FORWARD MASKING RECOVERY AND PERIPHERAL COMPRESSION IN NORMAL-HEARING AND COCHLEAR-IMPAIRED EARS

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Robert C. Bilger:

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ABSTRACT

Iso-response temporal masking curves were obtained from normal-hearing subjects at a probe frequency of 1000 Hz for masker frequencies between 500 and 1200 Hz. Time constants calculated from the temporal masking curves varied with masker frequency, from around 70 ms for low off-frequency maskers (500-600 Hz) to around 36 ms for on-frequency maskers (close to the probe frequency). Continuing Bilger's earlier pursuits of nonlinearities in hearing, estimates of peripheral compression were calculated under the assumption that the response to a low off-frequency masker is linear at the probe frequency place. Average compression exponents varied from close to 1.0 for remote off-frequency maskers (both below and above the probe) to below 0.4 for on-frequency maskers. Input-output transfer functions derived from the compression exponents were consistent with BM transfer functions recorded in animals with normal cochlear function. Comparisons of iso-response temporal masking curves in subjects with sizable cochlear hearing losses at the probe frequency yielded linear transfer functions consistent with BM data from cochlear-damaged animals. It is concluded that time constants for recovery from forward masking in ears with cochlear hearing loss are no different than those obtained from normal-hearing ears, once differences in peripheral compression are taken into account. [Work supported by NIH-NIDCD grant DC00149 and the Lion's 5M International Hearing Foundation.]

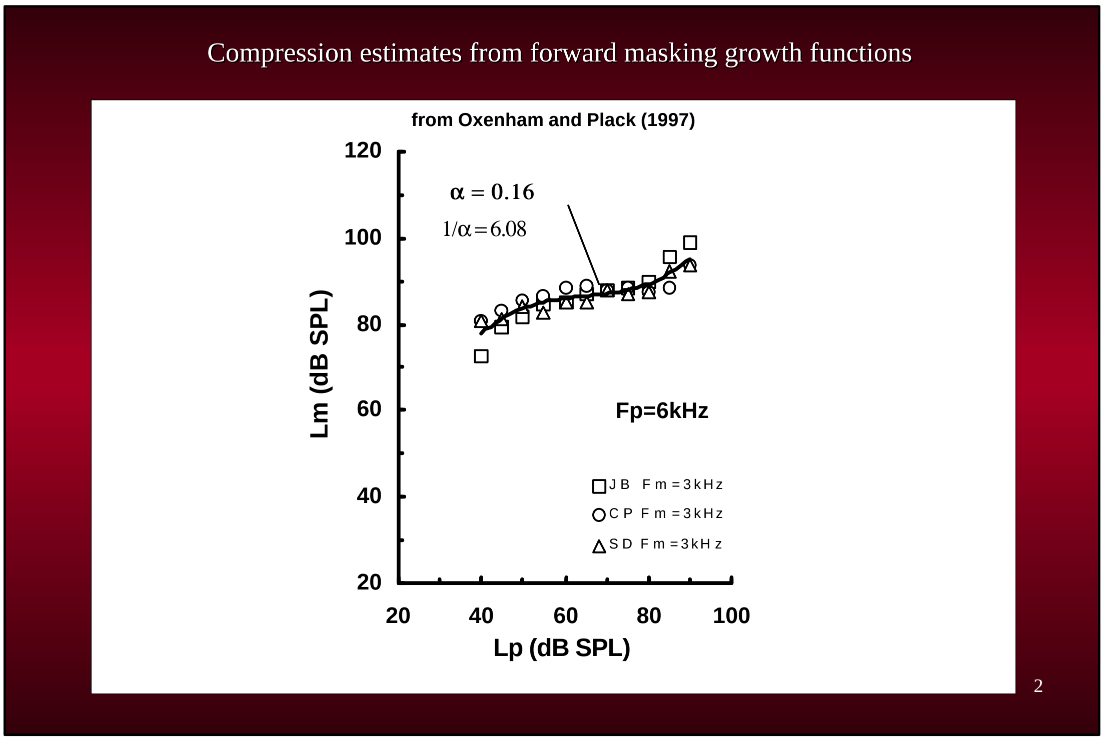
INTRODUCTION

I did my post-doc with Bilger, way back when, at the beginning of the '70s. In those days, one of Bilger's major research themes involved *auditory nonlinearities*. Those of you who were trained in Audiology in those days, may remember the popular mantra that: "persons with cochlear hearing loss have distorted hearing". In my early training, I was taught that people with cochlear impairment exhibited *more* Aural Distortion than did people with normal hearing. Back then, Bilger listened carefully to the physiologists, who, in those days, were just beginning to get a handle on cochlear nonlinearities. Bilger said to me: "No Nelson, they've got it wrong". It's the *normal* ear that is nonlinear. The cochlear impaired ear is more *linear*. That premise, uttered by Bilger in 1970, set the tone for much of my own research throughout the next three decades.

Since those early days, the physiologists have provided us with a fairly lucid story of cochlear nonlinearities in animals. On the other hand, psychophysical evidence of compression in human ears has lagged somewhat behind the physiological data. This is partially due to the fact that *psychophysical measures* always involve *population responses*, which means that the interpretation of psychophysical compression can be complicated by issues involving *spread of excitation*.

GROWTH-OF-MASKABILITY REFLECTS COMPRESSION?

The most recent psychophysical demonstration of cochlear compression in human ears comes from the work of Oxenham and Plack. They used forward masking, and some reasonable assumptions, to obtain estimates of peripheral compression that may directly reflect basilar-membrane compression.



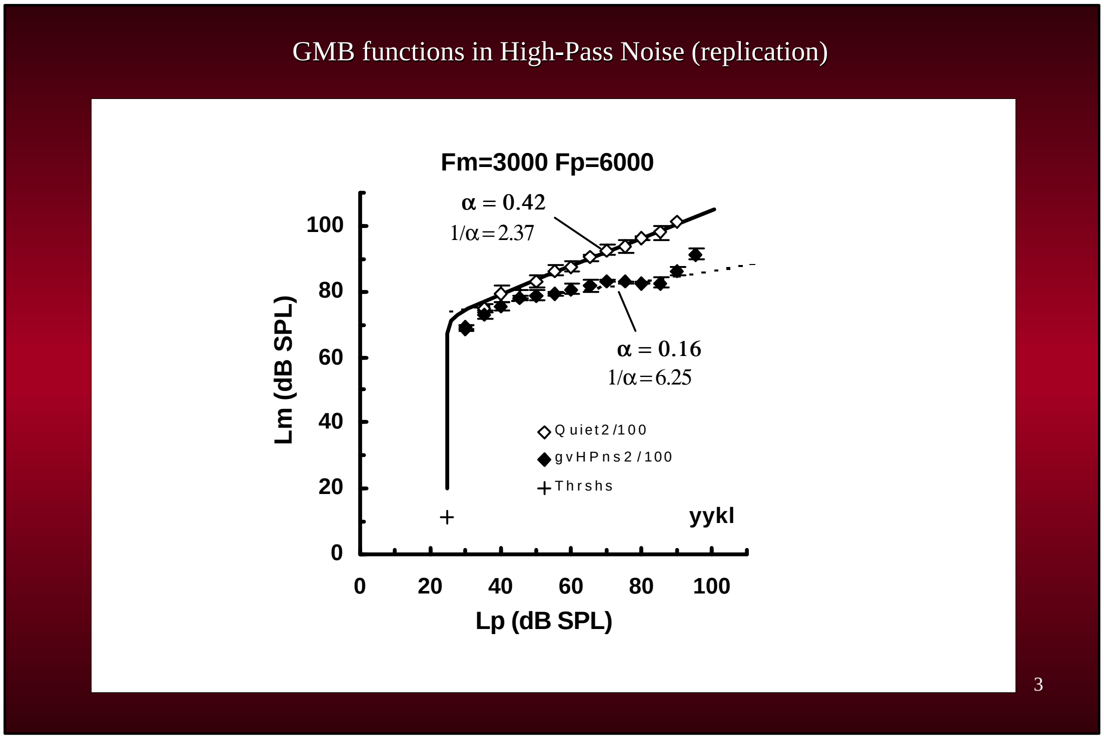
This slide re-plots their results from 3 normal-hearing ears. In this graph the masker level required to mask a fixed level probe tone is plotted against probe level, or amount of masking. This is essentially the inverse of a growth-of-masking function, therefore we call it a growth-of-maskability function. The open symbols show the masker levels required by a 3-kHz masker to forward mask a 6-kHz probe tone. From basilar-membrane data in animals, it is reasonable to assume that the rate of growth of response to the 3-kHz tone, at the 6-kHz place, is linear. Therefore, it follows that cochlear compression can be revealed by the instantaneous slope of this growth-of-maskability function.

Here the polynomial fit to the data suggests relatively linear growth at low and high probe levels, with strong compression at mid levels. The slope of the growth of maskability, given here as α, is 0.16 dB/dB. This suggests that cochlear compression in these normal-hearing ears approaches a compression exponent of 0.16.

For reference, the inverse of the compression exponent is the slope of the growth of masking, which in this case is 6 dB/dB, shown here as $1/\alpha$.

Thus, the most recent psychophysical data suggest that strong compression exists in normal-hearing human ears. The strong implication is that this psychophysical measure of compression reflects basilar membrane compression.

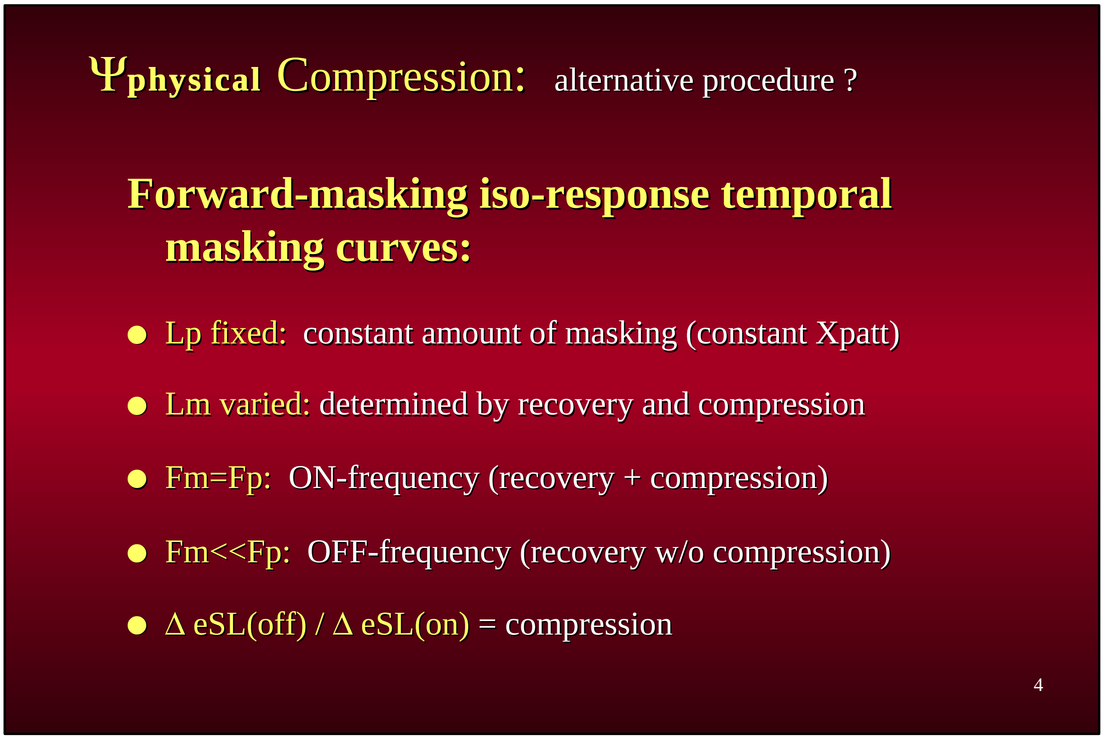
One problem with this psychophysical estimate of compression, is the *spread of excitation* that occurs in the cochlea when stimuli are increased in level. The steep growth-of-masking slopes and strong compression seen here are only realized when a high-pass masking noise is used to eliminate spread of excitation. The data shown here were obtained with a high-pass masking noise that had its steep low-frequency edge just 12% above the probe frequency. When Oxenham and Plack obtained similar data from one subject in quiet, without the high-pass noise, they reported much more gradual growth-of-masking slopes, which would translate into less peripheral compression.



Our replication of Oxenham and Plack's experiment is shown here in one normal-hearing subject The solid symbols show growth-of-maskability functions in high-pass noise, the open symbols in quiet. This figure presents the Off-frequency case where the masker is 3kHz and the probe is 6kHz. For this subject the slope of the growth of maskability, α, was 0.16 in noise and 0.42 in quiet. In other words, the estimate of compression was much less (i.e., a higher exponent) when spread of excitation was not controlled by a high-pass noise.

ISO-RESPONSE TEMPORAL MASKING CURVES (NH EARS)

This replication of Oxenham and Placks's result indicated to us that the growth of forward masking procedure is strongly influenced by spread of excitation toward higher frequency regions. Consequently, we wondered if there might be a way to avoid the confounding effects of spread-of-excitation that is inherent in the use of multiple probe levels.



Consequently, an alternative procedure was evaluated, one that involves what we call *iso-response temporal masking curves*. An iso-response temporal masking curve consists of the masker levels required to obtain a constant amount of forward masking as a function of the time delay between masker and probe. In this alternative procedure, time delay between masker and probe is the independent variable, so that only the masker level is varied, and therefore only the masker is subjected to compression.

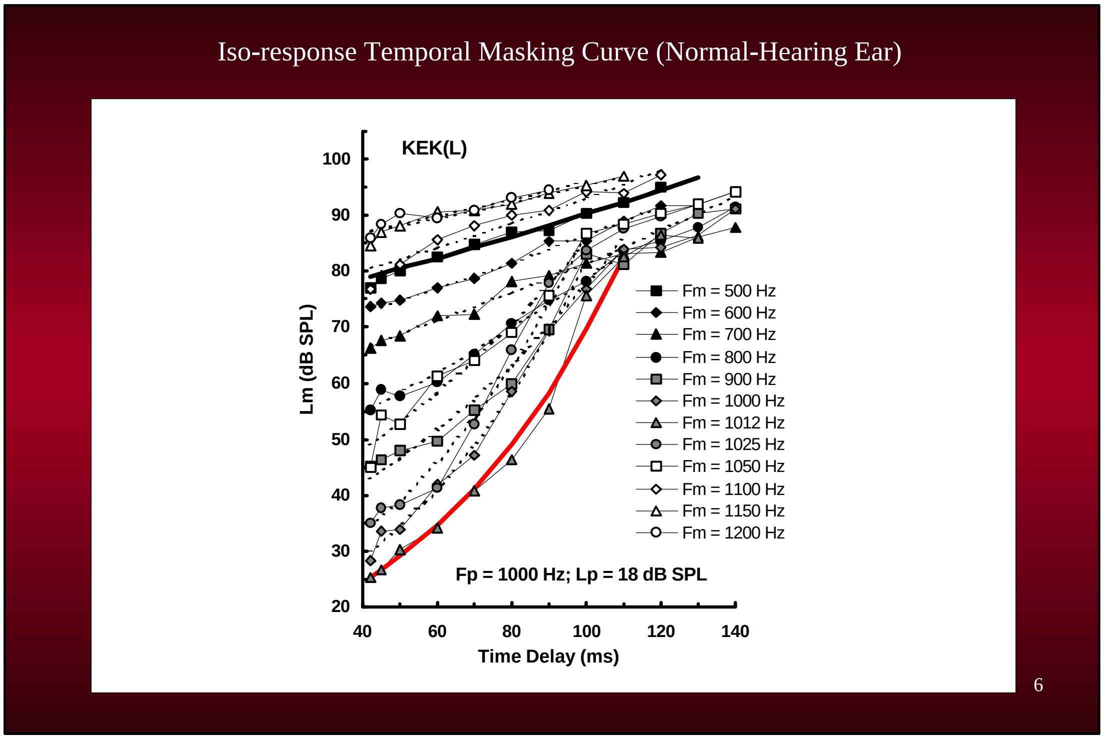
{**Lp fixed:**} The probe level is fixed at a low sensation level, which means it's excitation pattern is both constant and relatively narrow.

{**Lm varied:**} As time delay between masker and probe tone is changed, the masker level required to forward mask the fixed-level probe tone is determined. Masker level varies in this experiment as the dependent variable, and is therefore subject to recovery from forward masking. In addition, the masker is also subjected to compression as the masker level is varied over a wide range to accommodate changes in time delay. That compression, is very dependent upon the frequency ratio between masker and probe tone. That dependence is the key to estimating compression.

{**Fm=Fp:**} For an ON-frequency condition, in which masker and probe are close in frequency, both a recovery process and a compression process affect masked threshold.

{**Fm<<Fp:**} For an OFF-frequency condition, in which the masker is much lower than the probe, it is assumed that compression is absent, so that only the recovery process is involved.

{**Δ eSL(off) / Δ eSL(on)**} Therefore, when comparing OFF-frequency vs. ON-frequency masking, the recovery process effectively cancels, and an estimate of compression can be obtained by measuring the relative changes in masker level for OFF-frequency and ON-frequency maskers.



Iso-Response Temporal Masking curves from one of four normal-hearing listeners are shown in this slide. Masker level is shown on the y-axis as a function of the time delay between masker and probe. The probe tone is always at 1000 Hz and is fixed in level at 18 dB SPL, which is about 10 dB above absolute threshold. The parameter is masker frequency.

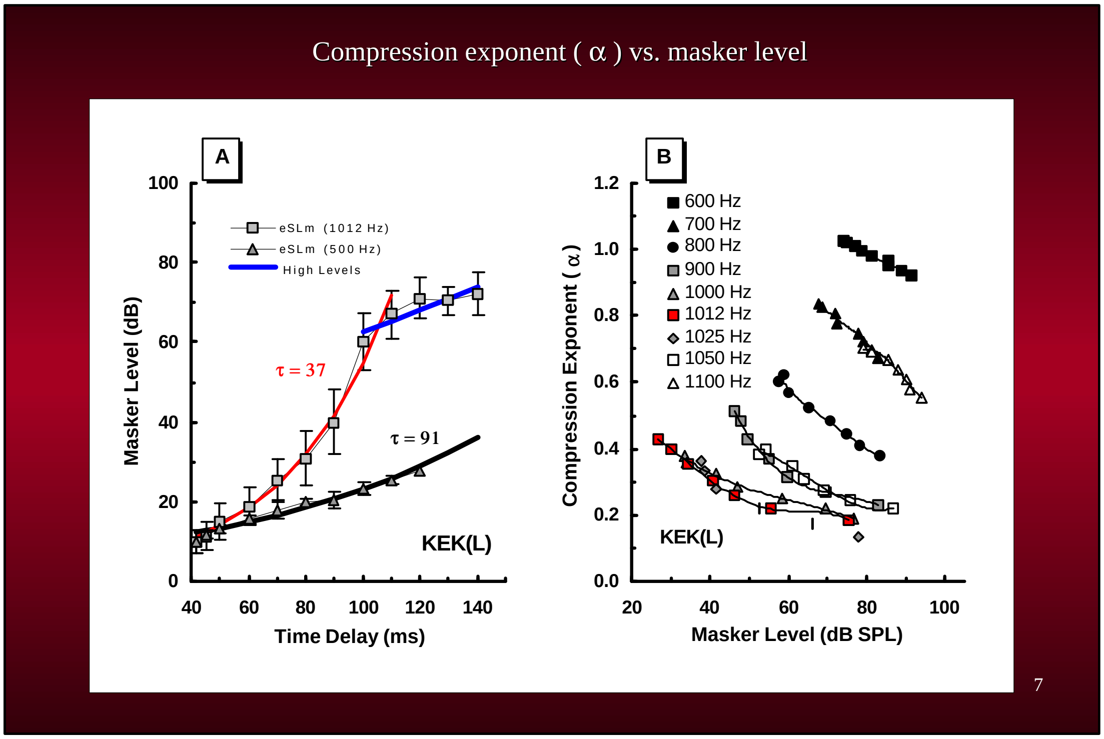
The important point of this slide is that the slope of an OFF-frequency temporal masking curve is different from that of an ON-frequency curve.

Compare, for example, the curve for the 500-Hz masker, shown by the black squares fit with the black curve, and the curve for the 1012-Hz masker, shown by the shaded triangles fit with the red curve. The change in masker level with time delay is much greater for the 1012-Hz ON-frequency masker, than it is for the 500-Hz OFF-frequency masker.

The slope for the OFF-frequency condition presumably only reflects the increase in masker level required to maintain a constant amount of forward masking in the face of increasing time delay. Compression is not contributing to this curve. This is because we assume that the 1000-Hz place responds linearly to the 500-Hz masking tone.

The slope for the ON-frequency condition not only reflects increased masker levels required to maintain a constant amount of forward masking in the face of increasing time delay, but, in addition, they presumably reflect compression that is applied to the ON-frequency maskers.

Thus, compression can be specified as the change in masker level for the 500-Hz OFF-frequency masker relative to the change in masker level for an ON-frequency masker.

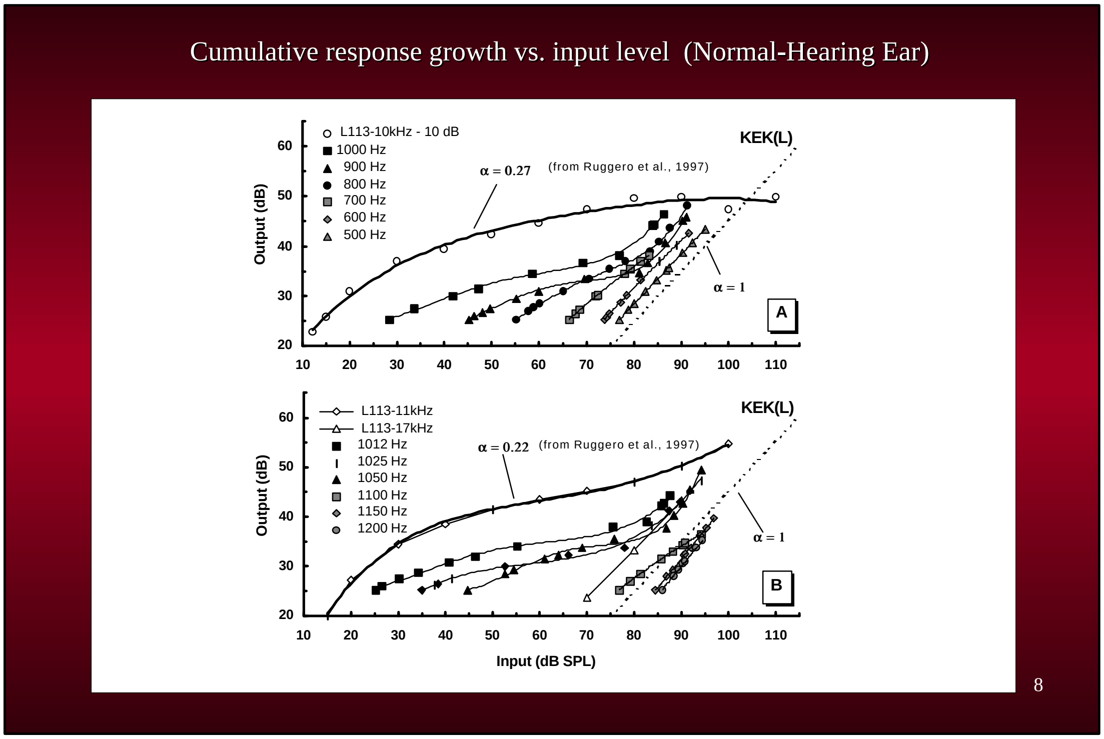


Panel A of this slide illustrates how compression was calculated for a 1012-Hz masker. Masker levels, here, have been normalized to those required with a 1000-Hz masker and a time delay of 42 ms. The temporal masking curve for the 500-Hz, OFF-frequency masker, is well described by the black curve with the more gradual slope. The temporal masking curve for the 1012-Hz, ON-frequency masker, is well described by the red curve with the steeper slope, but only for time delays up to 100 ms. At time delays longer than 100 ms, the temporal masking curve flattens out and is described by the upper blue curve with a more gradual slope. The ratio of the instantaneous slopes of the OFF-frequency and ON-frequency curves defines the compression exponent.

Panel B shows the compression exponents for this subject, plotted as a function of the sound pressure level of the maskers. Masker frequency is the parameter. The compression exponents for the 1012-Hz masker, that was illustrated in panel A, are shown in panel B by the red squares. The exponent tends to decrease with masker level, until masker levels around 80 dB SPL are reached. At that point, the slope of the temporal masking curve changes abruptly, and higher compression exponents result. These results suggest that psychophysical compression becomes stronger with level (*i.e.*, lower exponents), up to levels above 80 dB SPL, and then compression *may* become less strong at high levels.

The strongest compression, is also exhibited at masker frequencies nearest to the probe frequency. In this case the smallest compression exponent was about 0.16.

For the purposes of comparing the current estimates of compression in human ears with basilar-membrane compression measured in animals, we can reconstruct input-output transfer functions for response growth at each masker frequency.



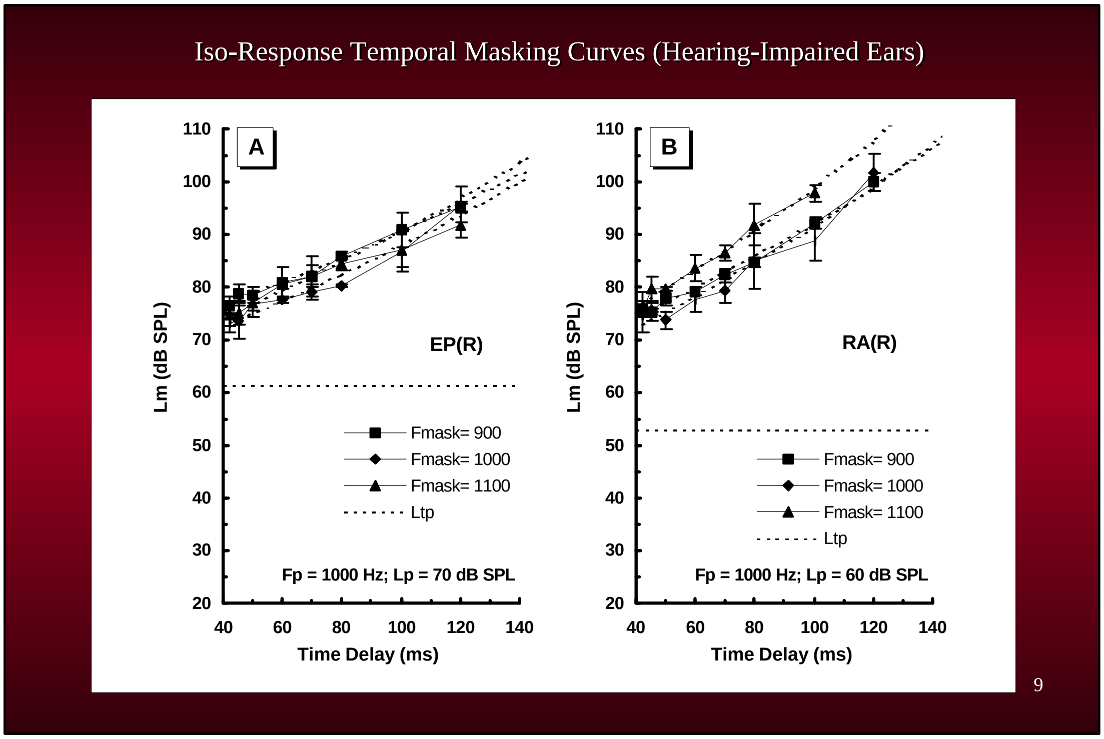
This slide shows response growth as a function of input level in the same normal-hearing ear, for all of the masker frequencies examined. Some basilar-membrane transfer functions from Ruggero et al. (1997) are also shown for comparison. As indicated here, *psychophysical* compression tends to behave similarly to *physiological* compression. It is level dependent, and strongest for masker frequencies close to the probe frequency. The return to linearity seen here at high levels in psychophysical compression may not have a counterpart in physiological data.

ISO-RESPONSE TEMPORAL MASKING CURVES (HI EARS)

So, for normal-hearing human ears we see that this alternative procedure, using iso-response temporal masking curves, yields compression estimates consistent with those obtained from basilar-membrane measurements in animals.

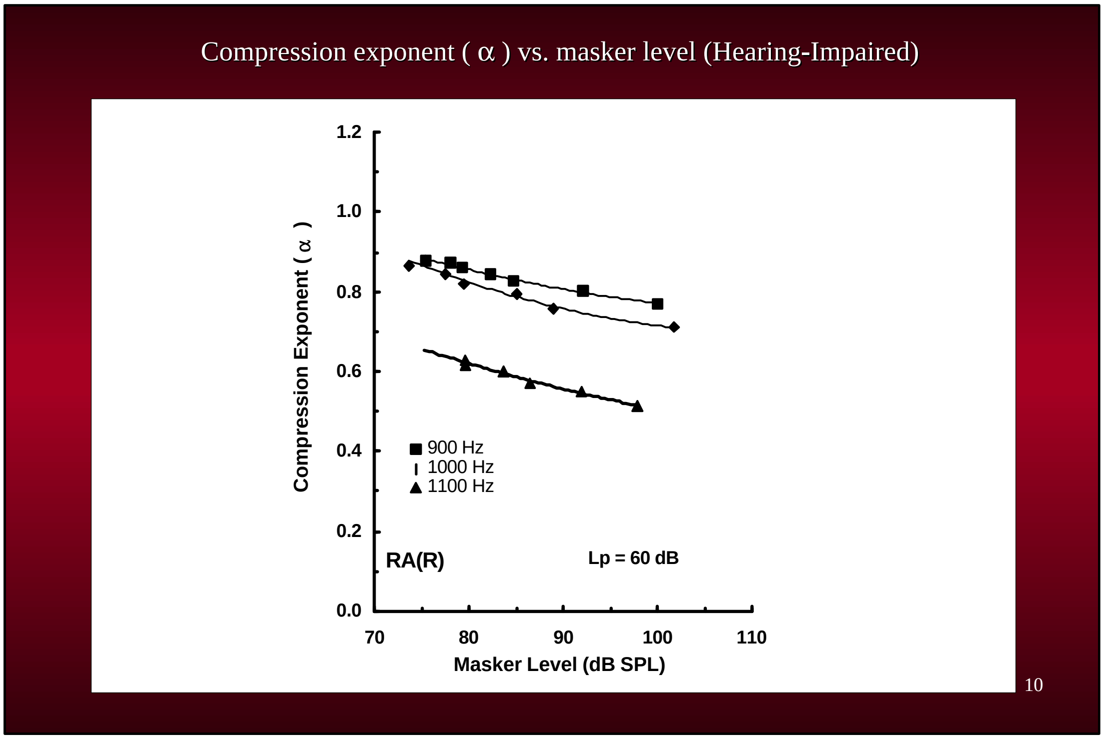
Not surprising, Bilger was right! The normal human ear behaves nonlinearly.

If Bilger's 1970 contention *that hearing-impaired ears behave linearly*, is also correct, one would expect that compression exponents obtained with this temporal masking procedure, from individuals with considerable hearing loss, should be close to unity.

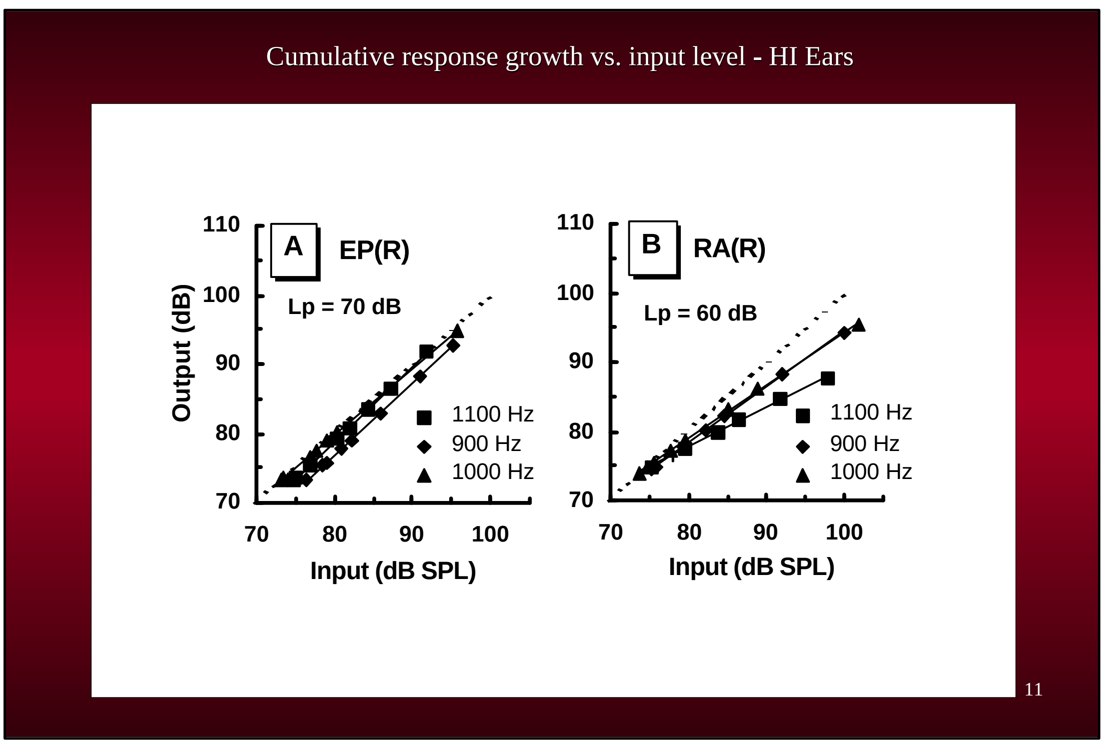


For those of you with good memories, and who also read JSHR, you might remember that Nelson and Pavlov carried out this experiment on four hearing-impaired subjects back in 1989. Even though the authors were not chasing compression in those days, the data can be re-used here to calculate compression in ears with cochlear hearing loss. This slide shows the iso-response temporal masking curves obtained from two of subjects who had the greatest amount of hearing loss at the 1000-Hz probe frequency.

Notice that masker level increases very gradually with time delay, even though the masker frequencies are close to the probe frequency. The slopes of these curves for ON-frequency maskers are similar to those obtained from normal-hearing ears for OFF-frequency maskers, particularly those slopes obtained with 500-Hz maskers. This result is entirely consistent with reduced compression in these ears with cochlear hearing losses.

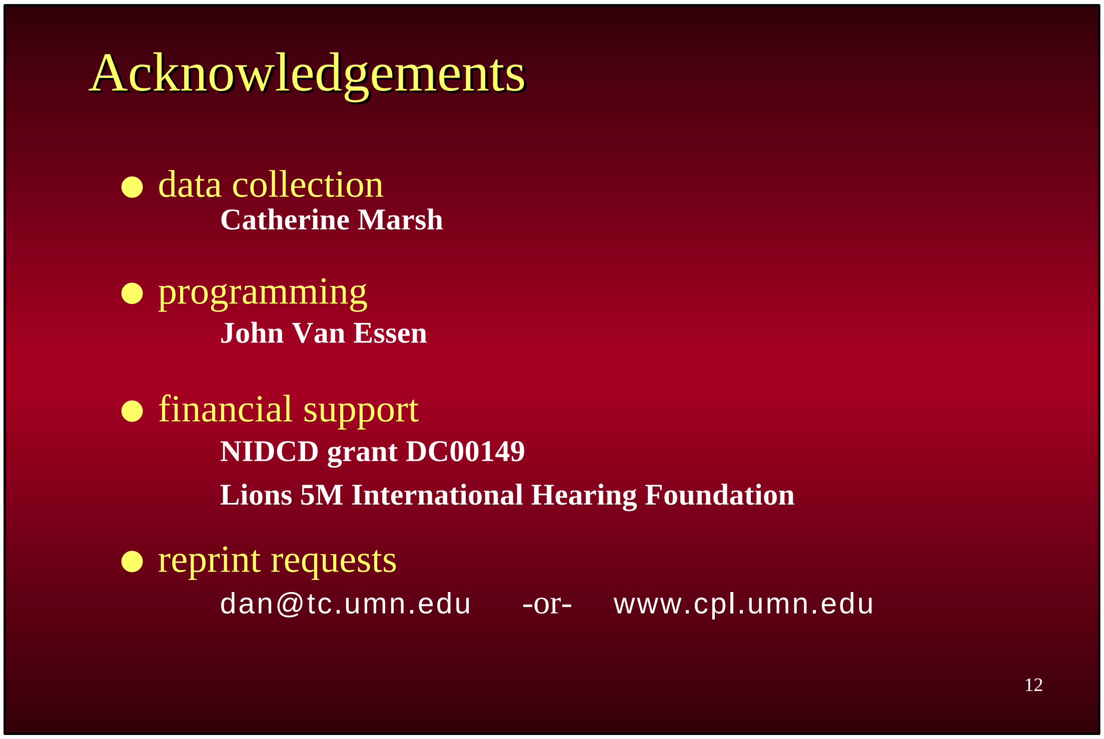


This slide shows the compression exponents calculated for one of the hearing-impaired subjects, plotted here as a function of masker level. In this case none of the exponents were below 0.5, suggesting that the underlying system is more linear, with less compression than seen earlier for normal-hearing ears.



Cumulative response growth for two of the subjects with the greatest hearing loss at the probe frequency is well described by linear functions with slopes closer to unity. The subject with the most hearing loss, in panel A, has the steepest response growth.

So, nearly 30 years after Bilger contended that hearing-impaired ears are more linear, the psychophysical data are proving him correct. Psychophysical estimates of compression, made from iso-response temporal masking curves, indicate that compression is lacking in ears with substantial hearing loss at the probe frequency.



We need to add a word of caution to the implication that what is reflected here is simply basilar membrane compression. Even this alternative procedure, which minimizes spread-of-excitation issues, is dependent upon measuring responses from regions of the cochlea or populations of fibers. Furthermore, we must still deal with issues related to OFF-time listening, and to potential confusions that may exist between masker and probe tones with this forward masking task. So, we still have some work to do.

Thank you.

ACKNOWLEDGMENTS

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