Comments

Comment by Divenyi:

If you substitute the equality in your equation (1) for the right-hand side of equation (3), you obtain exactly the format which, when integrated, yields Fechner's logarithmic law of sensory magnitude. Unfortunately however, as Zwislocki (1986) demonstrated, the law does not hold for loudness.

Zwislocki, J. J. and Jordan, H. N. (1986) On the relations of intensity jnd's to loudness and neural noise. J. Acoust. Soc. Am. 79, 772-780.

Reply:

We agree with Zwislocki that Fechner's law does not hold for loudness. Fechner postulated that the loudness JND (ΔN) was constant (i.e., level-independent). Fechner's law follows from this postulate and Weber's law, which states that the intensity JND (ΔI) is proportional to intensity (see Allen and Neely 1997). In our equation (1) we assume that the loudness JND is proportional to the square-root of loudness and therefore not constant, which is contrary to Fechner's postulate. Furthermore, we do not expect Weber's law to hold for the sinusoidal stimuli used in our experiment. We should not expect Fechner's law to hold for our results because neither of its prerequisites hold. It should also be noted that compression, which is represented by the variable α in equation (3), is not level-independent, as demonstrated by our results shown in Fig. 2. The level dependence of compression further complicates the relation between loudness and intensity. The integration that you describe will not yield Fechner's law because neither α or ΔN are constant. Fechner's law should have been repealed a long time ago (Stevens 1961).

Stevens, S. (1961) To honor Fechner and repeal his law. Science 133, 80-86.

Comment by Kollmeier:

I strongly disagree with your first conclusion that loudness growth is a more or less direct measure of cochlear compression. When looking at frequency-specific ABR responses as a function of stimulus level (Dissertation O. Fobel, Universität Oldenburg, http://medi.uni-oldenburg.de), neither the slope of loudness with level nor the interindividual differences are represented in the magnitude of the response of the first central stations of the auditory pathway. The same holds for other retrocochlear physiological measures in humans (such as, e.g., the increase in stapedius reflex reaction as a function of level) across normal listeners and hearing-impaired listeners with recruitment. It thus seems that the large interindividual differences in loudness perception are not due to differences in cochlear compression but primarily reflect the individual reference frame in intensity perception (i.e., they reflect a more cognitive effect). In other words: intensity coding and loudness perception reflect a variety of (yet not well understood) influences along the auditory pathway that makes a simple relation between cochlear compression and loudness improbable. One example of such an influence not yet accounted for is the fact that the fine structure of the hearing threshold also influences the shape of the individual isophones, up to 50 dB above threshold (Mauermann, M., Long, G., Kollmeier, B.; 2000 Comparison of fine structure in isophone contours, threshold in quiet and otoacoustic emissions. In Association for Research in otolaryngology Abstracts, ARO, 23, p. 284, or the paper by Glenis Long in the previous ISH in Mierlo).

Reply:

We view loudness growth as an indirect measure of cochlear compression. We disagree that the inter-subject variability we observe in our loudness measurements cannot be attributed to intersubject variability in cochlear response growth. Recently, we have made measurements of both distortion-product otoacoustic emissions (DPOAE) and loudness in five subjects. Our estimates of cochlear compression based on DPOAE growth were at least as variable as our estimates based on loudness growth. This result suggests that the inter-subject variability is largely due to differences in cochlear nonlinearity. This observation is further supported by a paper that will be published soon in JASA (Neely, Gorga, and Dorn 2003). Although we cannot, at this time, reconcile our observations with the study that you cite, this question apparently deserves further investigation.

Neely, S. T., Gorga, M. P. and Dorn, P. A. (2003) Cochlear compression estimates from measurements of distortion-product otoacoustic emissions. J. Acoust. Soc. Am. 114, 1499-1507.

Comment by Moore:

Your have assumed that the four components used in your study were sufficiently widely spaced for them “not to mask each other” and that “the ratio of the loudness of the complex to the loudness of each component will be equal to the number of components.” These assumptions may be reasonable for octave-spaced components at low levels. However, they are probably not correct for the higher levels used by you. To illustrate this, I used the loudness model of Moore, Glasberg and Baer (1997) to calculate the loudness of stimuli similar to yours. I first used as input to the model a 1000-Hz tone with a level of 80 dB SPL (specified in terms of level at the eardrum). The calculated loudness, assuming diotic presentation, was 13.4 sones. I then used as input a single tone with a frequency of 500, 2000 or 4000 Hz, and adjusted the input level so that the loudness of each was 13.4 sones. Finally, I used as input all four tones, 500, 1000, 2000 and 4000 Hz, each of which had a loudness of 13.4 sones when presented alone. If the loudness of the complex were simply equal to the sum of the loudness of the individual components, the complex would have a loudness of 53.6 sones. The calculated loudness was actually 44.8 sones. This is consistent with the fact that, according to the model, the excitation patterns of octave-spaced components overlap at high levels. The model predicts loudness summation effects rather well, including the effects of level, so its predictions are unlikely to be substantially wrong for your stimuli.

The failure of the loudness of the components to sum in a linear way at high levels may account for the steepening of your calculated loudness function at levels above 60 dB SPL (your Fig. 3B), a steepening that is not observed in empirical data.

Moore, B. C. J., Glasberg, B. R. and Baer, T. (1997) A model for the prediction of thresholds, loudness and partial loudness. J. Audio Eng. Soc. 45, 224-240.

Reply:

We agree that our loudness additivity assumption is questionable at high levels due to overlap of excitation patterns. However, the loudness growth functions that we observed for individual subjects, as such as shown in Fig. 3A, never exhibited an abrupt increase in slope at high levels. This result seems to support our loudness additivity assumption. The abrupt increase in slope that you noted at high levels for the group-average loudness functions in Fig. 3B was due to our computation of averages for the subsets of subjects with the most rapid loudness growth. Because these biased averages were misleading, we have omitted from Fig. 3B averages for loudness values that were not perceived by all six subjects. Additional work is needed to directly test loudness additivity at high levels.