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Published in:
Meeting on Acoustics. Proceedings

Link to article, DOI:
10.1121/1.4799637

Publication date:
2013

Citation (APA):
Marschall, M., MacDonald, E., & Dau, T. (2013). The effect of compression on tuning estimates in a simple nonlinear auditory filter model. Meetings on Acoustics. Proceedings, 19. DOI: 10.1121/1.4799637

Proceedings of Meetings on Acoustics

Volume 19, 2013 http://acousticalsociety.org/

ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Psychological and Physiological Acoustics
Session 3aPP: Auditory Physiology and Modeling (Poster Session)

3aPP19. The effect of compression on tuning estimates in a simple nonlinear auditory filter model

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Behavioral experiments using auditory masking have been used to characterize frequency selectivity, one of the basic properties of the auditory system. However, due to the nonlinear response of the basilar membrane, the interpretation of these experiments may not be straightforward. Specifically, there is evidence that human frequency-selectivity estimates depend on whether an iso-input or an iso-response measurement paradigm is used (Eustaquio-Martin et al., 2011). This study presents simulated tuning estimates using a simple compressive auditory filter model, the bandpass nonlinearity (BPNL), which consists of a compressor between two bandpass filters. The BPNL forms the basis of the dual-resonance nonlinear (DRNL) filter that has been used in a number of modeling studies. The location of the nonlinear element and its effect on estimated tuning in the two measurement paradigms was investigated. The results show that compression leads to (i) a narrower tuning estimate in the iso-response paradigm when a compressor precedes a filter, and (ii) a wider tuning estimate in the iso-input paradigm when a compressor follows a filter. The results imply that if the DRNL presents a valid cochlear model, then compression alone may explain a large part of the behaviorally observed differences in tuning between simultaneous and forward-masking conditions.

Published by the Acoustical Society of America through the American Institute of Physics

[DOI: 10.1121/1.4799637]
Received 21 Jan 2013; published 2 Jun 2013

INTRODUCTION

Frequency selectivity is one of the fundamental properties of the auditory system and describes the ability to separate frequency components of complex stimuli. This property of hearing in humans can be characterized behaviorally using masking experiments. However, it is known that the response of the basilar membrane of the inner ear exhibits a compressive response to stimuli at medium sound pressure levels, and that frequency selectivity at low levels is aided by an active mechanism in the cochlea (Pickles, 1986). Consequently, the application of linear analysis techniques to estimate frequency selectivity is not straightforward, as the involved nonlinearities need to be taken into account. This is especially relevant when comparing results from frequency selectivity measures obtained through different measurement paradigms. In particular, behavioral estimates of frequency tuning have been shown to depend on the temporal configuration of the stimulus, i.e., whether simultaneous or non-simultaneous masking is used (Moore et al., 1984; Oxenham and Shera, 2003); on the sound pressure level of the stimulus (Patterson and Moore, 1986); and on whether the input level ("iso-input" tuning) or the output level ("iso-response" tuning) of the filter is held constant in the measurement paradigm (Eustaquio-Martín and Lopez-Poveda, 2011).

Estimates of tuning derived from non-simultaneous 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 (Moore et al., 1984, Oxenham and Shera, 2003). Non-simultaneous masking conditions include forward masking, where the masker precedes the signal, and the pulsation threshold task, where the signal and the masker are alternated in time. It has been suggested that the difference between simultaneous and non-simultaneous estimates of frequency selectivity may be mostly due to effects of suppression, but the exact mechanism and the extent of suppressive contributions is under debate (see Moore, 1986, for a review). Suppression here refers to the nonlinear phenomenon whereby the auditory system's response to a sound can, under certain conditions, be decreased by the presence of another sound. In animal studies, suppression has been observed as two-tone rate suppression in auditory-nerve fibers (Sachs and Kiang, 1968) and also in the mechanical response of the basilar membrane (Ruggero, 1992). Houtgast (1972) found psychophysical evidence of two-tone suppression in humans where a decrease in the pulsation threshold of a tone was observed as a result of an added suppressor.

In this paper, we present an alternative explanation for the observed tuning differences, based on compression. For a linear system, tuning estimates measured using either an iso-input or iso-response method will be identical. However, for a nonlinear filter, the tuning estimates derived from each method may differ. Here, we explore how these tuning estimates differ depending on filter structure and the implication this has on behavioral estimates of frequency tuning in the auditory system.

ISO-INPUT AND ISO-OUTPUT TUNING ESTIMATES OF NONLINEAR FILTER STRUCTURES

In an iso-input paradigm, a constant signal input power is maintained for the frequency range of interest, and the tuning characteristics of the system are described by the output power as a function of the input frequency. Conversely, in an iso-response paradigm, the signal input power is adjusted instead, so that the output power (response) of the system remains constant at each frequency. The tuning in the system is then described by the input signal power required to achieve constant output, as a function of frequency. For a linear system, these two methods lead to the same result. This is illustrated in Panel A of Figure 1.

Now consider the case where a simple compressive non-linear element is added to before the filter (see Figure 1, Panel B). For an iso-input paradigm, the signal power as a function of frequency is still constant after compression. Therefore, the output levels reflect the underlying tuning of the filter and the tuning estimate remains unchanged. However, if an iso-response paradigm is used, this is not the case. For frequencies that are attenuated by the filter, a larger change in input level is required due to compression. Thus, the addition of the compressor before the filter leads to tuning estimates that are sharper than the underlying filter tuning when an iso-response method is used.

Conversely, consider the case where a compressor is added after the filter (see Figure 1, Panel C). If an iso-response method is used, the compressor has no effect as the output level of the filter is already constant. However, if an iso-input method is used, the compressor following the filter reduces the difference of the filter output across frequency. This leads to an estimate of tuning that is wider or less sharp than the underlying filter.

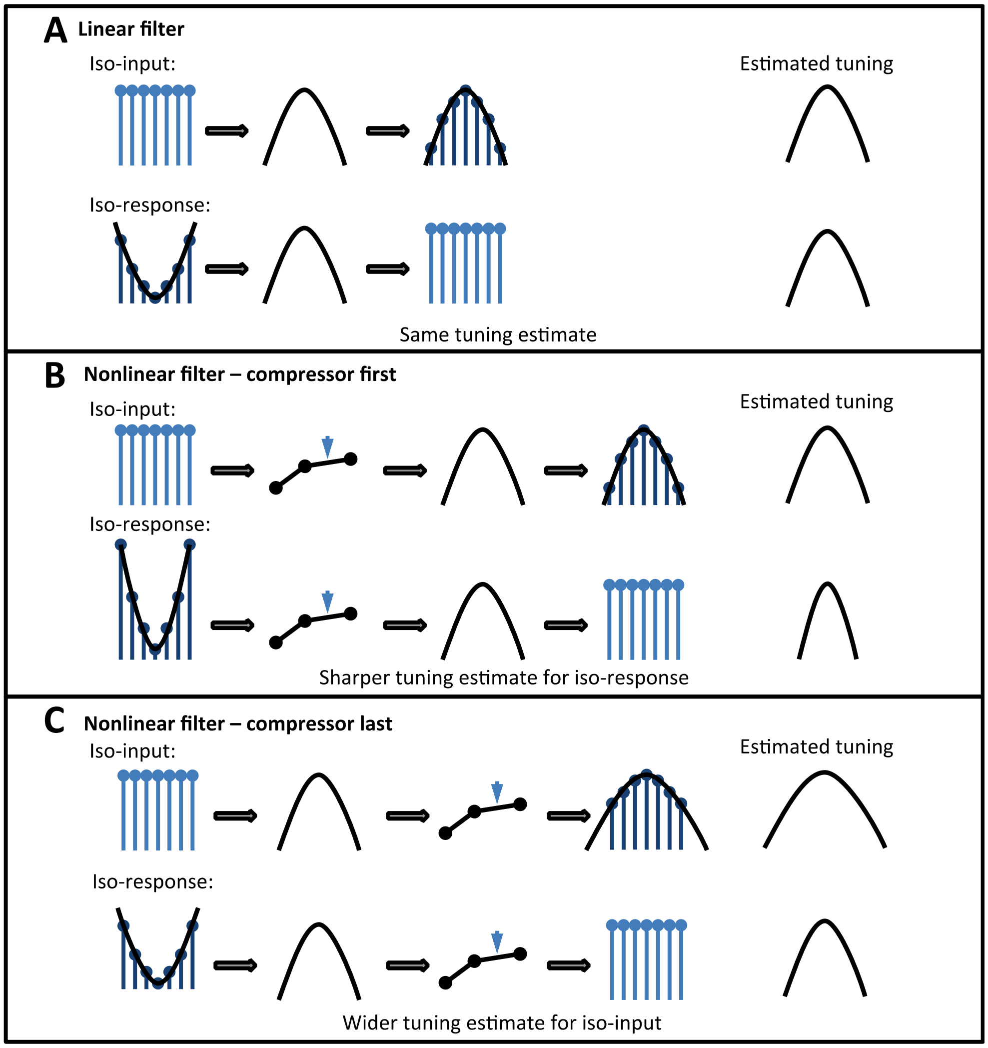

FIGURE 1. Schematic of tuning estimates from iso-input and iso-response methods when applied to a linear filter (A), a compressor followed by a linear filter (B), and a linear filter followed by a compressor (C),

Now consider the case of a bandpass nonlinearity, where the compressor is level dependent and sandwiched between two bandpass filters. Tuning estimates from simple simulations of both iso-input and iso-response methods are plotted in Figure 2. In the simulation, the compressor was set to be linear at low levels, compressive at medium levels (5:1 compression ratio), and linear again at high levels, to mimic the compressive behavior of the basilar membrane. For simplicity, triangular filters, as well as dimensionless, logarithmic input and output values were assumed. The input level for the iso-input condition was varied from 20 to 80 dB in 10 dB increments. The reference level for the iso-response condition was varied from 10 to 40 dB in 5 dB increments.

Due to the properties of the nonlinearity, at low and at high levels the behavior of the system is linear. Therefore the tuning estimate with both paradigms gives the same filter shape, and corresponds to the filtering produced by the two filters applied in succession. However, at medium levels, where the compressive function is active, the differences between the two paradigms become apparent. When the signal level at the nonlinearity reaches the compression threshold, the slopes of the estimated filter function are affected. A large level difference between two frequency points at the input of the compressor is transformed into a smaller one at the output. For the iso-input paradigm, the amplitude changes arising as a result of the first filter are compressed, while those resulting from the second filter are unaffected. Thus, in the region of compression, the estimated filter slope will be shallower than in the linear case. For the iso-response paradigm, due to the compression, larger differences are needed at the input of the compressor to counteract the attenuation of off-center frequencies by the second filter. This leads to a steeper estimated filter slope for the whole system.

A further consequence of the two filter arrangement, specifically that of a filter preceding the nonlinearity, is that the onset of compression is frequency dependent. More off-frequency components require a higher level at the input than on-frequency components to be processed compressively. This effect can also be seen in Figure 2. Changes in the filter slopes, indicating the onset and offset of compression, appear at different levels for different frequencies.

To summarize, when the bandpass nonlinearity is investigated with an iso-input paradigm, the estimated tuning is wider for the compressive region than in the linear case. Conversely, when an iso-response paradigm is used, the estimated tuning is narrower than in the linear case. This implies that the measurement paradigm has to be carefully considered when estimating tuning of nonlinear systems.

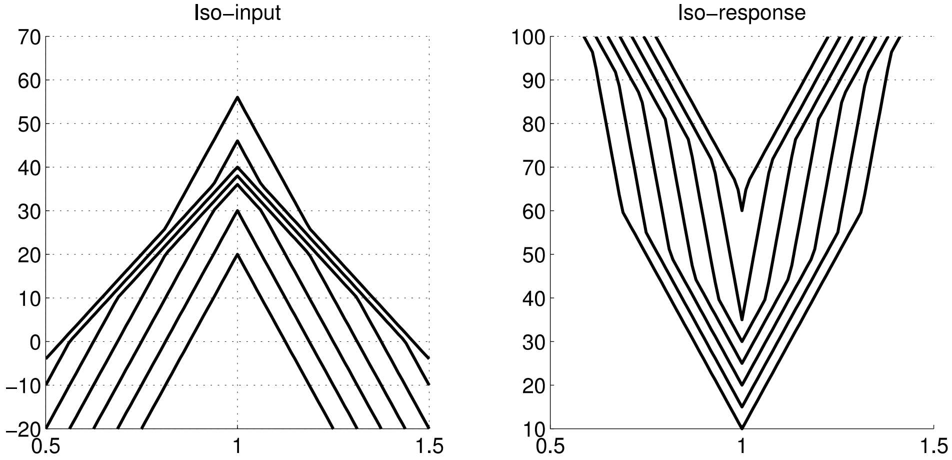

FIGURE 2. Simple simulation of tuning estimates at different levels from iso-input (left) and iso-response (right) methods when applied to a bandpass nonlinear filter. In the compressive region, a shallower tuning is observed with the iso-input method. In contrast, with the iso-response method, a sharper tuning is seen in the compressive region.

THE SHARPENING OF TUNING IN FORWARD MASKING

As mentioned previously, tuning estimates derived from non-simultaneous masking paradigms have been observed to be sharper than those derived from simultaneous masking paradigms. While this phenomenon has been attributed to suppression, it may also be a result of compression. So far, only single sinusoids have been considered. However, when investigating frequency selectivity using a psychophysical task, additional signals are required as it is not possible to access the output of the auditory filters directly. In a typical forward masking paradigm, a probe tone is used to gauge the excitation from a masker at the (frequency) place of the probe. Thus, the level of the probe tone is held constant and the level of the off-frequency masker is varied such that the probe tone is just audible. This corresponds to an iso-response paradigm where we assume that the probe tone will become audible when the signal-to-noise ratio (SNR) at the nonlinear filter output reaches some fixed level.

Consider the behaviour of a bandpass nonlinearity in a forward masking paradigm. Assuming that the impulse responses of the filters in the bandpass nonlinearity are short compared to the temporal separation of the masker and probe, then the masker and signal are processed independently. If the masker level is sufficiently high, the masker is compressed but the probe tone is not. As the masker moves further off-frequency, a greater change in masker level is needed at the input to the compressor in order to achieve a fixed SNR at the compressor output. This will result in a sharpened tuning estimate. In contrast, in a simultaneous masking paradigm, the masker and the signal are processed together. Thus, 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, the sharpened tuning observed in forward masking vs. simultaneous masking experiments could be explained directly by cochlear compression, without considering suppression explicitly. Here, it is further assumed that the bandpass nonlinearity presents a valid functional model of the nonlinear behavior of the basilar membrane. This assumption, however, is supported by a number of studies having successfully used models based on the bandpass nonlinearity (e.g., Lopez-Poveda and Meddis, 2001; Plack et al., 2002; Jepsen et al., 2008) to account for a wide range of human psychophysical data.

SUMMARY

In this paper we have demonstrated that tuning estimates of nonlinear filters can vary significantly depending on whether an iso-input or iso-response measurement paradigm is used. This suggests that the measurement paradigm used to estimate tuning of nonlinear systems needs to be considered carefully. Further, given a small set of plausible assumptions, we have demonstrated that cochlear compression can explain the sharpening of tuning observed in non-simultaneous masking paradigms.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of Siemens Audiology Solutions.

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