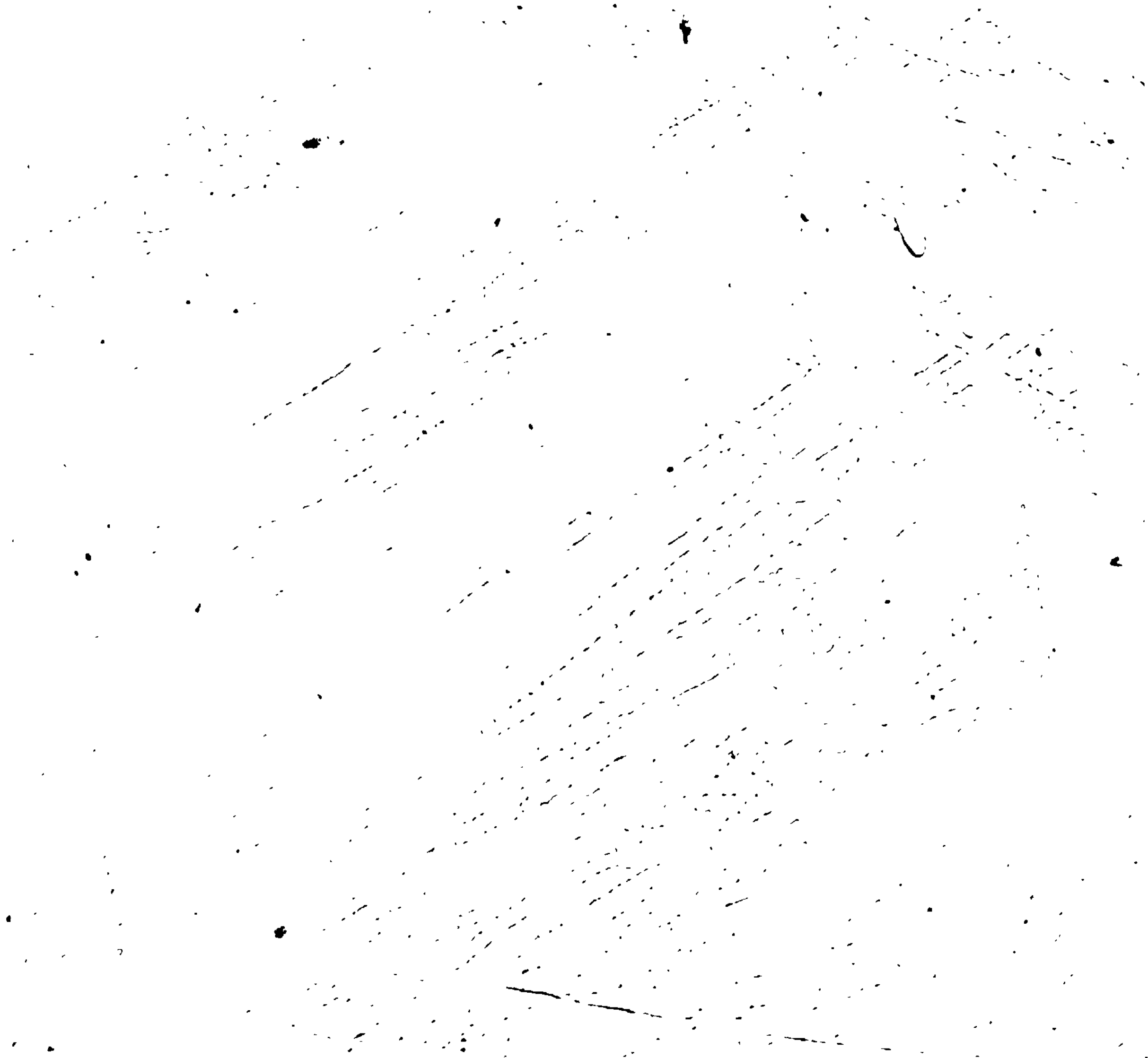
The following experiments were an attempt to determine the importance of temporal coding in auditory spectral processing. This was accomplished by examining the differences in detection of sinusoids and sinusoidal pairs in a forward masking task. The psychophysical tuning curve (masking) paradigm was chosen both because of its extensive usage in this field of research, and because of the kind of conclusions made from this task about spectral processing. In this paradigm, the level of a sinusoidal masker is adjusted until it just masks a low-level probe of fixed frequency. (At a neurophysiological level, forward masking is defined as the inability of the auditory system to respond to immediate stimulation, due to the amount and spread of residual excitation caused by the masker.) A simple model was developed where the amount of masker energy necessary to mask a probe consisting of two sinusoids could be predicted from knowledge of masker levels necessary to mask the single-frequency probes. Therefore, if factors such as two-tone suppression and combination tone generation are taken into account, and if no additional factors (e.g., temporal code) are important in such tasks, then accurate predictions of masker levels should be possible. Pilot studies had shown an inability of such a model to predict performance with double-frequency probes. Therefore, the first experiment examined this phenomenon more closely with a range of stimulus frequencies and intensities.

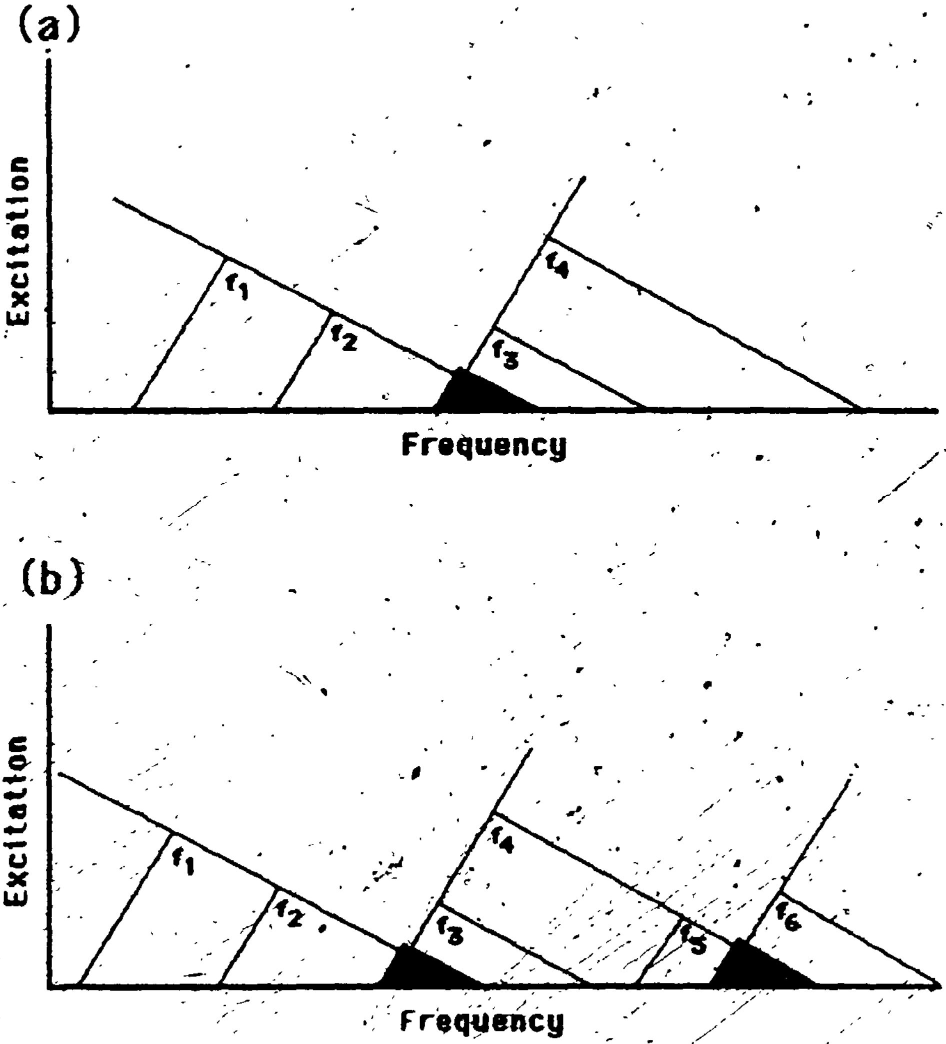
2. Experiment I: Effective Masker Levels of Single- and Double-Frequency Probes

2.1 Introduction

There has been a longstanding interest in the auditory system's frequency selectivity as revealed by sinusoidal masking studies. Notwithstanding known nonlinearities (e.g., suppression effects and combination tones), these studies have resulted in a particular interpretation in the literature: spectral information is generally thought to be coded and transmitted according to place of stimulation along the basilar membrane. For example, Johnson-Davies and Patterson (1979) developed a model where the discharge rate of response across the neural array is represented by asymmetric patterns of excitation. Figure 2.1(a) shows a schematic representation of the conventional psychophysical tuning curve data by plotting the amount of excitation as a function of the frequency of the stimuli. The patterns of four sinusoidal maskers (open triangles) and a sinusoidal probe (filled triangle) are shown, where f1, f2 and f3, f4 represent two low and two high masker frequencies, respectively. Further, the maskers are represented at specific levels such that a constant amount of excitation remains for probe detection at masked threshold. Therefore, a constant

Figure 2.1 A schematic representation of the conventional psychophysical tuning curve data according to the pattern of excitation model (Johnson-Davies and Patterson, 1979). Figure (a) displays the excitation of a low-level probe (filled) and four maskers (f1 to f4). Each masker produce the amount of excitation necessary for probe detection to be at masked threshold. Figure (b) shows the same patterns including a higher frequency probe and two additional masker patterns. Note that only masker f4 masks both probes.




(a)
Excitation
f1
f2
f3
f4
Frequency
(b)
Excitation
f1
f2
f3
f4
f5
f6
Frequency

area of the probe remains "unmasked" in all four masking conditions.

If this model adequately describes pure tone masking, then the masking or detection of additional spectral components could be represented in a similar fashion. Figure 2.1(b) shows a hypothetical representation of the excitation patterns produced by a probe comprised of two sinusoids (filled triangles) and six maskers. For the lower frequency probe, four maskers (f1 to f4) bring the detection of the probe to threshold, while for the higher frequency probe three maskers (f4 to f6) do so. If both probes are presented simultaneously, masker f1, f2, f3, f5, and f6 would "mask" one of the probe patterns, but not both. Only masker f4 produces the necessary excitation to mask both probe frequencies.

From these representations a simple model can be developed for predicting the amount of masker excitation (i.e., energy or intensity) necessary to mask a probe comprised of n sinusoids: A masker must have sufficient energy to produce a certain amount of excitation in the regions of all the probe frequencies. Therefore, with knowledge of the masker energy necessary to mask each probe component, a prediction of the masker energy necessary to mask a complex probe could be made.

However, it is plausible that this pattern of excitation model (Johnson-Davies and Patterson, 1979) is incomplete in describing the masking situation shown in Figure 2.1(b). For example, temporal interactions can be coded by the auditory nerve when two sinusoidal tones are presented at levels near threshold (Rose et al., 1974). Masker f4 in Figure 2.1(b) shows a situation where the detection of the two sinusoidal probes is at masked threshold. The question can be asked whether the residual excitation from each probe could be coded at the neural level (as with similar low-level tones shown by Rose et al., 1974), and whether this code produces an interaction that can be used for detection of the probe pair.

There is some psychophysical support for such a notion. Groen (1964) has shown a discrepancy between the detection of simple stimuli and that of tonal pairs. His work involved a dichotic presentation of two low-frequency tones (that differed only slightly in frequency), where one tone was presented at or below its detection threshold. Observers reported a subjective difference (a beating or wavering in the amplitude of the audible tone) when the second tone was added to the contralateral ear (above or below its threshold). Recognizing the discrepancy between a neuron's response rate threshold and the temporal pattern threshold, Groen argued that the subthreshold component in the tonal pair was coded by the temporal pattern of the neural array, which carried the information about the slight difference in frequency between the two tones. Similar beating effects have also been found when tones were presented at a level of masked threshold (see Groen, 1964).

More recently, Young and Barta (1986) suggest that neural discharge rate thresholds and behavioral thresholds can be shown to be highly correlated in the same test animal, despite the fact that temporal pattern thresholds were significantly lower. If this similarity in rate and behavioral thresholds also applies to masked thresholds (see Young and Barta), then our notions of frequency selectivity may have to be adjusted accordingly. Therefore, although there is support for the simple model of place/rate code excitation patterns in describing the neural mechanisms in the auditory periphery when processing simple stimuli, what remains to be shown is whether such a model holds with the use of more complex probes, and if the temporal coding may become important.

The purpose of the present investigation was to compare the effective masker levels for single- and double-frequency probes, as well as to examine the importance of the relative probe amplitudes. In a forward masking task a sinusoidal masker was followed by a brief low-level probe comprised of one or two sinusoids.

There were four parameters of interest in this experiment: fM (masker frequency), Lp1 (1 kHz probe level in dB SL), Lp2 (1.5 kHz probe level in dB SL), and LM (the effective masker level in dB SPL). The experiment involved measuring the masker level (LM) necessary to just mask the probes, either presented singly or together. The levels of the probes (Lp1 and Lp2) were fixed while the LM was varied by the subject. The masker frequency (fM) was an independent parameter.

The masking functions produced with the various fM values were compared. Specifically, this involved examining the masker levels for the conditions with the single- and double-frequency probes. Our simple model predicted the masker level in the double-frequency probe condition to be equal to the highest of the two masker sound pressure levels required for single-frequency probes. Deviations from this predicted value will suggest additional factors are relevent to the task.

The effects of changing the probe levels (Lp1 and Lp2) should reflect the relative influence of the added component on two-tone interaction. For example, adding the second component at a level near threshold would likely produce less interaction than if the added component was presented at a higher level.

2.2 Method

2.2.1 Subjects

Three young adults served as subjects (two males and one female). One male subject (RR) dropped out during this study, resulting in limited data. The subjects' hearing was within normal limits as assessed by pure-tone air-conduction thresholds for octave frequencies between 0.25 and 8.0 kHz (15 dB Hearing Level, ANSI S36 - 1969).

Each subject received ten hours of practice in the task. This period was sufficient to stabilize the masker thresholds in each subject. The experimental sessions were 2 hours in length with brief rest periods.

2.2.2 Stimulus presentation and procedure

Forward masking was used to measure the masker level thresholds. The subject's response was to adjust the masker level until the probe(s) were just masked. The masking thresholds were obtained by an adaptive two-interval forced-choice procedure that estimates the 70.7% correct point on the psychometric function (Levitt, 1971). The criterion for the adaptive procedure was two consecutive correct responses, which would increase the level of the masker, while one incorrect produced a decrease in the masker level. The first four reversals in the masker used a 4 dB step size, while for the remainder of the run a 2 dB step size was employed. Trials continued within a run until fourteen reversals were recorded. The first four reversals were discarded, while the average of the final 10 reversals was taken as the subject's threshold for that particular experimental run.

In the two-interval paradigm, both intervals contained the masker and in one of the intervals the masker was followed by the probe (which was assigned randomly to either interval with a probability of 0.5). The subject's task was to select the interval that contained the probe. The duration of each interval (masker plus signal) was 217 ms and was marked by a 215 ms light. A 498 ms pause separated the intervals. Following each response, the subject was presented with 200 ms feedback light indicating the correct interval containing the probe. The next trial began 500 ms after the offset of the feedback light.

The waveform envelopes and spectra of the stimuli are shown in Figure 2.2. The masker (fM) was comprised of a single sinusoid preceding the probe signal in time. The probe consisted of one (Figure 2.2a: fp1 or fp2) or two frequency components (Figure 2.2b: fp1 and fp2). The masker was shaped with a cosine square function rise/fall of 5 ms and had a total duration of 205 ms. The 12 ms probes were similarly shaped with 2 ms rise/fall times. There was no delay between the presentation of the masker and probes.

A block diagram of the equipment used in the study is shown in Figure 2.3. Three independent function generators produced the masker and probe frequencies (fM: Hewlett- Packard (HP) 3310A; fp1: General Radio 1310B; fp2: Wavetek 112). Each was electronically gated and attenuated before being mixed and delivered to the earphones (Telephonics TDH- 50P) in a double-walled acoustic chamber. All signals were

Figure 2.2 The waveform envelopes and spectra of the stimuli used in these studies. Figure (a) represents the test conditions with single-frequency probes, while Figure (b) represents the test conditions with double-frequency probes.

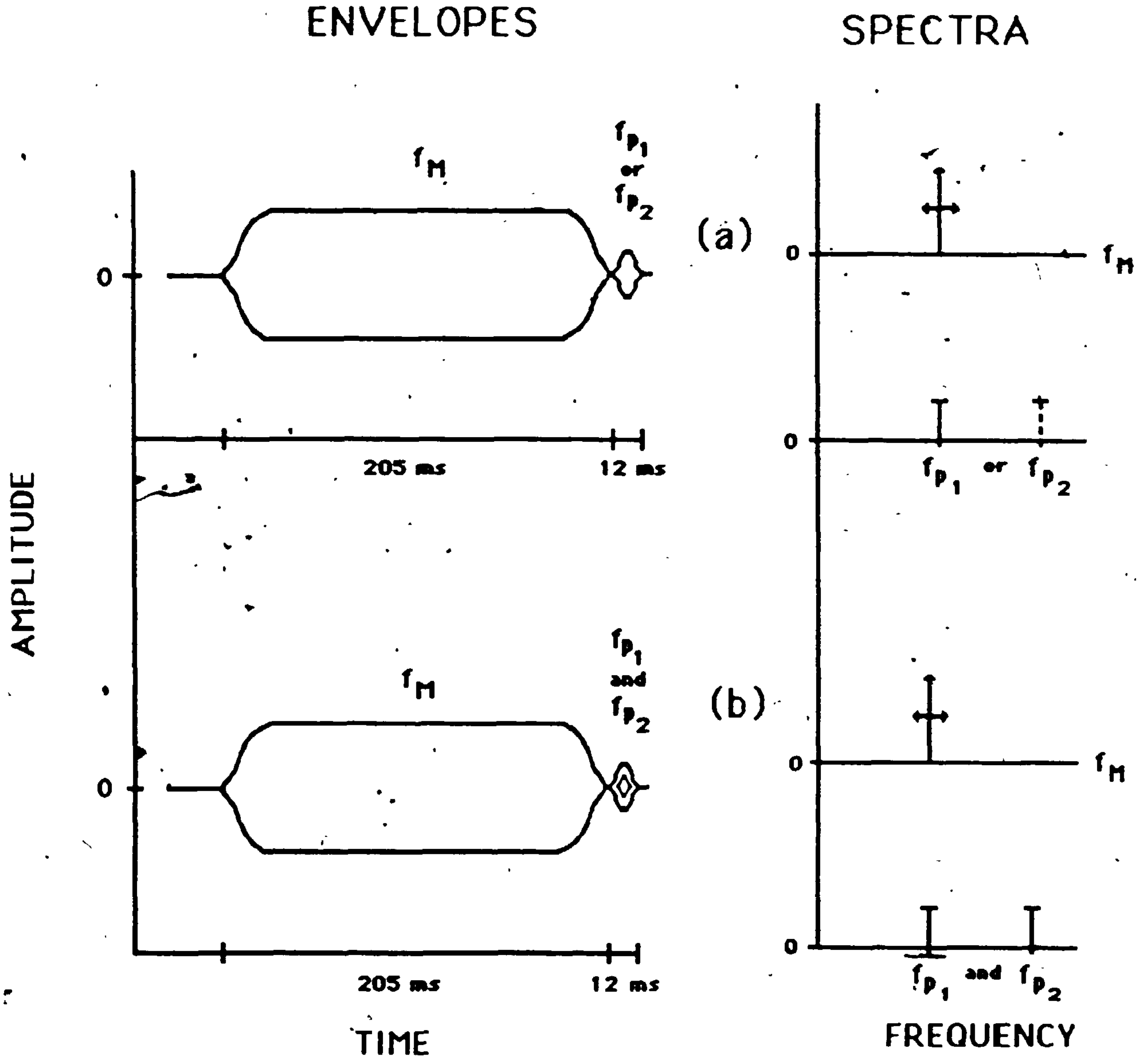
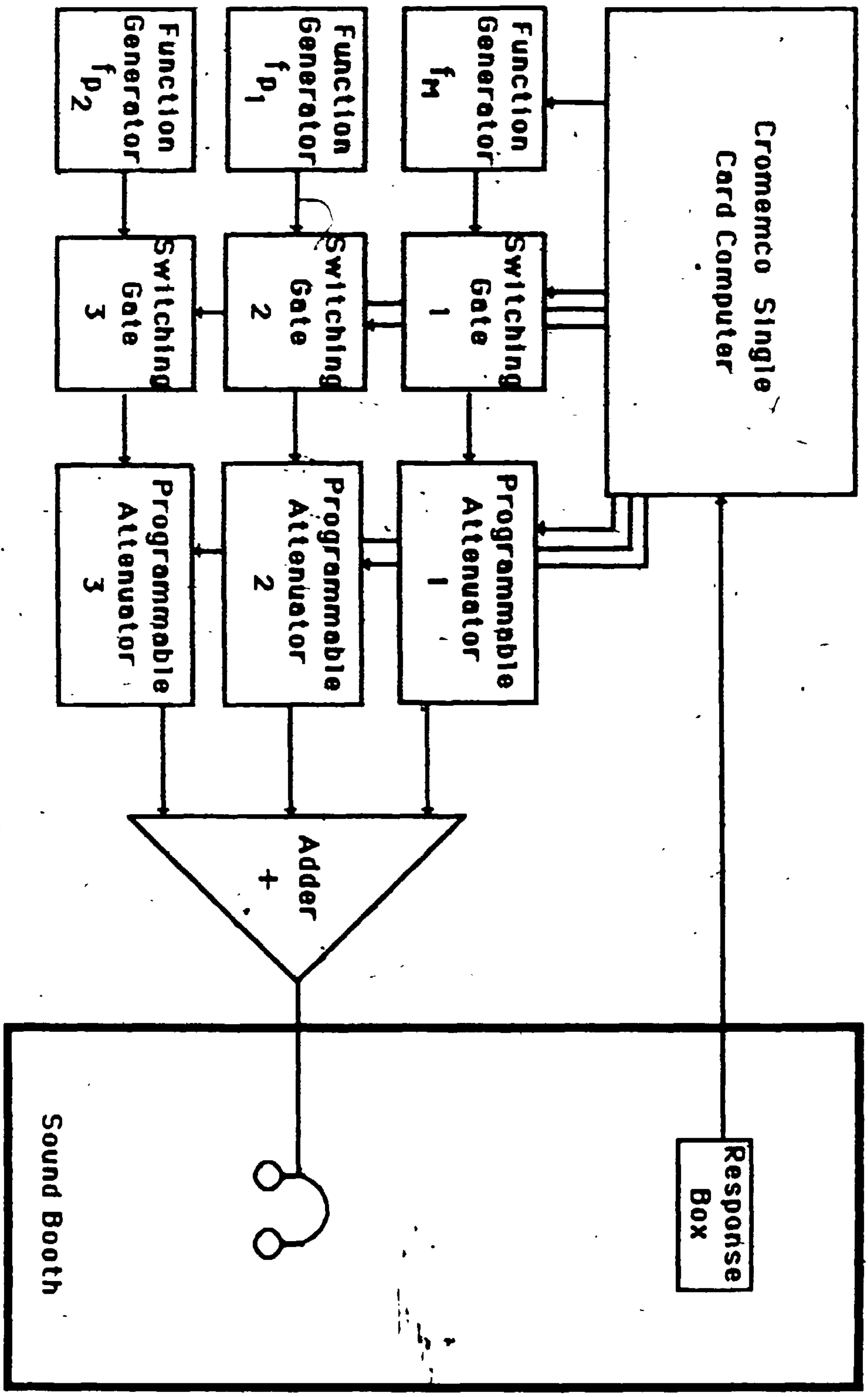

ENVELOPES
SPECTRA
AMPLITUDE
f_M
f_{p_1} or f_{p_2}
(a)
0
205 ms
12 ms
0
0
f_M
f_{p_1} or f_{p_2}
f_M
f_{p_1} and f_{p_2}
(b)
0
205 ms
12 ms
TIME
0
f_M
0
f_{p_1} and f_{p_2}
FREQUENCY

Figure 2.3 A block diagram of the equipment used in these studies. See text for a complete description.


Cromemco Single Card Computer
Function Generator f_M
Function Generator f_{P_1}
Function Generator f_{P_2}
Switching Gate 1
Switching Gate 2
Switching Gate 3
Programmable Attenuator 1
Programmable Attenuator 2
Programmable Attenuator 3
Adder +
Response Box
Sound Booth

calibrated while the signal was on continuously. The subject's responses were made on one of two buttons on the response box placed in the chamber. The timing of signals, stimulus presentation (gating and attenuation) and selection of the masker frequency (DA output to the HP voltage control input) were controlled by a digital computer (TecMar TecLab II). Also, the subject's response recording, and trial-by-trial feedback was controlled by the computer.

2.2.3. Experimental conditions.

Six different masker frequencies were used to mask the single- and double-frequency probes. Table I summarizes the parameters for each condition. The masker frequencies ranged from 1.0 to 1.5 kHz in 0.1 kHz intervals. Two probe frequencies were used: fp1 at 1.0 kHz and fp2 at 1.5 kHz. As well, a number of different conditions were studied with these six masker frequencies and two probe frequencies. With the single-frequency probes, masking level thresholds were obtained for three amplitudes of each probe frequency (1.0 and 1.5 kHz): 10, 5 and 0 dB SL. In the conditions with a double-frequency probe, these probe levels were combined to produce five different testing combinations at three specific pressure ratios. For example, presenting both the 1.0 and 1.5 kHz probe

Table I

Summary of Experimental Conditions in Experiment I

Probes		Difference	Pressure Ratio	Masker
fp1	fp2	in dB	fp2:fp1	fM
1.0 kHz	1.5 kHz		Lp1:Lp2	1.0 to 1.5 kHz (0.1 kHz steps)
10 dB SL	10 dB SL	0 dB	1.0	level adapted to threshold by S's response
5 dB SL	10 dB SL	5 dB	1.78	
10 dB SL	5 dB SL	5 dB	1.78	
0 dB SL	10 dB SL	10 dB	3.16	
10 dB SL	0 dB SL	10 dB	3.16	

components simultaneously at 10 dB SL produced an pressure ratio of 1.0 (or a 0 dB difference in the probe levels). Two other pressure ratios were also tested: 1.78 and 3.16 corresponding to a 5 and 10 dB difference in the level of the probes (see Table I).

There are two reasons for using three pressure ratios of the probe. First, if differences in performance between the single- and double-frequency probes were to be found, one might expect that the differences would be level dependent; that is, performance should differ with changes in the relative amplitude of each component. As the pressure ratio increases, the temporal waveform of the complex will be increasingly dominated by the highest amplitude component. Therefore, the influence of the lower amplitude component would be less.

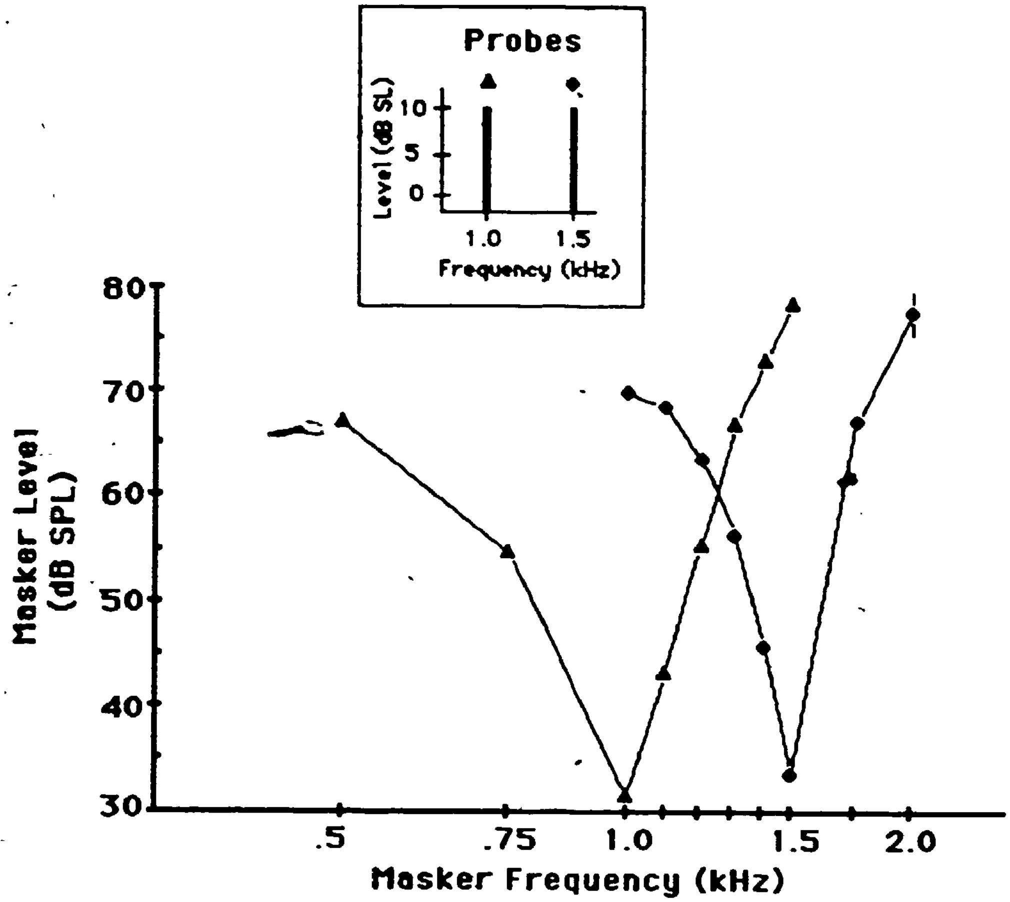
Second, if the auditory system is sensitive to large amplitude ratios (e.g., 10 dB difference in the probe levels; see Rose et al., 1971), then the condition of the 10 dB and 0 dB SL probe components presents an interesting situation. Adding the 0 dB SL component to the probe contributes very little additional power to the complex (actually only 0.4 dB). If the auditory system uses a power spectrum analysis of the signals, this should make little or no difference in performance. However, if differences in performance are found, they would be attributable to factors other than the increment in energy.

2.3 Results

2.3.1 Effective masker levels with a 0 dB difference in the probe levels

Figure 2.4 displays the typical masker levels necessary to mask a 10 dB SL 1.0 kHz and 10 dB SL 1.5 kHz single- frequency probe (subject RR). Included in these data are the additional masker frequencies of 0.5, 0.75, 1.75 and 2.0 kHz. The inclusion of these data points allowed an internal check on the shape of the psychophysical tuning curves. The general masking pattern was consistent with others' research; for example, the steep high-frequency tuning curve function reaching approximately 70 to 80 dB SPL at masker frequencies 0.5 kHz above the probe frequency. Also, the typical less steep low-frequency tuning curve function is also apparent in Figure 2.4 (cf. Green et al., 1981; O'Loughlin and Moore, 1981). Exact comparisons are difficult because of the differences in the stimulus parameters used in each study. Moore (1978) and others have shown that a number of parameters are important in determining the exact shape

Figure 2.4 The effective masker levels for single-frequency 10 dB SL probes at 1.0 kHz (triangles) and 1.5 kHz (diamonds) for subject RR. Included in these data are the masker frequencies 0.5, 0.75, 1.75 and 2.0 kHz. Standard errors are shown that exceed the size of the data point (i.e., 5 dB).


Probes
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)
80
70
60
50
40
30
Masker Level (dB SPL)
.5
.75
1.0
1.5
2.0
Masker Frequency (kHz)

of the psychophysical tuning curve -- the duration, level and shaping of the probe and masker, and the duration of the interval between the masker and the probe (Green et al., 1981; O'Loughlin and Moore, 1981; Widin and Viemeister, 1979a,b). All three subjects tested, though, showed similar masking functions.

According to the simple model of masking, the following prediction can be made. The effective masker levels for the double-frequency probes (each at 10 dB SL) should approximate the highest of the two masker levels found at each masker frequency. For example, in Figure 2.4, the masking pattern from the probe pair should be predicted by the filled diamond data at 1.0, 1.1, and 1.2 kHz and the filled triangles at 1.3, 1.4, and 1.5 kHz.

The results from two subjects are shown in Figures 2.5 and 2.6 for these same masker frequencies. The masking patterns show both the single-frequency (closed data points) and double-frequency (open data points) probe conditions. Each data point is the average of a minimum of four threshold trials, and only the standard deviations that exceeded 5.0 dB are plotted. Examination of the data reveals that masker levels with double-frequency probes are approximated by the levels with the single-frequency probes, as would be expected from the excitation model. A closer examination of each subject's performance, though, reveals some notable differences. In Figure 2.5 (subject DCB), as much as 4.8 dB more masker energy is necessary to mask the double-frequency probe, compared to the levels for the single-frequency probe (i.e., with masker frequency 1.3 kHz). Also, with maskers 1.0, 1.1 and 1.2 this subject's masker levels were between 1.5 to 2.0 dB higher than predicted by the excitation model. On the other hand, subject RR (Figure 2.6) shows masker levels with the double- frequency probes slightly less than the levels with the single-frequency probes. The difference is largest with the 1.0 kHz masker (-2.8), otherwise it varies about ± 1.0 dB for the other five maskers.

In general, the pattern of masking seems to be consistent with the predictions of the model; that is, the effective masker levels with a double-frequency probe are predicted from the effective levels for the single-frequency probes. Still, there remain obvious inter-subject differences. A couple of explanations are possible. The subject in Figures 2.5 needed slightly more energy than predicted while the other subject (Figure 2.6) needed less. Such differences could likely be due to the specific cues in the task utilized by each subject. It is not uncommon for

Figure 2.5 The effective masker levels for single-frequency 10 dB SL probes at 1.0 kHz (triangles) and 1.5 kHz (diamonds) and double-frequency probe (open squares) for subject DCB. Included in these data are the masker frequencies 0.5, 0.75, 1.75 and 2.0 kHz. Standard errors are shown that exceed the size of the data point (i.e., 5 dB).

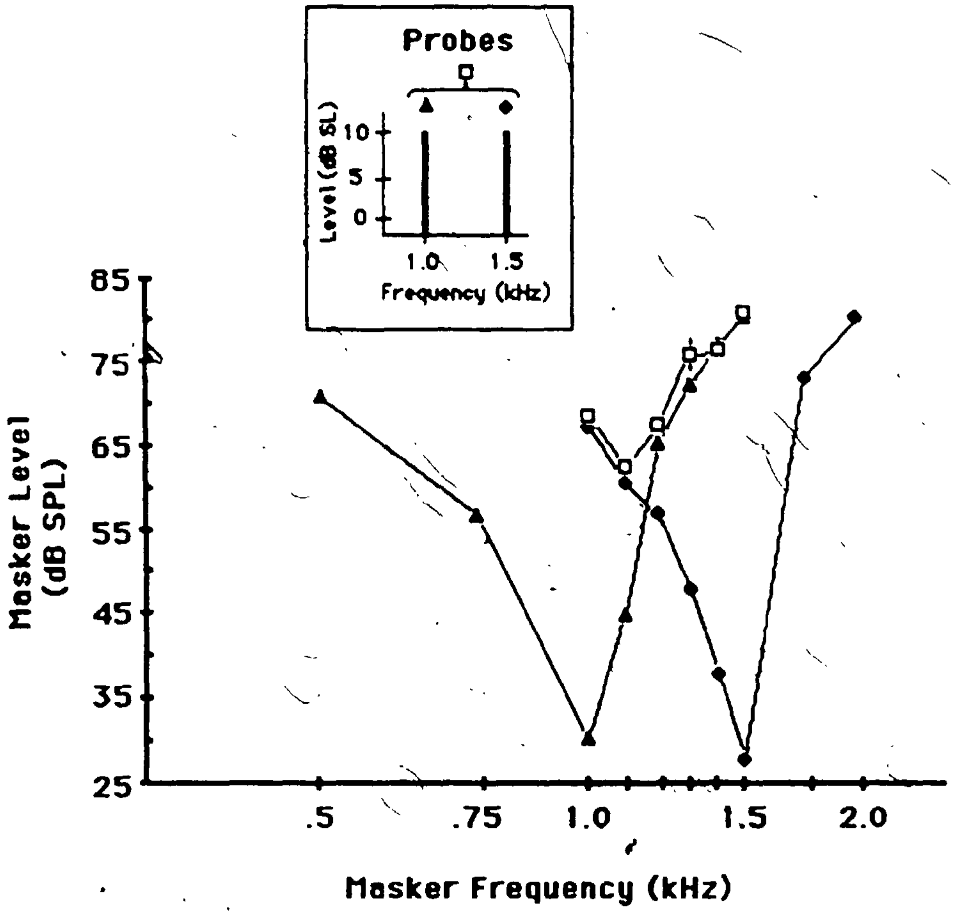
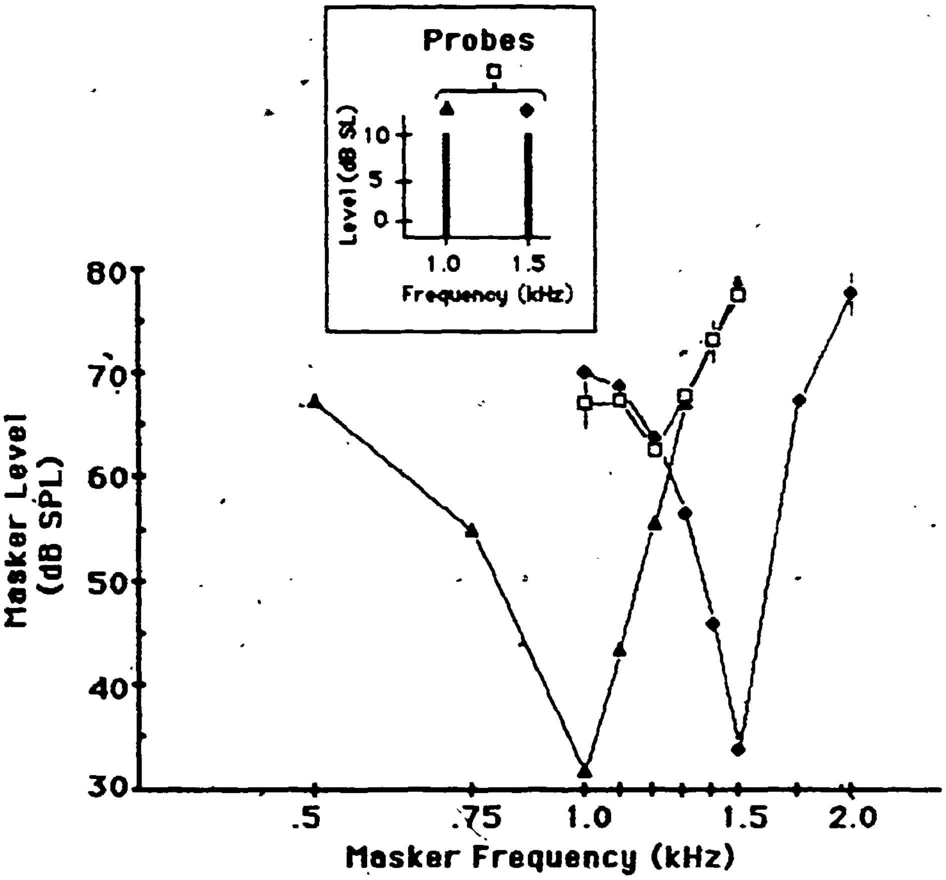

Probes
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)
Masker Level (dB SPL)
85
75
65
55
45
35
25
.5
.75
1.0
1.5
2.0
Masker Frequency (kHz)

Figure 2.6 The effective masker levels for single-frequency 10 dB SL probes at 1.0 kHz (triangles) and 1.5 kHz (diamonds) and double-frequency probe (open squares) for subject RR. Included in these data are the masker frequencies 0.5, 0.75, 1.75 and 2.0 kHz. Standard errors are shown that exceed the size of the data point (i.e., 5 dB).


Probes
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)
Masker Level (dB SPL)
80
70
60
50
40
30
.5
.75
1.0
1.5
2.0
Masker Frequency (kHz)

different subjects to rely on idiosyncratic cues for detecting the probe. Subject DCB (Figure 2.5) was likely able to use as a cue the additional energy that resulted from presenting two tones simultaneously at 10 dB SL. (This stimulus presentation produces an increase in the peak amplitude of the sinusoidal pair of 3 dB; Peterson and Gross, 1972).

It is also quite possible that these differences reflect the fact that the masking/detection task with the double-frequency probe is different from the task with a single-frequency probe, since there is no *a priori* reason to expect that the effective masker level should decrease with the double-frequency probes (as in Figure 2.6). For example, the detection of single-frequency probes have been described as involving a monitoring of specific channels in the auditory system (Moore, 1983). The detection of the double-frequency probes may also involve a channel monitoring strategy, but if information other than the frequency energy is present, other strategies may also be helpful. (For example, the pair may be heard not as two individual tones or frequencies, but as a single percept of both tones. Certainly a detection task in these two cases could be quite different.)

3

2.3.2 Effective masker levels with a 5 dB difference in the probe levels

As described in Table I, the stimulus conditions that produced a 5 dB difference in the probe can be obtained in two ways: the 1.0 and 1.5 kHz probes at either 10 and 5 dB SL or 5 and 10 dB SL levels, respectively. Figures 2.7 and 2.8 show the effective masker levels for both the single- and double-frequency probe conditions for the first test condition (subjects DCB and GJF). Only three masker frequencies are displayed since the maskers of 1.3, 1.4 and 1.5 kHz showed no significant difference between conditions. (This phenomenon was found consistently throughout the remaining conditions.) The filled triangles show the masker levels required to mask the 1.0 kHz 10 dB SL probe. Similarily, the filled diamonds show the effective masker levels for the 1.5 kHz 5 dB SL probe. The third masking function (open square data points) shows the effective masker levels for the double-frequency probes at these levels. Only the standard deviation scores that exceed 2.5 dB are shown.

One would expect, from the model, that the masking patterns for the combined probes would be approximated by the greater of the two single-frequency probe patterns. In this case, the masker levels should be similar to the data represented by the filled diamonds for the 1.0 and 1.1 kHz maskers, and the filled triangles for the 1.2 kHz masker. With these levels of the probes, the effective masker levels for the double-frequency probe were greater than predicted. Therefore, more masker energy was necessary to mask the double-frequency probes than expected from the single-frequency probe data. Also, inter-subject differences were evident. Subject DCB (Figure 2.7) shows large increases in all three masker levels (between 4 and 7 dB). Subject GJF (Figure 2.8), though, only showed a large difference with the 1.1 kHz masker frequency (8.7 dB). Despite these inter-subject differences, what remains to be explained is the magnitude of the increases in the effective masker levels. It is unlikely that these increases are the result of the additional 1.2 dB due to the energy summation of the probes (Peterson and Gross, 1972). For example, comparing the 1.1 kHz masker levels with the double-frequency probes and those obtained with a 10 dB 1.5 kHz single-frequency probe (Figure 2.5), it is evident that only 1 dB less energy was required to mask the double-frequency probe in this condition than the single-frequency 1.5 kHz probe. In other words, the effective 1.1 kHz masker level for the 1.78 amplitude

Figure 2.7 The effective masker levels for single-frequency probes: 1.0 kHz at 10 dB SL (triangles), 1.5 kHz at 5 dB SL (diamonds) and double-frequency probe (open squares) for subject DCB. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).

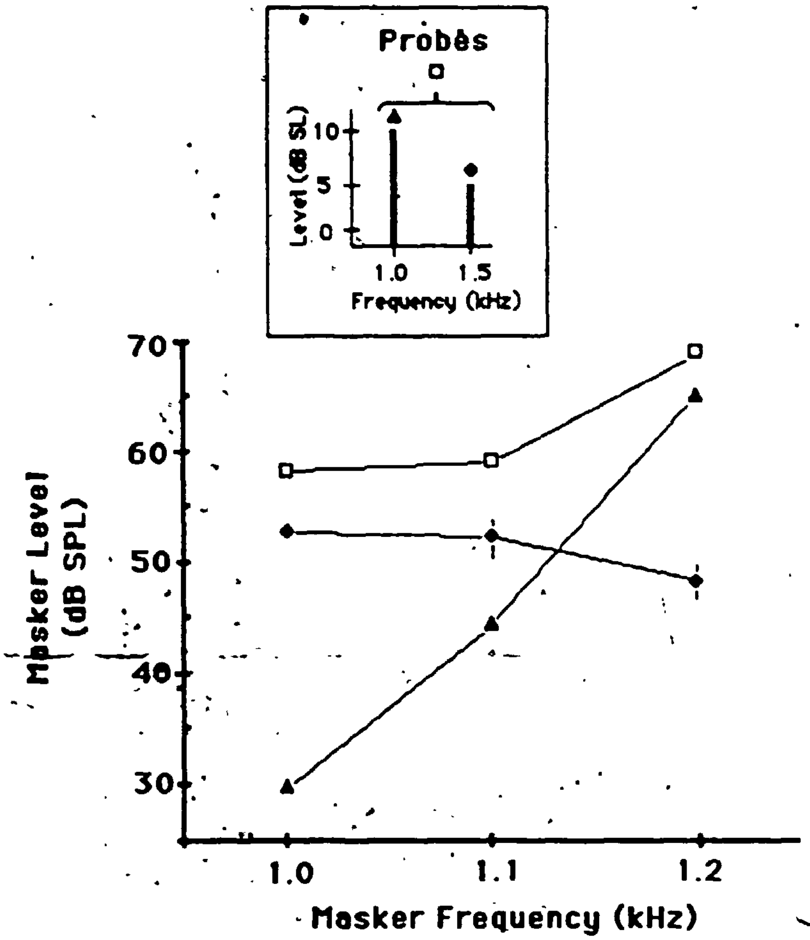
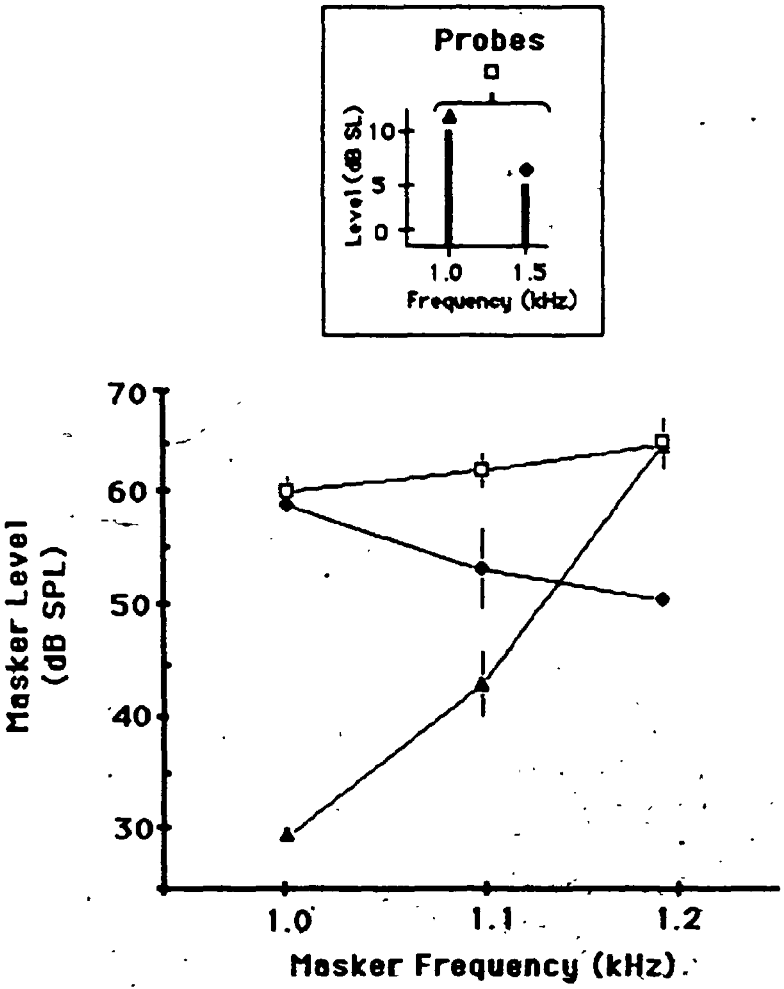

Probes
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)
70
60
50
40
30
Masker Level (dB SPL)
1.0
1.1
1.2
Masker Frequency (kHz)

Figure 2.8 The effective masker levels for single-frequency probes: 1.0 kHz at 10 dB SL (triangles), 1.5 kHz at 5 dB SL (diamonds) and double-frequency probe (open squares) for subject GJF. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).


Probes
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)
70
60
50
40
30
Masker Level (dB SPL)
1.0
1.1
1.2
Masker Frequency (kHz)

ratio probe is approximated by a single 10 dB SL probe. Such effects certainly cannot be explained by the additional energy in the simultaneous probe pair or by the excitation model.

The second combination of the probes at these levels was also tested, with the 1.0 kHz probe at 5 dB and the 1.5 kHz probe at 10 dB SL. Figures 2.9 and 2.10 show the masker levels obtained for two subjects, again for only three masker frequencies (in this case excluding 1.0, 1.1 and 1.2 kHz). As can be noted, the effective masker levels are more similar between the single- and double frequency probes than found above. Subject DCB (Figure 2.9) shows no difference between the effective masker levels for the single- and double-frequency probes (as evidence by the proximity of the data points and the overlapping error bars). The second subject (GJF: Figure 2.10), though, shows significant differences at all three masker frequencies. The 1.3kHz masker shows a difference of 1.8 dB ($t(3)=2.81$, $p<.05$, one tailed), 1.4 kHz masker; 4.6 dB difference ($t(3)=10.9$, $p<.005$, one tailed), 1.5 kHz masker; 3.8 dB difference ($t(3)=8.5$, $p<.005$, one tailed). (All t-tests in this report are one-tailed, since the hypothesis is that adding the second probe will improve detectability, therefore reject H_0 only if

Figure 2.9 The effective masker levels for single-frequency probes: 1.0 kHz at 5 dB SL (triangles), 1.5 kHz at 10 dB SL (diamonds) and double-frequency probe (open squares) for subject DCB. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).

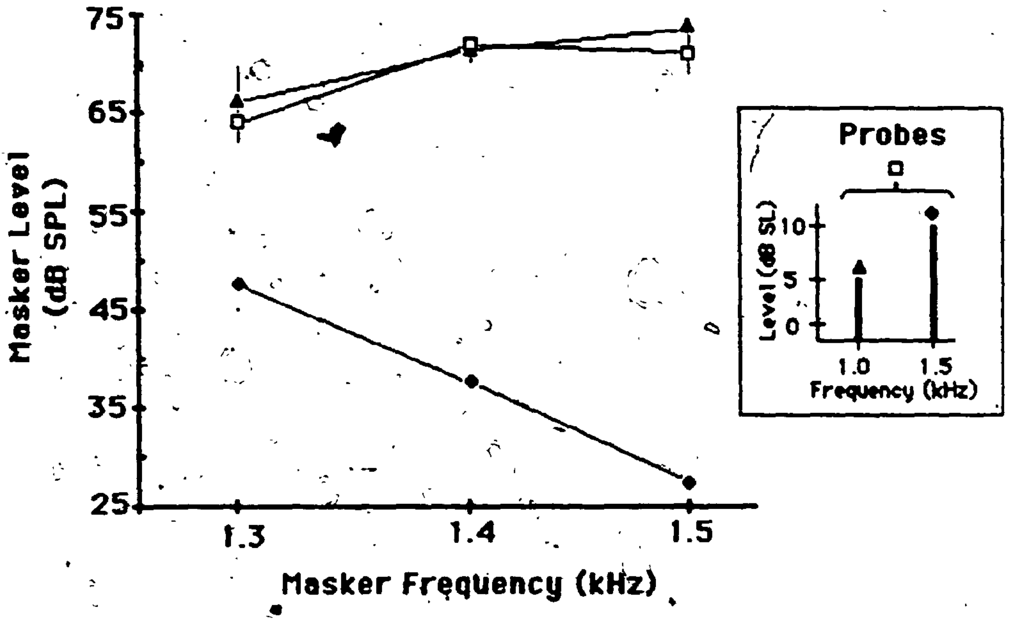
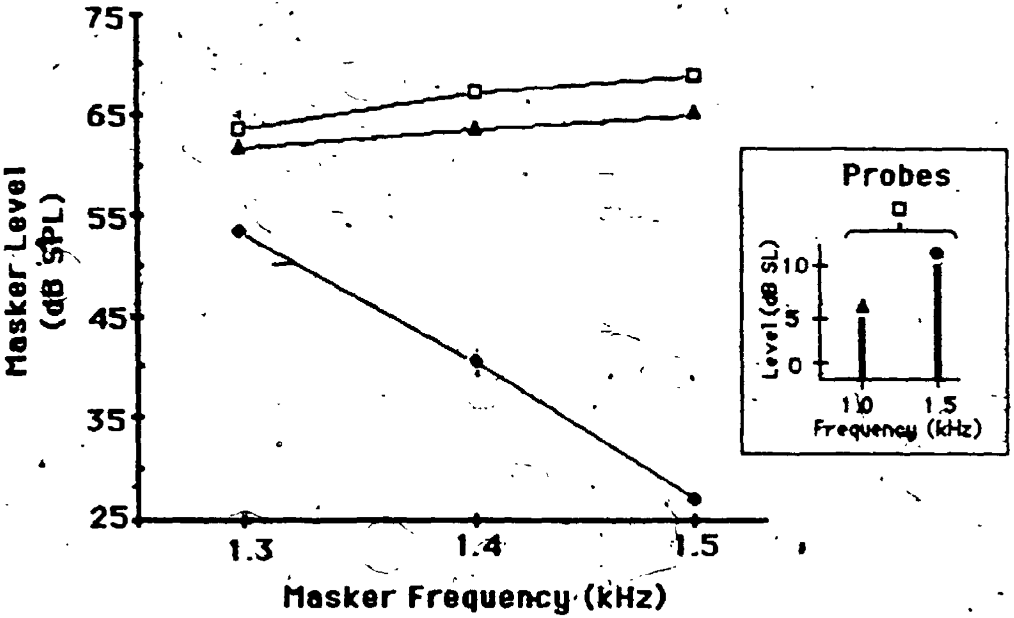

75
65
55
45
35
25
Masker Level
(dB SPL)
1.3
1.4
1.5
Masker Frequency (kHz)
Probes
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

Figure 2.10 The effective masker levels for single-frequency probes: 1.0 kHz at 5 dB SL (triangles), 1.5 kHz at 10 dB SL (diamonds) and double-frequency probe (open squares) for subject GJF. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).


75
65
55
45
35
25
Masker Level
(dB SPL)
1.3
1.4
1.5
Masker Frequency (kHz)
Probes
□
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

effective masker level is greater than single-frequency probes.)

Therefore, the 1.78 probe amplitude ratio data show interesting results. Performance is variable across subjects (the two subjects show differential detectability of the probe pair in the same stimulus condition). Also, performance varies across conditions (each subject does not always show effects in the same test condition). In fact, in one full test condition, no differences between the single- and double-frequency tests were shown in subject DCB (Figure 2.9).

Although there were inter-subject differences, the trend of these data suggests that in a number of test conditions, substantial increases in the effective masker level were necessary to mask the double-frequency probes. Such increases are difficult to explain by either the proposed excitation model or an energy summation of the probes. This improved detectability of the double-frequency probes may be the result of a differential coding of the sinusoidal pair by the auditory system. For example, if the masked threshold of the single-frequency probe is coded by the neuron's firing rate, then we might expect such behavioral effects due to the higher sensitivity of the temporal coding of the double-frequency stimuli (Rose et al., 1974).

2.3.3 Effective masker levels with a 10 dB difference in the probe levels

Two final test conditions were examined with a 10 dB difference in the level of the probes. Figures 2.11 and 2.12 show the data for the probes at 1.0 kHz at 10 dB SL and 1.5 kHz at 0 dB SL and three masker frequencies. Again, the masker levels for the 1.0 kHz 10 dB SL single probe are shown (filled triangles), as well as the approximate masker levels for the 1.5 kHz 0 dB SL probes (filled diamonds). It is important to note that the masker levels for the 0 dB SL probes were difficult to obtain (as evidenced by the large error bars). Not only do these data points show a large variability across a block of trials, but also within the block of trials. The probe is detectable, in quiet, only 70.7% of the time, and introducing a forward mask easily disrupted its detectability. (On a number of trials the subjects would note that the perception of the probe would disappear completely only to reappear when the masker was reduced to imperceptible levels.)

Figure 2.11 The effective masker levels for single-frequency probes: 1.0 kHz at 10 dB SL (triangles), 1.5 kHz at 0 dB SL (diamonds) and double-frequency probe (open squares) for subject DCB. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).

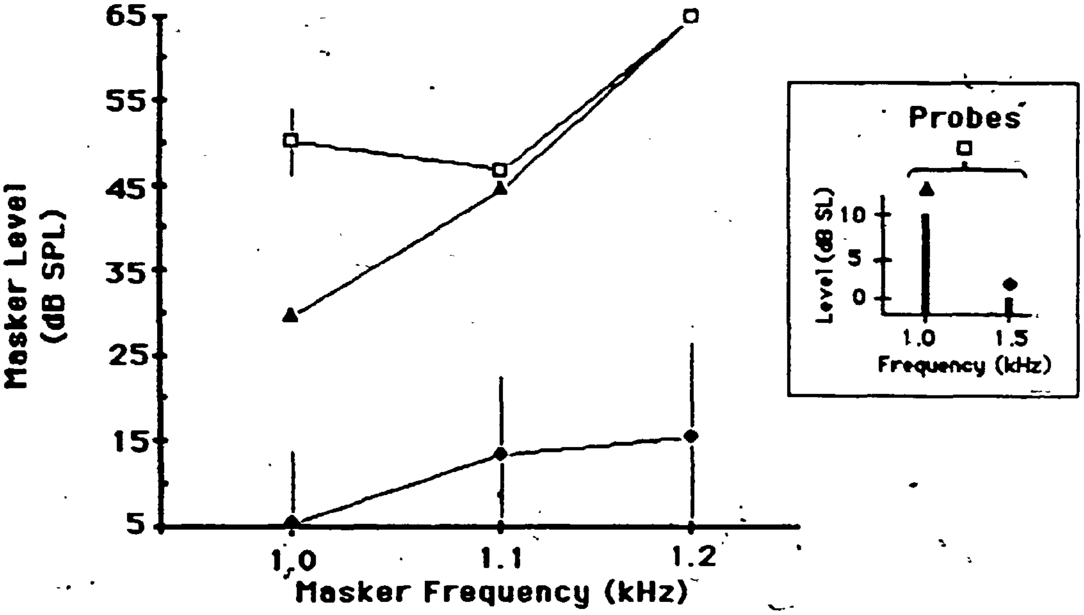
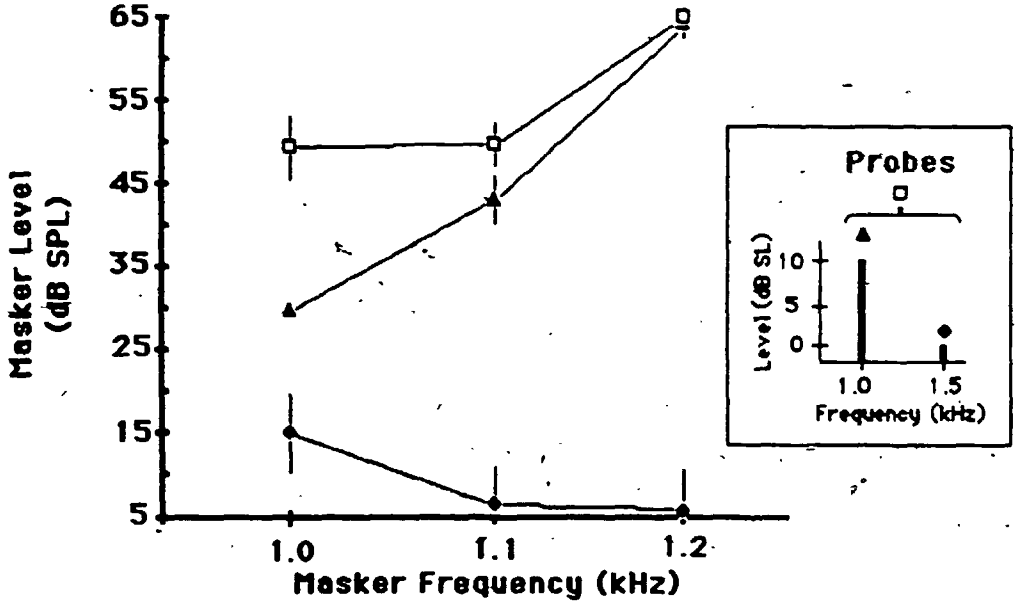

65
55
45
35
25
15
5
Masker Level (dB SPL)
1.0
1.1
1.2
Masker Frequency (kHz)
Probes
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

Figure 2.12 The effective masker levels for single-frequency probes: 1.0 kHz at 10 dB SL (triangles), 1.5 kHz at 0 dB SL (diamonds) and double-frequency probe (open squares) for subject GJF. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).


65
55
45
35
25
15
5
Masker Level
(dB SPL)
1.0
1.1
1.2
Masker Frequency (kHz)
Probes
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

The masking function for the double-frequency probe (open squares) is very similar for both subjects. Each subject shows a marked increase in the effective masker level for the 1.0 kHz masker, with a smaller but significant increase with the 1.1 kHz masker. In Figure 2.11, subject DCB shows a 2.2 dB difference in the probe conditions (t(3)=5.0, p<.01, one-tailed). In Figure 2.12, subject GJF shows a 6.8 dB difference in the probes (t(3)=4.9, p<.01, one-tailed). (Using these same stimulus parameters, the subject RR was found to show large increases in the effective masker levels with all three masker frequencies: 11, 8 and 4 dB increases for the double-frequency probe with the 1.0, 1.1 and 1.2 kHz masker frequencies, respectively). This increase in 10 kHz masker level of up to 20 dB cannot be predicted by the excitation model or by the additional 0.4 dB in the summation of the probe energy (Peterson and Gross, 1972). This suggests a strong interaction of the two probe frequencies is present in the task and detected by the subjects. Examining the specific values, it can be noted that for subject DCB, the 50 dB SPL 1.0 kHz masker level for the double-frequency probe condition is only 2 dB below that of the 1.0 masker level for a single-frequency 5 dB 1.5 kHz probe (see Figure 2.7; filled diamonds). Therefore, this masker level approximates that level necessary to mask a suprathreshold 1.5 kHz probe.

The data for the second combination of probe levels with the 10 dB difference in the probe levels are shown in Figures 2.13 and 2.14 for the 1.3, 1.4 and 1.5 kHz maskers. Again, the effective masker levels for the 0 dB SL probes were quite variable. But when this threshold-level probe was added to the 10 dB SL 1.5 kHz probe, the effective masker levels increased substantially (only the 1.3 kHz masker for subject GJF (Figure 2.14) showed no difference).

Obviously, the combined probe condition results in additional information not present or utilized in the single probe conditions. These differences in the effective masker levels are most noticeable with a 10 dB difference in the levels of the probes, but are also evident with a 5 dB difference. (Some differences were found with both probes at equal sensation levels (10 dB SL), but these findings may be explained by the energy summation of the probes.) It has been shown that the excitation model is unable to predict these findings. As well, the energy summation of the probes cannot produce the magnitude of such effects. The neurophysiological data show that two sinusoids can interact even at these levels (Rose et al., 1974). If such coding is utilized by the subject, it may be that

Figure 2.13 The effective masker levels for single-frequency probes: 1.0 kHz at 0 dB SL (triangles), 1.5 kHz at 10 dB SL (diamonds) and double-frequency probe (open squares) for subject DCB. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).

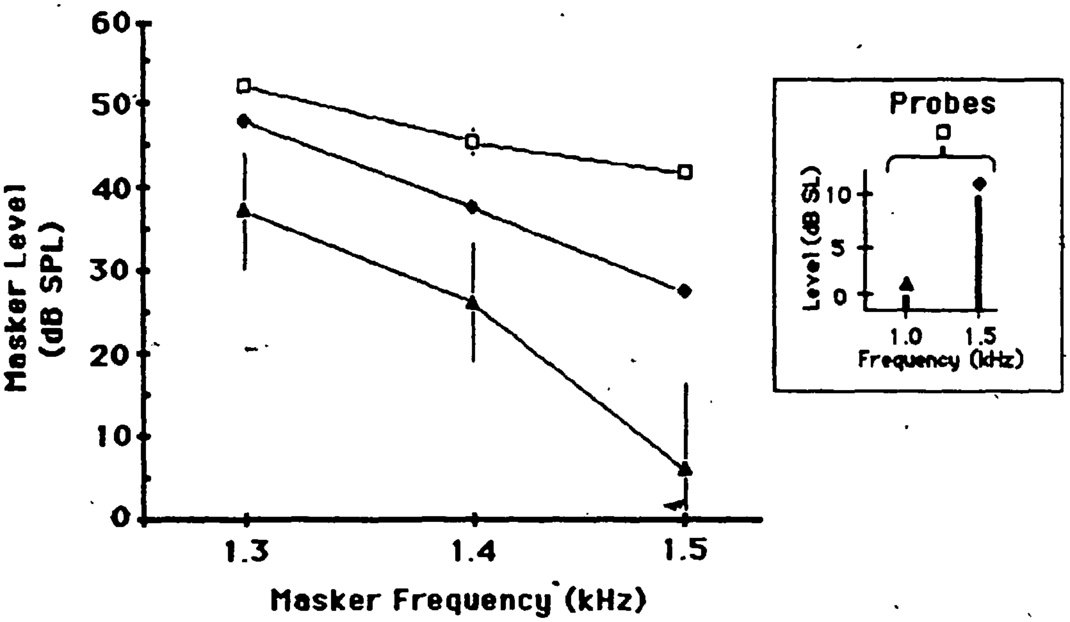
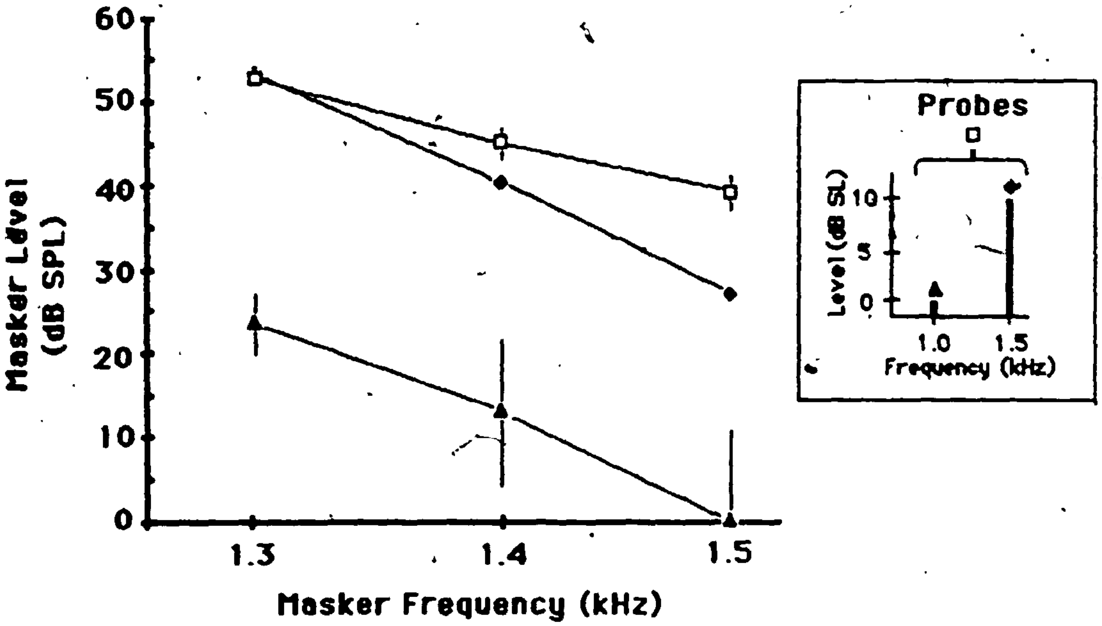

60
50
40
30
20
10
0
Masker Level
(dB SPL)
1.3
1.4
1.5
Masker Frequency (kHz)
Probes
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

Figure 2.14 The effective masker levels for single-frequency probes: 1.0 kHz at 0 dB SL (triangles), 1.5 kHz at 10 dB SL (diamonds) and double-frequency probe (open squares) for subject GJF. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).


Masker Level (dB SPL)
60
50
40
30
20
10
0
1.3
1.4
1.5
Masker Frequency (kHz)
Probes
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

this would explain the differences between the effective masker levels for the single- and double-frequency probes. Therefore, masking of the single-frequency probe would involve masking only the frequency information coded at a specific frequency. The masking of the double-frequency probe, on the other hand, would involve a masking of the coded interaction of the probes. This type of model could, then, explain the data shown above.

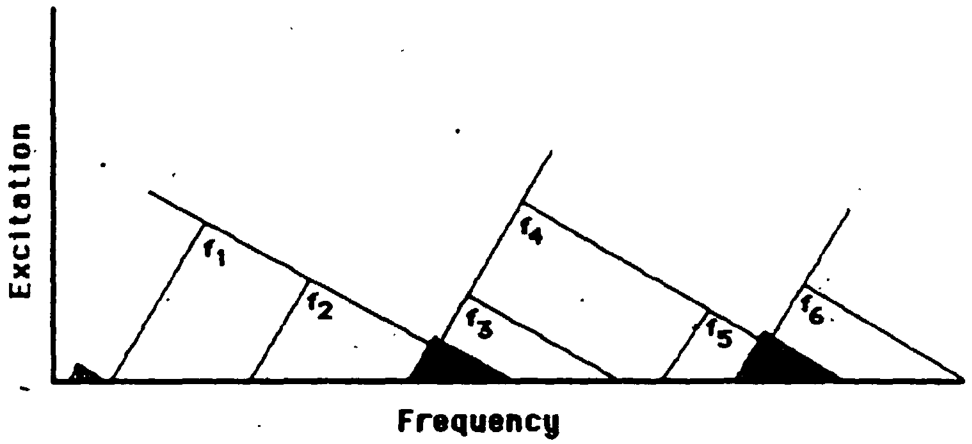
There remains a possibility, though, that combination tones may influence the task. During the double-frequency probe presentation, energy may be present in the combination tone region. This too could explain the effects found above. Experiment II specifically addresses this question.

3. Experiment II: Effective Masker Levels of Single- and Double-Frequency Probes in a Dichotic Presentation

3.1 Introduction

In this experiment, we examined whether the presence of combination tones may have led to the differences in the effective masker levels found necessary to mask the single- and double-frequency probes. It is certainly possible that the double-frequency probe condition may have produced combination tones at a frequency region below that of the masker and probes. The two simultaneous probes then would produce, through the nonlinearities in the auditory system, stimulus energy in the difference tone regions. This situation is depicted in Figure 3.1. Here, the patterns of excitation for a double-frequency probe (filled triangles) are displayed with the patterns for six pure tone maskers (open triangles). At the far left of the frequency spectrum, there is represented a small amount of excitation, as would be produced by a combination tone, that falls in a low (and unmasked) frequency region. If this energy was detectable in the experimental task, then greater masker levels would be necessary to mask the combination tone energy.

Figure 3.1 A schematic representation of the typical masking patterns with two probes (filled) and six maskers (open). The small filled triangle at the far left of the frequency spectrum represents energy at the combination tone region.


Excitation
Frequency
f_1
f_2
f_3
f_4
f_5
f_6

It is also important to note the probe frequency relationship used in the first study. This stimulus arrangement (f2/f1 = 1.5) produces two difference tones with the same frequency; that is, the simple difference tone (f2- f1) at 0.5 kHz, and cubic difference tone (2f1- f2) also at 0.5 kHz. In certain phase relationships between the probes, the DT and CDT could, in fact, reinforce each other to produce a greater amplitude combination tone (Hall, 1972; Kim et al., 1980).

In Experiment I, very low-level probes were used (0, 5 and 10 dB SL) which were thought to be too low to make combination tone generation possible. The lowest stimulus levels found to produce combination tones (when the level of both tones is equal, i.e., Lp1 = Lp2, and the frequency ratio, f2/f1, is approximately 1.2), are approximately 20 dB SL (Goldstein, 1967; using the cancellation method). With unequal levels of the primaries (Lp1 ≠ Lp2), Smoorenburg (1972) found combination tones could be perceived with primary levels of 40 and 0 dB SL.

It was noted earlier, though, that these levels necessary to produce combination tones may be overestimated (Humes, 1980; Shannon and Houtgast, 1980). It is certainly possible that the masking procedure in

Experiment I may be more sensitive to the presence of combination tones than previous paradigms. For example, Shannon and Houtgast (1980) found that a nonsimultaneous pulsation threshold method produced significantly lower estimates of the combination tones than the cancellation method. Unlike Shannon and Houtgast, in our paradigm no comparison probe was used to estimate the level of the combination tone. Therefore, there would be no masking confounds, as is possible in all other methods for estimating the combination tone level.

The production of combination tones requires a simultaneously monaural or diotic presentation of each tone. It was argued earlier that combination tones result from the nonlinear propagation of the travelling wave or the nonlinear transduction at the level of the receptors. Whether they result from one or both of these nonlinearities is, at present, unknown, but combination tone generation does require that the tones be processed by the same ear.

The results from Experiment I showed that the masking performance with double-frequency probes was not predictable from the performance with single-frequency probes. It was suggested that these differences may have been due to a mechanism that compared the temporal code of the probe pair. If this is accurate, then a dichotic presentation of each probe should not effect this phenomena. On the other hand, if the results of Experiment I are due to the presence of combination tones, then the dichotic presentation of the probes would have profound effects, eliminating the distinction between the single- and double-frequency probe presentations.

3.2 Method

3.2.1 Subjects

Two subjects were used in this study, one male (GJF) and one female (DCB), both of whom had served as subjects in Experiment I.

3.2.2 Stimulus presentation

The forward masking procedure used in Experiment I measured masker level thresholds for the single- and double-frequency probes. One difference in these experiments was the use of the dichotically presented double-frequency probes. The probes were presented to opposite ears; that is, the 1.0 kHz probe to the subject's right ear, and the 1.5 kHz probe to the left ear. It was not thought necessary to counterbalance the presentation of the two probe frequencies to different ears, since there has been no indication that hemispheric differences play a role in psychophysical masking studies as they do in speech processing studies. The masker was always presented binaurally (in both the single- and double probe conditions). When measuring the masker levels for the single-frequency probes, the masker was binaural and the probes monaural to the appropriate ear. With the double-frequency condition, the masker was binaural and the probes were presented dichotically.

In order to accomodate the monaurally presented probes and binaurally presented maskers, the apparatus was set up somewhat differently from that shown in Figure 1.3. The output from the programmable attenuator 1 (fM), which controls the masker intensity, was directed to two different adders that fed each earphone. The outputs of the attenuators carrying fp1 and fp1.5 were fed into the appropriate adder such that fp1 was output at the right earphone and fp1.5 at the left earphone.

Performance was measured for only two amplitude ratios (where the probes differed in level by 5 and 10 dB), since the effects found in Experiment I with the 1.0 amplitude ratio may have been confounded by the significant energy summation of the probes. All data were collected with this experimental arrangement for the two subjects. Other aspects of the experiment was the same as described above (Sections 2.2.2 and 2.2.3).

3.3 Results

3.3.1 Effective masker levels with a 5 dB difference in the probe levels

Figures 3.2 and 3.3 show the effective masker levels for the monaural and binaural probes in the first test configuration: 1.0 kHz at 10 dB SL and 1.5 kHz at 5 dB SL. Throughout these results only three masker frequencies are plotted as in Experiment I, and for the same reasons as explained there. The levels for the binaural masker to just mask the 1.0 kHz 10 dB SL probe presented to the subject's right ear are shown for the masker frequencies of 1.0, 1.1 and 1.2 kHz (filled triangles). Similarily, the binaural masker levels for the 1.5 kHz 5 dB SL probe presented to the left ear are shown (filled diamonds). Finally, the effective masker levels with a dichotic presentation of the two probes are shown by the open squares.

Before comparing the single- and double-frequency conditions, it is important to note the slight quantitative differences in the data between Experiments

Figure 3.2 The effective masker levels for single-frequency probes: 1.0 kHz at 10 dB SL (triangles), 1.5 kHz at 5 dB SL (diamonds) and double-frequency probe (open squares) for subject DCB. The single-frequency probes are presented monaurally (1.0 kHz to the right ear, 1.5 kHz to the left ear) while the double-frequency probes are presented dichotically. The masker, in all test conditions was presented binaurally. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).

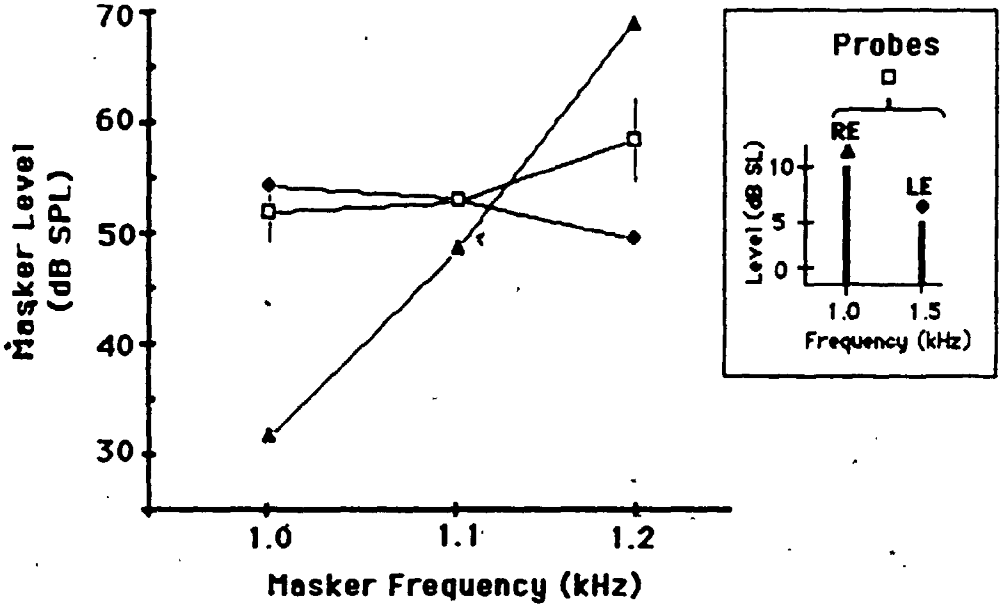
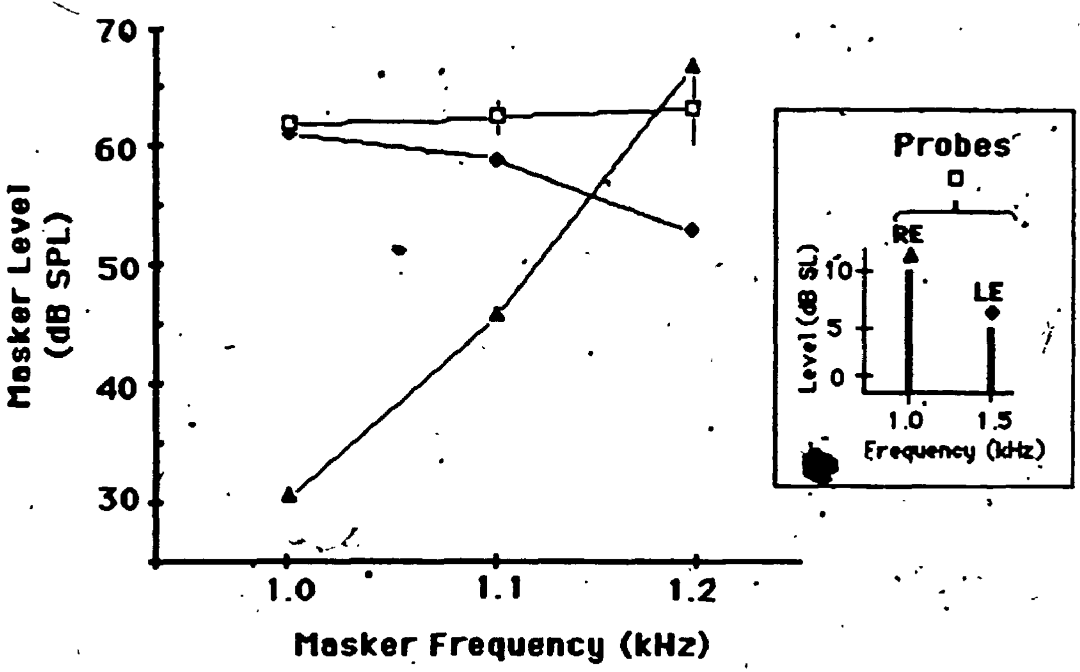
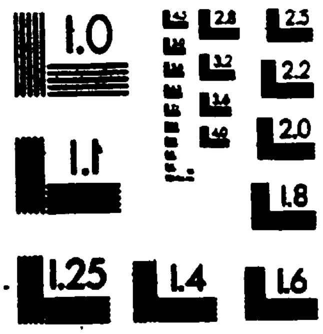

70
60
50
40
30
Masker Level
(dB SPL)
1.0
1.1
1.2
Masker Frequency (kHz)
Probes
RE
LE
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

Figure 3.3 The effective masker levels for single-frequency probes: 1.0 kHz at 10 dB SL (triangles), 1.5 kHz at 5 dB SL (diamonds) and double-frequency probe (open squares) for subject GJF. The single-frequency probes are presented monaurally (1.0 kHz to the right ear, 1.5 kHz to the left ear) while the double-frequency probes are presented dichotically. The masker, in all test conditions was presented binaurally. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).


Masker Level (dB SPL)
70
60
50
40
30
1.0
1.1
1.2
Masker Frequency (kHz)
Probes
□
RE
LE
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

2

MICROCOPY RESOLUTION TEST CHART
NBS 1010a
(ANSI and ISO TEST CHART No. 2)



I and II. On the average, the subjects needed up to 3 dB more binaural masker energy than monaural masker energy to mask the monaural probes. This effect is common in auditory research and is known as the binaural masking level difference. Therefore, a monaural signal is more detectable following the presentation of a binaural masker. The magnitude of the differences, shown in the following figures, is certainly within the range of expected differences with stimuli in this frequency range (Green and Yost, 1975). Further, there is an obvious between-subject difference in the binaural masking level difference; that is, subject DCB generally shows smaller values.

In contrast to the data in Experiment I, the effective masker levels for the single- and double-frequency probe conditions were not different when presented dichotically. For example, in Figures 2.7 and 2.8, both subjects showed that the effective masker level for the monaurally presented probe pair was between 7 and 9 dB greater than the effective levels for the single-frequency probes with the 1.1 kHz masker. Only one subject shows evidence of such differences in these data, and only for one masker frequency (a 5.0 dB difference with the 1.1 kHz masker; Figure 3.3, subject GJF; $t(3)=6.7$, $p<.005$, one-tailed).

Figures 3.4 and 3.5 show the results when the 1.0 kHz probe was presented at 5 dB SL, and the 1.5 kHz probe at 10 dB SL. In Experiment I, only one subject showed increases in the effective masker levels with single- and double- frequency probes (Figure 2.10). With the binaural masker and dichotic probes the effect disappears for this subject (Figure 3.5). Surprisingly, the other subject's data (Figure 3.4; DCB) show that the effective masker levels for the dichotic probe condition are below those obtained with the contrasting monaural condition (compare the open square data with the closed diamond data points). The reason for such differences is uncertain. One possibility, though, is the difficulty in the task itself. When both probes were presented at suprathreshold values (i.e., 5 and 10 dB SL), the subject reported difficulties in deciding which earphone to attend to, since the detection of each probe would change (become masked or "unmasked") as the masker level increased or decreased with a block of trials. In summary, other than the one data point in one subject's data (Figure 3.3), there is no demonstration of differences in the effective masker levels with dichotically presented probes with a 5 dB difference in the levels.

Figure 3.4 The effective masker levels for single-frequency probes: 1.0 kHz at 5 dB SL (triangles), 1.5 kHz at 10 dB SL (diamonds) and double-frequency probe (open squares) for subject DCB. The single-frequency probes are presented monaurally (1.0 kHz to the right ear 1.5 kHz to the left ear) while the double-frequency probes are presented dichotically. The masker, in all test conditions was presented binaurally. Standard errors are shown that exceed the size of the data point [illegible] 2.5 dB).

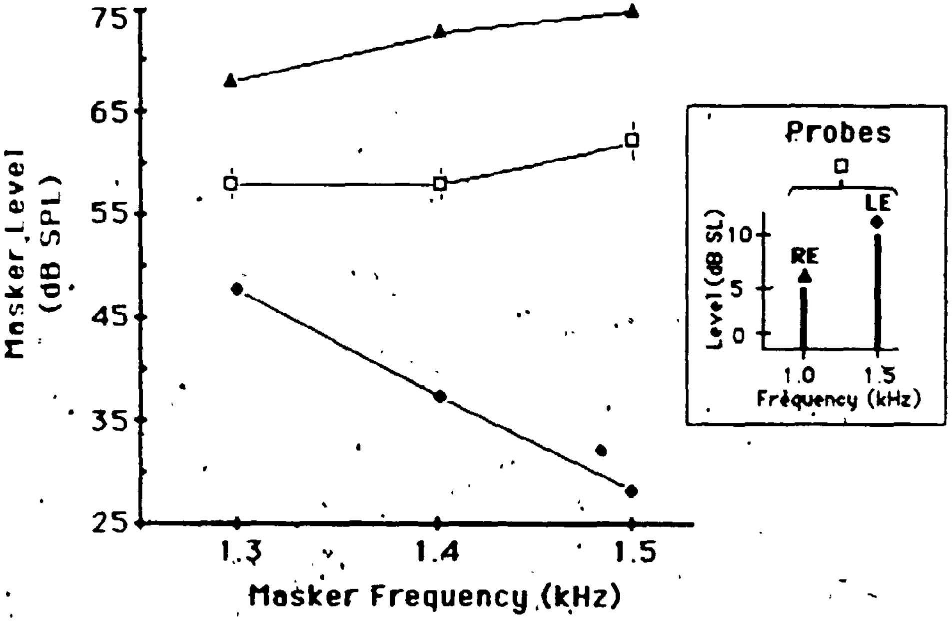
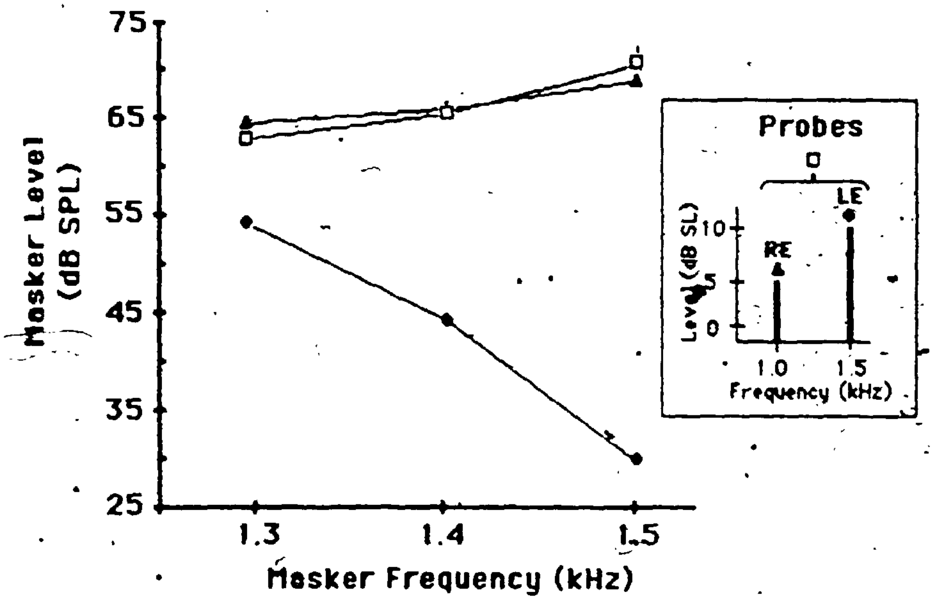

75
65
55
45
35
25
Masker Level
(dB SPL)
1.3
1.4
1.5
Masker Frequency (kHz)
Probes
LE
RE
10
5
0
Level (dB SL)
1.0
1.5
Frequency (kHz)

Figure 3.5 The effective masker levels for single-frequency probes: 1.0 kHz at 5 dB SL (triangles), 1.5 kHz at 10 dB SL (diamonds) and double-frequency probe (open squares) for subject GJF. The single-frequency probes are presented monaurally (1.0 kHz to the right ear, 1.5 kHz to the left ear) while the double-frequency probes are presented dichotically. The masker, in all test conditions was presented binaurally. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).


75
65
55
45
35
25
Masker Level (dB SPL)
1.3
1.4
1.5
Masker Frequency (kHz)
Probes
LE
RE
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

3.3.2 Effective masker levels with a 10 dB difference in the probe levels

With this amplitude ratio, differences in the effective masking levels with the single-frequency monaural probes and the double-frequency dichotic probes were found. Figures 3.6 and 3.7 show the stimulus configuration with the 1.0 kHz probe at 10 dB SL and the 1.5 kHz probe at 0 dB SL. Again, the 0 dB probe data were quite variable, within and across a set of trials, yet the double-frequency probe resulted in increased masker levels. Comparing these double-frequency masking patterns with those in Experiment I (Figures 2.11 and 2.12), the same general masking functions are found. For example, the 1.0 kHz masker shows a large difference between the effective masking levels with the single- and double-frequency probe (approximately 12 dB). Subject DCB (Figure 3.6) also shows a small but significant difference at the 1.1 kHz masker (2.9 dB difference: $t(3)=7.1$, $p<.005$, one-tailed).

Results obtained from testing the masker frequencies of 1.3 to 1.5 kHz, with the probe levels reversed (1.0 kHz at 0 dB SL and 1.5 kHz at 10 dB SL) are shown in Figures 3.8 and 3.9. Again, the

Figure 3.6 The effective masker levels for single-frequency probes: 1.0 kHz at 10 dB SL (triangles), 1.5 kHz at 0 dB SL (diamonds) and double-frequency probe (open squares) for subject DCB. The single-frequency probes are presented monaurally (1.0 kHz to the right ear, 1.5 kHz to the left ear) while the double-frequency probes are presented dichotically. The masker, in all test conditions was presented binaurally. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).

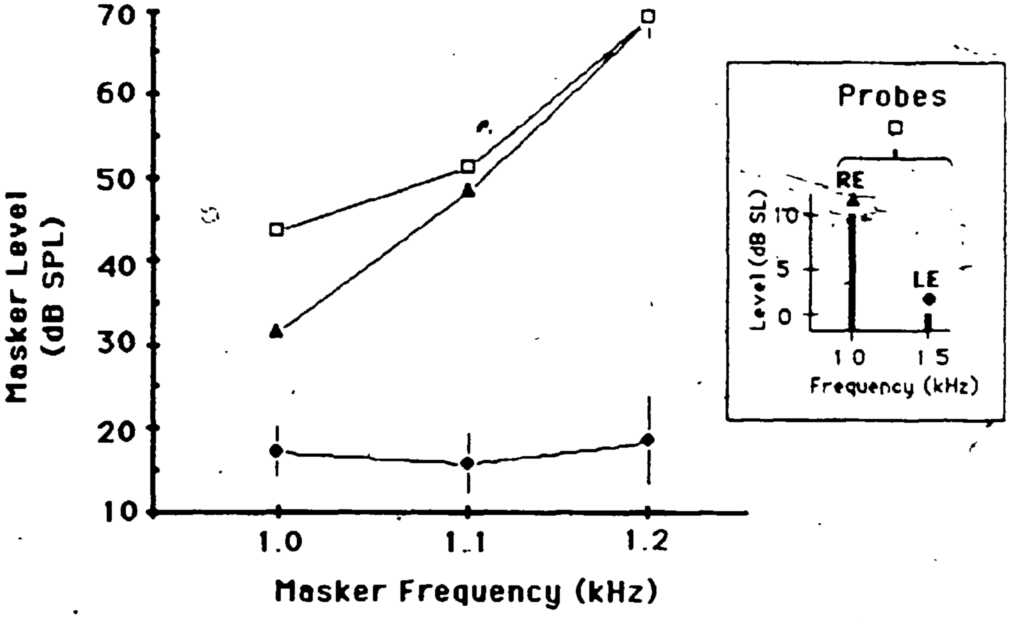

70
60
50
40
30
20
10
Masker Level (dB SPL)
1.0
1.1
1.2
Masker Frequency (kHz)
Probes
RE
LE
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

Figure 3.7 The effective masker levels for single-frequency probes: 1.0 kHz at 10 dB SL (triangles), 1.5 kHz at 0 dB SL (diamonds) and double-frequency probe (open squares) for subject GJF. The single-frequency probes are presented monaurally (1.0 kHz to the right ear, 1.5 kHz to the left ear) while the double-frequency probes are presented dichotically. The masker, in all test conditions was presented binaurally. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).

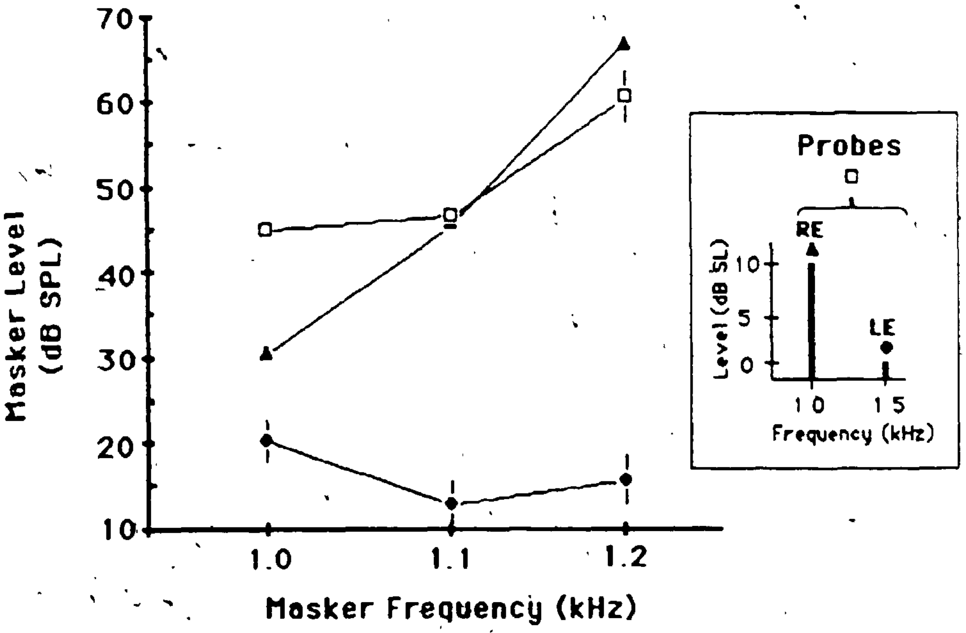

70
60
50
40
30
20
10
Masker Level (dB SPL)
1.0
1.1
1.2
Masker Frequency (kHz)
Probes
RE
LE
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

Figure 3.8 The effective masker levels for single-frequency probes: 1.0 kHz at 0 dB SL (triangles), 1.5 kHz at 10 dB SL (diamonds) and double-frequency probe (open squares) for subject DCB. The single-frequency probes are presented monaurally (1.0 kHz to the right ear, 1.5 kHz to the left ear) while the double-frequency probes are presented dichotically. The masker, in all test conditions was presented binaurally. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).

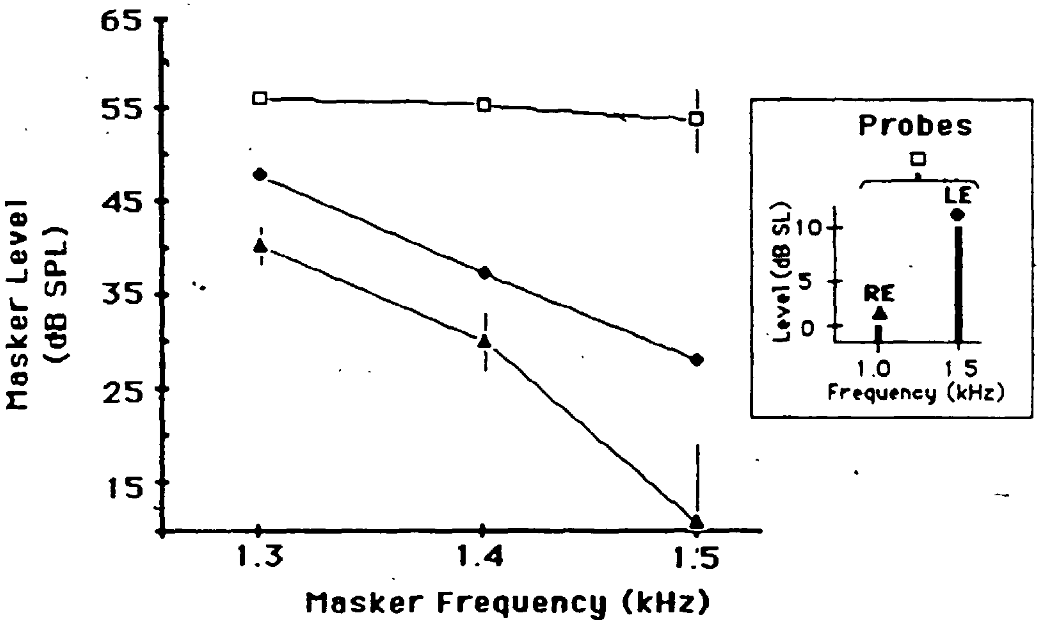
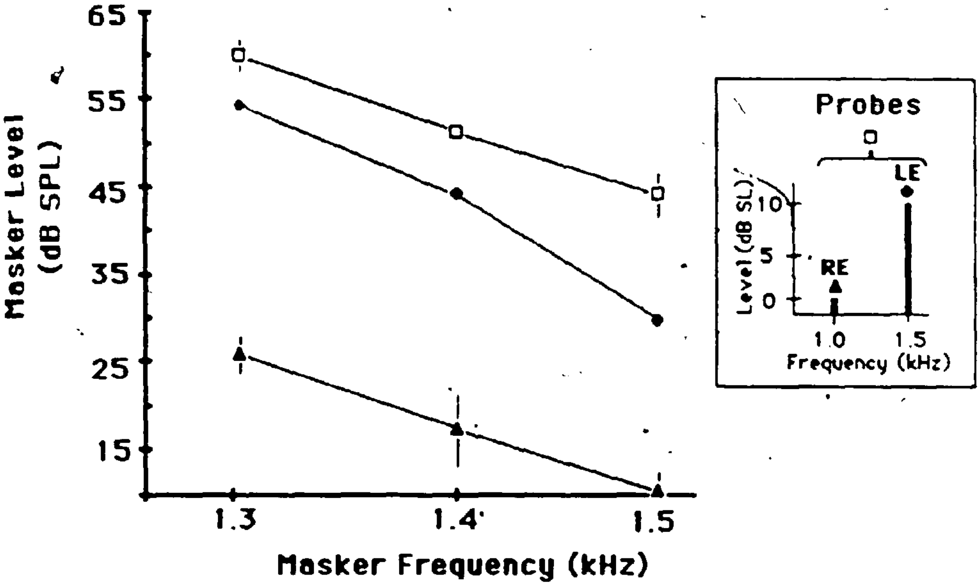

65
55
45
35
25
15
Masker Level (dB SPL)
1.3
1.4
1.5
Masker Frequency (kHz)
Probes
LE
RE
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

Figure 3.9 The effective masker levels for single-frequency probes: 1.0 kHz at 0 dB SL (triangles), 1.5 kHz at 10 dB SL (diamonds) and double-frequency probe (open squares) for subject GJF. The single-frequency probes are presented monaurally (1.0 kHz to the right ear, 1.5 kHz to the left ear) while the double-frequency probes are presented dichotically. The masker, in all test conditions was presented binaurally. Standard errors are shown that exceed the size of the data point (i.e., 2.5 dB).


65
55
45
35
25
15
Masker Level (dB SPL)
1.3
1.4
1.5
Masker Frequency (kHz)
Probes
LE
RE
Level (dB SL)
10
5
0
1.0
1.5
Frequency (kHz)

double-frequency dichotic probe conditions show very large increases in detectability over the single-frequency conditions, comparable to the data in Experiment I (Figures 2.13 and 2.14).

Showing these differences in the effective masker levels with a dichotic presentation of the probes (at this amplitude ratio) demonstrates that such interaction effects can be found without combination tone generation. Differences inthe experimental effects between single- and double-frequency probes suggest that some additional cue is present in the double-frequency probe code that is not present with the single-frequency probes. Neurophysiological data have shown similar detection discrepancies with sinusoids and sinusoidal pairs as measured by the neural phase-locking responses. These differences in the effective masker levels may be a behavioral demonstration of similar effects.

In summary, the results of Experiments I and II have shown that neither the excitation model or the presence of combination tones can predict or account for these effective masking level differences. The existence of these effects with such low-level stimuli suggests that aspects of the temporal code of the stimuli may be useful. Therefore, if masking is generally understood in terms of the analysis of the spectral energy of the stimuli, it would seem probable that the "release from masking" observed in these two experiments is due to aspects of the temporal coding of the stimuli.

The last experiment examined the various stimulus parameters that produced these effects with a different masking paradigm by determining the level of the probes necessary for differential detection.

4. Experiment III: The Importance of Subthreshold Levels with Double-Frequency Probe Stimuli

4.1 Introduction

The purpose of this experiment was to extend the results found in Experiments I and II. The data in these experiments suggest that adding a second, near-threshold level sinusoid to the probe, in a forward masking task, makes the probe more detectable. Specifically, Experiment III determined the necessary amplitude of the added probe component for producing this effect.

In a different psychophysical study, Groen (1964) has shown that subjects can detect the temporal interactions (i.e., beating) of two sinusoids even when the level of one of the tones is 20 dB below threshold. It is possible, then, that similar subthreshold effects could be demonstrated with the forward masking paradigm.

4.2 Method

4.2.1 Subjects

The same two subjects participated in this experiment as in Experiment II.

4.2.2 Stimulus presentation and paradigm

The forward masking paradigm was altered such that instead of adapting the masker levels to threshold, the probe levels were adapted to levels at which they were just masked by a constant level masker. Again, a two-interval forced-choice procedure was used to estimate the 70.7% probe threshold. Presentation of all stimuli was monaural, to the subject's right ear.

Six masker frequencies and two probe frequencies were tested in two different studies. Table IIA shows the various parameters used in the probe masking study. Six fixed-level maskers were tested, ranging from 25 to 75 dB SPL. Depending on the specific masker frequency, between three and six masker levels would be examined. The masker levels excluded were those that had been shown in earlier experiments not to mask the 10 dB SL

Table II

Summary of Experimental Conditions in Experiment III

A. Probe masking study

Masker	Probes		
fM	fp1	fp2	
1.0 to 1.5 kHz	1.0 kHz	1.5 kHz	
			Masker Levels
1.0 kHz (+)	10 dB SL	adapted	25 dB SPL (+)
1.1 kHz (*)	10 dB SL	adapted	35 dB SPL (+)
1.2 kHz (x)	10 dB SL	adapted	45 dB SPL (+ *)
1.3 kHz (x)	adapted	10 dB SL	55 dB SPL (+ * x)
1.4 kHz (*)	adapted	10 dB SL	65 dB SPL (+ * x)
1.5 kHz (+)	adapted	10 dB SL	75 dB SPL (+ * x)

(symbol denotes intensities tested for each fM)

Table II (continued)

Summary of Experimental Conditions in Experiment III

B. Probe detection (d') masking study

Masker	Probes		
fM	fp1	fp2	
1.0 to 1.5 kHz	1.0 kHz	1.5 kHz	
			Masker Levels
1.0 kHz (+)	10 dB SL	0 dB SL	25 dB SPL (+)
1.1 kHz (*)	10 dB SL	0 dB SL	35 dB SPL (+)
1.2 kHz (x)	10 dB SL	0 dB SL	45 dB SPL (+ *)
1.3 kHz (x)	0 dB SL	10 dB SL	55 dB SPL (+ * x)
1.4 kHz (*)	0 dB SL	10 dB SL	65 dB SPL (+ * x)
1.5 kHz (+)	0 dB SL	10 dB SL	75 dB SPL (+ * x)

(symbol denotes intensities tested for each fM) probe component for that masker frequency (compare with Figures 2.1 and 2.2). For example, only the masker levels greater than 45 dB SPL were used with the 1.2 and 1.3 kHz maskers.

The probe frequencies were again set at 1.0 and 1.5 kHz. With masker frequencies of 1.0, 1.1 or 1.2 kHz, the 1.0 kHz component was set at 10 dB SL, while the 1.5 kHz component was adapted to masked threshold. Similarily, with masker frequencies of 1.3, 1.4 or 1.5 kHz, the 1.0 kHz component was adapted while the 1.5 kHz component was fixed at 10 dB SL.

Both the single- and double-frequency probe conditions were tested with the two-interval forced-choice paradigm. In the single-frequency probe condition, both intervals contained the fixed level masker, while only one interval contained the probe. In the double-frequency probe condition, both intervals contained a fixed-level masker and one of the probes (set at 10 dB SL). In one interval, the second probe component was also be presented simultaneously with the 10 dB SL probe. The degree to which this second probe added additional information to the detection task should be reflected in the subject's detectability of that interval.

To supplement these data, a signal detection paradigm was also used. In this study, all stimulus levels (masker and probes) were held constant. The data with single- and double-frequency probes were again compared. For the single-frequency probe conditions, the probe was presented at a level of 0 dB SL for the block of trials. In the double-frequency condition, the probe levels were set at 10 and 0 dB SL, such that both intervals contained the 10 dB SL probe, while only one interval contained the added 0 dB probe (see Table IIB for all the specific parameters). The subject's task was simply to indicate which interval contained the 0 dB probe. One block of trials consisted of fifty presentations of the two intervals. Values of d' were estimated from the percentage of correct responses to the threshold-level probe (Elliot, 1964).

An additional procedural change was made in Experiment III. Instead of using analog-produced sinusoidal tones for the probes, the sinusoids were produced digitally. In this way, the experimenter had full control of the phase of the probes. Previously, the phase of the probes was allowed to vary randomly (in Experiments I and II). If a temporal mechanism is responsible for the masking effects, then fixing the phase relationship between the two tones allowed a constant temporal pattern to be coded on each trial (see Rose et al., 1967). Further, Hall (1972) noted that with a 0 degree phase of each (simultaneous) probe, the ratio of the positive to negative peak amplitude will be greatest (i.e., when the stimuli have a frequency ratio of 2:3). Therefore, in Experiment III, the probes were always presented in phase for a duration of 10 ms with a linear 2 ms rise/fall time. Again, the maskers were produced by the HP function generator. All other temporal parameters and remaining experimental details were exactly as described in section 2.2.2. (except that each interval was 215 ms and separated by a 500 ms pause).

4.3 Results

The data for each of the six masker frequencies will be examined in the light of three questions. First, do the data show that the added probe component improves the detectability of the probe pair compared to the detectability of the same probe component presented singly? In other words, the subject's performance with single- and double-frequency probes will be compared with this paradigm for evidence of a two-tone interaction between the probes. Second, if there is evidence of an interaction, at what level is the added probe component presented to produce these effects (suprathreshold or subthreshold levels)? For example, when examining the effects found in Experiment I and II, can we expect to find that one component in the probe can be reduced to subthreshold levels? Finally, if such interactions are found, are they sufficient to produce the magnitude of the effects demonstrated in the earlier experiments?

4.3.1 Probe levels and d' values with the 1.0 kHz masker

In the first study, the level of the 1.5 kHz probe was adapted when presented singly or simultaneously with the 10 dB SL 1.0 kHz probe following a 1.0 kHz masker. Figures 4.1 and 4.2 show the data for the two subjects. Six masker levels were tested from 25 to 75 dB SPL. Both the single 1.5 kHz masked probe levels and the levels with the double- frequency probe are shown.

There are two aspects of these data that require discussion. First, there is the examination of the differences in probe levels in the two test conditions (single- and double-frequency presentations), and second, the data point for the single-frequency probe with a 45 dB SPL masker. The latter point will be discussed below.

Figure 4.1 The 1.5 kHz probe-level masked thresholds for the 1.0 kHz masker at six masker levels for subject DCB. The closed data points represent the thresholds of the 1.5 kHz probe presented alone, while the open data points represent the threshold with the 1.0 kHz 10 dB SL presented simultaneous to the 1.5 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).

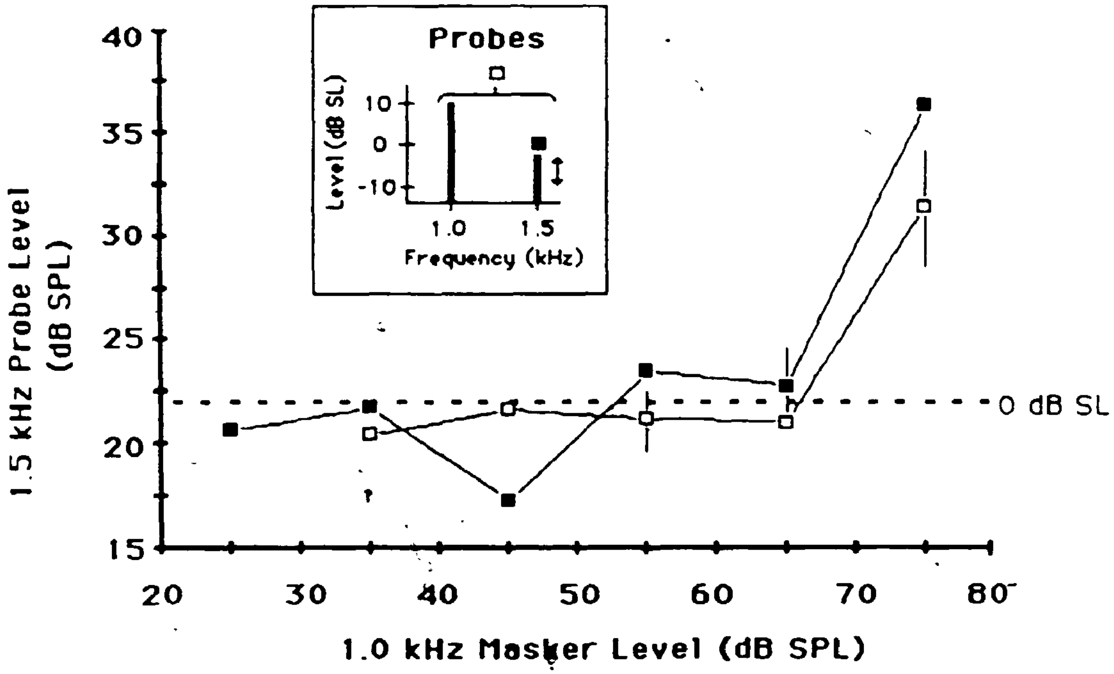
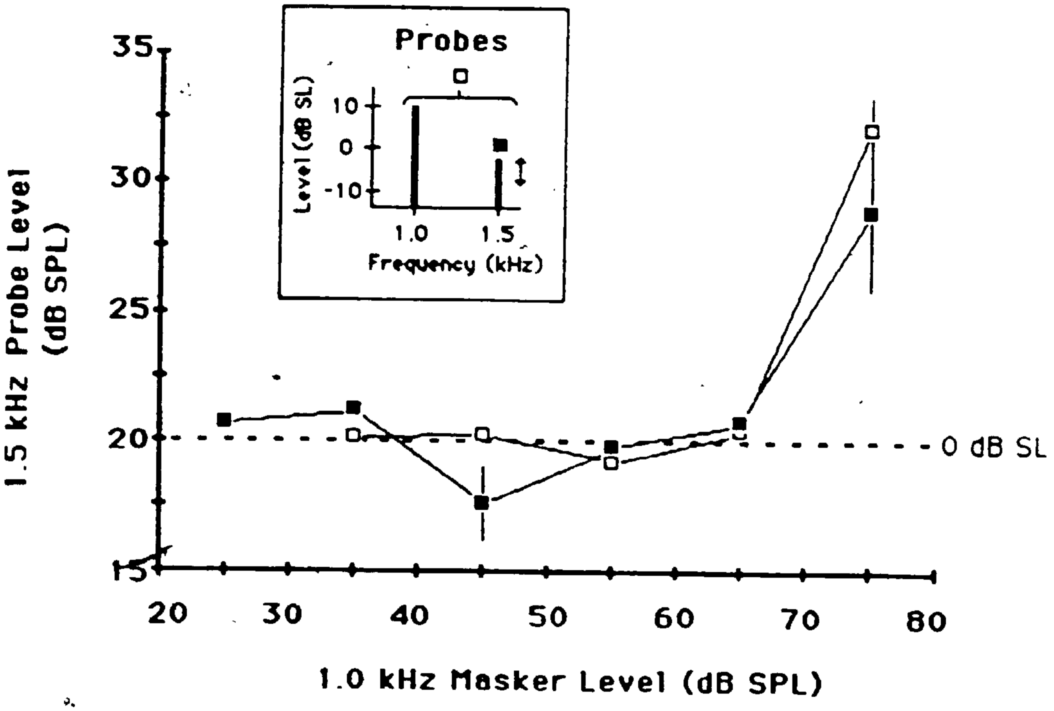

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
1.5 kHz Probe Level (dB SPL)
40
35
30
25
20
15
0 dB SL
20
30
40
50
60
70
80
1.0 kHz Masker Level (dB SPL)

Figure 4.2 The 1.5 kHz probe-level masked thresholds for the 1.0 kHz masker at six masker levels for subject GJF. The closed data points represent the thresholds of the 1.5 kHz probe presented alone, while the open data points represent the threshold with the 1.0 kHz 10 dB SL presented simultaneous to the 1.5 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).


Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
1.5 kHz Probe Level (dB SPL)
35
30
25
20
15
20
30
40
50
60
70
80
1.0 kHz Masker Level (dB SPL)
0 dB SL

Examining the two masking functions, it can be seen that with a number of masker levels the 1.5 kHz probe could be detected at lower levels in the double-frequency presentation (open data points), than the single-frequency presentation (closed data points). Therefore, less probe energy is necessary when the 1.5 kHz probe is presented simultaneously with the 1.0 kHz probe than presented singly. Although this effect is small (approximately a 1 to 3 dB difference), some of these effects are significant. In Figure 4.1, a 1.4 dB probe level difference is found with the 35 dB masker (t(3)=3.3, p<.05, one-tailed). The 55 dB masker produced a 2.5 dB difference in probe levels (t(3)=3.5, p<.025, one-tailed). Also, the 65 dB masker produced a 1.8 dB difference in the probe levels that was not significant (t(3)=2.1, p>.05, one-tailed). In Figure 4.2, the same two masker levels show significant effects. The 35 dB masker produced a 2.7 dB difference in probe level detection (t(3)=4.5, p<.01, one-tailed). The 55 dB masker produced a 1.5 dB difference (t(3)=2.4, p<.05, one-tailed). These results confirm the findings in Experiments I and II that adding only minimal energy to a probe can improve its detectability in a masking task. There is no evidence, in these data, of large subthreshold effects. The levels of the 1.5 kHz probe (open squares) are only slightly below threshold for subject DCB (Figure 4.1), and at threshold for subject GJF (Figure 4.2). Therefore, subthreshold interaction of the probes is very small if present at all.

The data from the probe detection study are shown in Figures 4.3 and 4.4. In this paradigm, the level of the 1.5 kHz probe was held constant at threshold (0 dB SL). Therefore, if including this 0 dB component with the 10 dB probe adds detectable information to the probe, the detectability data should reflect higher d' values for the double-frequency probe. The detectability functions in Figures 4.3 and 4.4 show patterns very similar to those in the probe level data. Overall, the double-frequency probes are slightly more detectable than the single-frequency probes. Finally, it can be noted that, as in the probe level data, masker levels of 75 dB SPL disrupt the detectability of the probe substantially.

The question remains whether these differences in the probe levels or detectability functions are produced by similar mechanisms that produced the differences in the effective masker levels (of 10 to 20 dB) found in Experiments I and II (Figures 2.11, 2.12; and 3.6, 3.7). Certainly, before an adequate answer can be given, the data with the 45 dB masker need to be examined. In Figures 4.1 through 4.4, both subjects

Figure 4.3 The masked detectability (d') functions for the single-frequency probe (1.5 kHz at 0 dB SL) and double-frequency probe (1.0 kHz at 10 dB SL and 1.5 kHz at 0 dB SL) for the 1.0 kHz masker at six masker levels (subject DCB). Standard errors are shown that exceed the size of the data points (i.e., 0.25).

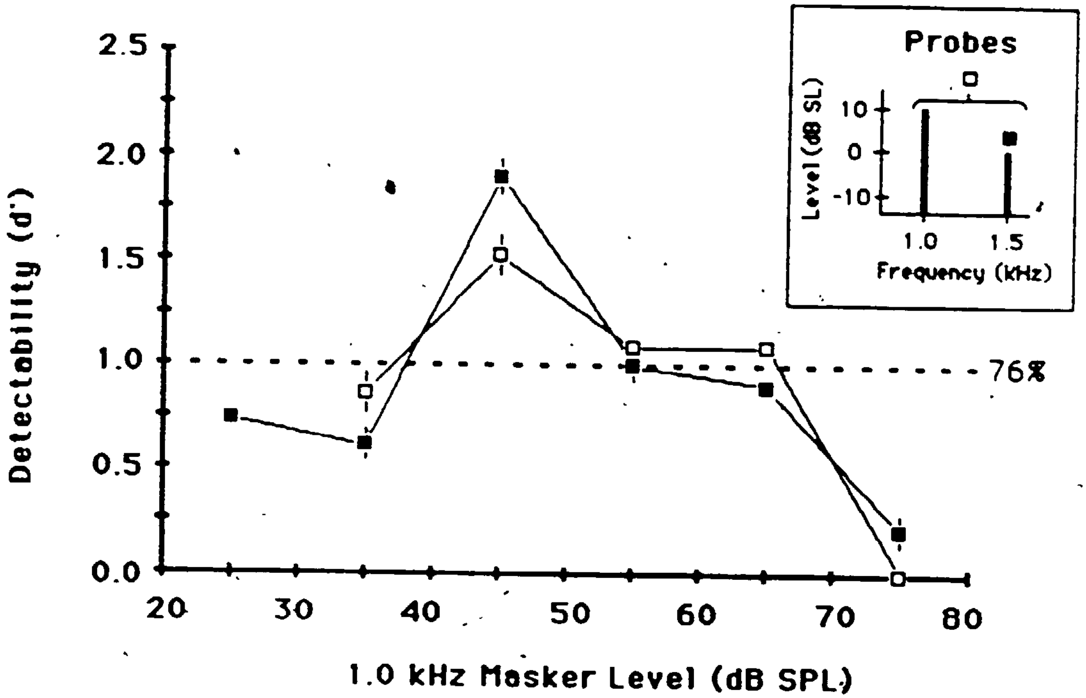
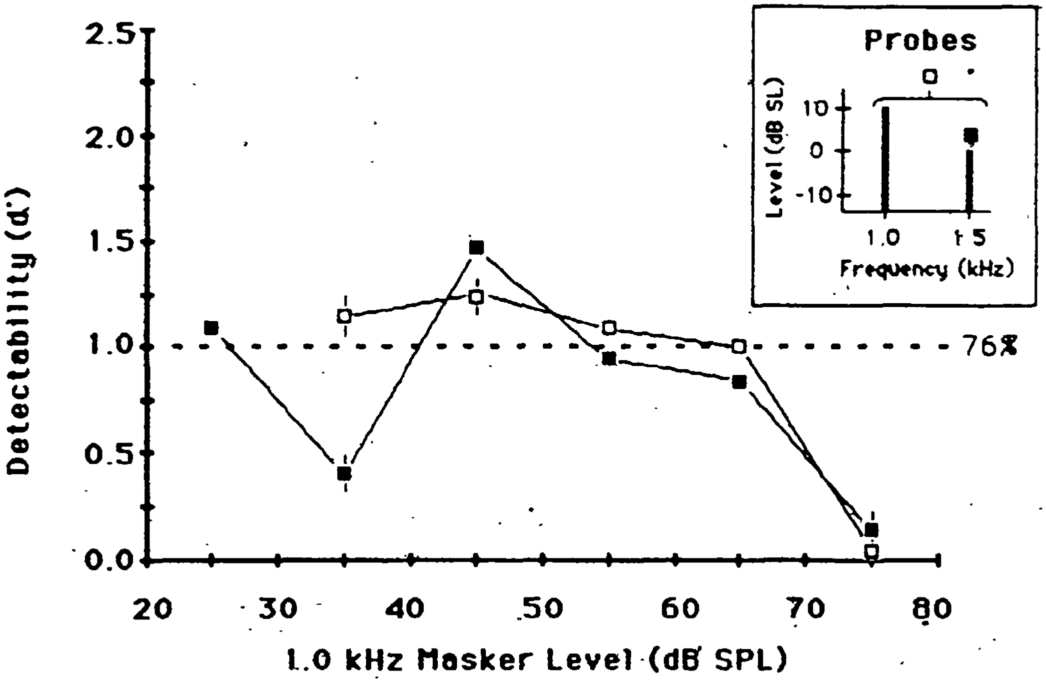

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
Detectability (d')
2.5
2.0
1.5
1.0
0.5
0.0
20
30
40
50
60
70
80
1.0 kHz Masker Level (dB SPL)
76%

Figure 4.4 The masked detectability (d') functions for the single-frequency probe (1.5 kHz at 0 dB SL) and double-frequency probe (1.0 kHz at 10 dB SL and 1.5 kHz at 0 dB SL) for the 1.0 kHz masker at six masker levels (subject GJF). Standard errors are shown that exceed the size of the data points (i.e., 0.25).


Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
Detectability (d')
2.5
2.0
1.5
1.0
0.5
0.0
76%
20
30
40
50
60
70
80
1.0 kHz Masker Level (dB SPL)

showed that the 1.5 kHz probe (presented singly) was more detectable with the 45 dB SPL 1.0 kHz masker than with masker levels above or below this value. Subject DCB (Figure 4.1) showed that the 1.5 kHz probe can be detected at a level 5 dB below the detection threshold determined in quiet, when a 1.0 kHz masker preceded it at 45 dB SPL. Subject GJF also shows this effect (Figure 4.2), but at levels of approximately -3 dB SL. The data in Figures 4.3 and 4.4 further show that high d' values were found for the 0 dB probe with the 45 dB masker.

An explanation may be found in the mechanics of sound propagation in the cochlea. Sound energy is known to produce an asymmetric travelling wave pattern to occur along the basilar membrane such that the energy from a sinusoid will spread more into the higher than lower frequency regions. Further, the auditory system (i.e., basilar membrane) obviously must perform some form of rapid damping to be able to distinguish successive stimulus patterns. The atypical masking pattern found in our data with the 45 dB masker may be a demonstration of the membrane's damping limitations. The explanation, then, is as follows: the 45 dB masker energy which spreads into the 1.5 kHz probe region causes this region to be more sensitive to immediate low level stimulation in that area. Therefore, less probe energy is necessary for detection, and compared to threshold in quiet, the masked probe level actually becomes more detectable. The loss of this effect with higher masker levels shows that this effect is level (and presumably frequency) dependent. (Similar arguments have been proposed by Zwicker (1981) with a simultaneous masking paradigm and very low-frequency maskers.)

A second interesting finding is also shown in Figures 4.1 through 4.4. The 1.5 kHz probe, presented singly, is shown to be detectable at levels near threshold with masker levels as high as 45 to 55 dB SPL for both subjects. Earlier, it was shown that very low masker levels (less than 20 dB SPL) were sufficient to mask the 0 dB SL probe (see Figures 2.11 and 2.12). The procedural differences between each task may explain the discrepancy.

In Experiment I, the probe level was held constant on a block of trials, and the subject was to report which of two intervals contained the 0 dB probe. The large variability in each trial run and across trials was indicative of the difficulty the subjects had in detecting the probe when preceded by the forward mask. In Experiment III, though, the probe level was varied over a number of trials. If on any trial the subject could not detect the low-level probe, the paradigm adjusted the probe level such that in subsequent trials it was presented at higher (i.e., more perceptible) levels. Therefore, the subjects were able to track the probe more consistently within each block of trials, and subsequently detect a near threshold level probe at higher masker levels.

We would conclude that with a 1.0 kHz masker, there is evidence of a two-tone interaction, both in the probe level and detectability values, but the magnitude of the interaction is limited to between 1 and 3 dB. There is only weak evidence for a subthreshold interaction, and this is not consistent between subjects. Further, the variable detectability of the single-frequency probe (with the 45 dB masker as well as being found more detectable at higher masker levels) suggests that some additional factors may be influential in producing the large differences in the masker levels with the 1.0 kHz masker in Experiments I and II.

4.3.2 Probe levels and d' values with the 1.1 kHz masker

Figures 4.5 through 4.8 show the 1.5 kHz probe levels and detectability values under the single- and

Figure 4.5 The 1.5 kHz probe-level masked thresholds for the 1.1 kHz masker at four masker levels for subject DCB. The closed data points represent the thresholds of the 1.5 kHz probe presented alone, while the open data points represent the threshold with the 1.0 kHz 10 dB SL presented simultaneous to the 1.5 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).

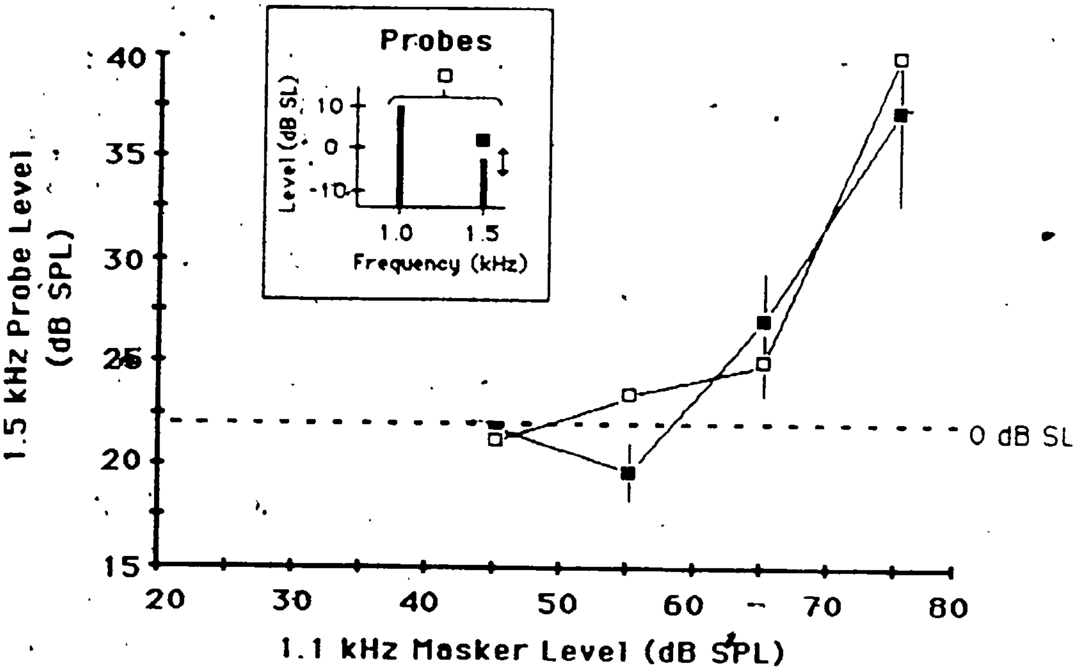

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
1.5 kHz Probe Level (dB SPL)
40
35
30
25
20
15
20
30
40
50
60
70
80
1.1 kHz Masker Level (dB SPL)
0 dB SL

Figure 4.6 The 1.5 kHz probe-level masked thresholds for the 1.1 kHz masker at four masker levels for subject GJF. The closed data points represent the thresholds of the 1.5 kHz probe presented alone, while the open data points represent the threshold with the 1.0 kHz 10 dB SL presented simultaneous to the 1.5 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).

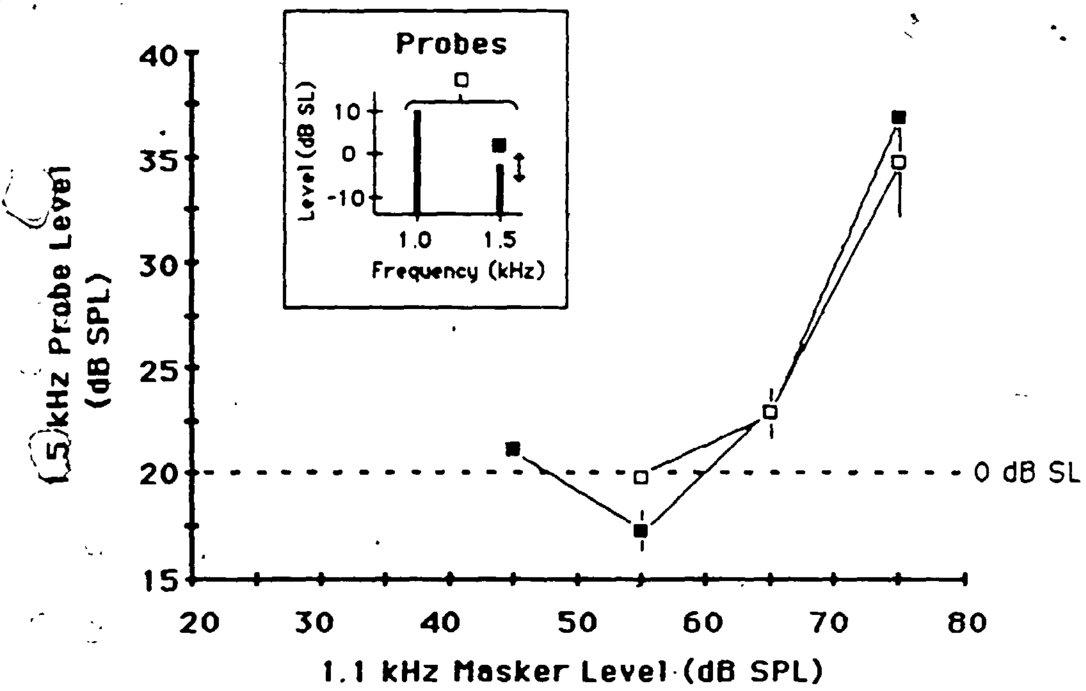

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
1.5 kHz Probe Level (dB SPL)
40
35
30
25
20
15
0 dB SL
20
30
40
50
60
70
80
1.1 kHz Masker Level (dB SPL)

Figure 4.7 The masked detectability (d') functions for the single-frequency probe (1.5 kHz at 0 dB SL) and double-frequency probe (1.0 kHz at 10 dB SL and 1.5 kHz at 0 dB SL) for the 1.1 kHz masker at four masker levels (subject DCB). Standard errors are shown that exceed the size of the data points (i.e., 0.25).

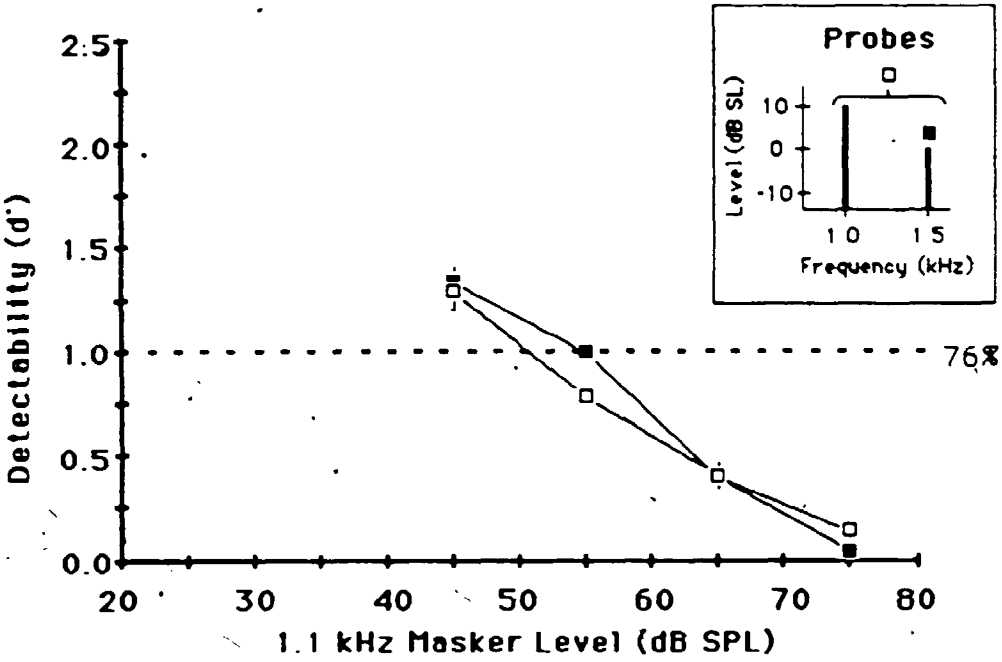
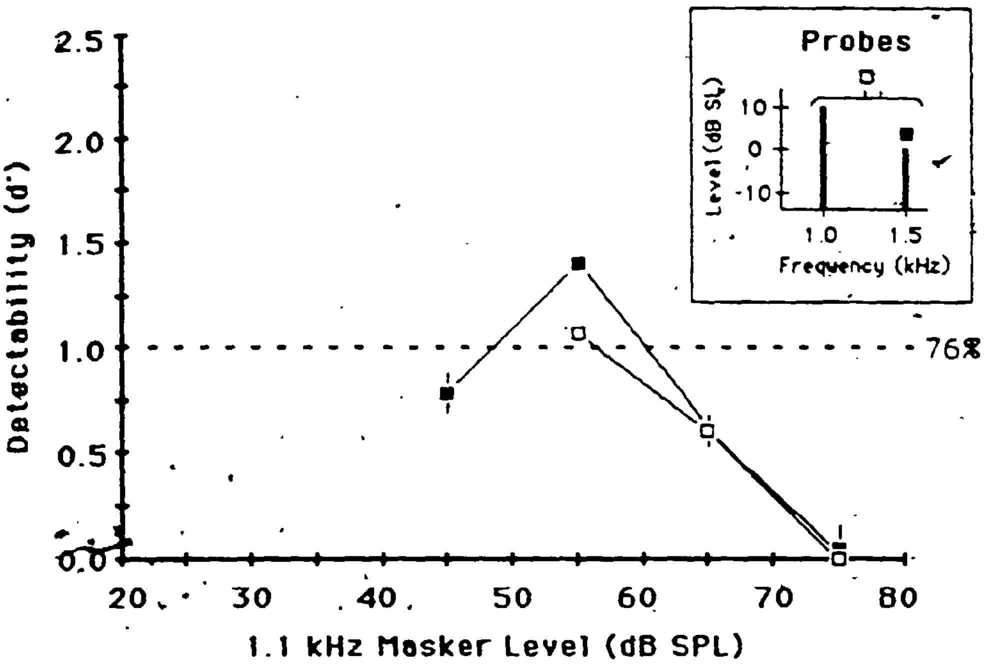

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
Detectability (d')
2.5
2.0
1.5
1.0
0.5
0.0
76%
20
30
40
50
60
70
80
1.1 kHz Masker Level (dB SPL)

Figure 4.8 The masked detectability (d') functions for the single-frequency probe (1.5 kHz at 0 dB SL) and double-frequency probe (1.0 kHz at 10 dB SL and 1.5 kHz at 0 dB SL) for the 1.1 kHz masker at four masker levels (subject GJF). Standard errors are shown that exceed the size of the data points (i.e., 0.25).


Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
Detectability (d')
2.5
2.0
1.5
1.0
0.5
0.0
76%
20
30
40
50
60
70
80
1.1 kHz Masker Level (dB SPL)

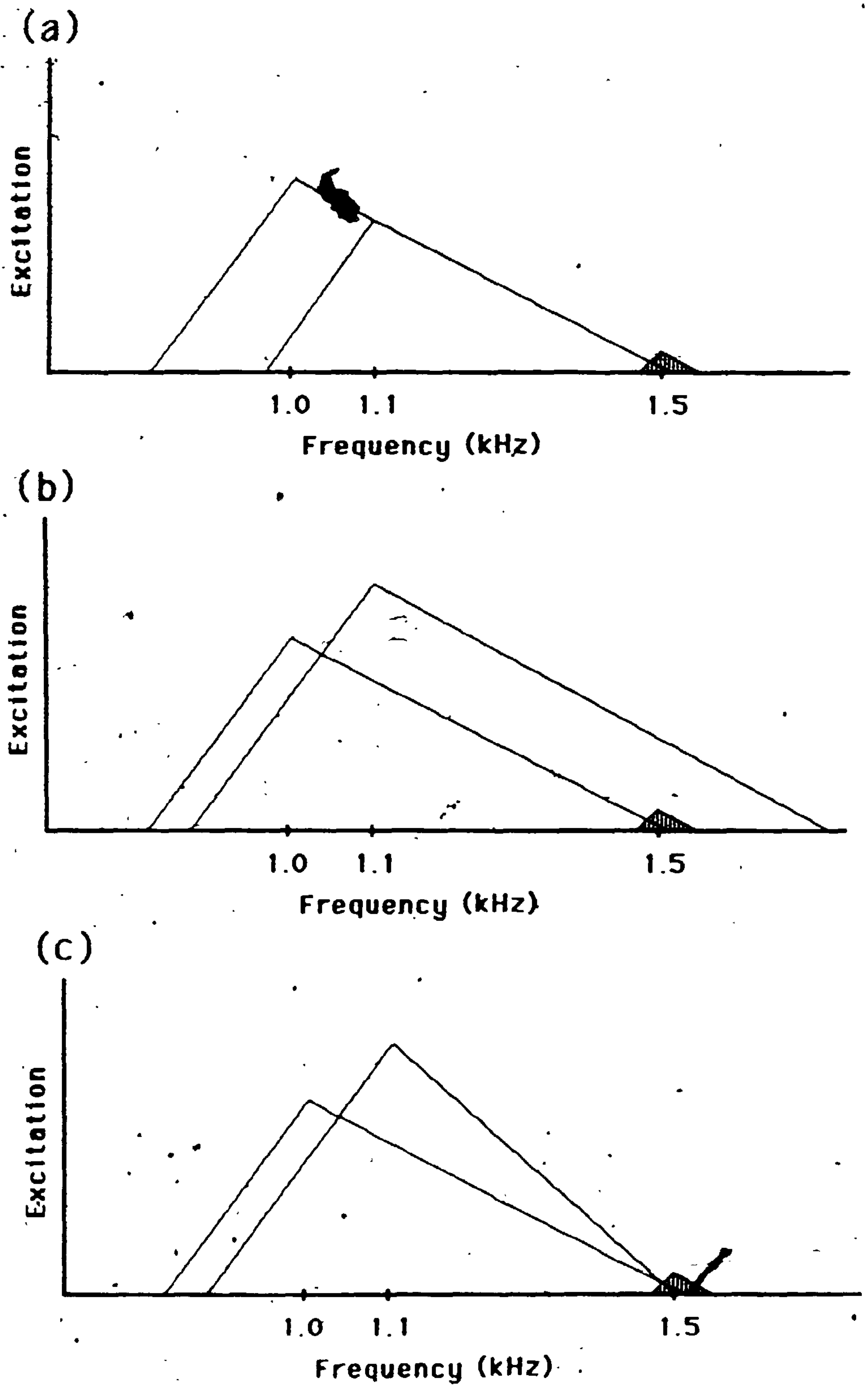
double-frequency conditions with the 1.1 kHz masker. Only four masker levels were tested;, the lower three masker levels were found to be insufficient to mask the 1.0 kHz probe component (for subject GJF at least a 55 dB masker was necessary to mask the 1.5 kHz probe).

Earlier, it was shown that each subject performed differently with this masker frequency. For example, subject DCB showed a 2 dB difference between the single- and double-frequency probe conditions (as shown in Figure 2.11), while subject GJF showed a 6.5 dB difference (Figure 2.12). Only very small, although not significant differences between the adapted probe levels in the single- and double-frequency conditions are found in Figures 4.5 and 4.6. Also, the d' values in Figures 4.7 and 4.8 show functions of detectability similar to the probe level functions. There is no evidence of a subthreshold interaction of the double-frequency probes other than the small but insignificant effect in Figure 4.5 at 45 dB SPL (subject DCB).

The differences in the effective masker levels for this masker frequency in Experiments I and II may be explained by a type of masker level-probe level interaction. As can be seen in Figures 4.5 and 4.6, the 1.5 kHz probe again becomes more detectable with a specific level 1.1 kHz masker (55 dB SPL) than in quiet or with the other masker levels. Therefore, the 1.5 kHz probe can be reduced from 2 to 3 dB below threshold and still be detected when preceded by the 55 dB masker. This phenomena is also reflected in the detectability data (Figures 4.7 and 4.8).

The improved detectability of the single-frequency probe with the 55 dB SPL masker cannot be explained as easily in terms of an interaction at the basilar membrane. For example, this effect was shown with a 45 dB SPL 1.0 kHz masker and a 55 dB SPL 1.1 kHz masker. But, according to the explanation given previously, the 1.1kHz masker should produce the effect at an intensity less than 45 dB. I have represented the situation schematically in Figure 4.9. Figure 4.9a shows the excitation displacement pattern expected to produce small amounts of displacement in the 1.5 kHz frequency region with the two masker frequencies. This model assumes that the spread of excitation pattern is proportional to the magnitude of the peak of displacment. Figure 4.9b shows how the effect of a more intense 1.1 kHz masker (as found in Figures 4.5 to 4.8) might be represented assuming the excitation pattern remains proportional to increases in the masker levels. Finally, Figure 4.9c shows how our data would have to be represented with such a model, by assuming that the spread of excitation is irregular with respect

Figure 4.9 The excitation patterns for a single-frequency probe (1.5 kHz) and maskers of 1.0 and 1.1 kHz. Figure (a) represents the patterns that would produce small but equal amounts of excitation in the probe frequency region. Figure (b) shows the representation of patterns according to the data found in Experiment III. Figure (c) shows the representation that is necessary to represent this model and our data.


(a)
Excitation
1.0
1.1
1.5
Frequency (kHz)
(b)
Excitation
1.0
1.1
1.5
Frequency (kHz)
(c)
Excitation
1.0
1.1
1.5
Frequency (kHz)

to masker level. Clearly, it is this final representation that can best represent these data, though, from present knowledge of the membrane's mechanics, this is an unlikely representation (Moore, 1984). Obviously, these data alone cannot determine what mechanims are responsible for these effects.

In conclusion, the evidence of temporal interaction of double-frequency probes is very limited in these data. The small differences in the effective masker levels (in Experiment III) may again be explained by a masker level- probe level interaction, although the exact mechanisms for this phenomena are undetermined.

4.3.3 Probe level and d' values with the 1.2 kHz masker

The data for the 1.2 kHz masker tested at three intensities are shown in Figures 4.10 through 4.13. Since subject GJF (Figure 4.11) could detect the 10 dB probe to masker levels of 65 dB SPL, only the 75 dB masker is tested with the double-frequeny probe, allowing only limited comparison to the single- and double-frequency data. As can be seen in these data, no important effects are found. The only difference in probe levels is found in Figure 4.10. Here, the

Figure 4.10 The 1.5 kHz probe-level masked thresholds for the 1.2 kHz masker at three masker levels for subject DCB. The closed data points represent the thresholds of the 1.5 kHz probe presented alone, while the open data points represent the threshold with the 1.0 kHz 10 dB SL presented simultaneous to the 1.5 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).

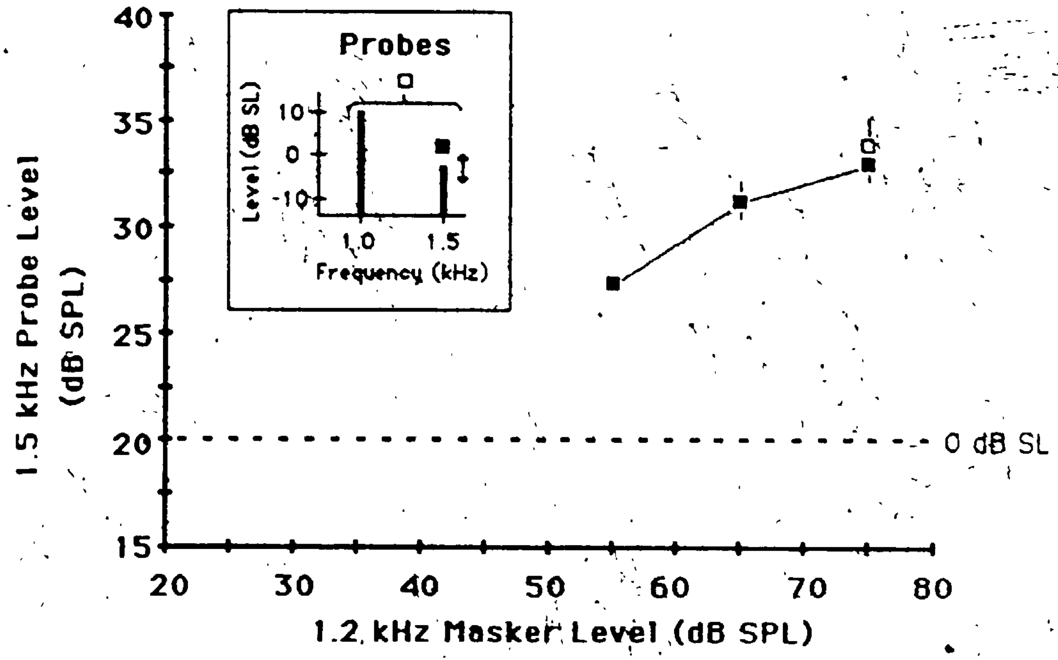

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
1.5 kHz Probe Level (dB SPL)
40
35
30
25
20
15
0 dB SL
20
30
40
50
60
70
80
1.2 kHz Masker Level (dB SPL)

Figure 4.11 The 1.5 kHz probe-level masked thresholds for the 1.2 kHz masker at three masker levels for subject GJF. The closed data points represent the thresholds of the 1.5 kHz probe presented alone, while the open data points represent the threshold with the 1.0 kHz 10 dB SL presented simultaneous to the 1.5 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).

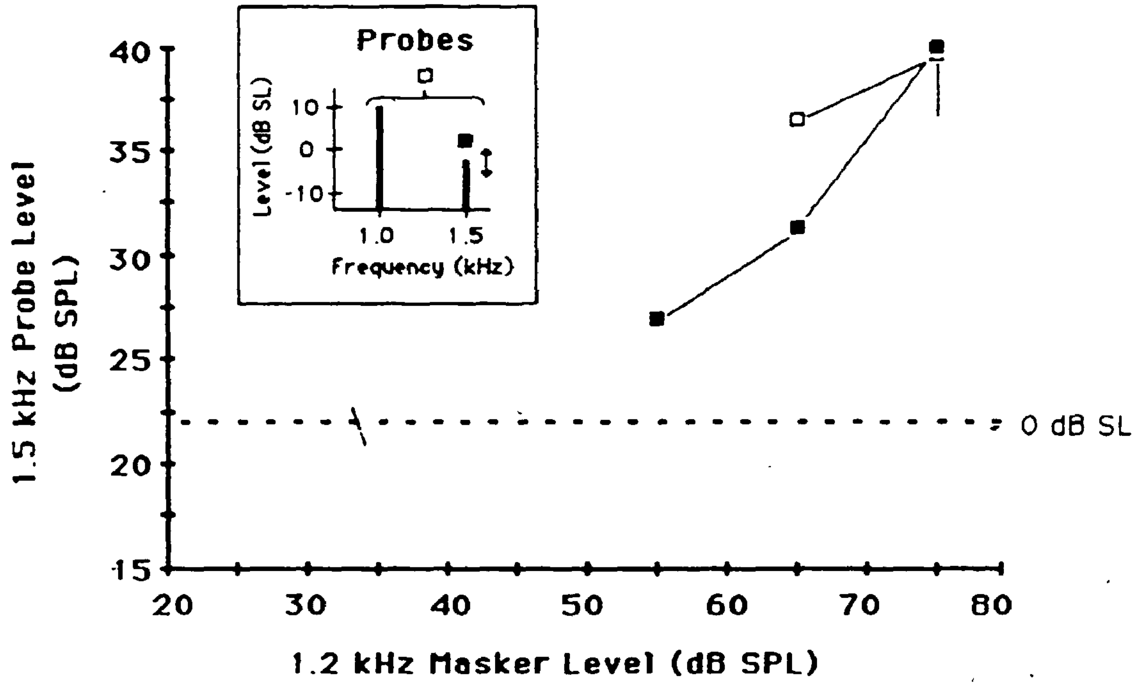

Probes
10
0
-10
Level (dB SL)
1.0
1.5
Frequency (kHz)
40
35
30
25
20
15
1.5 kHz Probe Level (dB SPL)
0 dB SL
20
30
40
50
60
70
80
1.2 kHz Masker Level (dB SPL)

Figure 4.12 The masked detectability (d') functions for the single-frequency probe (1.5 kHz at 0 dB SL) and double-frequency probe (1.0 kHz at 10 dB SL and 1.5 kHz at 0 dB SL) for the 1.2 kHz masker at three masker levels (subject DCB). Standard errors are shown that exceed the size of the data points (i.e., 0.25).

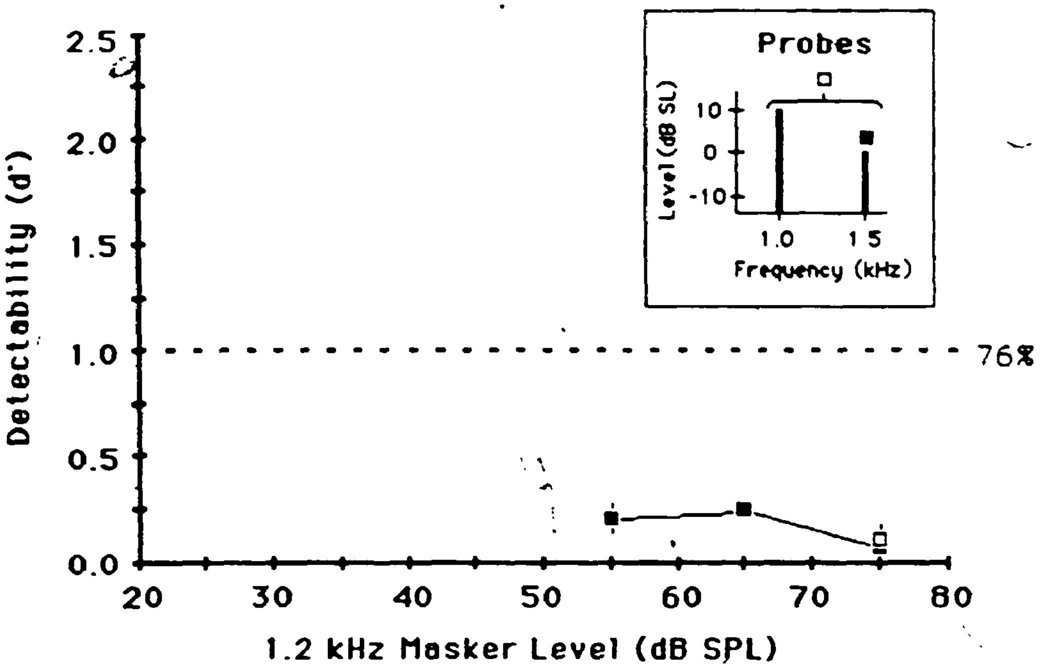
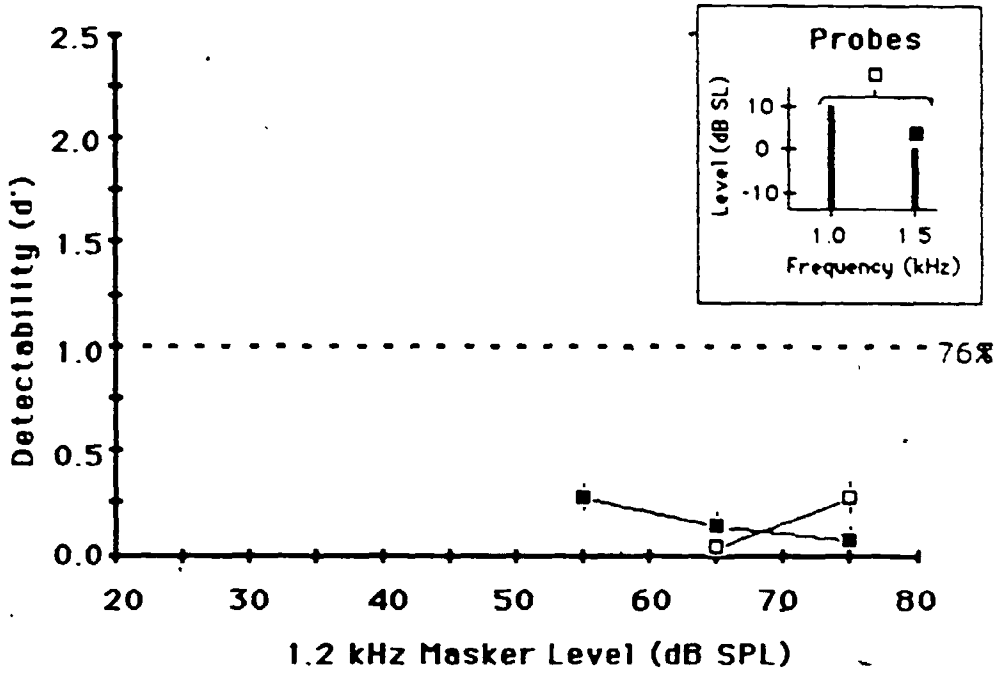

Detectability (d')
2.5
2.0
1.5
1.0
0.5
0.0
76%
20
30
40
50
60
70
80
1.2 kHz Masker Level (dB SPL)
Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)

Figure 4.13 The masked detectability (d') functions for the single-frequency probe (1.5 kHz at 0 dB SL) and double-frequency probe (1.0 kHz at 10 dB SL and 1.5 kHz at 0 dB SL) for the 1.2 kHz masker at three masker levels (subject GJF). Standard errors are shown that exceed the size of the data points (i.e., 0.25).


Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
2.5
2.0
1.5
1.0
0.5
0.0
Detectability (d')
76%
20
30
40
50
60
70
80
1.2 kHz Masker Level (dB SPL)

subject does show detection at a lower level of the single-frequency probe than the double-frequency probe, although not at subthreshold levels as before, but at a suprathreshold level of approximately 9 dB SL. When the 1.0 kHz probe component was added, the 1.5 kHz probe, surprisingly, had to be increased another 5 dB. No easy explanation can account for this finding.

Because all the adapted probe levels were above threshold, the detectability data (Figures 4.12 and 4.13) are very near chance performance (with the 0 dB SL probe). These results are not totally unexpected considering Experiment I, where both subjects showed less than 1 dB difference between the single- and double-frequency probe conditions (Figures 2.11 and 2.12).

4.3.4 Probe levels and d' values with the 1.3 kHz masker

With the 1.3 kHz masker, the probe levels were reversed. The 1.0 kHz probe was adapted to masked threshold while the 1.5 kHz probe was set at 10 dB SL (see Table IIA and B). Figures 4.14 and 4.15 show the probe level data. Four masker levels were tested in the single-frequency probe conditions; only three

Figure 4.14 The 1.0 kHz probe-level masked thresholds for the 1.3 kHz masker at four masker levels for subject DCB. The closed data points represent the thresholds of the 1.0 kHz probe presented alone, while the open data points represent the threshold with the 1.5 kHz 10 dB SL presented simultaneous to the 1.0 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).

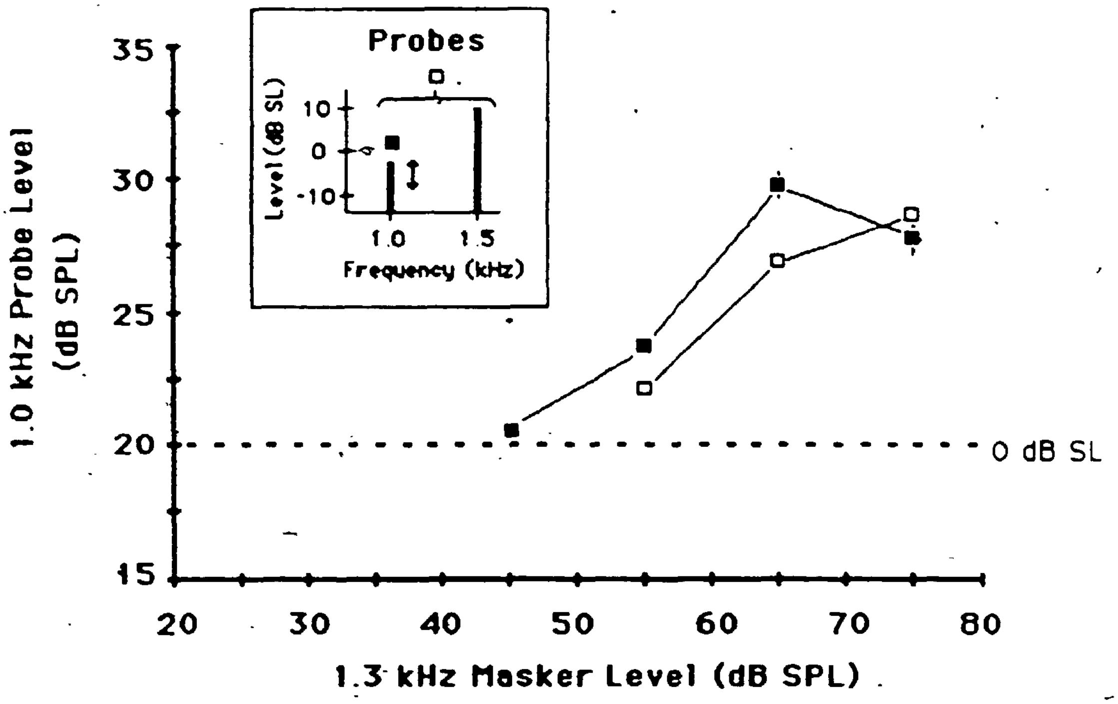
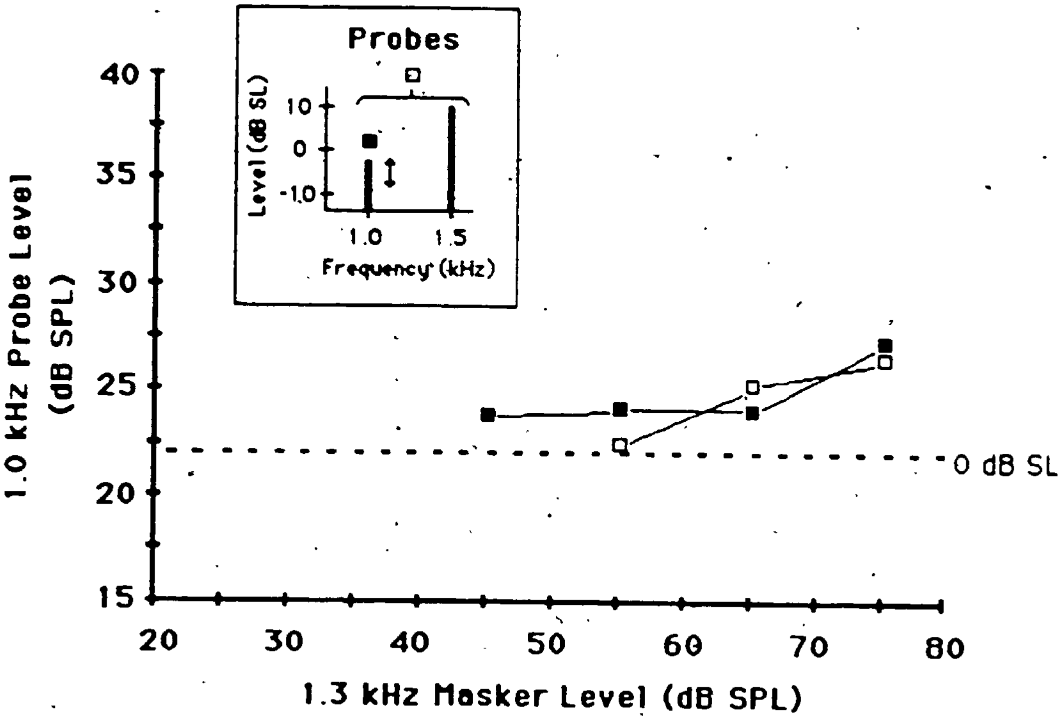

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
1.0 kHz Probe Level (dB SPL)
35
30
25
20
15
0 dB SL
20
30
40
50
60
70
80
1.3 kHz Masker Level (dB SPL)

Figure 4.15 The 1.0 kHz probe-level masked thresholds for the 1.3 kHz masker at four masker levels for subject GJF. The closed data points represent the thresholds of the 1.0 kHz probe presented alone, while the open data points represent the threshold with the 1.5 kHz 10 dB SL presented simultaneous to the 1.0 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).


Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
40
35
30
25
20
15
1.0 kHz Probe Level (dB SPL)
0 dB SL
20
30
40
50
60
70
80
1.3 kHz Masker Level (dB SPL)

masker levels were used in the double-frequency probe conditions.

The two functions are quite different between subjects. Subject DCB (Figure 4.14) needed less 1.0 kHz probe energy at all masker levels except the 45 dB masker. Both subjects show a two-tone interaction; the 1.0 kHz probe could be presented at lower levels in the double-frequency condition than the single-frequency condition (for the 55 dB SPL masker with subject DCB and both the 55 and 65 dB masker with subject GJF). No subthreshold interaction is present in these data.

The detectability of the single- and double-frequency probes for these conditions are shown in Figures 4.16 and 4.17. Not surprisingly, the d' values are all generally below threshold performance, and reflect performance found with the adapted 1.0 kHz probe in Figures 4.14 and 4.15, respectively. The differences between the subjects' performance in these data correspond to the differences in the effective masker levels found in Experiments I and II, where only subject DCB showed any consistent and significant effects.

Figure 4.16 The masked detectability (d') functions for the single-frequency probe (1.0 kHz at 0 dB SL) and double-frequency probe (1.5 kHz at 10 dB SL and 1.0 kHz at 0 dB SL) for the 1.3 kHz masker at four masker levels (subject DCB). Standard errors are shown that exceed the size of the data points (i.e., 0.25).

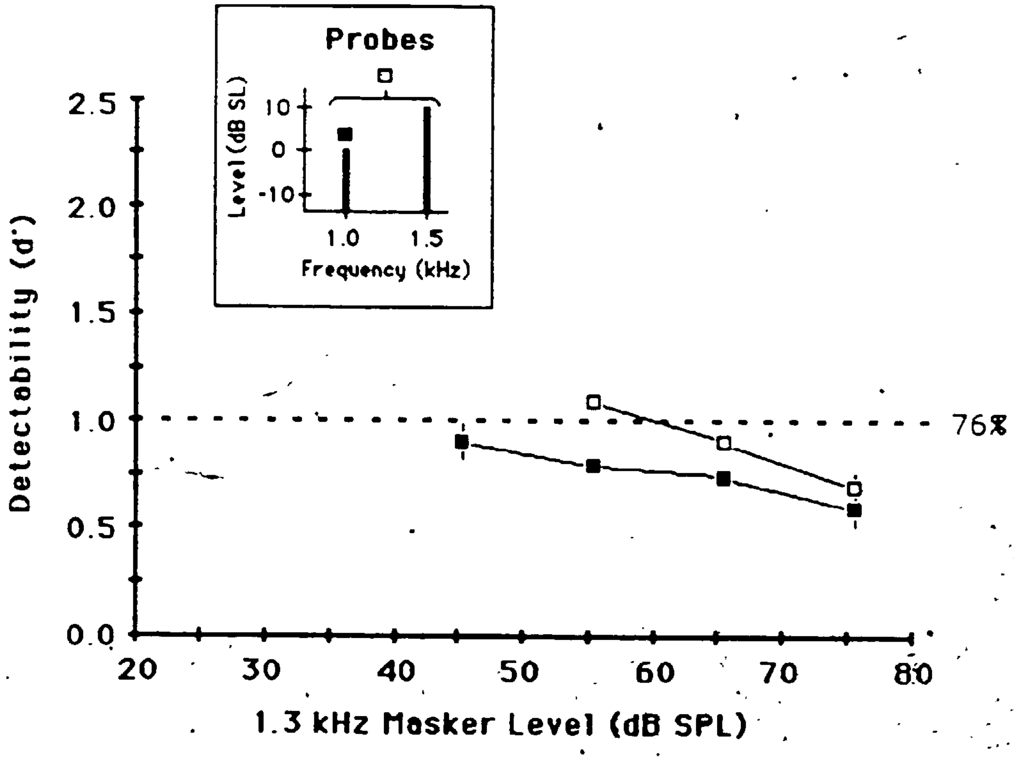
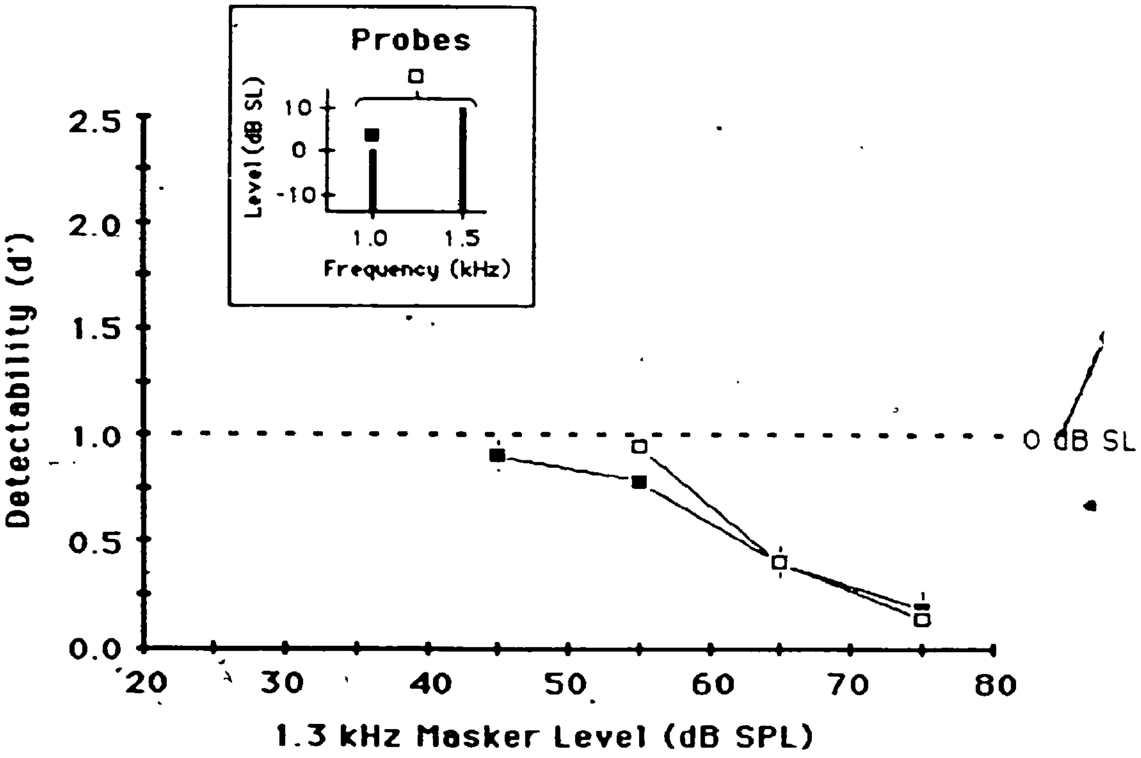

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
Detectability (d')
2.5
2.0
1.5
1.0
0.5
0.0
20
30
40
50
60
70
80
1.3 kHz Masker Level (dB SPL)
76%

Figure 4.17 The masked detectability (d') functions for the single-frequency probe (1.0 kHz at 0 dB SL) and double-frequency probe (1.5 kHz at 10 dB SL and 1.0 kHz at 0 dB SL) for the 1.3 kHz masker at four masker levels (subject GJF). Standard errors are shown that exceed the size of the data points (i.e., 0.25).


Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
Detectability (d')
2.5
2.0
1.5
1.0
0.5
0.0
20
30
40
50
60
70
80
1.3 kHz Masker Level (dB SPL)
0 dB SL

4.3.5 Probe levels and d' values with the 1.4 kHz masker

Figures 4.18 and 4.19 show the 1.0 kHz probe levels with and without the 1.5 kHz 10 dB SL probe. The data in Experiment I (Figures 2.13 and 2.14) had shown that the effective masker levels for the double-frequency probes were between 5 and 10 dB greater than the levels required for the single-frequency probes. The adapted 1.0 kHz probe levels in this experiment seem to reflect these effects.

The double-frequency probe function shows lower 1.0 kHz probe levels were necessary for detection than when the probes were presented singly. Again, obvious intersubject differences exist. For subject DCB (Figure 4.18) the effects remain for all four masker levels, while subject GJF shows effects only with the 55 dB masker. Also, both subjects show interactions with the 1.0 kHz probe at subthrehold levels. The detection data (Figures 4.20 and 4.21) show d' values very comparable to the probe level data, including the two-tone interaction effects. In Figure 4.21, subject GJF here shows larger detection differences than in the probe level study. It does seem possible that such differences in these data are large enough to produce

Figure 4.18 The 1.0 kHz probe-level masked thresholds for the 1.4 kHz masker at four masker levels for subject DCB. The closed data points represent the thresholds of the 1.0 kHz probe presented alone, while the open data points represent the threshold with the 1.5 kHz 10 dB SL presented simultaneous to the 1.0 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).

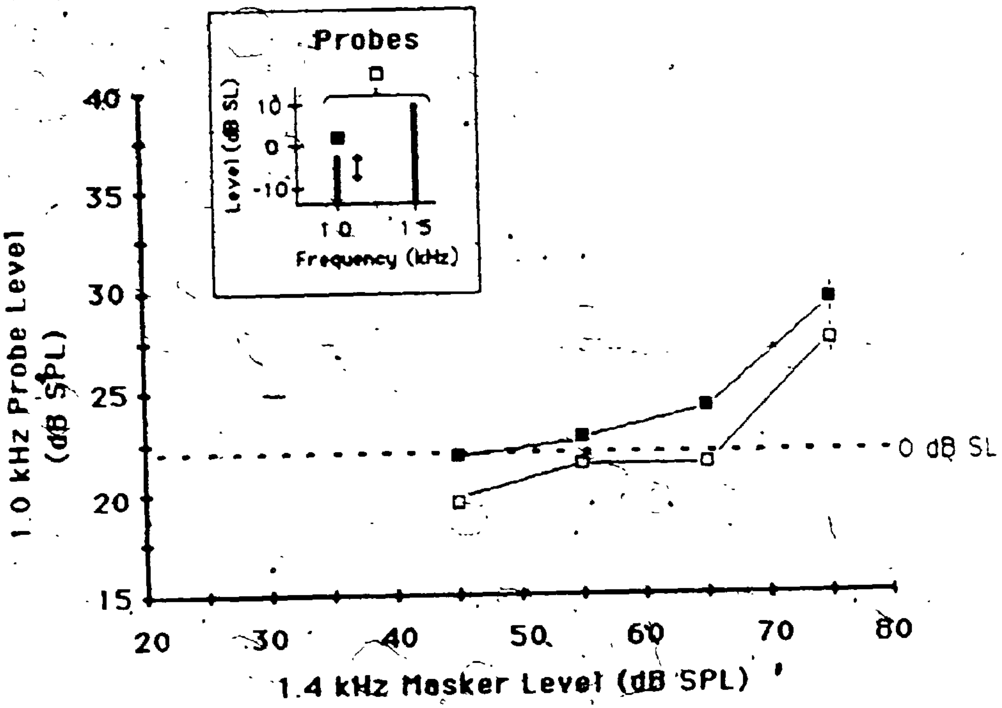

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
40
35
30
25
20
15
1.0 kHz Probe Level (dB SPL)
0 dB SL
20
30
40
50
60
70
80
1.4 kHz Masker Level (dB SPL)

Figure 4.19 The 1.0 kHz probe-level masked thresholds for the 1.4 kHz masker at five masker levels for subject GJF. The closed data points represent the thresholds of the 1.0 kHz probe presented alone, while the open data points represent the threshold with the 1.5 kHz 10 dB SL presented simultaneous to the 1.0 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).

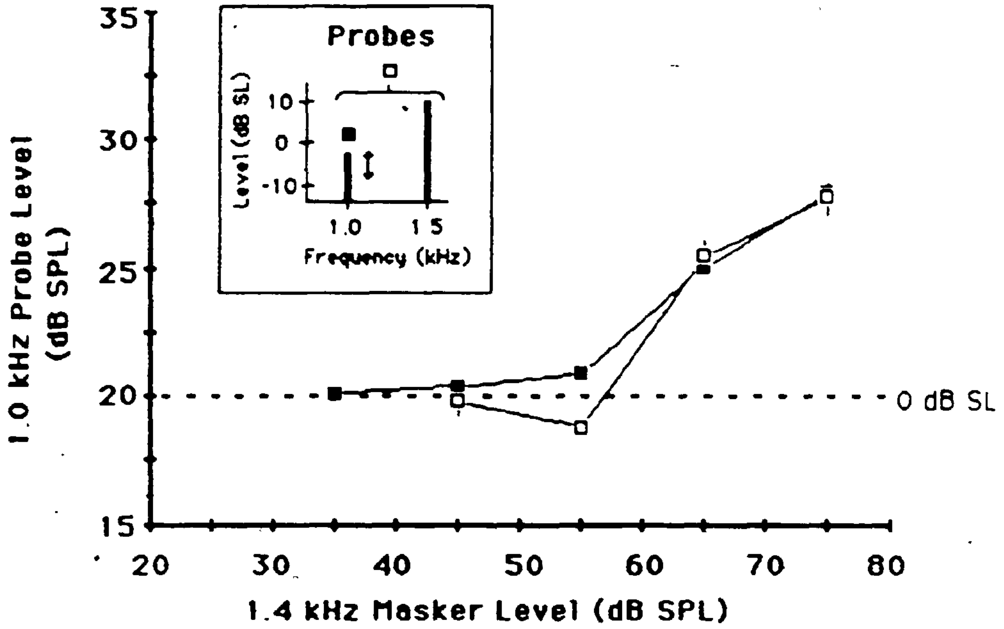

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
35
30
25
20
15
1.0 kHz Probe Level (dB SPL)
0 dB SL
20
30
40
50
60
70
80
1.4 kHz Masker Level (dB SPL)

Figure 4.20 The masked detectability (d') functions for the single-frequency probe (1.0 kHz at 0 dB SL) and double-frequency probe (1.5 kHz at 10 dB SL and 1.0 kHz at 0 dB SL) for the 1.4 kHz masker at five masker levels (subject DCB). Standard errors are shown that exceed the size of the data points (i.e., 0.25).

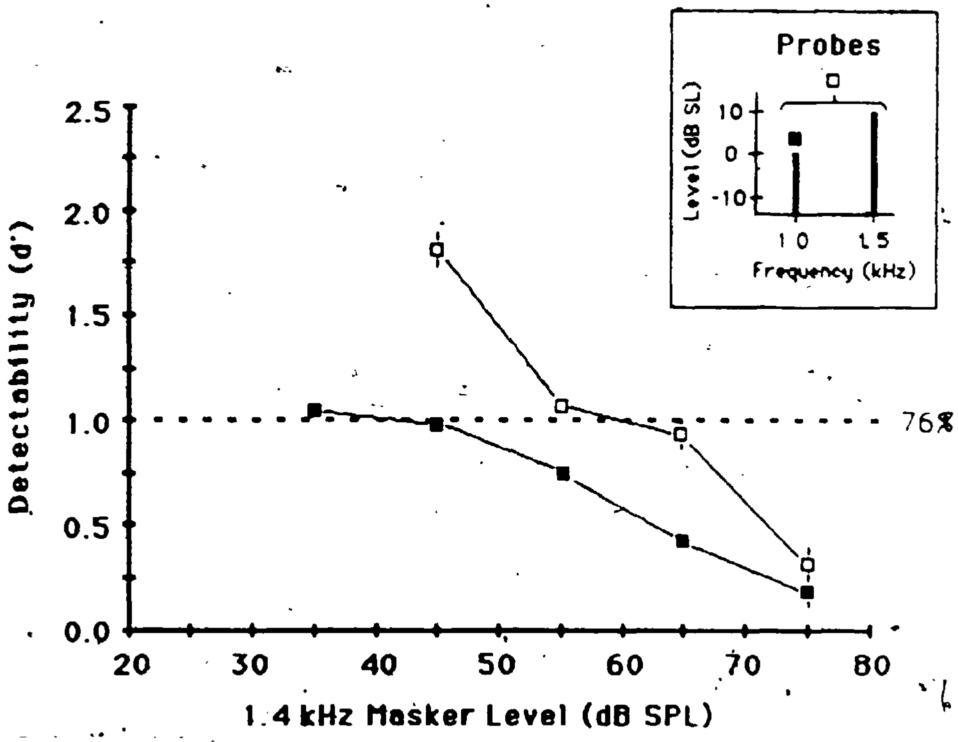
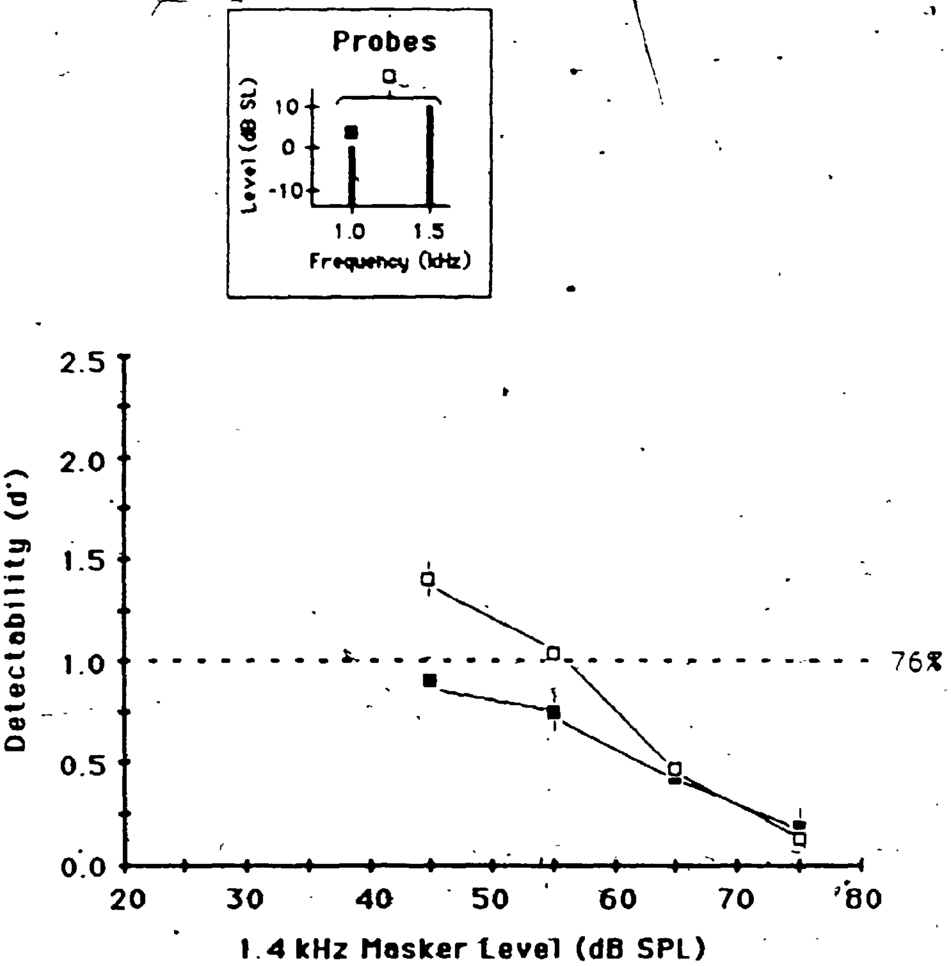

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
2.5
2.0
1.5
1.0
0.5
0.0
Detectability (d')
76%
20
30
40
50
60
70
80
1.4 kHz Masker Level (dB SPL)

Figure 4.21 The masked detectability (d') functions for the single-frequency probe (1.0 kHz at 0 dB SL) and double-frequency probe (1.5 kHz at 10 dB SL and 1.0 kHz at 0 dB SL) for the 1.4 kHz masker at five masker levels (subject GJF). Standard errors are shown that exceed the size of the data points (i.e., 0.25).



Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
Detectability (d')
2.5
2.0
1.5
1.0
0.5
0.0
20
30
40
50
60
70
80
76%
1.4 kHz Masker Level (dB SPL)

the 5 to 10 dB differences in the effective masker levels in Experiments I and II.

Similar to the data with the 1.0 and 1.1 kHz masker, the single-frequency (1.0 kHz) probe was found to be detectable at levels near threshold for masker levels up to 55 dB SPL. These data are again at odds with the data in Experiment I, where much lower masker levels were sufficient to mask the 1.0 kHz probe. The procedural differences between the two experiments, though, is the best explanation for the discrepancy. Finally, there is no evidence of the type of masker level-probe level interactions that occurred with the lower frequency maskers (see sections 4.4.1 and 4.4.2). (This is what is expected for the displacement pattern explanation, since the travelling wave pattern along the basilar membrane displays a steep low-frequency cut-off, i.e., very little spread into lower frequency regions.) Both the probe levels and detectability data with the 1.4 kHz masker show evidence for two tone interaction effects demonstrated in earlier experiments.

4.3.6 Probe levels and d' values with the 1.5 kHz masker

Figures 4.22 and 4.23 display the 1.0 kHz probe levels functions with the 1.5 kHz masker. Both subjects show significantly lower probe level functions with the double-frequency conditions than with the single-frequency 1.0 kHz probe. The 1.0 kHz probe also remains detectable at levels below threshold (in the double-frequency condition) until masker levels greater than 55 dB SPL are used. The magnitude of these effects in Experiment I show comparable findings. In fact, Experiment III shows that higher masker levels are necessary to mask the double-frequency probe than previously found. Therefore, adding the 1.0 kHz probe component improves detectability of the 1.5 kHz probe with masker levels as high as 60 dB SPL.

The detectability data show similar effects, although more in the range of 55 dB SPL (Figures 4.24 and 4.25). These findings, along with the subthreshold adapted levels of the 1.0 kHz probe, argue strongly for a significant interaction between the probe components, and supplement the large effects found in Experiment I.

Figure 4.22 The 1.0 kHz probe-level masked thresholds for the 1.5 kHz masker at five masker levels for subject DCB. The closed data points represent the thresholds of the 1.0 kHz probe presented alone, while the open data points represent the threshold with the 1.5 kHz 10 dB SL presented simultaneous to the 1.0 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).

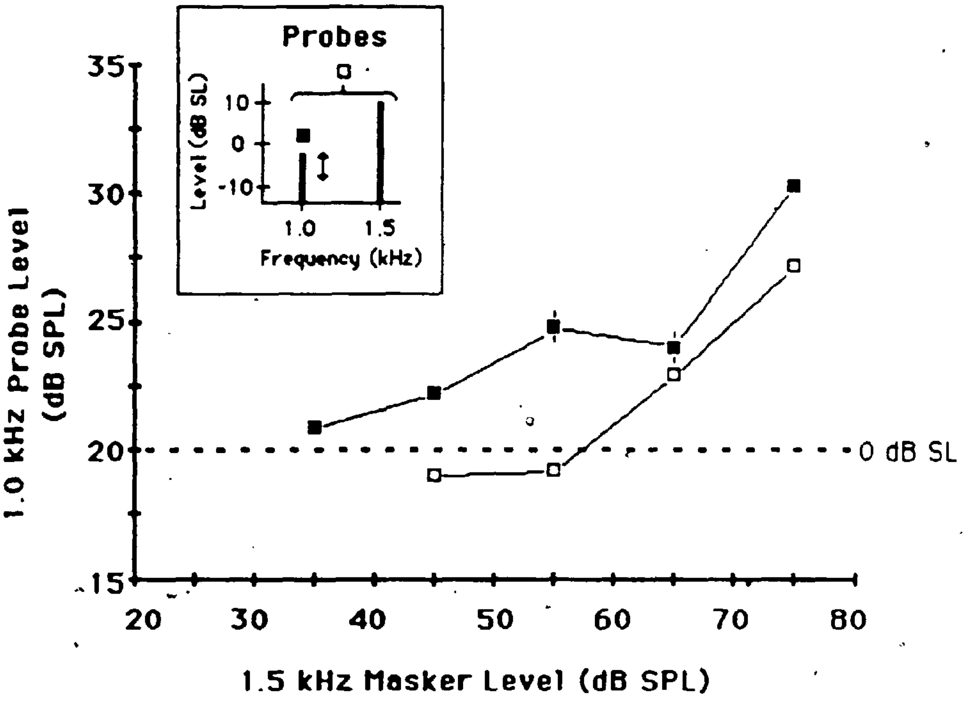

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
1.0 kHz Probe Level (dB SPL)
35
30
25
20
15
0 dB SL
20
30
40
50
60
70
80
1.5 kHz Masker Level (dB SPL)

Figure 4.23 The 1.0 kHz probe-level masked thresholds for the 1.5 kHz masker at five masker levels for subject GJF. The closed data points represent the thresholds of the 1.0 kHz probe presented alone, while the open data points represent the threshold with the 1.5 kHz 10 dB SL presented simultaneous to the 1.0 kHz probe. Standard errors are shown that exceed the size of the data points (i.e., 1 dB).

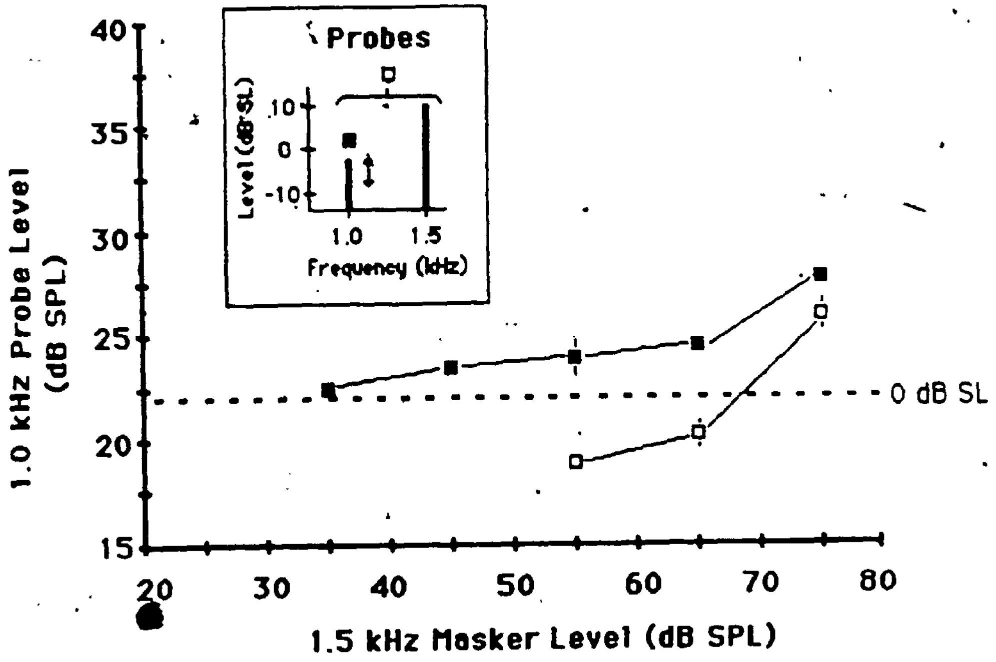

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
40
35
30
25
20
15
1.0 kHz Probe Level (dB SPL)
20
30
40
50
60
70
80
1.5 kHz Masker Level (dB SPL)
0 dB SL

Figure 4.24 The masked detectability (d') functions for the single-frequency probe (1.0 kHz at 0 dB SL) and double-frequency probe (1.5 kHz at 10 dB SL and 1.0 kHz at 0 dB SL) for the 1.5 kHz masker at five masker levels (subject DCB). Standard errors are shown that exceed the size of the data points (i.e., 0.25).

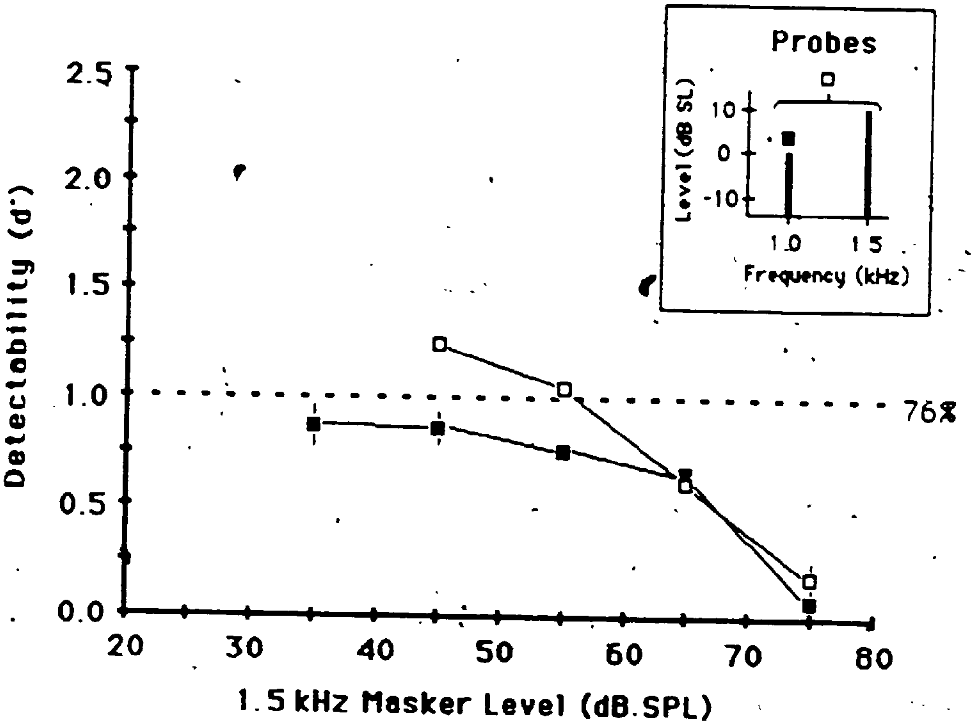
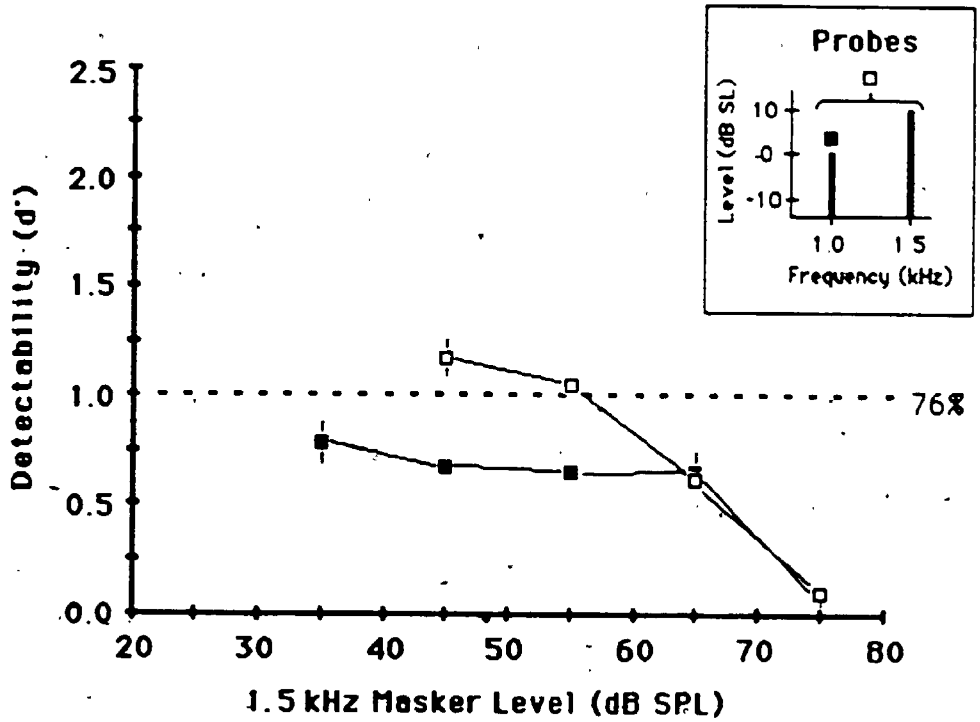

Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
Detectability (d')
2.5
2.0
1.5
1.0
0.5
0.0
76%
20
30
40
50
60
70
80
1.5 kHz Masker Level (dB.SPL)

Figure 4.25 The masked detectability (d') functions for the single-frequency probe (1.0 kHz at 0 dB SL) and double-frequency probe (1.5 kHz at 10 dB SL and 1.0 kHz at 0 dB SL) for the 1.5 kHz masker at five masker levels (subject GJF). Standard errors are shown that exceed the size of the data points (i.e., 0.25).


Probes
Level (dB SL)
10
0
-10
1.0
1.5
Frequency (kHz)
Detectability (d')
2.5
2.0
1.5
1.0
0.5
0.0
76%
20
30
40
50
60
70
80
1.5 kHz Masker Level (dB SPL)

In summary, the results in Experiment III support the hypothesis that the differences in the effective masker levels in Experiment I and II are due to a two-tone interaction of the probes. As might be expected from the earlier data, the range of interaction was dependent on the masker frequency. For example, the masker frequencies of 1.2 and 1.3 kHz did not show very large effects in previous experiments, therefore little evidence of an interaction was expected or found in Experiment III. The remaining four masker frequencies (1.0, 1.1, 1.4 and 1.5 kHz) produced the strongest support for two-tone interaction. Further, a second factor of importance was found in these data. With the masker frequencies of 1.0 and 1.1 kHz, a masker level- probe level interaction was discovered, such that the single-frequency probe could be detected at levels below threshold when preceded by a specific level of masker. It is quite possible that the large differences in the effective masker levels at these frequencies in Experiment I and II could be at least partially explained by this phenomenon.

These masker level-probe level interactions also revealed a further dissociation between detection performance with the single- and double- frequency probes. Although the single-frequency probe could be detected below threshold, when presented in the double-frequency condition detectability was not as good. This does seem to be incongruent with what one might expect. At the same time, it does support the notion that single- and double-tone stimuli are processed differently. There is no reason to expect that the subthreshold detection of the probe would disappear or lessen when the 10 dB probe is added to the stimulus. Yet, this is what does occur. If we assume that an interaction is taking place in the processing of the two probes, and the tonal pair is therefore recoded in some combined fashion, then we might expect such effects.

5. Discussion

5.1 Summary of Results

Three experiments examined the interaction of two sinusoids and their effect on detection in a forward masking task. In Experiment I, detection of the double-frequency stimuli was shown to improve substantially compared to detection of the single-frequency components. Specifically, in the forward masking task greater masker levels were needed to mask the double-frequency probes than predicted from the masker levels necessary to mask each probe presented singly. These effects were most evident with a large differential level in the probes, that is, when the added probe component was at or near threshold. With some stimulus conditions, the difference in effective masker levels (for the single- and double-frequency probes) were found to be as large as 20 dB.

The two-tone interaction effects were also found to occur in a task that made nonlinear processing, such as combination tones, impossible. In the second experiment, a dichotic presentation of the two sinusoids was used to remove the confounding influence of combination tones, since the generation of combination tones require a monaural (or diotic) presentation of each tone. Differences in the effective masker levels were still present with certain masker frequencies.

Finally, it was shown in Experiment III that the interactions were not limited to suprathreshold stimuli, but were demonstrated when one of the two sinusoids was presented at levels slightly below threshold. It was also discovered that peripheral interactions of the tones occur with some stimulus relationships. The residual excitation from the low-frequency masker improved the detection of subsequent and higher frequency stimuli. It is likely that this phenomenon is also playing a partial role in producing the differences in the effective masker levels found in earlier experiments.

5.2 Temporal interaction of the probes

As stated earlier, the common view of processing by the peripheral auditory system is one which emphasizes the energy analysis of the stimulus, illustrated by the pattern of excitation model. This view, though, does not include the role of the neural temporal code in frequency analysis. An explanation for this emphasis on energy analysis and lack of concern for the importance of temporal coding may be due to the type of stimuli and kinds of paradigms used to examine this process. The pattern-of-excitation model, for example, has been based on a vast amount of auditory masking research. The typical paradigm is the forward masking procedure, where the level of a sinusoidal tone is adjusted until it just masks a second sinusoid that temporally follows the first. At any moment, then, the auditory system is processing only one sinusoid. Therefore, while temporal coding of the tonal period may be taking place, there is no dynamic comparison of the temporal patterns as is the case with complex stimuli.

Neurophysiological studies have shown that the temporal discharge pattern of the auditory nerve, in response to tonal pairs, is a more sensitive indicator of intensity than neural rate discharge patterns (Rose et al., 1967). Therefore, the two sinusoids interact at some level of the auditory system and allow a "richer" encoding of the stimuli to take place. If this information is used at a behavioral level, than we would expect performance differences between the processing of simple and complex sounds. The use of forward masking in these experiments examined whether the kind of temporal processing between two sinusoids demonstrated at a neural level could be demonstrated in a psychophysical task that is generally considered to deal specifically with power spectrum analysis. By adding a second pure tone component to the probe, we were interested in whether there was evidence of a two-tone interaction as measured by the effective masker levels for single- and double-frequency probes resulting from different processing mechanisms. This type of model of spectral processing would also have important implications for current models of spectral analysis, such as the pattern-of-excitation model.

As summarized above, the data did show that more masker energy was needed to mask the probe pairs than each probe presented alone. In some stimulus conditions the effect was small (less than 3 dB), while in others the increases in the effective masker levels exceeded 10 and 15 dB. An explanation of these effects is difficult without including a temporal coding hypothesis that states that the intensity of each component of the probe is compared and analyzed in a way different from the processing of each tone separately.

In Experiment III, there were two stimulus conditions that produced an opposite effect from that described above. It was shown, with two of the masker frequencies, that a low frequency masker at a specific level could improve the detection of a single-frequency probe presented immediately following the masker. This effect results in the masked detection of the probe at levels below the threshold measured in quiet. When a second sinsoidal component was added to the probe, this effect was found to diminish significantly, if not disappear. The reason for this decrease in detection is not obvious. Further, it is counter to the main effect found in these experiments. Still, it is quite possible that this is further proof that double-frequency tones are processed differently.

Two explanations can be proposed to account for the increased threshold with the added 10 dB probe. First, though, we will fully describe the effect. As shown in sections 4.4.1 and 4.4.2, when the masker was presented at a specific intensity, the probe could be detected at levels below its threshold in quiet. Therefore, the single-frequency probe was more detectable when preceded by this masker level than with higher or lower masker levels, or when presented alone in quiet. An explanation similar to Zwicker (1981) was proposed, where the residual excitation of the masker made the probe frequency region more sensitive to immediate low-level stimulation. In the double-frequency probe condition, a 10 dB probe was presented simultaneously with and 0.5 kHz below the threshold-level probe. The result was the loss of the subthreshold effect.

One possible explanation would be that the second 10 dB SL probe component masked the simultaneous low-level probe. Therefore, more probe energy would be necessary for detection than when the 10 dB probe was not present. There are two problems with this proposal. It is generally agreed that low-level and widely separated frequency components will not mask each other. Further, if some form of masking was occurring between these two sinusoids, then it would also be unlikely that we could find the kind of effects in other stimulus arrangements, where the two simultaneous probes are more detectable than each alone (Experiment I and II).

The second explanation for this effect is one that proposes that the single- and double-frequency probes are processed quite differently. When the 10 dB probe is added to the presentation, it is not processed as simply two tones each at a specific level and frequency, but as a complex where each component interacts and this signal becomes, thus, recoded. Therefore, the stimulus to be masked is not simply energy in a specific frequency region, but a more complex coding of energy, phase and period of the waveform.

5.3 Effective masker levels with specific stimulus parameters

In the summary, it was noted that the largest differences in the effective masker levels (and probe levels) were found with the largest amplitude ratio of the probes; i.e., when one of the probe levels was at threshold (0 dB SL). Further, these effects were largest with the most extreme masker frequencies (1.0 and 1.5 kHz). Therefore, these effects were displayed when the masker frequency was equal to the 10 dB probe frequency, and decreased as the masker frequency approached the frequency of the 0 dB probe. (In fact, in Experiments I and II, only three masker frequencies were tested for the 1.78 and 3.16 probe ratios, since the other three masker frequencies consistently showed no differences in the effective masker levels).

The fact that these effects are highly frequency and level specific corresponds to other defined cochlear nonlinearities in the auditory system. For example, although it was shown that combination tones are not necessarily a factor in these data, the production of additional spectral components depends on

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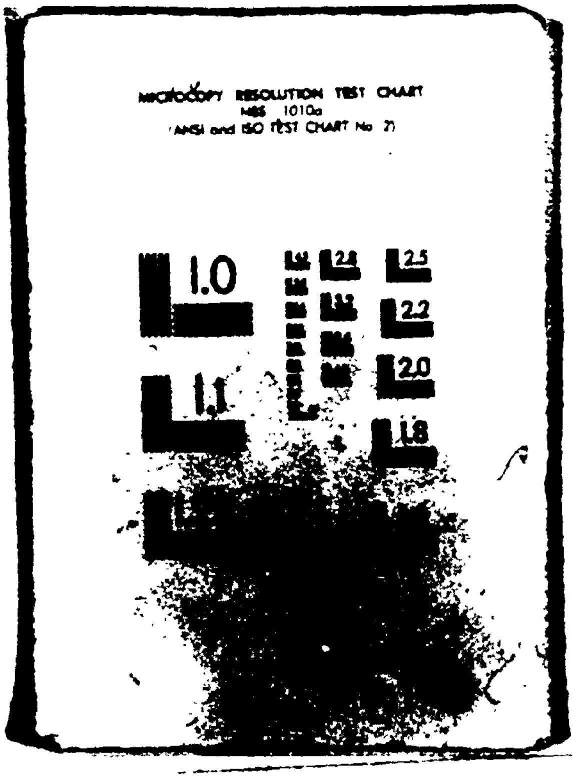
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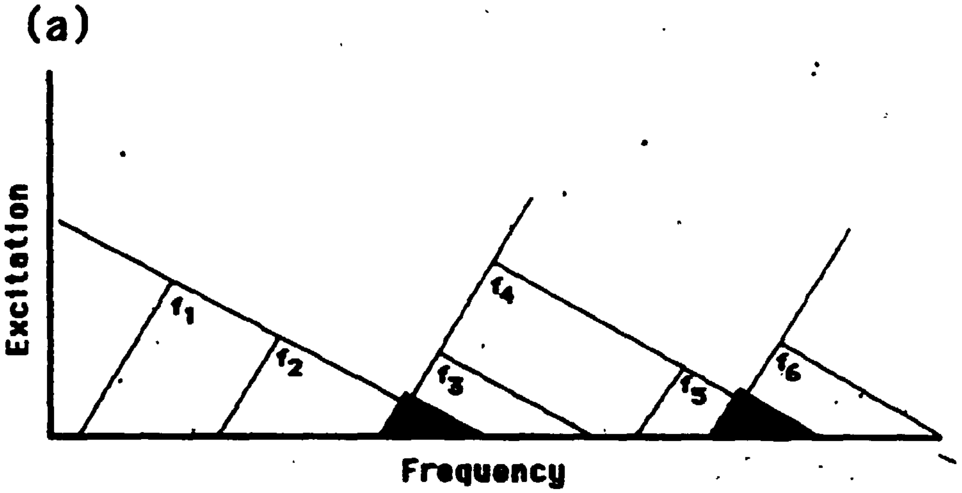
the frequency and intensity relationship of the stimuli. Both neurophysiological and psychophysical data show that the production of combination tones diminish with an increasing frequency separation and/or decreasing level of the primaries (see section 1.2.2).

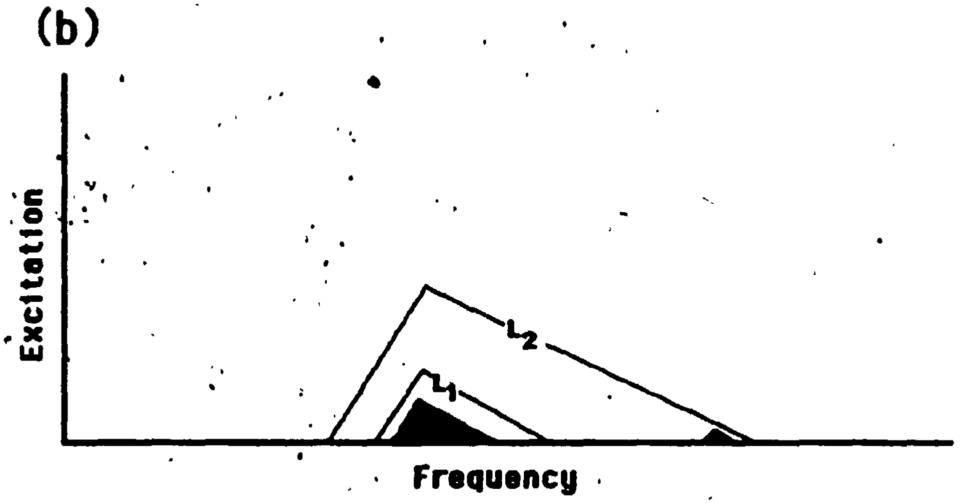
The phenomenon of two-tone suppression is similarly dependent on the frequency and intensity relationship of the primaries. In this case, the two tones interact to produce an effect that is less than the response of each tone separately. These effects are most dramatic when measuring the suppression of the temporal firing patterns of auditory neurons (Arthur, 1976). At the same time, the coding of such interactions must involve complex mechanisms in order to compare the differences in the phase-locked patterns across the neural array (see section 1.2.1).

The data presented in these experiments do not examine the effect of the frequency separation of the probes on masked thresholds (i.e., the probes were always presented at 1.0 and 1.5 kHz), but the data do show that the differences in the effective masker levels are level dependent (see summary). It is somewhat counter-intuitive, though, that the effective masker level differences actually increase as the levels of the stimuli decrease (in that other nonlinearities are found to decrease with decreasing levels). There are a number of reasons for this effect.

First, in each of the stimulus conditions where no or very little differences in the effective masker levels were found, the masker energy exceeded levels of 60 dB SPL. Although this may suggest that our two-tone interactions are a low-level phenomenon, it is also possible that the interactions are due to the fact that the masker levels are too high to allow the lower level probes to be detected (i.e., the spread of excitation from the high level maskers is great enough to make low-level probes over a range of frequencies difficult to detect). This can be clarified by returning to the excitation schematic shown earlier (Figure 5.1a). Masker f4 is described as representing the excitation of a masker that just masks the detection of each probe component. The main effect in our experiment was described as an interaction that occured between the residual excitation of each probe. Certainly, then, we would expect that independent of masker frequency, there would be some masker level that would make the coding of each low-level probe difficult (considering the level of the probe that we used). Therefore, in these cases, the spread and amount of excitation would be too great for subsequent coding of the two probes.

Figure 5.1 The schematic representation of cochlear excitation. Figure (a) represents the excitation produced by two probes (filled) and six maskers (open). The residual excitation of each probe interacts such that masker f4 is no longer an effective masker. Figure (b) represents the stimulus conditions with a 0 dB SL probe 0.5 kHz above the 10 dB SL probe. The masker levels L1 and L2 represent the effective masker levels for the single-frequency 1.0 kHz probe and


(a)
Excitation
f_1
f_2
f_3
f_4
f_5
f_6
Frequency


(b)
Excitation
L_2
L_1
Frequency

The conditions that produced the largest differences in the effective masker levels are schematically represented in Figure 5.1(b). Here the interaction of the residual excitation of each probe produces a more detectable complex as described above. But in this case, the masker levels have to be increased substantially before excitation from the masker spreads into the 0 dB probe frequency region. When this occurs, the interaction can no longer be coded and the probe becomes masked (compare L1 and L2 in the figure). Therefore, although the data suggest that the demonstrated differences in the effective masker levels are a low-level effect, it is more likely a reflection of the masking paradigm and its inability to demonstrate the effect at other stimulus levels.

These data have important implications for any theory of spectral processing; that is, complex sounds are processed in ways not predictable from the performance with simple tones. Others have argued this point at the neural level. For example, Moller (1980) has studied extensively the response of the auditory system to more complex sounds. His work has specifically examined the transformations of the neural information that occurs in the cochlear nucleus. He has found that changes in both frequency and amplitude are actually enhanced in the cochlear nucleus. Also, the importance of the temporal coding has been seen as necessary for giving a complete description of the differences between neurophysiological data and psychophysical data in loudness growth (Evans, 1980). Others have shown indirectly the importance of temporal coding in auditory processing (as in Groen's (1964) binaural beating phenomenon). The demonstration of a temporal interaction in this forward masking task broadens this data base and supports the thesis that the auditory system may enhance features of a complex sound, rather than simply convey the spectrally analyzed information of the sound's energy distribution.

5.4 An examination of the phenomenon of temporal cueing

An important phenomenon that has been previously demonstrated in forward masking tasks needs to be examined in light of these data. In the following section, we will re-examine the basic findings of Experiment I with respect to temporal cueing. It should be noted that the idea of temporal cueing is not specifically related to the temporal neural code, as will be made clear below.

A number of studies have shown that forward masking measurements can involve a high degree of temporal uncertainty. For example, in a task where a sinusoidal masker and probe are equal in frequency, there may be uncertainty as to where the masker ends and the probe begins. Therefore, in a two-interval task, where the masker and probe are presented in one interval and only the masker in the other interval, the subject may be responding to the duration difference between the masker-probe and the masker presentations and not to the masked detectability of the probe.

The phenomenon has been most clearly demonstrated by Moore and Glasberg (1982). A 500 ms masker was generated with a center-frequency and bandwidth similar to a 20 ms 1 kHz probe. With these stimuli, they could produce a forward masking situation where there was very little qualitative difference between the masker and probe. The task involved adjusting the level of the probe until it was just masked by the 70 dB masker. In order to overcome any temporal uncertainty as to when the masker ended or the probe began, a broadband noise cue was presented simultaneously with the masker or probe to the contralateral or ipsilateral ear.

The results showed that the cued probe could be detected 1 to 25 dB below the levels found when no cue was used. (This 24 dB range was dependent on the manner of cue presentation, as well as a reflection of a large variability found across subjects.) The results clearly demonstrate that with stimuli that are similar in quality, the amount of masking may be partially a reflection of a temporal uncertainty in the task. This finding is supplemented by Pastore and Freda (1980) who were unable to show cueing effects in a forward masking task with a noise masker and cue and sinusoidal probe. In other words, there is no evidence for cueing when the masker and probe differ in quality; cueing has only been observed when there is an uncertainty in the temporal order of the stimuli.

The question can be asked whether the presence of cueing could have been a factor in explaining the differences in the effective masker levels found in Experiment I. Before making this comparison it is useful to note the differences in the typical cueing paradigm and that used in Experiment I. In Moore and Glasberg's (1982) study, the cue is a segment of broadband noise presented simultaneously with the masker or probe. Therefore, while the sinusoidal masker may mask some of the noise cue, there should be sufficient information in unmasked frequency regions to cue the temporal intervals. Also, typical to the cueing paradigm, the cue is presented in both comparison intervals (i.e., in a two-interval forced-choice task), so as not to confound the ipsilateral cueing condition.

In our experiments, we compared masking performance between conditions with single probes and with a second probe presented with the first probe. If the second probe is seen as a cue for the first, then certain comparisons and contrasts can be made between the two paradigms.

The "cues" that we used were sinusoidal and presented simultaneously with the probe. Further, they were presented only in the same interval as the probe. This arrangement differs somewhat from the cueing paradigm producing a situation where the cue could itself become the stimulus to detect. As well, since the cue was sinusoidal, the cue could become fully masked with certain masker levels. Finally, when the second probe component or "cue" is a 0 dB SL tone, it is difficult to understand how this could work effectively as a cue.

Since off-frequency cueing does not occur (Pastore and Freda, 1980), the only stimulus conditions where cueing is possible in our studies are those where the masker and one of the probe components are similar in frequency. These are the conditions that showed the largest differences in the effective masker levels. Table III shows these conditions with the various masker level differences (obtained from the data in Figures 4.4 through 4.11). In Table III sections (a) and (b), the cue is considered to be the 5 dB SL tone which was presented to the ipsilateral ear in the masking sequence. The measures under these conditions show a 30 to 40 dB increase in the masker levels is necessary to overcome these "cueing" effects. However, since the cue is presented only in the same temporal interval as the probe that is to be detected, the perception of the cue itself should be taken into account. When the masker levels necessary to mask the cue are subtracted from these values, the cueing effects are reduced substantially. The values remaining vary between -2 and 5.5 dB. A question remains, though, whether these resultant differences are due to some form of residual cueing by the 5 dB probe.

Sections (c) and (d) of Table III show the effective masker levels with a 0 dB SL probe or cue.

Under these conditions, the measures show that between 12 to 20 dB more masker energy is needed to mask the

Table III

Data from Experiment I analyzed by temporal coding

Conditions

(a)	Masker 1.0 kHz	Probes	1.0 kHz 10 dB SL 1.5 kHz 5 dB SL (cue)
(b)	Masker 1.5 kHz	Probes	1.5 kHz 10 dB SL 1.0 kHz 5 dB SL (cue)
(c)	Masker 1.0 kHz	Probes	1.0 kHz 10 dB SL 1.5 kHz 0 dB SL (cue)
(d)	Masker 1.5 kHz	Probes	1.5 kHz 10 dB SL 1.0 kHz 0 dB SL (cue)

Measures

		subject DCB Masker Level	subject GJP Masker Level
(a)	Single Probe (no cue)	29.8	29.7
	Double Probe (ipsilateral cue)	58.25	59.9
		28.45	30.2
(b)	Single Probe (no cue)	27.35	26.95
	Double Probe (ipsilateral cue)	70.85	69.0
		43.5	42.05
(c)	Single Probe (no cue)	29.8	29.7
	Double Probe (ipsilateral cue)	50.1	44.9
		20.3	15.2
(b)	Single Probe (no cue)	27.35	26.95
	Double Probe (ipsilateral cue)	41.65	39.2
		14.3	12.25

"cued" probe. Again, the 0 dB cue was present only in the probe interval, but attempts to measure the effective masker levels required for the cue itself were quite variable (in Experiment I). Therefore, these differences between the single- and double- frequency probes may be the result of a cueing effect as found by Moore and Glasberg (1982). However, in a strict sense, this form of cueing is not exactly the type described earlier.

A typical cueing effect occurs when a perceivable marker indicates the end of the masker and/or beginning of the probe. In other words, the cue acts as an indicator for the probe when there is a temporal ambiguity as to when the masker ends or the probe begins. In our experiments, it is somewhat difficult to imagine how a 0 dB probe could act as this kind of cue, because when it is presented in quiet it is perceived only 70.7% of the time. Placing this "cue" in a masking situation, detection should not be any better than 70.7%, and would likely be worse (as demonstrated in Experiment I with the single-frequency probes).

On the other hand, if a two-tone interaction (of the probes) is coded at a neural level (via the temporal coding of the two frequencies), then these interactions could be understood as a form of cueing. Therefore, as stated earlier, the residual excitation from the 0 dB SL probe could be seen to act as a cue for the 10 dB SL probe. The difference between Moore and Glasberg's (1982) cueing and cueing defined in our studies would be that Moore and Glasberg's cue is a perceivable marker, while our cue is "perceivable" through the processing of the interactions of each probe.

5.5 Conclusions

In a series of studies, we have demonstrated a nonlinearity in a masking paradigm that is not predictable from theories of spectral processing. This work is limited in that all the factors that may be responsible for producing this effect could not be isolated. Experiment II showed that combination tones were not necessary to produce the effect. On the other hand, Experiment III did show some form of masker-probe interaction to be important.

The hypothesis was proposed that a temporal coding of the probe pair may play a major role in producing this nonlinearity. This is supported by the following findings: first, the lack of the excitation/energy models to explain the data; second, the production of the effect in a binaural task; and finally, the evidence of improved detection with subthreshold stimuli. There is some peripheral support for this hypothesis, despite the dominance of the spectral energy models, but it comes mainly from neurophysiological studies. Groen (1964), who conducted the only other psychophysical study of related effects, makes conclusions that temporal coding interactions can occur in a binaural system. Other researchers have based their arguments for such a mechanism on the observed discrepancies between the temporal pattern and firing rate thresholds, suggesting that simple models of spectral processing are inadequate in describing complex sound analysis.

Our data demonstrate in a subjective task similar behavioral discrepancies. It is on the basis of these data that we propose a hypothesis that described spectral processing the auditory system as less static than the excitation models. Our model, then, suggests a system that analyzes complex sounds in a way that enhances or highlights the differences in the spectral components instead of simply conveying the absolute distribution of energy with a specific frequency range. Such a model of frequency analysis may play significant roles in speech or music processing. Clearly, the broad types of frequency discrimination suggested by masking studies and energy models is insufficient for explaining fine spectral processing or envelope coding as seems necessary in tasks such as speech recognition. Recognizing the types of complex processes necessary for speech perception, it is not surprising to find differences in behavioral performance as demonstrated in these studies.

5.6 General applications and discussion

The main focus of this dissertation has been restricted to a "simple auditory psychophysical task" and the relation between the results and the literature from which these types of studies are found. There has been only brief mention of alternate theories. In this final section, some discussion will be presented of such theories. Notwithstanding the major scientific leap from the data above and these ideas, at the same time they do present interesting comparisons to these findings.

5.6.1 Pitch models

Theories of pitch perception (the auditory quality of sound that is musically ordered) have long postulated the temporal processing of sound. The two major arguments in support of such processing are: 1) the case of the missing fundamental - subjects can hear a lower pitched tone even when all the energy in the stimulus is in the higher harmonics, and 2) the fact that the sense of musical pitch is lost for stimuli above 5 kHz, the region where temporal code is no longer recorded in the auditory nerve.

Due to these findings, models of pitch processing generally include a stage where the temporal pattern is processed for each "frequency region", as well as a stage where these patterns are then compared across different frequency regions (e.g., Terhardt, 1974). The comparison of the temporal code in different frequency channels allows the system to determine common time intervals in the individual components in the sound stimulus, such as when the sound contains a number of harmonics of the fundamental.

A further and critical stage at this point in pitch processing is a decision stage, where factors such as context play a major role (aided by memory and attention). As is evident in the dissertation, discussion of this stage is absent in describing the differences in the effective masker levels. Certainly, this absence is not due to the fact that memory is not seen as important, but that masking is generally considered from a "bottom-up approach.

The use of pitch processors in producing the nonlinearities found in our masking data is certainly plausible hypothesis, although difficult to prove from these data alone. Interestingly, the probe stimuli in the above experiments were harmonically related. The 1.0 and 1.5 kHz probes were a "perfect fifth" apart in frequency (a musical relationship with a frequency ratio of 2:3), as well as being the second and third harmonics of a 0.5 kHz tone. If these relationships are processed by the auditory system, then it may not be surprising that the effective masker levels are different for the single- and double-frequency probes. The second experiment did show that nonlinear distortion products (at 0.5 kHz) were not necessary to produce the increase in the effective masker levels, but it did not rule out the possibility that a pitch at the 0.5 kHz fundamental may have may been detected by the subjects. Such a hypothesis would, unlike our simple masking model, require additional mechanisms for determining this information content of the stimuli.

5.6.2 Envelope or Phase Sensitivity

Similar to pitch processing, an additional hypothesis would propose that the differences in the effective masker levels were due to a sensitivity to the envelope of the probes. One area of the literature that examines this phenomenon is amplitude modulation sensitivity. Amplitude modulation is similar to difference tone generation, except it does not occur due to nonlinearities in the auditory system.

Typically, in amplitude modulation, the amplitude of a sinusoid (or carrier) is varied so as to follow the amplitude of a second (modulating) sinusoid. This produces a waveform that is complex and periodic. The periodicity can be analyzed into individual sinusoidal components corresponding to the carrier frequency and both the sum and difference of the carrier frequency and the modulating frequency. In our experiment, the 1.5 kHz probe would be considered the carrier, while the 1.0 kHz probe would modulate the carrier and produce components at 0.5 and 2.5 kHz.

In our masking experiments, the double-frequency probe condition, then, would produce a complex with frequency components at 0.5, 1.5 and 2.5 kHz. Therefore, increases in the effective masker level may be a reflection of the sensitivity to these amplitude modulations of the 1.5 kHz probe. (This may be the same argument used above for pitch perception; i.e., a pitch at the 0.5 kHz fundamental would likely be most prominent.) This hypothesis, though, is not without problems. Most notably is the question of how much modulation (or the percent of modulation) would occur when the 1.0 kHz modulating waveform is 5 or 10 dB below the level of the carrier. Clearly, the detection of these small amounts of modulation would require a very sensitive algorithm, that, in our data, would have to be very robust in the face of the masking stimuli.

Still, there is some evidence that we may be more sensitive to the phase relationships between stimuli that are harmonically related (as were our probe stimuli) than stimuli that are non-harmonically related (see Lamore, 1972).

5.6.3 Cortical functions and other hypotheses

Typical of psychophysical masking data, the previous discussions were limited to peripheral explanations of auditory processing. Likely due to the still limited understanding of the peripheral coding of auditory stimuli, there is much less literature discussing the role of the cortex in auditory functioning (except in speech processing, where stimulus processing necessarily requires large memory banks).

Along these lines, quite a different approach could be suggested. For example, there is the possibility that the detection/processing/perception of simple stimuli (sinusoids and sinusoidal combinations) is somewhat artificial. Therefore, the effective masker levels for the double-frequency probe more closely represents performance of the auditory system than the effective masker levels for the single-frequency stimuli. Compared to more "real-world" stimuli, these experimental signals are relatively "information-less". The auditory system's performance with such stimuli could be seen as unrepresentative and possibly "erratic". This would place the hypothesis of the dissertation on it's head, (i.e., the performance of the auditory system to simple stimuli is not predictable from performance with more complex stimuli). Certainly this idea presents an interesting counter-hypothesis to that describe above, but it is more than radical with respect to the whole body of psychophysical literature.

The conclusion of the dissertation is very "low-key" in comparison to this last point. It seeks only re-examine the thinking in a very small area of auditory processing. Auditory masking, despite the convenience, should not be described by simple energy detection models. The kinds of processing recognized as important in speech and pitch, can also be found in a forward masking task. alternate theories. In this final section, some discussion will be presented of such theories. Although there is a major scientific leap from the data above and these following ideas, they do present interesting collalaries to these findings.

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