Temporal Resolution Within the Upper Accessory Excitation of a Masker

D. A. Nelson, A. C. Swain

Clinical Psychoacoustics Laboratory, University of Minnesota, 396 UMHC Rm 8-323, 516 Delaware St. S.E., Minneapolis, MN 55455.

Dedicated to the Memory of Professor Eberhard Zwicker

Summary

Professor Eberhard Zwicker observed that the dynamic range of masking period patterns for amplitude-modulated maskers was larger for frequencies above the masker (in the upper "accessory excitation" where no physical masker energy exists) than for frequencies near the masker (in the "main excitation" where masker energy exists), which implies that temporal resolution of acoustic envelopes is substantially better within the upper accessory excitation than in the main excitation. His finding has significant implications for speech perception in fluctuating-masker environments, but unfortunately it has received little attention since his original report. The present research investigated temporal envelope resolution in normal-hearing subjects by measuring masking at the peaks and valleys of a 500 Hz 100% amplitude-modulated tonal masker as a function of test frequency and stimulus level. Modulation rate was 4 Hz. Masked thresholds were measured using amplitude-modulated signals with envelope peaks that corresponded with envelope peaks and valleys of the masker. The results confirmed Zwicker's earlier observation. Peak-to-valley masked-threshold ratios averaged 14.4 dB for signals within the main excitation, compared to average ratios as large as 33.4 dB within the upper accessory excitation. Slopes of the growth of masking support the interpretation that masking during envelope peaks is associated with simultaneous masking, for both the main excitation and the upper accessory excitation. Masking during envelope valleys appears to be determined by non-simultaneous masking in the upper accessory excitation, but behaves more like simultaneous masking in the main excitation of the masker.

PACS no. 43.66.Dc

1. Introduction

The ability to hear signals in the presence of maskers with slowly (<100 Hz) fluctuating amplitude envelopes is important for daily communication. For example, in the presence of a competing speech background (Festen and Plomp, 1990) or amplitude-modulated noise (Gustafsson and Arlinger, 1994), the ability to hear speech cues during brief moments of reduced masker energy can improve speech recognition considerably. This ability, which we refer to here as temporal envelope resolution, has been characterized in the past using several different measurement paradigms (Rodenburg, 1977; Zwicker and Schorn, 1982; Humes, 1990). One commonality among those investigations was the restriction of measurements to frequency regions that contained physical masker energy, what Zwicker has termed the main excitation region of a masker. To our knowledge, only one investigator has compared envelope resolution in the main excitation with envelope resolution at frequency regions where a masker has no physical energy but still produces substantial masking, what Zwicker has termed the accessory excitation region of a masker. Zwicker (Zwicker, 1976) measured masking period patterns for 100% amplitude-modulated (AM) tones at test frequencies within the upper and lower accessory excitations, as well as within the main excitation. Modulation rates were 4, 10, 30 and 100 Hz. Examination of masked thresholds at peaks and valleys of his masking period patterns, which corresponded to peaks and valleys of the envelopes of the AM maskers, indicates that envelope resolution was considerably better within the upper accessory excitation than it was in the main excitation or in the lower accessory excitation. For example, the peak-to-valley ratio of the masking period pattern for a 4 Hz 100% amplitude-modulated masker was only 12 dB when the probe tone was within the main excitation, at 1000 Hz, while that ratio was as large as 36 dB when the probe tone was within the upper accessory excitation, at 3200 Hz. This observation of better envelope resolution in the upper accessory excitation region, than in the main excitation, has important implications for hearing higher-frequency consonant cues in the presence of lower-frequency vowel energy, either preceding or following the consonant. Since most previous investigations examined envelope resolution within the main excitation of a fluctuating masker, and little attention has been given to Zwicker's finding since his original report, further research into envelope resolution within the upper accessory excitation region was clearly indicated. The present research investigates masking at envelope peaks and valleys of a 500 Hz 100% AM masker, as a function of test frequency and masker level.

2. Method and procedure

2.1. Stimulus Parameters

The masker stimulus, shown by the top waveform in Figure 1, was a 100% sinusoidal amplitude-modulated (AM) tone with a carrier frequency at 500 Hz. Modulation rate was 4 Hz. The masker was presented for a total duration of 1000 ms, which resulted in four complete envelope cycles of the AM masker.

Received 9 January 1995, accepted 25 July 1995.

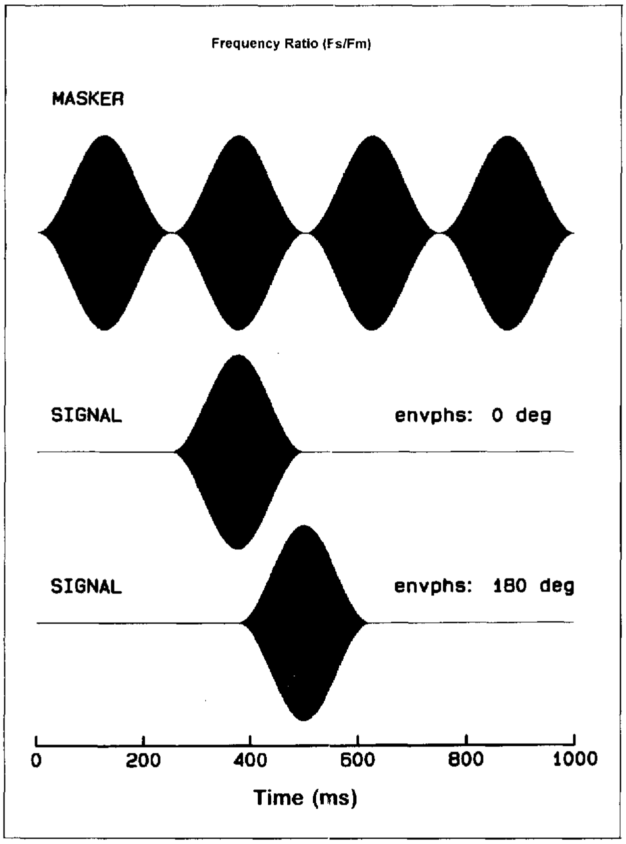

Figure 1. Sinusoidally amplitude-modulated (AM) waveforms (depth of 100%) used as maskers and signals. *Top:* AM waveform used as masker. Carrier frequency was 500 Hz. Modulation rate was 4 Hz. Total duration was 1000 ms for each listening interval. *Middle:* AM waveform used to measure masking during masker envelope peaks. Envelope phase (envphs) was set to 0 degrees relative to the masker envelope so that the signal envelope maximum corresponded with the second masker envelope maximum. *Bottom:* AM waveform used to measure masking during masker envelope valleys. Envelope phase was set to 180 degrees relative to the masker envelope so that the signal envelope maximum corresponded with the second masker envelope minimum. Signal carrier phase was delayed by 90 degrees so that when masker and signal carrier frequencies were identical their fine structure added in quadrature phase.

When masked thresholds were obtained as a function of test frequency (frequency masking pattern), the overall level of the AM masker was 90 dB SPL. When masked thresholds were obtained as a function of masker level (growth-of-masking function), the level of the AM masker was varied from 30 to 100 dB SPL. The signal, or probe stimulus, was also a 100% AM tone, but with a variable carrier frequency between 500 and 1500 Hz. It was presented for one complete envelope cycle of the AM masker (total duration of 250 ms) and was delayed so its envelope peak coincided with the second envelope peak or second envelope valley of the AM masker, as shown in Figure 1 by the middle and bottom waveforms with envelope phases of 0 and 180 degrees, respectively. The phase of the signal carrier frequency was 90 degrees relative to the masker carrier frequency, so when masker and signal were both at 500 Hz the fine structure of the signal and masker were added in quadrature phase.

The long-term power spectrum of the AM masker consisted of three components spaced 4 Hz apart with the center component at the carrier frequency and the other two components 6 dB below the center component. An AM tone was chosen as the signal, rather than a very short gated tone burst as in a masking period pattern, to insure that the spectra of the masker and the signal would be identical when masker and signal were at 500 Hz. This was done to avoid mismatched spectra between a long duration masker (one period of the 4 Hz AM waveform) and a very short duration probe tone (e.g., less than 5 ms). The spectra of the short probe tone being broader than that of the masker could result in off-frequency listening below the masker frequency, which might limit masked thresholds within the main excitation at 500 Hz.

Maskers and signals were generated digitally by a computer, played through separate 14-bit digital-to-analog converters at a sampling rate of 20 kHz, low-passed filtered at 10 kHz, added together in a resistive mixer, and presented monaurally through a UTC L-33 transformer and a TDH-49 earphone mounted in an MX/AR-1 cushion. Subjects were seated comfortably in a double-walled sound-treated booth during the experiment, where they conveyed their responses to the computer via a custom response panel with indicator lights and response buttons.

An additional low-pass masking noise was presented continuously at 80 dB SPL during some of the measurements to interfere with the detection of combination-tone cues below the masker (Greenwood, 1971). The cutoff frequency of that noise was 400 Hz. The low-pass filter had a slope of 96 dB per octave.

2.2. Subjects

Four normal-hearing subjects participated in the experiment, three females and one male. Their ages ranged between 22 and 29 years. All four subjects were paid for their participation, had hearing threshold levels lower than 15 dB HL in the frequency range from 250 to 8000 Hz, and had a negative history of hearing difficulties. Two subjects (ACW and EAS) had extensive experience in other psychoacoustic listening experiments prior to participation, and two subjects (ALK and SDO) were inexperienced listeners at the beginning of the study. Masked thresholds as a function of test frequency (frequency masking patterns) were measured in four subjects. Masked thresholds as a function of masker level (growth of masking functions) were measured in one subject for signal frequencies at 500, 800, 1000 and 1200 Hz.

2.3. Psychophysical Procedures

Quiet thresholds and masked thresholds were measured with a three-interval three-alternative forced-choice adaptive procedure in which the signal level was varied to estimate 71% correct detection threshold. The adaptive procedure began with signal levels well above threshold. To quickly reach signal levels near threshold at the beginning of each adaptive track, signal level was decreased by 8 dB for each correct

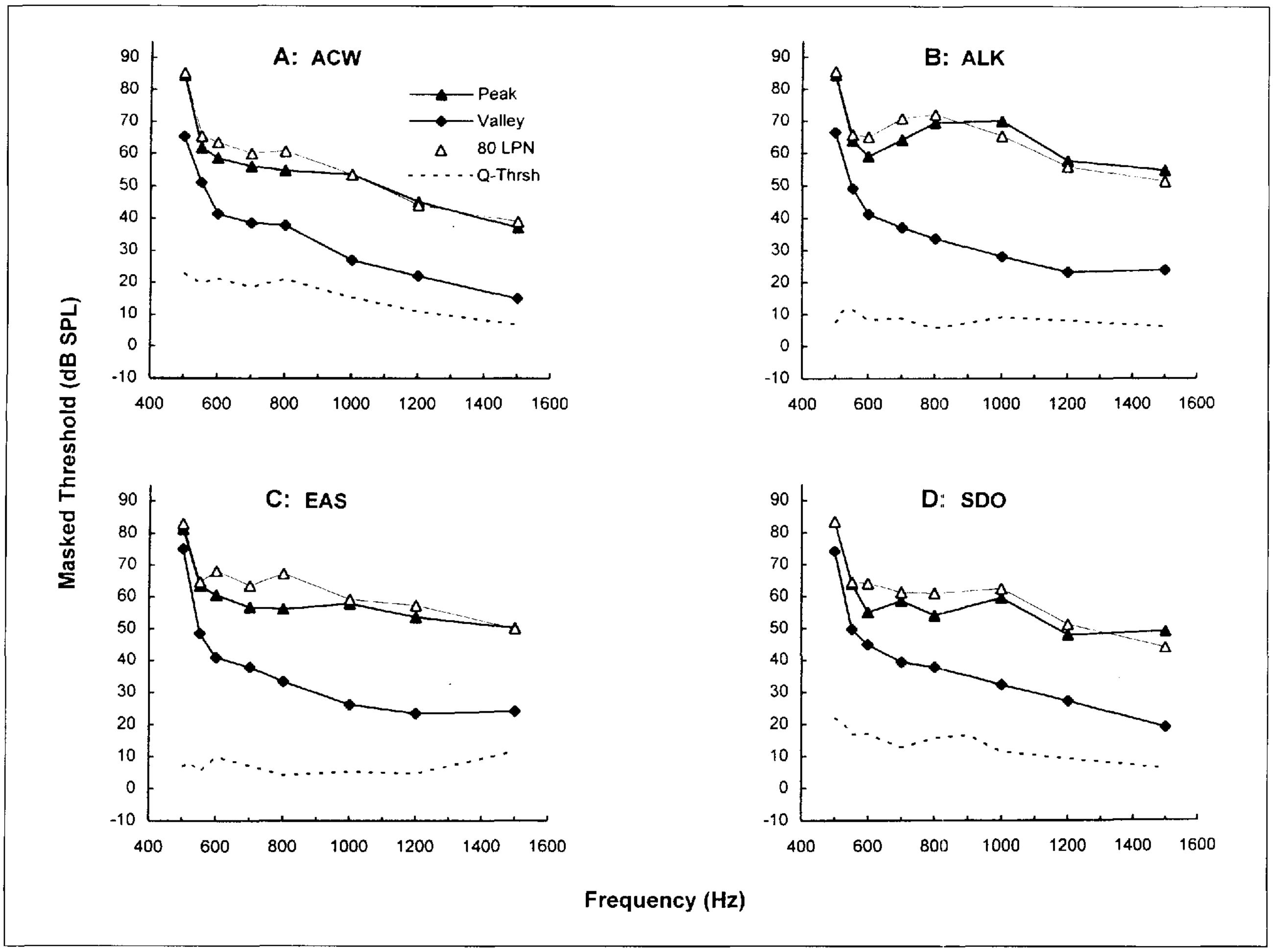

Figure 2. Frequency masking patterns for AM maskers from four normal-hearing subjects. Signal envelope maxima were synchronous with masker envelope peaks or valleys as shown in Figure 1. Masker level was 90 dB SPL. *Filled triangles:* masked thresholds when signal envelope peaks corresponded to masker envelope peaks. *Unfilled triangles:* same but in presence of a low-pass noise to mask combination tones below the masker. The low-pass noise was presented at 80 dB SPL and had a cut-off frequency of 400 Hz. *Filled diamonds:* masked thresholds when signal envelope peaks corresponded to masker envelope valleys. *Light dashed curve:* quiet thresholds for AM signals.

response and increased by 8 dB for each incorrect response until four reversals in signal level occurred; then signal level was decreased or increased by 2 dB for the next two level reversals. For the final six level reversals, the level was reduced by 2 dB following two correct responses and increased by 2 dB following one incorrect response. Threshold was taken as the average signal level on the last six reversals. Each response received correct-answer feedback. During a single listening session, either a complete frequency masking pattern or a complete growth of masking function was measured. Complete functions were measured during repeated sessions until three threshold determinations for every condition fell within a range of 3 dB. Those three thresholds were averaged together to obtain the final threshold estimates reported here. Typical standard deviations across the three tests were around 1 dB (the average standard deviation across retests from four subjects was 0.97 dB, 84% of the standard deviations were less than 1.36 dB, and none of them were greater than 1.65 dB).

3. Results

3.1. Frequency masking patterns for AM maskers

Frequency masking patterns for the 500 Hz AM masker are shown in Figure 2 for each of the four subjects. Masked thresholds at masker envelope peaks are shown by the filled triangles. At 500 Hz, where masked thresholds were the largest, the masker spectrum and the signal spectrum were identical, thus the signal was within the main excitation of the masker. The carrier frequency of the AM signal was delayed by 90 degrees, so the addition of the AM signal preserved the 100% amplitude modulation of the masker, and the only signal cue available was an increment in the intensity of the AM masker. The average masked threshold was 83.5 dB SPL. This corresponds to a Weber fraction of -6.5 dB [$10 \log(\Delta I/I)$] or an intensity increment threshold of 0.88 dB [$10 \log(1 + (I/\Delta I))$], which is consistent with 500 Hz intensity discrimination thresholds from normal-hearing listeners at 90 dB SPL (Schroder *et al.*, 1994). At signal frequencies above 600 Hz, all signal energy was well above any physical masker energy, thus the signal was within the upper accessory excitation. Here a gradual decrease in masked threshold was seen as signal frequency increased.

Masked thresholds at masker envelope valleys are shown by the filled diamonds. Again masked threshold was largest within the main excitation at 500 Hz. However, the drop in masked threshold with test frequency within the upper accessory excitation was much larger for masking in the valleys than for masking at the peaks.

For the signal frequencies between 552 and 800 Hz, the possibility existed that combination tones below the masker were responsible for masked threshold. The unfilled triangles in Figure 2 show that the low-pass continuous noise elevated masked thresholds slightly for test frequencies up through 800 Hz. These elevated thresholds indicate that combination tones were involved, but not sufficiently to alter the general form of the frequency masking pattern. In subject ALK the low-pass noise may not have completely removed combination-tone cues because the notch at 600 Hz was not completely removed from the masking pattern.

3.2. Peak-to-valley masked-threshold ratios

Of primary interest in this investigation were the differences between masked thresholds in masker peaks and valleys, which reflect the limits of temporal envelope resolution. As seen in Figure 2, differences between peak and valley masked thresholds were considerably smaller at 500 Hz, within the main excitation, than they were above 500 Hz within the upper accessory excitation. These differences are plotted in Figure 3 as a function of the frequency ratio between masker and signal carrier frequencies. Figure 3 shows that peak-to-valley masked-threshold ratios were as small as 6 dB for subject EAS within the main excitation at a frequency ratio of 1.0, and as large as 42 dB for subject ALK within the upper accessory excitation at a frequency ratio of 2.0. The average peak-to-valley ratio (heavy shaded curve in Figure 3) increased from 14.4 at a frequency ratio of 1.0 up to 33.4 at a frequency ratio of 2.0, and then it decreased somewhat at higher frequency ratios. This increase in peak-to-valley ratio within the upper accessory excitation occurred in each of the four subjects.

For comparison, peak-to-valley masked threshold ratios from masking period patterns published by Zwicker (Zwicker, 1976) are shown by the filled squares in Figure 3. In this case the masker was a 100% AM tone at a carrier frequency of 1000 Hz presented at 86 dB SPL. Peak-to-valley ratios were smallest at 1000 Hz, within the main excitation. The increase in peak-to-valley ratio with increased frequency ratio followed the average results of the present study, and the largest peak-to-valley ratio Zwicker measured occurred within the upper accessory excitation (at 3200 Hz).

The maximum peak-to-valley masked-threshold ratios were seen at 1000 Hz, which was due to a maximum at 1000 Hz in the masking patterns for envelope peaks; a similar maximum at 1000 Hz was not seen for envelope valleys. This could reflect the limits of the influence of combinations tones at masker/signal frequency ratios greater than 1.6. Alternatively, it could also be the result of reduced pitch cues, because the pitch of the masker is not as easily distinguished from that of the signal for octave relations.

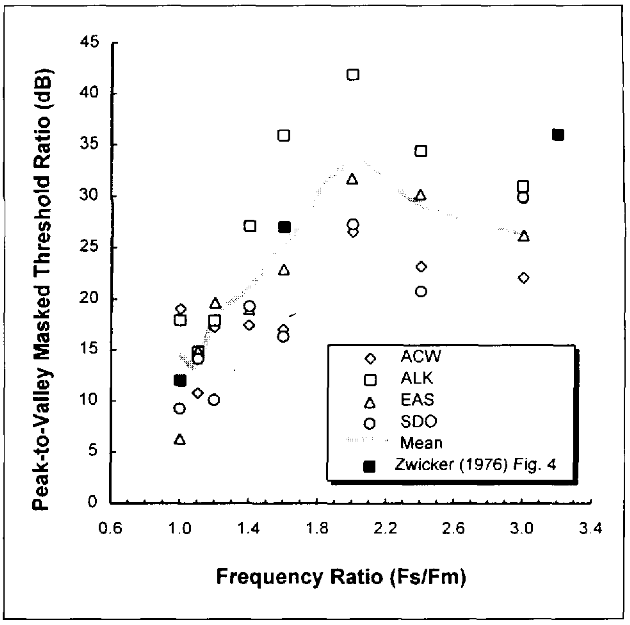

Figure 3. Peak-to-valley masked threshold ratios (dB) are shown as a function of the frequency ratio between signal carrier frequency (Fs) and masker carrier frequency (Fm). *Unfilled symbols:* Peak-to-valley ratios from individual subjects. *Heavy shaded curve:* Group mean peak-to-valley ratios. *Filled squares:* Peak-to-valley masked-threshold ratios for an 86 dB SPL 1000 Hz 100% AM masker, which were obtained from masking period patterns published by Zwicker (Zwicker, 1976).

3.3. Growth-of-masking curves

The behavior of envelope resolution across a range of stimulus levels from one normal-hearing subject is shown in Figure 4, at four different signal frequencies. Masked thresholds as a function of masker level define growth-of-masking curves, which are shown for masker envelope peaks and valleys by the filled triangles and diamonds, respectively. Each growth-of-masking curve was fitted with a least-squares procedure to the power function shown in the inset of panel A (using only those data where there was more than 3 dB of masking), where β is the exponent that defines the rate of the growth of masking and κ is the constant that determines the masker intensity at which masking begins. The exponent (β) of the power function (the slope of the growth of masking) is shown next to each curve. At 500 Hz (panel A), within the main excitation of the masker, the two masking curves were nearly parallel, with slopes of 0.89 and 0.81 dB/dB for masker peaks and valleys, respectively. In this case, peak-to-valley ratios remained relatively constant over a wide range of masker levels. At 800 Hz (panel B), within the upper accessory excitation of the masker where masking did not begin until the masker was above 50 dB SPL, the two masking curves for peaks and valleys were not parallel but diverged as

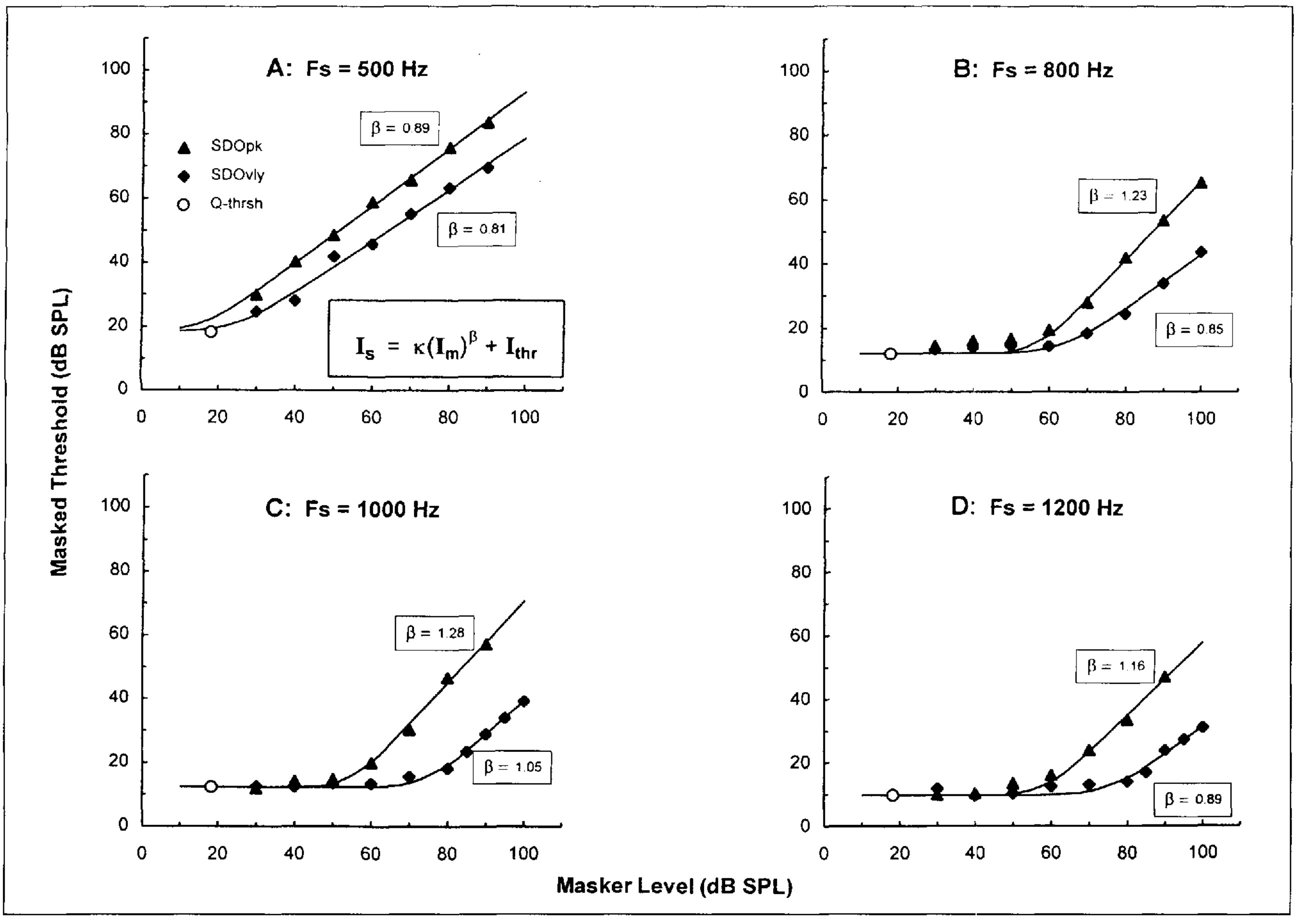

Figure 4. Growth-of-masking curves at AM masker peaks and valleys for different signal frequencies (Fs) from normal-hearing subject SDO. *Filled triangles:* Masked thresholds during masker envelope peaks. *Filled diamonds:* Masked thresholds during masker envelope valleys. *Thin solid curves:* Least-squares regression fits to the masking curves using the power function shown in the inset of panel A. The slope of the growth of masking, given by the exponent (β) of the power function, is shown in the box associated with each masking curve. *Unfilled circle:* Quiet threshold for the AM signal, plotted on the abscissa at quiet threshold for the AM masker.

level increased. The slope of the masking curve for masker peaks was 1.23, reflecting the nonlinear growth of masking typical of upper accessory excitation. The slope of the masking curve for masker valleys was much more gradual at 0.85. Similarly, at 1000 and 1200 Hz (panels C and D), the other two frequencies within the upper accessory excitation, peak-to-valley ratios increased with stimulus level. Slopes for masking in the valleys were substantially smaller than those for masking in the peaks.

4. Discussion

Masked thresholds in the present study for AM masker peaks and valleys confirm Zwicker's observation that envelope resolution is better within the upper accessory excitation than in the main excitation of a fluctuating masker. The comparison of peak-to-valley ratios obtained here for maskers at 500 Hz in four subjects show excellent agreement with Zwicker's measurements at 1000 Hz in one subject. This suggests that the phenomenon of better envelope resolution within the upper accessory excitation should be applicable to other frequency regions and is repeatable among normal-hearing subjects using slightly different procedures. Zwicker (Zwicker, 1976) investigated modulation rates of 10, 30 and 100 Hz, where envelope resolution was better in the upper accessory excitation as well, so the phenomenon appears to be applicable to faster modulation rates.

Better envelope resolution within the upper accessory excitation also seems to apply to randomly fluctuating waveforms such as narrow-band noise. Zwicker and Schütte (Zwicker and Schütte, 1973) measured masking period patterns for narrow-bands of frozen noise and correlated masked thresholds with corresponding instantaneous levels throughout the envelope of the noise. They found that the envelope of the frozen noise was much better represented in the masking period pattern when the test tone was in the upper accessory excitation than in the main excitation.

The excellent envelope resolution exhibited within the upper accessory excitation appears to be determined by well-known psychoacoustic phenomena. Masking during envelope peaks grows steeply, with slopes greater than 1.0, reflecting the well known non-linear growth of simultaneous masking in the upper accessory excitation (Zwicker, 1958). That non-linear growth of simultaneous masking is thought to involve neural masking and suppression mechanisms (Delgutte, 1988; Delgutte, 1990a; Delgutte, 1990b; Javel, 1980; Javel *et al.*, 1983). Masking during envelope valleys grows less steeply, with slopes less than 1.0. The more gradual slopes are consistent with non-simultaneous masking mechanisms (forward masking), which involve an exponential recovery process, presumably from neural adaptation (Luscher and Zwislocki, 1949; Plomp, 1964; Duifhuis, 1973; Fastl, 1977; Jesteadt *et al.*, 1982; Nelson and Freyman, 1987).

Experiments measuring the release from masking within the upper accessory excitation (Buus, 1985; Mott and Feth, 1986; Moore and Glasberg, 1987) have reported masked thresholds for maskers with fluctuating envelopes that are substantially better than those for maskers with relatively flat envelopes. The frequency masking patterns reported for flat-envelope maskers are similar to those observed in the present experiment for masking at envelope peaks. The frequency masking patterns reported for maskers with fluctuating envelopes are similar to those observed here for masking during envelope valleys. The magnitude of the release from masking in those experiments is also comparable to the peak-to-valley masked-threshold ratios observed in the present experiment. These similarities suggest that the release from masking within the upper accessory excitation demonstrated earlier for fluctuating envelope maskers (Buus, 1985; Mott and Feth, 1986; Moore and Glasberg, 1987) is probably governed primarily by within-channel non-simultaneous masking mechanisms, consistent with a listening in the valleys explanation. Unfortunately, those experiments did not evaluate envelope resolution for signals within the main excitation, so comparisons of the release from masking in the main excitation and the upper accessory excitation could not be made.

The lack of excellent envelope resolution within the main excitation for the 4 Hz AM maskers in the present experiment is somewhat perplexing. First of all, one can rule out limitations imposed by the auditory filter, because the stimulus bandwidth is at least an order of magnitude smaller than the critical bandwidth at the masker frequency (Zwicker, 1961). Secondly, there is a considerable period of time during which recovery from adaptation should occur as it does in the upper accessory excitation. The AM masker envelope period was 250 ms, which means that the time between masker peak energy and masker minimum energy was 125 ms. Yet, on average, signal detection during masker valleys was only around 14 dB lower than during masker peaks. A larger amount of non-simultaneous masking during the valleys might account for this, which would be comparable to a decrease in the internally represented (neural) modulation depth, but it is not clear why recovery from forward masking (neural adaptation) should be so much less within the main excitation. Furthermore, if non-simultaneous masking mechanisms were responsible for elevated thresholds during the masker valleys, then the slope of the growth of masking should have been much more gradual than it was. It appears as if the temporally wide valley that was evident in the upper accessory excitation was somehow shortened in duration within the main excitation, so that masking in the valleys behaved more like simultaneous masking. A compressive nonlinearity evident in the main excitation but not in the upper accessory excitation could account for this. Clearly more research is needed to understand this phenomenon.

Regardless of its explanation, the demonstration of better envelope resolution in the upper accessory excitation has important implications for listening to speech sounds in the presence of fluctuating acoustic interference, such as competing talkers. It appears that the ear should do better at perceiving higher-frequency consonant cues, in the presence of primarily lower-frequency vowel energy from the competing talkers, if it can listen within the upper accessory excitation of the interfering sound. Furthermore, persons with high-frequency hearing loss in the frequency region corresponding to the upper accessory excitation should experience considerable difficulty perceiving the appropriate speech cues. Additional research is needed to explore these implications.

Acknowledgement

This research was presented to the Acoustical Society of America at the Memorial Session for Prof. Dr.-Ing. Eberhard Zwicker held at Salt Lake City in May of 1992. The first author is indebted to Eberhard Zwicker for his stimulating discussions and challenging questions during the first author's study visit to Zwicker's laboratory during the Summer of 1987. This research was funded by NIDCD grants DC00149 and DC00110. The authors wish to thank J. Van Essen for developing the computer software that made this work possible, A. C. Schroder for assisting in data collection and analysis and for valuable suggestions to the manuscript, and Sid Bacon for his thorough review of this manuscript. Portions of this research were carried out as part of the requirements for a Master of Arts degree at the University of Minnesota by A.C. (Wilker) Swain.

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