THE HUMAN COCHLEAR MECHANICAL NONLINEARITY INFERRED THROUGH THE SCHAIRER ET AL. (2003) MODEL

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Abstract

Schairer et al. (2003) hypothesized that a multiplicative internal sensory noise, combined with the cochlear mechanical nonlinearity, causes a probe's detection threshold under forward-masking to systematically determine its psychometric function's slope. Here, psychometric functions of unprecedented precision are shown for forward-masked probe-tone detection as a function of intensity of same-frequency forward-masker at fixed masker-probe time gap. Within the Schairer et al. model, these psychometric functions imply that the cochlear nonlinearity's rate-of-change declines as a power function of dB SPL. Rates-of-change, once integrated, give the hypothetical nonlinearity itself, as a function of a single unknown parameter for which suitable values are inferred by comparing hypothetical rates-of-change in man to actual rates-of-change in animals. The model cochlear mechanical nonlinearity in man has similar magnitude and shape to those in animals.

Schairer et al. (2003) introduced a model of the hypothetical influence of the cochlear compressive mechanical nonlinearity upon the slopes of psychometric functions for probe detection under forward-masking. The present paper presents psychometric functions for detection of forward-masked probe tones, and examines whether the slopes of those functions support the Schairer et al. (2003) model. The psychometric functions have a distinct advantage over others, in that they are probably the most precise ever obtained, the inferred probe-detection thresholds having 95% confidence intervals of <2 dB in most cases, and of <1 dB in some cases.

Schairer et al. (2003) imagined that when the cochlear nonlinearity is plotted in scales of dB of output versus dB SPL of input, it forms two line segments, conjoined sharply at a point. Schairer et al. (2003) next noted that the detection of any probe stimulus is empirically characterized by a psychometric function, which, they assumed, exists not because of the nonlinearity per se, but due to the effect of distributions of internal noise upon the output of the nonlinearity in response to input. That is, internal noise was assumed to be multiplicative, thereby having the same distribution at any point along a logarithmic output scale, such as a decibel scale. *For any probe-detection threshold, therefore, which represents some agreed-upon point on a psychometric function, the psychometric function's span would correspond to a constant decibel range of output*. Figure 1 shows the Schairer et al. (2003) model.

The cochlear input-output response is hypothetically linear when the probe's intensity is low, as for weaker forward-maskers (left side of Fig. 1). Then, a given number of decibels of cochlear output will hypothetically correspond to the same given number of decibels SPL, i.e., the psychometric function will have a constant width. The cochlear input-output response is hypothetically compressive (but of constant slope) at moderate threshold probe intensities (right side of Fig. 1). Then, a larger number of decibels SPL will be required in order to span the same given range of decibels of output as before – that is, the psychometric function for forward-masked probe detection will hypothetically have a greater, but constant, width.

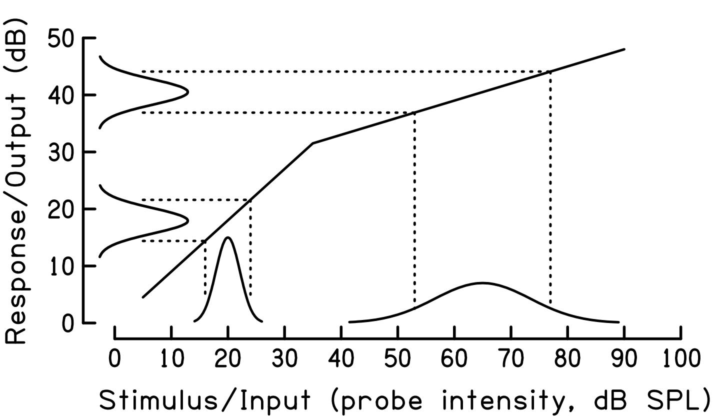

Figure 1. The Schairer et al. (2003) model of the effect of the cochlear mechanical nonlinearity upon the slopes of the psychometric functions for forward-masked probe detection. A pure tone of given intensity evokes a fixed internal response. Internal noise adds to that response, creating a probabilistic distribution of internal responses to a given pure tone (vertical axis). The distribution is assumed to be Gaussian (Green & Swets, 1988). The internal noise is presumably multiplicative, which makes the tone-evoked response distributions on the vertical axis identical, in a decibel scale of internal response, for any tone intensity. Hypothetically, then, the system is tantamount to one being internally noiseless but stimulated by a pure tone whose intensity over repeated presentations follows a Gaussian distribution in a decibel intensity scale (horizontal axis). The mean value of that Gaussian is the detection threshold for the tone (modified from Schairer et al., 2003). Note well that the true amplitudes of the probability density functions are not dB or dB SPL, as might appear from the graph, but rather are probability density, imagined as the label of a z-axis rising perpendicularly out of the page from {0,0}. As such, the shown probability density functions are projections upon the input/output plane of the graph. Also, for illustration's sake, the input distributions shown here are at least twice as wide as will be eventually implied from empirical psychometric functions.

The wider the psychometric function, the shallower it's slope. Within the Schairer et al. (2003) model of the cochlear nonlinearity as two line segments, the psychometric functions for forward-masked probe-detection should therefore have just two possible slopes. But those slopes cannot be known until the detection thresholds are actually established, because two elements of the Schairer et al. (2003) model - the human cochlear input-output response, and the level of the hypothesized internal noise - are unknown. Altogether, then, testing the Schairer et al. (2003) model requires reliably documenting the slopes of the psychometric functions for probe detection, over a broad range of probe-detection thresholds.

Psychometric functions to test the Schairer et al. (2003) model

One way to provide a broad range of probe-detection thresholds is to strongly forward-mask a probe tone, so that its detection threshold will be highly elevated at very short time-gaps between the constant forward-masker and the probe. Here, the probe was a 2 kHz tone having a Gaussian envelope with a standard deviation of 0.5 ms, equal to the tone's period. The forward-masker was a 97 dB SPL 200-ms (not including ramps) 2-kHz tone. Each probe-detection threshold was found using blocks of 100 self-paced two-interval two-alternative forced choices (2I2AFC), during which the forward-masker and probe intensities remained constant (method of constant levels). A double-walled, single-seat soundproof chamber was used, and testing took sufficiently long that only two male adults participated, but with extensive practice. Actual detection thresholds were estimated through Probit Analysis (Finney, 1971), in which the subject's scores (out of 100) are fitted to a cumulative Gaussian, an ogive that is taken to be the psychometric function. It is the integral of an underlying Gaussian probability density function (Gaussian distribution), and is characterized by two numbers inherent to that distribution, namely (1) its mean value in dB SPL, which corresponds to the midpoint of the psychometric function, at which the psychometric function's slope is evaluated, and (2) its standard deviation, which is inversely proportional to the psychometric function's slope.

The Schairer et al. (2003) model in the context of the experiment

According to Schairer et al. (2003), the slope of the psychometric function should take on just two values, one for low probe-detection thresholds, and one for moderate probe-detection thresholds. (High probe-detection thresholds are beyond the scope of most experiments, and were therefore absent from the model.) But the Schairer et al. (2003) nonlinearity is the simplest one imaginable, and a more sophisticated model might posit a nonlinearity that resembles those recorded from animals – an increasingly compressive one, i.e., one whose slope declines monotonically with increasing probe intensity.

In the present experiment, the masker-probe time-gap was fixed at 3 ms, just beyond the range of physical overlap of forward-masker and probe. With increase in forward-masker intensity, the probe-detection threshold rises monotonically, as generally seen in the literature and as found by Schairer et al. (2003, Figs. 2 & 6) and by Schairer et al. (2008, Fig. 2). Also, the psychometric functions generally widen, as found by Schairer et al. (2003, Figs. 3 & 8 [slopes]) and by Schairer et al. (2008, Fig. 3 and Fig. 4 [slopes]). Figure 2 shows the empirical psychometric functions. Subject 1 had more time than Subject 2, who did not experience the 35, 45, 65, 80-, or 90 dB SPL forward-maskers. Generally, the psychometric-function slope decreases with increase in probe-detection threshold, and for either subject, the decrease is adequately fitted by power functions. Figure 3 shows the fits. Hence, if psychometric-function slope is indeed determined by a multiplicative internal noise and the cochlear nonlinearity (Schairer et al., 2003), then the slope of the nonlinearity itself decelerates with increasing sound-pressure-level over roughly 20-80 dB SPL.

The human cochlear nonlinearity by extension of the Schairer et al. (2003) model

The Schairer et al. (2003) model was extended here in order to reveal the human cochlear nonlinearity. The extension starts with a key assumption: that the Gaussian-shaped "input distribution" of the model is, in fact, the same Gaussian probability density function which can be integrated to make the psychometric function for the detection of the forward-masked probe. Two realizations were also required, viz., that (1) the average slope of the cochlear nonlinearity itself can be measured between any two points on said nonlinearity, and (2) that those two points can correspond to the "edges" of a (symmetric) psychometric function which is centered midway between the two points on the nonlinearity. The psychometric-function width therefore forms the denominator of the average slope of the nonlinearity; the numerator, according to the Schairer et al. (2003) model, is some unknown, but fixed, number of decibels of output. Figure 4 shows the extension of the Schairer et al. (2003) model.

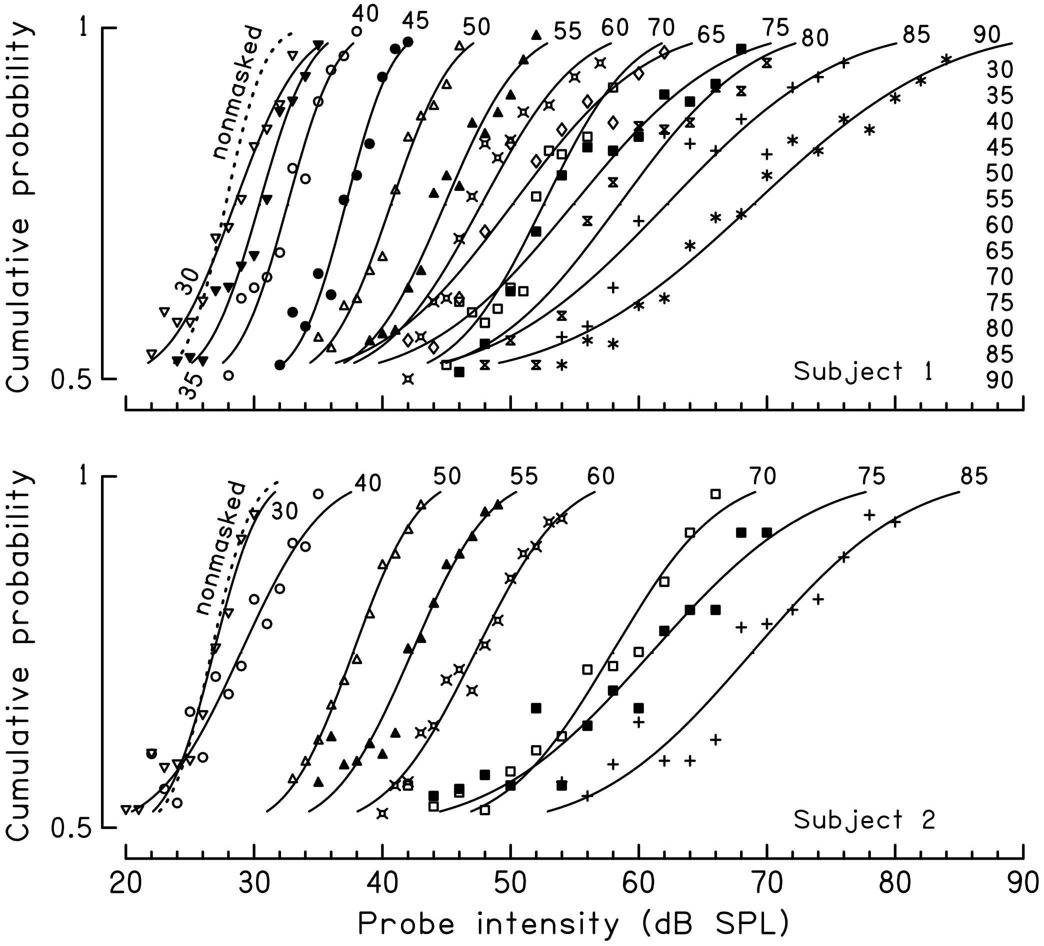

Figure 2. Psychometric functions for forward-masked probe detection and the percentages-correct on which they were based. The two columns on the right-hand-edge of the upper frame match forward-masker intensity to data-plotting symbol.

The widths of the obtained psychometric functions are inversely proportional to their slope. Altogether, then, the average slope of the cochlear nonlinearity over some interval centered on a particular intensity is directly proportional to the slope of the psychometric function for forward-masked probe detection whose centroid corresponds to that intensity. Therefore, quantifying psychometric-function slope as a function of intensity leads to a further equation, in one unknown multiplicative parameter, for the average slope of the cochlear nonlinearity with intensity. Plotting the latter on the same graph as empirical animal-derived curves of the nonlinearity slope allows comparisons which suggest appropriate values of the unknown parameter. To do so, however, the animal-derived curves must be shifted to higher SPLs, because the present probe is much shorter in duration and lower in frequency than the probe tones used in animals, and hence, overall, has much less energy.

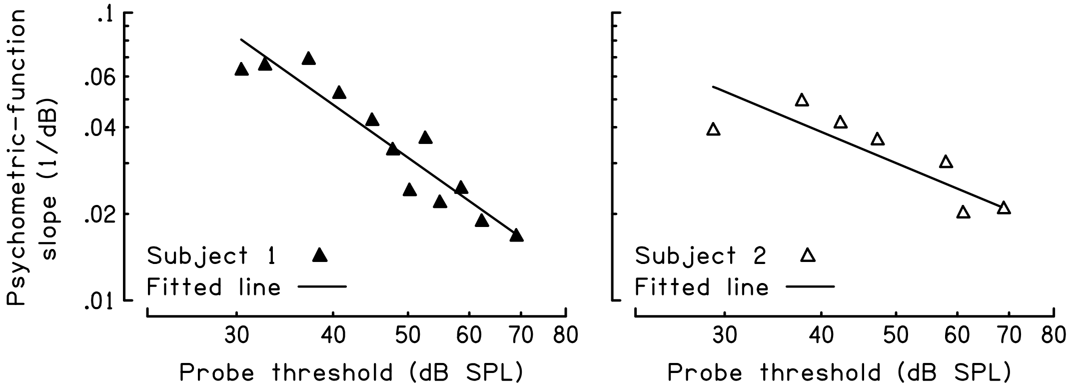

Figure 3. The slopes of the psychometric functions for probe detection (the functions of Fig. 2), versus the actual probe-detection thresholds. The straight lines are fitted power functions.

Equations for the inferred average slope of the cochlear nonlinearity can be integrated to give the nonlinearity itself. The integrals have a lower limit, which is the starting point of the nonlinearity, here assumed to be the probe's detection threshold in the absence of the forward-masker. The cochlear nonlinearities predicted from the experimental results resemble animal recordings, in that they show no distinct point of bending. The upper slopes of the inferred nonlinearities are similar to that of the Schairer et al. (2003) model. The range (in decibels) from maximum to minimum output of the inferred nonlinearity is of the same order of magnitude as those seen in animals. Figure 5 shows the inferred cochlear mechanical nonlinearities.

Finally, it is conceivable that the value of the unknown parameter in the present model could change from tone frequency to tone frequency within a single subject, and could change from subject to subject for a given tone frequency.

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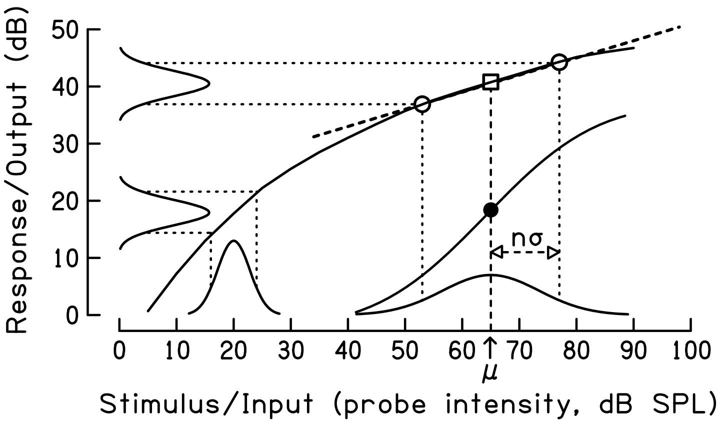

Figure 4. The average slope of the cochlear nonlinearity vs. the width of the psychometric function. Fig. 1 is modified such that the hypothetical cochlear nonlinearity is smoothly-changing (after chinchilla cb24 of Rhode and Recio, 2000). Each of the input distributions is now presumed to be integrated to yield the probe-detection psychometric function, which runs from 0.5 to 1 in the (2I2AFC) experiment. For the right-hand input distribution here, the mean value (and probe-detection threshold) is μ, coinciding with the centroid of the psychometric function (solid dot). The open square is the corresponding locus on the cochlear nonlinearity. The width of the psychometric function is defined as $2n\sigma$, where $n \in {}^{+}\mathrm{I}$; its corresponding points on the nonlinearity are marked by the open circles. Through those circles passes the dashed slanted line, whose slope is the average of the slopes between the two open circles, approximating the nonlinearity's slope at the open square. The approximate slopes are better than apparent, as the input distributions (and corresponding psychometric functions) shown here are (as in Fig. 1) at least twice as wide as implied from the empirical psychometric functions. The psychometric function does not have units of dB, but rather percentage correct, and as such is a projection upon the plane of the graph.

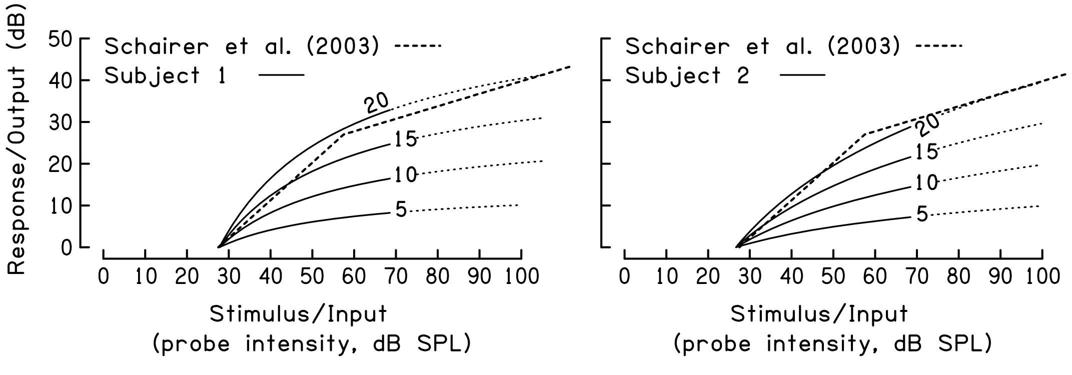

Figure 5. The inferred cochlear nonlinearity (solid lines). The plot labels are suitable values of the one unknown parameter, inferred from cochlear nonlinearities in animals. The dashed lines show the hypothetical nonlinearity of Schairer et al. (2003), adjusted to start at the same point as the solid lines, which are made to originate at an "output" of 0 dB and at the subject's absolute probe-detection threshold. The dotted lines extrapolate.