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Evidence that adaptation of suppression cannot account for auditory enhancement or enhanced forward masking

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SUMMARY

Delaying the onset of a signal relative to the onset of a simultaneous notched masker often improves the ability of listeners to 'hear out' the signal at both threshold and suprathreshold levels. Viemeister & Bacon (*J. acoust. Soc. Am.*, **71**, 1502–1507 (1982)) suggested that such auditory enhancement effects could be accounted for if the suppression produced by the masker on the signal frequency adapted, thereby releasing the signal from suppression. In support of their hypothesis, Viemeister & Bacon reported that a masker preceded by an enhancer having no component at the signal frequency produced more forward masking than did the masker by itself. Here evidence is provided from five new experiments showing that adaptation of psychophysical two-tone suppression is inadequate to account either for auditory enhancement effects or for the enhanced forward masking demonstrated by Viemeister & Bacon.

1. INTRODUCTION

When a group of harmonics of equal amplitude are gated on and off together, it is difficult to 'hear out' a single target harmonic. However, if the onset of the target is delayed relative to the onset of the other harmonics, the detectability of the target improves with increasing onset delay (e.g. Viemeister 1980). Similar results are obtained with non-harmonic stimuli (see Viemeister, 1980). Such improvements in both the suprathreshold and threshold salience of a delayed target have been referred to as auditory enhancement (see, for example, Viemeister 1980; Summerfield *et al.* 1987), but here the term signal enhancement will be used to emphasize that the signal is enhanced in simultaneous masking experiments.

Most proposed explanations for signal enhancement have appealed to physiological short-term adaptation (e.g. Smith and Zwislocki 1975), but Viemeister & Bacon (1982) suggested an intriguing alternative. They hypothesized that signal enhancement was the result, not of the reduced masking ability of adapted, non-target maskers, but rather of a true gain in the effective level of the delayed target or signal, caused by adaptation of the psychophysical suppressive effect of the masker on that signal. According to this hypothesis, the psychophysical level of the masker remains unchanged throughout its timecourse, but the suppressive power of the masker declines over time. Hence, a delayed signal is more detectable because it is introduced into a partially, or completely, unsuppressed region. Viemeister & Bacon acknowledged that this proposed adaptation of psychophysical suppression could not be mediated at the level of the 8th nerve, where it has been shown that physiological two-tone suppression does not adapt (Liff & Goldstein 1970).

In apparent support of their hypothesis of adaptation of suppression, Viemeister & Bacon (1982) reported that a harmonic complex produced approximately 8 dB more forward masking when it was preceded by an enhancer that was a longer version of the same complex, but with the component at the signal frequency deleted. Because the enhancer in Viemeister & Bacon's task increased the effectiveness of their forward masker, the difference in forward-masked thresholds obtained with the unenhanced and enhanced maskers will be referred to as masker enhancement.

Here the results of five experiments are reported that confirm and extend Viemeister & Bacon's report of masker enhancement. However, the present data appear to indicate (i) that signal and masker enhancement may not be as closely related as has previously been assumed, and (ii) that neither signal nor masker enhancement can be accounted for by adaptation of psychophysical two-tone suppression.

2. GENERAL METHOD

The same six normal-hearing subjects served in all five experiments. All had a minimum of one year's experience on other psychoacoustic tasks, and all of their data were monitored for evidence of learning. The procedure was adaptive, two-interval, forced-choice, with feedback. Thresholds are expressed as the

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signal level estimated to be required for 79% correct detections. The threshold for each subject in each condition was based on the average of 4–18 blocks of 60 trials each. Standard errors of the mean were typically less than 1 dB within subjects. All listening was monotic. All waveforms were gated with a cosine-squared rise-decay time of 10 ms.

3. EXPERIMENTS AND RESULTS

(*a*) *Psychophysical two-tone suppression*

Viemeister & Bacon (1982) suggested that adaptation of suppression was the mechanism responsible both for signal enhancement in simultaneous masking and masker enhancement in forward masking. Therefore, in the first experiment, psychophysical two-tone suppression (see, for example, Houtgast 1972; Shannon 1976) was measured in the six subjects. The task was forward masking. The signal was a 1000 Hz tone, 20 ms in duration. The masker was a 1000 Hz tone having a level of 50 dB SPL, and the suppressor was a 1150 Hz tone having a level of 70 dB SPL. The common duration of the masker and suppressor was either 50, 100, or 500 ms. The onset of the signal coincided with the offset of the masker and supppressor. A contralateral wideband noise (300–4700 Hz, 40 dB SPL overall) was gated on and off with the masker or suppressor to help reduce any confusion effects that might have contributed to the results (see Moore & Glasberg 1982; Neff 1986). The amount of suppression was calculated as the difference in signal threshold obtained when the masker was presented alone and when the masker and suppressor were presented together.

The six subjects fell into two groups of three each based both upon their signal thresholds in the various conditions, and the magnitudes of their two-tone suppression effects. Three subjects consistently showed the lowest thresholds in the masker-only, suppressor-only, and masker-plus-suppressor conditions. These same subjects also showed typical amounts of psychophysical two-tone suppression, averaging 4, 5 and 8 dB for the 50, 100 and 500 ms stimuli, respectively. The other three subjects always had the highest thresholds in the various conditions, and showed small or even negative two-tone suppression. For these subjects, the average amount psychophysical suppression was about −6, −6 and −1 dB for the 50, 100 and 500 ms stimuli, respectively. (Note that for both groups, the amount of psychophysical suppression increased, or became less negative, with increasing stimulus duration. We return to this point in a later section.)

A close relationship between psychophysical suppression, signal enhancement, and masker enhancement is implicit in Viemeister & Bacon's (1982) proposal of adaptation of suppression. It was therefore predicted that the three subjects who had normal suppression would show the largest amounts of signal and masker enhancement, and that the three subjects who had negative suppression would show the smallest amounts. The results of the following experiments did not meet these predictions.

(*b*) *Signal enhancement*

In the second experiment, signal enhancement was measured in the same six subjects who had participated in the experiment on two-tone suppression. The task was simultaneous masking. Prompted by the stimuli used in the masker-enhancement experiments described below, in this signal-enhancement experiment, the masker covered the frequency range from 100–10000 Hz and contained a spectral notch, 800 Hz in width, centred at 1000 Hz. The signal was a narrowband noise, 800 Hz in width, arithmetically centred at 1000 Hz. The duration of the signal was always 62 ms. The signal and masker were gated off together, but the onset of the masker preceded the onset of the signal by a variety of fringe durations. The spectrum level of the masker was 33 dB SPL. The results are shown separately for the six subjects in figure 1.

For all subjects, the signal became easier to hear as its onset was delayed from the onset of the masker. However, the six subjects fell into the same two distinct groups in terms of their signal thresholds and the magnitudes of their improvements with increasing signal delay. The three subjects who had normal two-tone suppression (open symbols) again showed the lowest thresholds, and also showed the smallest amount of signal enhancement, averaging about 7 dB. The three subjects who had negative two-tone suppression (filled symbols) again showed the highest thresholds, and also showed the largest amount of signal enhancement, averaging about 24 dB. These results are in sharp contrast to the predicted relationship between psychophysical two-tone suppression and signal enhancement, based upon Viemeister & Bacon's (1982) hypothesis of adaptation of suppression.

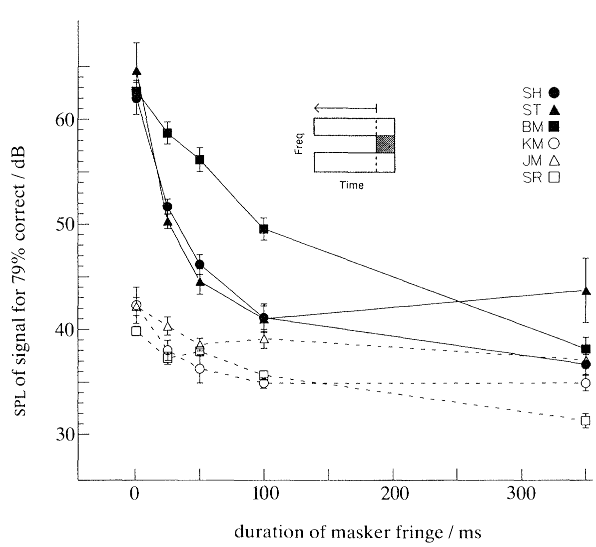

Figure 1. Signal enhancement in simultaneous masking for the three subjects who showed normal psychophysical two-tone suppression (open symbols) and the three subjects who showed negative psychophysical two-tone suppression (filled symbols).

(*c*) ***Masker enhancement***

In the final three experiments, masker enhancement was measured in the same six subjects. The task was forward masking. The signal was a 1000 Hz tone, 20 ms in duration. The masker was a wideband noise covering the frequency range from 100 to 10000 Hz, and the enhancer that preceded the masker covered the same frequency range as the masker, but contained a spectral notch of various widths centered on the signal frequency. The typical duration of the masker was 62 ms, and that of the enhancer was 350 ms. Both the masker and the enhancer were presented at a spectrum level of 33 dB SPL. The results of all three experiments were at odds with the hypothesis of adaptation of suppression.

(*i*) *Notch width in the enhancer*

In the first experiment on masker enhancement, the relative effectiveness of enhancers having a variety of notch widths was examined. Figure 2*a* shows the result for the three subjects with normal two-tone suppression and figure 2*b* shows the results for the three subjects with negative two-tone suppression. All six subjects performed similarly. For both groups, thresholds were higher when the masker was enhanced (squares) than when the masker was presented alone (dotted line), confirming the central result of Viemeister & Bacon (1982). The amount of masker enhancement was greatest for both groups (averaging about 7 dB) when the notch width in the enhancer was 400 Hz, but there was considerable masker enhancement for wider notch widths. The difference in the total duration of the stimuli across the masker-only and enhanced conditions appears to have contributed substantially to the observed masker enhancement only for the narrowest notch widths. This is because thresholds with the wider notch widths were fairly similar when only the enhancer was presented for the duration of the masker-only (62 ms, circles) or for the duration of the enhanced (412 ms, triangles) conditions. As in the experiments above, here, and in the following two experiments, the subjects who showed normal two-tone suppression had somewhat lower thresholds than the subjects who showed negative two-tone suppression. However, because this difference was roughly constant across conditions, the amount of masker enhancement was nearly always within 2 dB across the two groups.

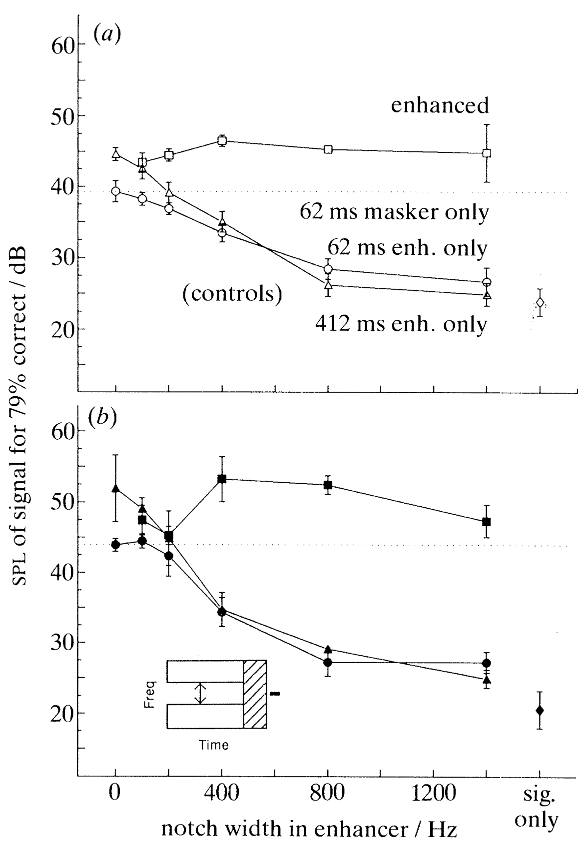

Figure 2. Masker enhancement in forward masking as a function of the notch width in the enhancer for (*a*) the three subjects who showed normal psychophysical two-tone suppression (open symbols) and (*b*) the three subjects who showed negative psychophysical two-tone suppression (filled symbols).

The results of this experiment appear to contradict the proposal that adaptation of two-tone suppression can account for masker enhancement, and therefore signal enhancement. Psychophysical two-tone suppression is greatest when the frequency of the suppressor is about 1.15 times the frequency of the masker and signal (Shannon 1976), and declines as that separation is increased. To the extent that the present results are influenced by two-tone suppression, it would therefore be expected that masker enhancement should be greatest with the notch width of 200 Hz (where the upper edge of the notch was closest to the ideal ratio of 1.15), and should decrease thereafter. However, masker enhancement was minimal with the 200-Hz notch, but was substantial at the wider notch widths.

(*ii*) *Enhancer duration*

In the second experiment on masker enhancement, the growth of the effect of the enhancer upon the masker was investigated by varying the duration of the enhancer. The duration of the masker was always 62 ms. The notch width in the enhancer was 800 Hz. The results were again similar across the two groups of subjects. For both groups, thresholds were higher in the enhanced than in the masker-only condition for all durations of the enhancer, and the difference in the threshold between the two conditions increased from approximately 3 to 9 dB as the enhancer duration was increased from 25 to 450 ms. These results also appear to be inconsistent with the proposal that adaptation of suppression could account for both masker and signal enhancement, because the amount of masker enhancement increased over the same timecourse that psychophysical two-tone suppression increases (see Weber & Green 1978; suppression experiment above).

(*iii*) *Masker duration*

In the final experiment on masker enhancement, the persistence of the enhancer's effect on the wideband masker was examined by varying the duration of the masker. The duration of the enhancer was always

350 ms, and the notch width in the enhancer was 800 Hz. Again the results were similar across the two groups of subjects. For both groups, thresholds were consistently higher in the enhanced than in the masker-only conditions. In the masker-only condition, thresholds increased by about 8.5 dB as the duration of the masker was increased from 22 to 302 ms. In the enhanced condition, however, thresholds increased by approximately 7 dB as the masker duration was increased from 22 to 102 ms, but declined by about 3 dB as the masker duration was increased from 102 to 302 ms. Therefore, the amount of masker enhancement was greatest for masker durations of 42 to 102 ms, reaching a peak of about 7 dB, and then decreased to about 3 dB for the 302 ms masker duration.

These results also do not support Viemeister & Bacon's (1982) proposal that adaptation of suppression can account for masker and signal enhancement. Psychophysical suppressors lose their ability to suppress when they are separated from the signal by only 50 ms (Weber & Green 1978), but enhancers have the ability to produce masker enhancement when they are separated from the signal by as much as 300 ms.

4. CONCLUSIONS

In summary, the results of five experiments appear to indicate that adaptation of psychophysical two-tone suppression cannot account for either signal or masker enhancement, and that signal and masker enhancement may not be as closely related as has previously been supposed. Perhaps the strongest evidence for the dissociation between adaptation of psychophysical two-tone suppression and signal enhancement was that the three subjects who showed negative two-tone suppression exhibited the largest amount of signal enhancement. The close relationship between signal and masker enhancement was also brought into question because subjects showing markedly different amounts of signal enhancement showed very similar amounts of masker enhancement. Finally, the parametric manipulations of the notch width in the enhancer, the duration of the enhancer, and the duration of the masker in the masker-enhancement experiments all were inconsistent with previous results obtained with psychophysical two-tone suppression, and thus also appeared to indicate that neither signal nor masker enhancement could be accounted for by an adaptation of suppression.

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Discussion

B. C. J. Moore (*Department of Experimental Psychology, University of Cambridge, U.K.*). In the interpretation of her results, I think that Dr Wright should carefully consider the possible cues used by the subjects in the various tasks. Whenever I see large individual differences between normally hearing subjects, I suspect that these arise from differences in the use of cues or processing strategies, rather than from differences in peripheral auditory processing.

In the case of 'unmasking' effects in forward masking, we have presented evidence that these can be strongly affected by the cues available to the subjects. In the 'reference' condition (on-frequency narrowband masker alone) thresholds may be high because the subjects lack an effective cue to distinguish the signal from the masker. Adding extra components to the masker can provide such a cue, thereby reducing thresholds (Moore 1980*a*, *b*) 1981; Terry & Moore 1977). Reductions in threshold in such cases should not be taken as indicating physiological suppression. Subjects may fail to show an unmasking effect for two reasons; firstly, they may 'find' an adequate cue in the reference condition, so that the added masker component provides no extra cue; secondly, they may not make effective use of the potential cue provided by the added masker component. The addition of a contralateral cue may be sufficient to provide an effective cue for some subjects (Moore & Glasberg 1982) but not for all subjects.

In the experiments showing 'enhanced' forward masking, it is possible that part of the enhancement effect arises from a kind of 'distraction'. Close to threshold, the perceptual cue associated with the presence of the signal is rather subtle. When the spectrum of the masker is changed substantially just before the signal occurs, the highly salient perceptual change associated with this may distract the subject from the subtle change associated with the signal, thereby raising threshold. A related explanation has been proposed by Bacon & Moore (1987) to account for certain temporal effects in simultaneous masking.

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B. A. WRIGHT. As Dr Moore has indicated, there is considerable evidence that the amount of forward masking can be influenced by the available listening cues. However, we list below our reasons for believing that such differences cannot easily account for our results. First, in Dr Moore's example, the masker in the reference condition was a narrowband noise, a stimulus which appears to be optimum for producing high thresholds in forward masking due to confusion about when the masker ends and the signal begins. In our experiment, the masker was a pure tone, a stimulus for which such confusion effects are considerably smaller or non-existent (Neff 1986). Second, we gated a contralateral wideband noise with the masker or suppressor to help mark the end of the masker (Moore & Glasberg 1982; Neff 1986) to reduce any small confusion effects that might have been present. Third, Dr Moore implies that thresholds are reduced in masker-plus-suppressor conditions simply because the suppressor helps to indicate the end of the masker. According to this interpretation, none of our subjects had suppression. Rather, the subjects who showed normal suppression were very good at using the timing information provided by the offset of the suppressor or the contralateral noise, and the subjects who showed negative suppression were unable to use these offset cues. Even if Dr Moore were correct, because all of our subjects had at least some signal enhancement and all showed masker enhancement, the resulting conclusion would be the same as we offered: that adaptation of psychophysical two-tone suppression cannot account for those enhancement effects.

We also think it unlikely that enhanced forward masking or masker enhancement results simply from 'distraction'. Our reasons are as follows. First, the greatest amount of masker enhancement was seen for notch widths in the enhancer of 400 Hz and greater. It is not clear how a distraction interpretation could account for a small amount of masker enhancement with a 200 Hz wide notch, and greater enhancement with wider notch widths. Second, Dr Moore suggests that the spectral change in the masker occurring 'just before' the signal distracts the subject. It would therefore seem that the amount of masker enhancement should steadily decrease as the duration of the masker was increased, and the signal onset correspondingly delayed relative to masker onset. However, in the present experiments, the amount of masker enhancement was greatest and relatively constant across the intermediate masker durations (42–102 ms). Third, confusion effects in forward masking are greatest when the masker and signal are similar in their temporal properties (Moore & Glasberg 1982; Neff 1985). One might thus predict that the greatest amount of distraction would occur when the masker and signal durations were equal. However, in the present experiments, the greatest effects were for masker durations that exceeded the 20 ms duration of the signal. Fourth, Viemeister & Bacon (1982) showed masker enhancement at signal delays greater than could be easily accounted for by confusion (Neff 1985). Fifth, we have pilot data using a signal located at the centre frequency of the notch in the enhancer (a standard masker-enhancement task) and for signals located at frequencies above and below the presumably enhanced region. According to the distraction hypothesis, masker enhancement should be obtained with all three of these signals. In our pilot experiment, thresholds were always higher in the enhanced condition than in the masker-only condition. However, these theshold differences were greater than could be accounted for by differences in the duration of the masker only for the signal centered in the notch of the enhancer. Thus, contrary to the prediction of a general distraction process, masker enhancement appears to require that the enhanced region overlap the signal in frequency.

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