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Comparison of the compressive-gammachirp and double-roex auditory filters

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1 Introduction

The comparison of psychophysical and physiological measures of frequency selectivity is often described either in terms of the rounded exponential, or roex, auditory filter, which was introduced to explain tone-in-noise masking in humans, or the gammatone auditory filter, which was introduced to characterize the reverse-correlation, or 'revcor' data in cats. Recently, a descendent of the gammatone filter, referred to as the gammachirp (GC) auditory filter, has been developed to describe both the level-dependent physiological data from small mammals and the level-dependent notched-noise masking data from humans. The architecture of the compressive GC filter is intended to reflect recent developments in cochlear physiology, and in particular, how the tip and tail components of the cochlear filter interact as a function of stimulus level. In this paper, we describe a double roex filter system with comparable functionality to the GC filter. It has separate tip and tail filters that interact to produce the appropriate level-dependent gain in the passband of the filter. Both the double roex filter and the compressive GC were fitted to two large sets of simultaneous masking data to provide a basis for comparing the filter systems in detail.

2 The compressive gammachirp auditory filter

Irino and Patterson (1997, 2001) developed the gammachirp filter as an asymmetric level-dependent version of the gammatone filter with the advantages of both the gammatone and roex filters. They showed that an 'analytic' form of the GC filter could explain level-dependent tone-in-noise masking data (e.g., Rosen and Baker 1994), and that a 'compressive' form of the GC filter could explain the frequency

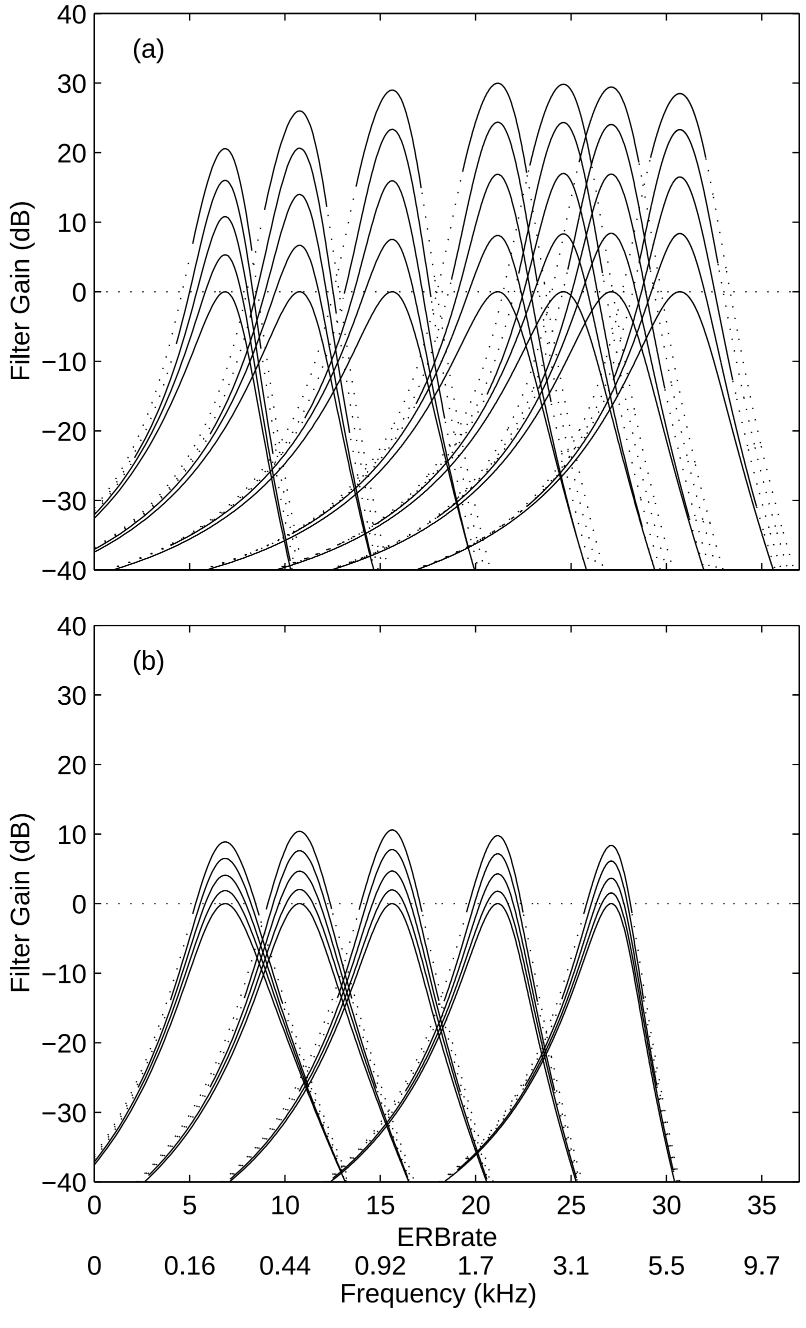

Fig. 1. Compressive gammachirp filters for the threshold data of (a) Baker *et al.* (1998) with probe frequencies 0.25, 0.5, 1.0, 2.0 3.0, 4.0 and 6.0 kHz, and (b) Glasberg *et al.* (2000) with probe frequencies 0.25, 0.5, 1.0, 2.0 and 4.0 kHz.

glide, or chirp, observed at the onset of the impulse response of the cat's cochlear filter (de Boer and Nuttall 2000). Recently, Patterson, Unoki and Irino (2003) fitted the compressive GC filter to the data of Baker, Rosen and Darling (1998) and Glasberg and Moore (2000), both of whom measured threshold for a probe tone in the presence of an asymmetric notched noise over, what is effectively, the entire range of frequencies and levels encountered in everyday hearing. A version of the PolyFit procedure (Baker *et al*, 1998) was used to fit the data for all probe frequencies simultaneously. The result for the data of Baker *et al.* (1998) was the seven families of compressive GC filters shown in Fig. 1a. The five functions in each family show filters at probe levels from 30 to 70 dB in 10-dB steps. The families of filters all have the same general form; the bandwidth is roughly uniform across frequency on this ERBrate scale (Glasberg and Moore 1990), and the gain of the filter *decreases* monotonically with increasing stimulus level in the passband of the filter, as would be expected. The range of the gain, or compression, is a little under 30 dB at the lower probe frequencies (0.25, 0.5 and 1.0 kHz) and a little over 30 dB at the higher probe frequencies (2.0, 3.0, 4.0 and 6.0 kHz). When the compressive GC was fitted to all five probe frequencies in the data of Glasberg *et al.* (2000), the result was the five families of compressive GC filters shown in Fig. 1b. The families of filters have the same general form; the bandwidth is roughly uniform across frequency and the gain of the filter *decreases* monotonically with increasing stimulus level. However, the two data sets produce quite different estimates of the asymmetry and maximum gain in the system. The filters in Fig. 1b are more symmetric and the maximum gain is limited to about 10 dB. Moreover, the maximum gain is slightly less at the higher probe frequencies.

3 The double-roex auditory filter

The term 'roex auditory filter' actually describes a family of ***ro***unded-***ex***ponential filters developed to explain the masking of a sinusoidal probe by a notched noise (Patterson 1976). When the noise bands are close to the signal, threshold is dominated by masker components in the passband of the auditory filter and the data can be explained with a simple, one-parameter roex; that is, a filter composed of a pair of back-to-back exponentials, $\exp(-pg)$, multiplied by a term, $(1+pg)$ that rounds the peak and makes the filter continuous at its center frequency (Patterson, Nimmo-Smith, Weber and Milroy 1982); g is a normalized frequency variable that describes the distance in frequency from the probe frequency f_0 to the edge of the noise in terms of the center frequency, so $g=|f-f_0|/f_0$. The parameter, p, describes the rate of decay of the exponentials that form the ***p***assband of this roex(***p***) filter. When the notch is very wide, the roex(*p*) filter underestimates threshold badly, indicating that the tails of the auditory filter at frequencies remote from the center are much shallower. So, the model was extended to include a second roex to represent the ***t***ails of the auditory filter. The two filters operate in parallel and their relative ***w***eighting is ***w***.

In experiments like those performed by Baker *et al.* (1998) and Glasberg and Moore (2000), the noise bands are positioned both symmetrically and asymmetrically about the signal frequency, and the level of the masker is varied.

Such experiments reveal that the auditory filter becomes progressively more asymmetric and the tip filter becomes less prominent as stimulus level increases. These effects can be accommodated by allowing p and t to have different values in the ***l***ower and ***u***pper halves of the filter, and allowing w to vary with level in which case there are five filter parameters, t_l, t_u, w, p_l, p_u. The centre frequency of the tip filter is also allowed to shift relative to the centre frequency of the tail filter. If the normalized frequency variables of the tail and tip filters are g_1 and g_2, and f_{rat} is the ratio of the two centre frequencies, then $g_1 = |f - f_0| / f_0$, $g_2 = |f - f_{\mathrm{rat}} \cdot f_0| / f_0$, the tail and tip filters are

$$
\begin{aligned}
W_{\mathrm{tail}}(g_1) &= \begin{cases} (1+t_l g_1)\exp(-t_l g_1) & f < f_0 \\ (1+t_u g_1)\exp(-t_u g_1) & f \geq f_0 \end{cases} \\
W_{\mathrm{tip}}(g_2) &= \begin{cases} (1+p_l g_2)\exp(-p_l g_2) & f < f_{\mathrm{rat}} \cdot f_0 \\ (1+p_u g_2)\exp(-p_u g_2) & f \geq f_{\mathrm{rat}} \cdot f_0 \end{cases}
\end{aligned} \tag{1}
$$

and, the frequency response of the double roex auditory filter is

$$W(f) = W_{\mathrm{tail}}(f) + w \cdot W_{\mathrm{tip}}(f). \tag{2}$$

This double roex auditory filter was fitted to the data of Baker *et al.* (1998) and Glasberg *et al.* (2000) using the PolyFit procedure (Baker *et al.* 1998) which enabled us to fit all probe frequencies simultaneously. The result for the Baker *et al.* (1998) study is the seven families of double roex filters shown in Fig. 2a. The five functions in each family show filters at probe levels from 30 to 70 dB in 10-dB steps. The families of filters all have the same general form; the bandwidth is roughly uniform across frequency and the gain of the filter *decreases* monotonically with increasing stimulus level in the passband of the filter. The maximum gain is around 20 dB. Both the bandwidth and the maximum gain are less than estimated with the compressive GC; the asymmetry is similar for the two different filters.

Figure 2b shows the tail filters and sets of tip filters that together produced the families of double roex filters in Fig. 2a. Each of the double roex filters in the family associated with one probe frequency is produced by combining the fixed tail filter for that probe frequency with the appropriate tip filter, weighted by the factor w. The weight, or gain, is largest at low stimulus levels and decreases as stimulus level increases. The low-frequency side of the tail filter is much shallower than the high-frequency tail, as on the passive basilar membrane observed at high stimulus levels. However, low-frequency side becomes shallower, and the filter more asymmetric, as probe frequency increases. The five tip filters shown are for levels from 30 to 70 dB in 10 dB steps. The low-frequency slope of the tip filter becomes slightly steeper as probe frequency increases, and as a result, the passband of the double roex filter becomes more symmetric as probe frequency increases.

The simultaneous fit for the Glasberg *et al.* (2000) data is shown by the five families of double roex filters in Fig. 3a. The families of filters all have the same general form and the gain of the filter *decreases* monotonically with increasing stimulus level in the passband of the filter. However, the gain provided by the tip filter is greatest at 1.0 kHz and decreases at both lower and higher probe frequencies. The tail filters in Fig. 3b have a uniform shape across frequency and

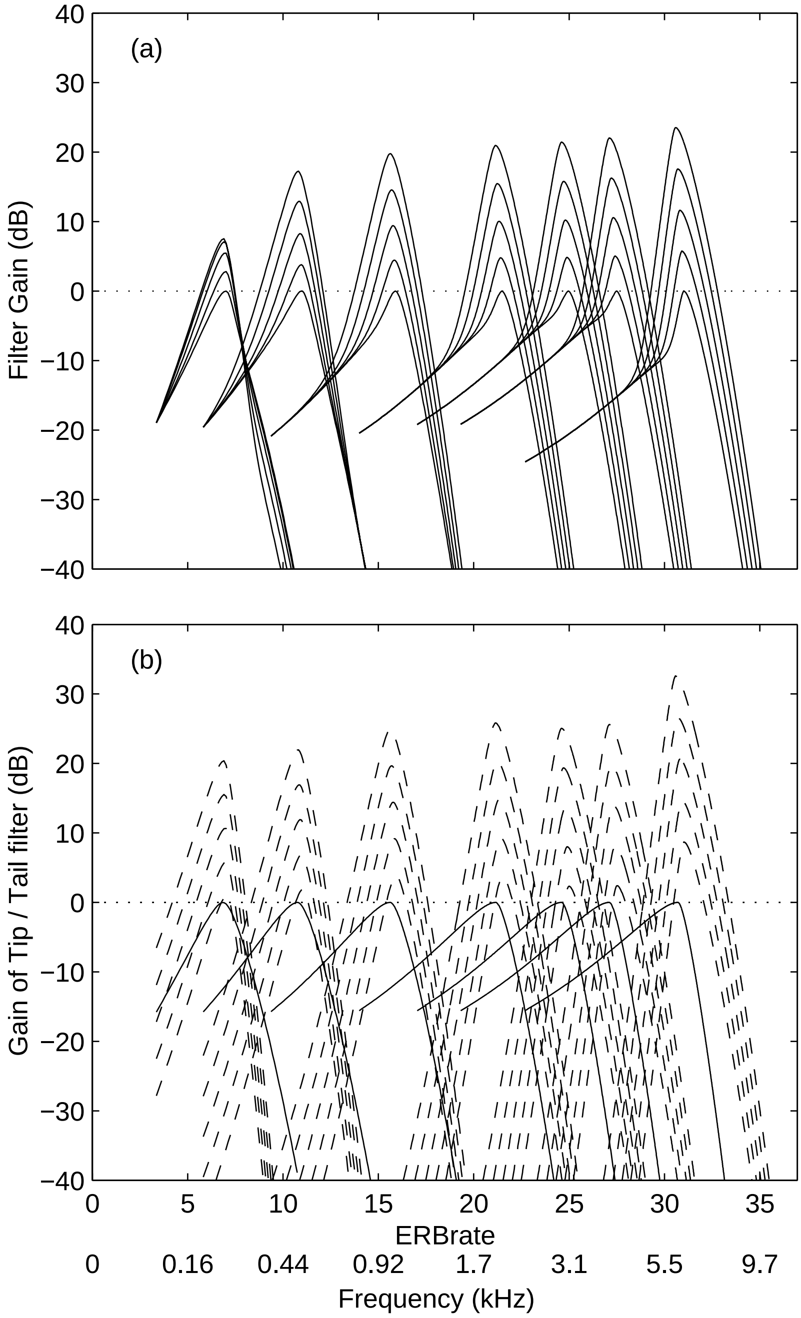

Fig. 2. Families of (a) double roex filters for the data of Baker *et al.* (1998), with (b) the corresponding tail filters (solid line) and sets of tip filters (dashed lines).

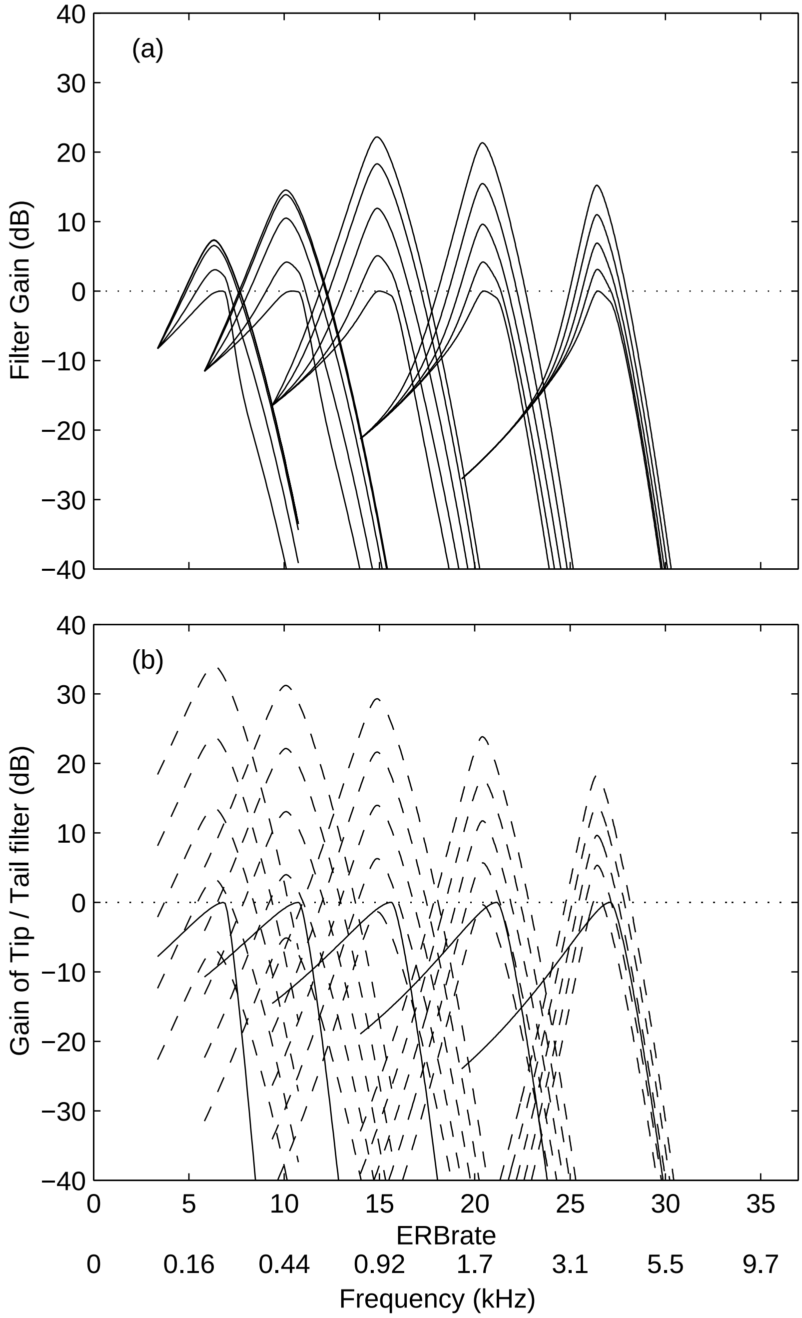

Fig. 3. Families of (a) double roex filters for the data of Glasberg *et al.* (2000), with (b) the corresponding tail filters (solid line) and tip filters (dashed lines).

are reasonably asymmetric. The tip filters are much broader at the lower probe frequencies than those in Fig 2b, and the maximum gain of the tip filter is much greater at the lower probe frequencies than for the Baker *et al*. data (Fig. 2b).

In summary, even when the PolyFit procedure is used to fit all probe frequencies simultaneously, the estimates of filter bandwidth, asymmetry and maximum gain vary considerably from study to study and from the double roex filter to the compressive GC auditory filter. The fitting process includes two additional parameters, for the efficiency constant, K, and the threshold asymptote observed with wide notches at low levels. These parameters reduce the gain of the filters at the lowest and highest probe frequencies in Figs 2a and 3a, relative to what might have been expected from the corresponding tip and tail filters in Figs 2b and 3b, respectively. However, this does not explain the variability of bandwidth, asymmetry and maximum gain across studies and filter types.

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