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Psychophysical response growth under suppression

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1 Introduction

A reduction of a response to a tone in the presence of another tone, called two-tone suppression, has been demonstrated at different levels of the auditory processing and linked to the operation of the active mechanism in the cochlea. Since two-tone suppression is a product of nonlinear processing, it is of interest to study the effects of level on the size of this phenomenon. Duifhuis (1980) measured level effects in psychophysical suppression and observed that suppression is not exclusively dependent on the level of the suppressor nor does it stay constant for a constant ratio of the suppressor and suppressee amplitudes. Data of Ruggero, Robles, and Rich (1992) provided more insight into the effect of an off-frequency suppressor on basilar-membrane (BM) responses to CF tones. They demonstrated that the BM response to a CF tone grows in a compressive manner when the tone is presented alone. Adding an off-frequency suppressing tone changes the shape of the response function measured at CF by shifting the threshold for detecting the tone toward higher levels and increasing the slope of the function. Consequently, for a fixed-level suppressor, the magnitude of suppression decreases with increasing level of the suppressed (CF) tone. This finding is inconsistent with Duifhuis's observation that two-tone suppression "increases as the overall level increases". It may also be inconsistent with the auditory-nerve data of Javel, Geisler, and Ravindran (1978), which showed a parallel shift of rate-level functions in the presence of a suppressor. Their data, however, were obtained from high-spontaneous-rate fibers with low thresholds and small dynamic ranges, and thus they only covered a range of levels, for which BM processing is linear.

A reduction of the response at CF in the presence of a suppressing tone presumably reflects a reduction in gain. An important question is whether the effective reduction in gain is simply attenuative or whether it is proportional to the gain at CF in the absence of the suppressor. These two gain reduction schemes lead to different predictions about the magnitude of suppression across levels of the suppressed tone. In the former case, a constant magnitude of suppression across levels of the suppressee would be observed whereas in the latter case, the magnitude of suppression would decrease with increasing suppressee level.

Previous psychophysical studies of suppression did not provide data that could be used to make inferences about the magnitude of suppression across suppressee

levels since they varied the suppressor level while keeping the suppressee level constant or they covaried both levels keeping the difference between them constant (Shannon 1976; Duifhuis1980). In contrast, the present experiment measured suppression for different levels of the tone to be suppressed presented with a fixed-level suppressor. The purpose of this experiment was to determine whether psychophysical suppression measured for a fixed-level suppressor decreases with increasing level of the suppressee, consistent with the mechanical data of Ruggero *et al.* (1992), or suppression stays constant across suppressee levels, consistent with the auditory-nerve data of Javel *et al.* (1978).

2 Methods

Using a three-interval forced-choice procedure, detection of a 10-ms 4-kHz probe was measured in forward masking for a 100-ms 4-kHz masker in one condition and a two-tone complex consisting of a 4-kHz masker and a simultaneous 4.8-kHz suppressor in another condition. The probe was temporally separated from the masker (and the suppressor when present) by a 2-ms gap. Within an experimental run, the level of the probe was fixed and the level of the masker was varied adaptively using a 3-up, 1-down stepping rule. When the suppressor was present, its level was fixed within a run. Several levels of the probe, ranging from 45 to 80 dB SPL (for one subject a 40-dB SPL probe was also included) were used to obtain growth-of-masking functions. The growth-of-masking functions were obtained for five suppressor levels between 40 and 80 dB SPL in steps of 10 dB. A band of noise extending from 3 to 5 kHz was presented simultaneously with the probe. This was done to reduce the advantage of using spread of excitation toward higher frequencies for probe detection in the masker-alone condition (the spread of excitation was at least partially masked by the excitation produced by the suppressor, in the masker-plus-suppressor condition). For each probe level, the noise level was set 15 dB below the level that would mask the probe. Additionally, a 50-dB-SPL 1-ERB band of noise centered at 4 kHz was presented to the non-test ear for the duration of the masker, to help listeners temporally resolve the probe from the masker. All stimuli were gated with 5-ms raised-cosine ramps. Visual feedback indicating the correct response was provided after each trial. Final threshold estimates were obtained by averaging threshold masker levels obtained in six separate runs.

Three normal-hearing listeners participated in the study.

2 Results

Figure 1 shows data for the individual listeners. Masker levels necessary to mask the probe are plotted as a function of the level of the probe for the masker-alone (open circles) and the masker-plus-suppressor (filled symbols) conditions. These plots will be referred to as growth-of-maskability (GMB) functions. Different symbols in each panel represent results for a different suppressor level. For lower probe levels, all three subjects required higher masker levels to mask the probe

when the suppressor was present, consistent with the notion that the suppressor had the effect of reducing the gain. At higher probe levels, similar masker levels had to be used in the presence and absence of the suppressor. In some cases, lower masker levels were sufficient to mask the probe with the suppressor present (subjects S2 and S3 at two highest probe levels). Possible explanations for this effect will be discussed below.

Generally, the GMB functions measured with a suppressor present have a shallower slope over a wide range of probe levels than the GMB functions measured without a suppressor. For a given probe level, the masker levels necessary to just mask the probe in the presence and absence of a suppressor presumably produce the same internal response. Thus, any increase in probe level would require the same increase in internal response to the masker in the presence and absence of a suppressor. A shallower slope of the GMB function implies that to produce the same increase in internal response, a smaller increase in masker level was required when the suppressor was present. This, in turn, implies a steeper growth of response to the masker in the presence of a suppressor, consistent with the notion that the BM response to a CF tone is more linear in the presence of an off-frequency suppressor.

Figure 2 shows the amount of suppression computed by taking the difference between masker levels required to mask a fixed-level probe, in the presence and absence of the suppressor. Different symbols represent the estimated suppression for different suppressor levels. For a fixed suppressor level, the magnitude of suppression was the largest for low masker/suppresser levels. As the level of the masker increased the estimated magnitude of suppression decreased. At the highest levels, negative magnitudes of suppression were obtained,

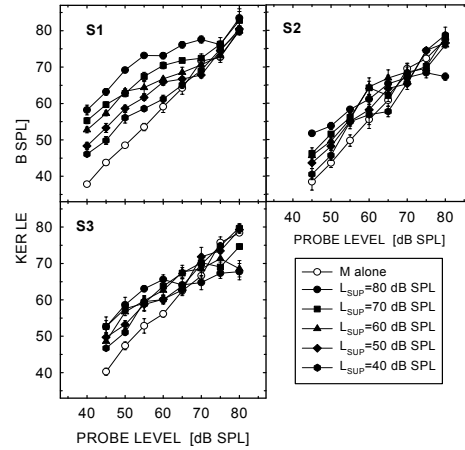


Fig. 1. Masker levels necessary to mask the probe in the presence (filled symbols) and absence (open symbols) of a suppressor.

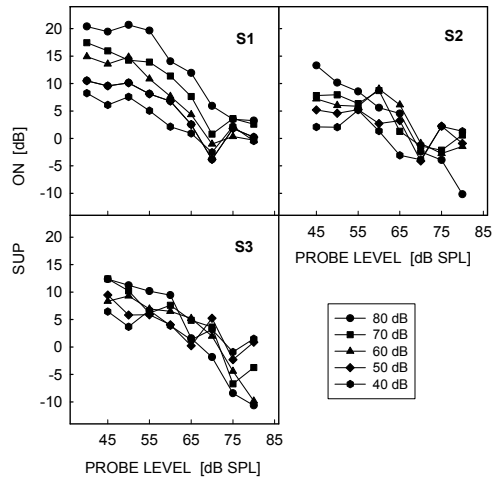


Fig. 2. The estimated magnitude of suppression.

indicating that at these levels the suppressor aided forward masking.

For subject S1, the magnitude of suppression increased with increasing level of the suppressor, except for the highest probe levels. The other two subjects show the same result for the lowest probe (and masker) levels, but this trend is not clearly represented by their data for medium and high levels, mainly because they generally exhibited much less suppression than S1.

3 Model

Since all the masked thresholds were measured for the same short probe-masker delay, a simple power spectrum model representing peripheral processing can be used to account for the data under the assumption that the temporal integrator that is operating at a higher processing stage is linear. The most commonly used power spectrum model is based on a sum of ROEX filters. The recent version of this model proposed by Glasberg and Moore (2000) included nonlinear processing. Although their model can be used to successfully predict data from simultaneous masking, it should not be used to account for forward masking by complex maskers because it does not allow for separation of excitatory and suppressive masking. An alternative approach proposed here assumes the presence of two cascaded filters in the peripheral processing. The first, “passive filter”, is linear and is assumed to control the gain and bandwidth of the second, level-dependent “active filter”. The idea of modeling the peripheral processing at a given place on the BM by two cascaded filters with a nonlinearity sandwiched in-between has been used in the past (e.g., Pfeiffer 1970; Duifhuis 1980; Plack, Oxenham, and Drga 2002). The difference between the present approach and the past studies is that in our model, the second filter has a bandwidth that co-varies with the gain applied by this filter to the input stimulus. A filter with variable gain and bandwidth was used in the auditory-nerve model of Zhang, Heinz, Bruce, and Carney (2001). The bandwidth of the active filter is controlled by making the damping time of this filter a function of gain, which in turn is a function of the total level at the output of the passive filter. The function is such that the damping time decreases as the output of the passive filter increases. The decreasing time constant results in a broadening of the active filter with increasing level.

Predictions by the proposed model are shown in Fig. 3 along with the data for listeners S1 and S2 (for clarity, predictions are shown only for selected levels). Data from S3 were generally similar to those from S2, and therefore predictions for S3 are not shown here. The predictions were produced with two 3-rd order gammatone filters. The frequency response of the passive filter was

$$G_{pf}(2\pi f) = \frac{(n-1)!}{2[1 + j2\pi \cdot \tau_{pf} \cdot (f - cf)]^n}, \quad (1)$$

where n is the order of the filter ($n=3$), τ_{pf} is the time constant describing the damping of the passive filter. The frequency response of the active filter was

$$G_{af}(2\pi f) = \frac{g \cdot (n-1)!}{2[1 + j2\pi \cdot \tau_{af}(g) \cdot (f - cf)]^n}, \quad (2)$$

where g is a function of the level at the output of the passive filter and is expressed in linear units. The dependence of time constant τ_{af} on the output of the passive filter was defined through the gain function using the following formula

$$\tau_{af}(g) = (\ln(10 \cdot g) / \ln(10)) \cdot \tau_{pf}. \quad (3)$$

This formula was chosen arbitrarily to ensure that when there is no gain applied by the system ($g=1$), the active filter is identical to the passive filter and that for large gain values, the bandwidth of the active filter is not unrealistically narrow.

In pilot simulations, the gain function proposed by Glasberg and Moore (2000) was used. Although their function led to reasonable qualitative agreement with our data, the quantitative agreement was poor for lower probe levels. More accurate predictions were obtained using a three-segment function to describe the response growth on the BM, with each segment represented by a straight line. The first and third

segment had a slope of 1, and the middle segment had a slope less than 1 and represented compressive nonlinearity. The following parameters defining the nonlinear input-output (I/O) function were changed iteratively to obtain predictions shown in Fig. 3: the maximum gain, G_{max} , which is defined as the gain applied to the 0-dB SPL input stimulus; the breaking points (x-values) between the linear and compressive sections of the I/O function, B_1 and B_2 ; and the slope of the compressive segment, α . The gain function in dB was derived for the iterated parameters of the I/O function. It was then converted to gain g in linear units. Table I shows values of all the parameters used in the model and the ERB values for the active filter computed for $g=G_{max}$.

Subj.	τ_{pf} [ms]	G_{max} [dB]	B_1 [dB SPL]	B_2 [dB SPL]	α [dB/dB]	ERB _{af} [Hz]
S1	0.4	50	45	75	0.18	133
S2	0.4	35	40	70	0.4	178

Table I. Parameter values used to produce model predictions shown in Fig. 3.

The predictions are reasonable although their agreement with the data could be improved by optimizing the choice of the function relating the damping time of the active filter to the gain function.

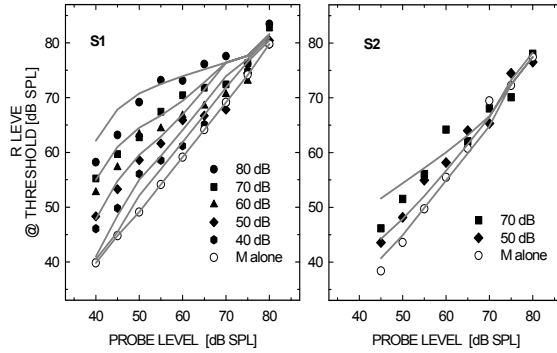


Fig. 3. Model predictions and data for S1 and S2.

4 Discussion

The experimental data presented in Fig. 1 revealed that the response to a 4-kHz tone can be reduced in the presence of a 4.8-kHz tone when the tones are presented at appropriate levels. Generally, for a fixed-level suppressor, the difference between the response to the suppressee presented without and with the suppressor is greater when the suppressee level is low. As the suppressee level increases, that difference becomes smaller indicating less suppression of the response. This finding disagrees with the observation by Duifhuis (1980) that suppression increases as the overall stimulation level increases. Duifhuis varied the probe level to find its forward-masked thresholds for a fixed-level masker presented with and without the suppressor and his estimated suppression was, therefore, affected by the nonlinear processing of the probe. The decreasing suppression with increasing suppressee level is consistent with the mechanical data of Ruggero *et al.* (1992).

At the highest probe levels, negative suppression was observed for subjects S2 and S3, when the suppressor level was high. One explanation for this result is in terms of spread of excitation. Since the probe has shorter duration than the masker, it produces a broader excitation pattern due to energy splatter across frequency. If the probe energy falling into higher-frequency channels contributes to probe detection, the presence of the high-level higher-frequency suppressor may reduce the detectability of the probe. In this case, lower masker levels would be required to mask the probe. To test the plausibility of this explanation, thresholds for detecting the probe in forward masking were measured in the presence of the suppressor presented alone. The highest level of the suppressor used in this study (80 dB SPL) elevated threshold for detecting the probe by 7-8 dB. The usability of spread of excitation was also limited by the bandpass noise presented simultaneously with the probe. Therefore, it seems unlikely that the suppressor would have such a big effect on the detectability of the probe when the probe is presented at levels that are well above its threshold. It is possible that some other, non-sensory, factors played a role when the probe and the suppressor levels were high (e.g. a greater perceptual similarity between the probe and the suppressor).

Generally, the data are consistent with the notion that the effect of a suppressor is to reduce the gain applied at the place corresponding to the frequency of the suppressee. A power spectrum model assuming two cascaded filters, one (linear) representing passive processes, and the other (level dependent) representing the active process in the cochlea, produces reasonable predictions for the level effects. The variable bandwidth of the active filter allows for suppressive only and combined excitatory and suppressive masking. The parameter values used to produce predictions shown in Fig. 3 are reasonable and are in agreement with the values that were used in other studies of the effects of nonlinear processing on masking.

5 Conclusions

The following conclusions may be drawn from this psychophysical experiment:

(1) The response to a tone becomes less compressive in the presence of a suppressing tone, consistent with the mechanical data of Ruggero *et al.* (1992).

(2) The magnitude of suppression for a fixed-level suppressor decreases with increasing level of the suppressed tone.

(3) The observed level effects are consistent with a reduction of gain that is proportional to the amount of gain applied to the test tone in the absence of a suppressor.

(4) A power spectrum model implementing two filters, a linear filter followed by a level-dependent filter with varying gain and bandwidth, reasonably predicts the observed level effects in psychophysical suppression.

Acknowledgments

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