Modeling the effects of compression and suppression on estimates of auditory frequency selectivity

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Introduction

Frequency selectivity is one of the basic properties of the auditory system: it describes its ability to partly separate the frequency components of complex stimuli. This property of hearing in humans can be characterized behaviorally using masking experiments. Estimates of tuning derived from nonsimultaneous masking conditions, when the signal and the masker do not overlap in time, tend to show sharper tuning than those derived from simultaneous masking conditions. It has been suggested that a major part of the difference between estimates of frequency selectivity in the two masking conditions may be due to effects of suppression (see [1] for a review). Suppression refers to the phenomenon that the auditory system's response to a sound can be decreased by the presence of another sound.

The present study investigates, using a modeling approach, an alternative explanation based on the effect of peripheral compression alone. To this end, a computational auditory model was used to simulate two behavioral measures of frequency selectivity: psychophysical tuning curves (PTCs) and notched-noise thresholds.

As the underlying tuning of the auditory system is of interest, it is relevant to consider which estimates reflect this tuning better, those obtained from simultaneous masking or those from nonsimultaneous masking experiments. Further, as the temporal position of the signal causes an apparent change in frequency selectivity, the processing of dynamic signals, such as speech, may be affected if the auditory filters change with time. It is therefore important to understand these effects of frequency selectivity and their relation to the active processes in the cochlea.

Model and method

The model used in this study was the computational auditory signal processing and perception model (CASP) [2], with some modifications. Instead of using a modulation filterbank stage, a modulation lowpass filter with a cutoff frequency of 8 Hz was considered. The model uses the dual-resonance nonlinear (DRNL) filterbank as the frequency selective stage [3]. The basic structure of the DRNL filter is shown in Figure 1. The filter consists of two paths: a linear path representing the high-amplitude linear response of the basilar membrane, and a nonlinear path accounting for the low-amplitude linear and medium amplitude compressive response. The nonlinear element in the filter is an instantaneous "broken-stick" function that is composed of a linear and a compressive part.

The parameters of the DRNL were modified based on suggestions by [4] to better account for suppression-related data.

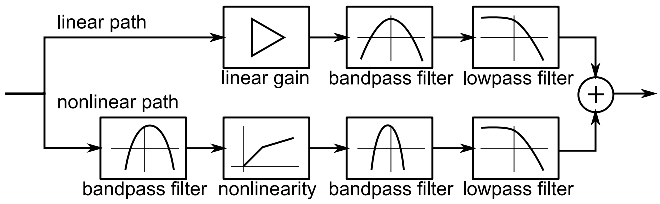

Figure 1: The basic structure of the DRNL filter (see text).

Specifically, the two bandpass filters in the nonlinear path had different bandwidths and center frequencies (CF). The first filter had a somewhat higher bandwidth and was centered slightly above CF, whereas the second filter had a somewhat narrower bandwidth and was centered slightly below CF. The exact filter bandwidths were adjusted to get a reasonable match with measured pilot notched-noise and PTC data.

In order to investigate the effect of peripheral compression on the estimates of tuning, two versions of the model were used to simulate each experiment. A "nonlinear" version, as described above, and a "linear" version, in which the broken-stick function was replaced by a linear function with all other parameters unchanged.

All simulations were performed at 1 kHz, with only one frequency channel. The nominal center frequency of the filter corresponded to the frequency of the test tone. The configuration of the stimuli for the PTCs followed [5], with the exception that a low-level notched noise was not used. For the notched-noise simulation, the setup was as in [6].

Modeling suppression

The model can simulate some aspects of two-tone suppression, including suppression-areas that are broadly similar to human psychophysical data (not shown here, but see [4]). This is because it includes a *bandpass nonlinearity*, a structure composed of a compressive nonlinearity between two bandpass filters, which has previously been shown to be a simple model of two-tone suppression [7]. In the context of the model, suppression refers to the reduction of the level of the signal at the output of the DRNL stage due to the addition of another (masker) tone or noise. If the masker level is sufficiently high and off-frequency to the signal, the masker and the signal are compressed together, but subsequently most of the masker energy is removed by the second filter. This leaves a lower signal level at the output than in the case without the masker due to the compression of the signal. It is clear that this interaction between the masker and the signal can only occur if they are present at the same time, i.e. in simultaneous masking, but not in forward masking.

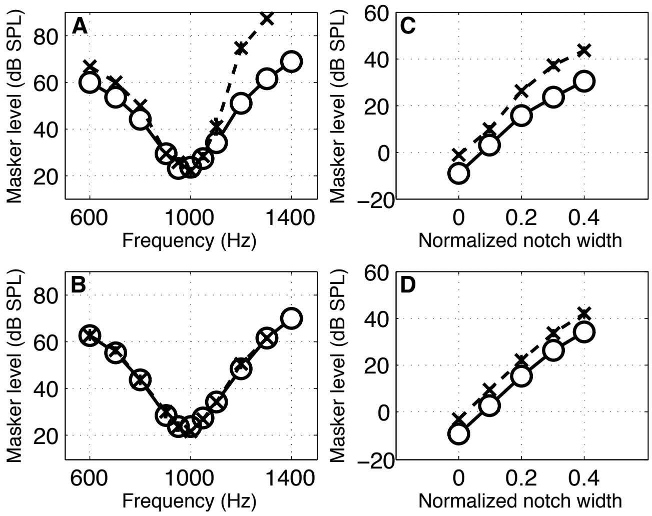

Figure 2: Simulation results. Panels A and B show simulated PTCs, and panels C and D show simulated notched-noise thresholds. The top panels (A and C) show the predictions of the nonlinear model, the bottom panels (B and D) show predictions of the linear model. Circles indicate simultaneous, crosses forward masking thresholds.

Results

The results of the simulations are shown in Figure 2. The nonlinear model (upper panels) predicts a sharper tuning for forward masking, as evidenced by the narrower tuning curve and the steeper slope of the notched-noise function in forward masking (marked by crosses). The differences in tuning are similar to those observed in human data [5, 6]. The linear model (lower panels) shows similar tuning for both masking conditions, and this tuning is close to the simultaneous-masking prediction of the nonlinear model.

Discussion

Suppression and frequency selectivity

To explain the link between changes in frequency selectivity and suppression, one hypothesis has been that the influence of suppression is more widely tuned than that of excitation. Then, in simultaneous masking, a combination of suppression and excitation produces masking, whereas in forward masking, this additional, more widely-tuned influence of the masker on the signal is absent. Hence, the measured tuning in forward masking is sharper.

This hypothesis can be tested in the framework of the model by comparing the frequency-selectivity estimates for the nonlinear and the linear model versions. In the model, suppression arises as a result of compression; therefore both suppression and compression are absent in the linear version. If suppression would cause a broadening of tuning in simultaneous masking in the nonlinear model, then with suppression removed, the tuning should be narrower in the linear model.

The simulation results from the present study are clearly not consistent with this hypothesis. In fact, the opposite was observed: the simultaneous tuning estimate remains the same between the model versions, and it is the forward masking estimate that is broader in the linear model.

The effect of compression

Consider that in forward masking the masker is processed independently from the signal because of the temporal gap between them. If the masker level is sufficiently high, the masker is compressed by itself. As a result, a greater change in masker level is needed before the compressor to achieve the same change in level as when the masker is processed linearly. If a filter follows the nonlinearity, as in the current model, the compressive function before the second filter effectively sharpens the second filter (viewed from the input). In simultaneous masking, the masker and the signal are processed together, and any compression of the masker also reduces the signal level, such that the relative levels of the signal and the masker do not change. Therefore, this sharpening caused by the compressive function only occurs in forward masking.

From this reasoning, it follows that in the linear model, where compression is removed, the tuning in forward masking should be wider than in the nonlinear model. This is consistent with the simulation results.

In summary, two possible mechanisms affecting tuning estimates in the different masking paradigms have been identified: (1) suppression, as a result of compression, causing a *widening* of tuning in *simultaneous* masking; and (2) compression directly leading to a *narrower* tuning in *forward* masking. In the framework of the model, explanation (2) seems to be dominant, based on a comparison of the linear and nonlinear model versions. Consequently, the simultaneous masking estimates reflect the underlying tuning of the model more closely. The critical assumption here is that some sort of filtering follows the compressive function, and that the bandpass nonlinearity structure used in the DRNL filter is an appropriate model of the behavior of the basilar membrane.

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