

Inferring properties of IHC excitation from psychophysical growth of masking

S. T. Neely and H. Dai

*Boys Town National Research Hospital
555 North 30 Street, Omaha, Nebraska, 68131, U.S.A.
neely@boystown.org*

1. Introduction

Fletcher and Munson (1937) derived a transformation from masking level to specific loudness $N_x(M)$ that was independent of frequency or place. They showed that when $N_x(M)$ was applied to a masking pattern for an arbitrary, broadband stimulus, the area under the resulting specific-loudness pattern predicted the loudness of that stimulus. Steinberg and Gardner (1937) used this specific-loudness transformation and measured masking patterns (Wegel and Lane, 1924) to model the abnormally rapid growth of loudness known as “recruitment”. Likewise, the recent model of loudness described by Moore and Glasberg (1997) also assumes that the specific-loudness transformation is the same across all places on the basilar membrane (BM).

Intermediate between the acoustic masking stimulus and specific loudness is the mechanical excitation to hair bundles of the inner hair cells (IHC). Just as specific-loudness transformation is independent of frequency and place, we expect that the transformation from masking level to IHC excitation is also independent of frequency and place, because the anatomy of IHCs does not vary much along the length of the cochlea. We know from direct measurements that the growth of BM vibration at a given place is linear at frequencies well below the characteristic frequency (e.g., Rhode, 1971; Ruggero and Rich, 1991). Likewise, the transformation from BM vibration to IHC excitation (i.e., displacement of the stereocilia of the IHC) at a given place, although difficult to observe, should be linear. However, measurements of the growth of masking for a simultaneous, low-frequency masker show slopes that are steeper than linear (e.g., Wegel and Lane, 1924; Egan and Hake, 1950; Bacon, et al., 1999). Taken together, these observations suggest the presence of an expansive nonlinearity between IHC excitation and specific loudness. This expansive nonlinearity may be located at the IHC or at some neural stage of the central auditory system.

Bacon et al. (1999) computed slopes for the growth of masking for signal frequencies one half-octave above the masker frequencies and noted that a “change in slope” was better correlated with the amount of masking than with either signal or masker SPL. Such deviations from a slope of one suggest the presence of nonlinearity in the masking-to-IHC-excitation transformation. The observation that the variation in slope is best correlated with amount of masking supports the assumption that the IHC excitation transformation is not very dependent on frequency or place.

In this paper, we explore ways of making inferences about IHC excitation from tone-on-tone masking measurements.

2. Simulated masking patterns

A simple example will illustrate a possible technique for estimating IHC excitation patterns from measurements of masking patterns. For convenience, we use a formula from Moore and Glasberg (1997) to generate simulated masking patterns for a 1-kHz masker, which are shown in Figure 1. These masking patterns show rapid growth at high frequencies, a feature called *upward spread of masking* (USM). The shift in signal threshold due to the masking is the *amount of masking*. The same masking data can be plotted as a function of masker level for each signal frequency. The resulting growth-of-masking (GOM) curves are shown in Figure 2. The GOM curves each have a single slope due to the simplicity of the generating formula. We can use the GOM curves to help us derive a transformation from *masking patterns* in Figure 1 to *IHC excitation patterns*.

We know that (1) BM vibration is linear in the “tail” of its response pattern and (2) the transformation from BM vibration to IHC excitation is probably linear. Therefore, we can identify the level dependence of the USM as being due to the transformation from IHC excitation to masking. On the basis of causality, it is reasonable to assume the existence of a monotonic function $F()$ that determines the amount of masking (at a given place along the BM) from IHC excitation, $M = F(E)$. Because $F()$ is monotonic, its inverse will also exist, allowing us to derive IHC excitation from the amount of masking, $E = F^{-1}(M)$. If we can estimate $F^{-1}()$, then we can use this function to transform masking patterns into IHC excitation patterns.

Since the GOM curves in Figure 2 have slopes ranging from 1.0 to 2.2, we must choose a single frequency at which to force linear growth in the derived IHC excitation pattern. For example, we can obtain IHC excitation patterns with linear growth at 3 kHz by selecting $F^{-1}(M) = (M - 10) / 2.07$. The resulting estimates of IHC excitation patterns are shown in Figure 3. Note that the IHC excitation patterns grow linearly (1 dB/dB) at 3 kHz and show compressive growth at the place where the characteristic frequency (CF) equals

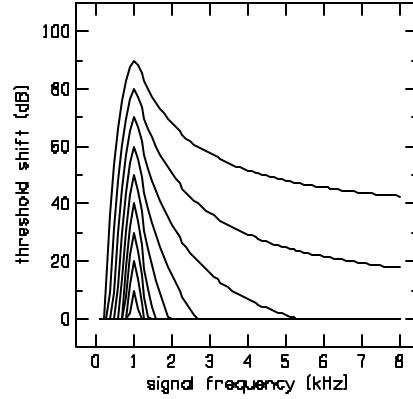


Figure 2. Masking patterns computed from the Moore-Glassberg formula. Each curve represents the amount of masking for a given masker level, in 10 dB steps.

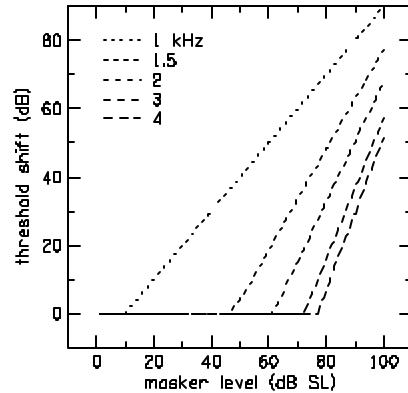


Figure 1. Growth of masking for several signal frequencies.

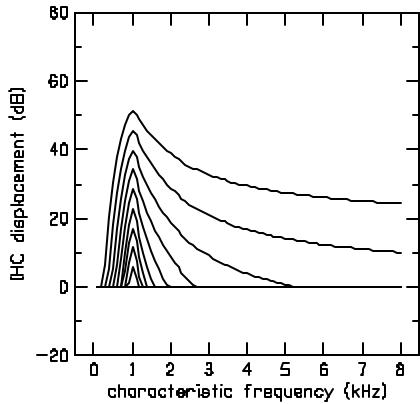


Figure 3. IHC excitation pattern.

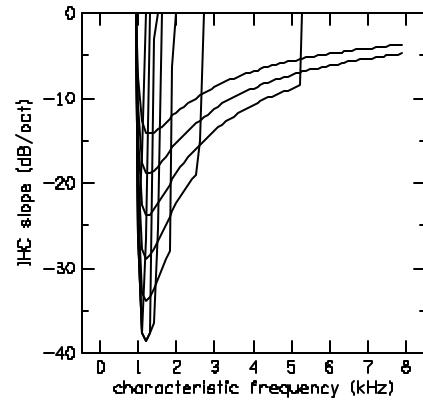


Figure 4. IHC excitation slope.

the masker frequency (1 kHz). These are two desirable properties for IHC excitation patterns and validate our choice for $F^{-1}()$.

3. Measured growth of masking

OHC and IHC contributions.

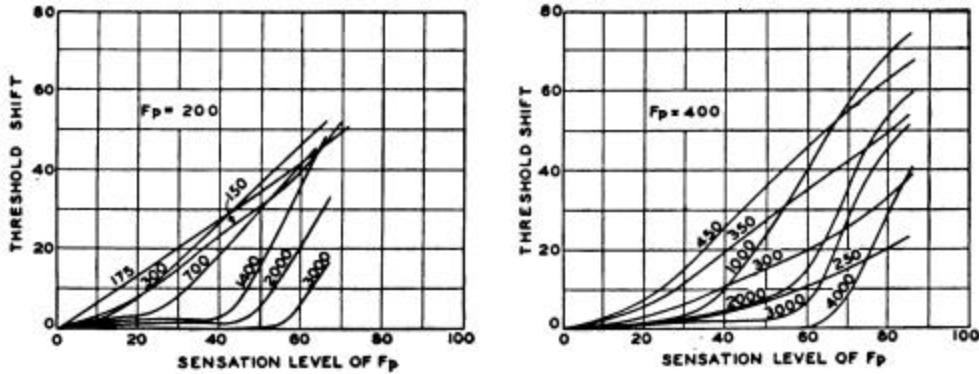


Figure 5. Growth of masking from Wegel and Lane (1924).

4. Discussion

This procedure for obtaining IHC excitation patterns from masking patterns can be extended and refined to obtain patterns that are usable for separating IHC and OHC losses.

Allen and Sen (1999) have recently argued that the “tail” slope (as a function of place) is much smaller for IHC excitation than for BM excitation. They base this argument, in part, on an analysis of GOM data (Wegel and Lane, 1924) for signal frequencies much higher than the masker frequency. This issue is of concern because we need to derive IHC excitation patterns. The masking pattern formula of Moore and Glasberg (1997) obscures details about the masking pattern “tail”, so it cannot be used to address this issue. Directly measured GOM curves based on simultaneous masking contain additional information that can be used to estimate the “tail” slope of the IHC excitation pattern. A novel procedure for

estimating the slope of the IHC excitation “tail” has been developed and is described in the Research Design and Methods section below.

5. Acknowledgements

Acknowledgements should follow the text and precede the references.

6. References

- Allen, J. B. and Sen, D. (1999). “Is tectorial-membrane filtering required to explain two-tone suppression and the upward spread of masking?” presented at the *Symposium on Recent Developments in Auditory Mechanics*, Sendai, Japan.
- Bacon, S. P., Boden, L. N., Lee, J., and Repovsch, J. L. (1999). “Growth of simultaneous masking for $f_n < f_s$: frequency and level,” *J. Acoust. Soc. Am.* **106**, 341-350.
- Egan, J. P. and Hake, H. W. (1950). “On the masking pattern of a simple auditory stimulus,” *J. Acoust. Soc. Am.* **22**, 622-630.
- Fletcher, H. and Munson, W. A. (1937). “Relation between loudness and masking,” *J. Acoust. Soc. Am.* **9**, 1-10.
- Moore, B. C. J. and Glasberg, B. R. (1997). “A model of loudness perception applied to cochlear hearing loss,” *Auditory Neuroscience* **3**, 289-311.
- Rhode, W. S. (1971). “Observations of the vibration of the basilar membrane in squirrel monkeys using the *49*, 1218-1231.
- Ruggero, M. A. And Rich, N. C. (1991). “Furosemide alters organ of Corti mechanics: evidence of feedback of outer hair cells upon the basilar membrane,” *J. Neuroscience* **11**, 1057-1067.
- Steinberg, J. C. and Gardner, M. B. (1937). “The dependence of hearing impairment on sound intensity,” *J. Acoust. Soc. Am.* **9**, 11-23.
- Wegel, R. L. and Lane, C. E. (1924). “Auditory masking of one pure tone by another,” *Phys. Rev.* **24**, 266-285.