Predicting Behavioral Thresholds From DPOAE I/O Functions

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Introduction

- DPOAEs are used primarily to make dichotomous decisions: i.e., is hearing normal or impaired?

- With few exceptions, they have not been used to predict threshold.

- Recent work by Boege and Janssen (2002) suggests that the DPOAE I/O function can be used to predict behavioral thresholds

Our Extension of the Boege and Janssen (2002) Approach

- Effects of frequency were evaluated
- Auditory status was determined in those cases in which the Boege and Janssen (2002) approach could not be applied.
- Thresholds were truncated, additional stimulus conditions were tried, and other inclusion criteria were used in an effort to improve the accuracy with which behavioral thresholds were predicted from DPOAE I/O functions.

Subjects

- Data were available on a total of 278 ears of 97 subjects with normal hearing and 130 subjects with hearing loss.

- All ears produced normal typanometric patterns prior to each DPOAE measurement.

- Audiometric data were available, including data that were consistent with a cochlear lesion for those subjects with hearing loss.

Stimuli

- f_2 frequencies ranging from 0.5 to 8 kHz (1/2 octave steps). $f_1 = f_2/1.22$.

- L_2 ranging from 10 to 85 dB SPL.

- $L_1 = 0.4L_2 + 39$ dB for L_2 levels up to 65 dB SPL. $L_1 = L_2$ for higher levels.

- L_2 incremented in 5-dB steps.

First, A Replication of the Boege and Janssen (2002) Results

- Data collapsed across frequency.

- Stimulus levels (L_2) restricted to levels from 20 to 65 dB SPL.

- At least 3 points on the I/O function had SNRs $\geq$ 6dB

- DPOAE levels (dB SPL) converted to pressure and then fit with a linear equation relating pressure to input level (L_2)

Inclusion Criteria Related to the Linear Fits

- The slopes of the individual linear functions had to be > 0.2 μPa/dB.
- The variance accounted for (r^2) was > 0.8
- The standard error of the fit was < 10 dB.
- If these criteria were met, the equations were solved for the L_2 (in dB SPL) at which DPOAE amplitude = 0 μPa, which was defined as DPOAE threshold.
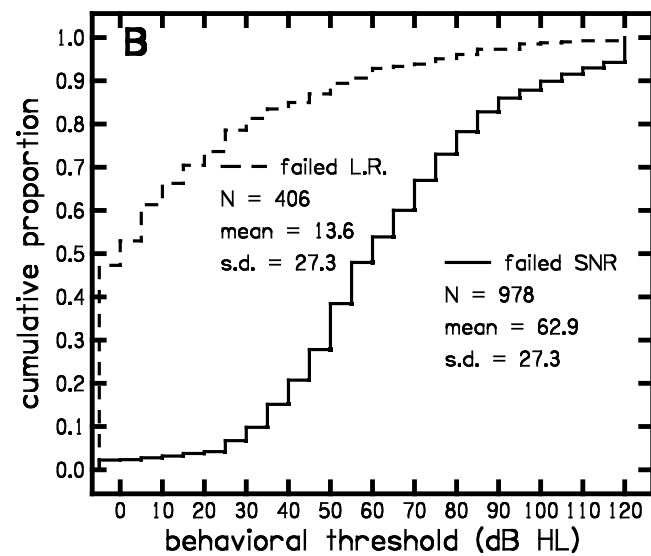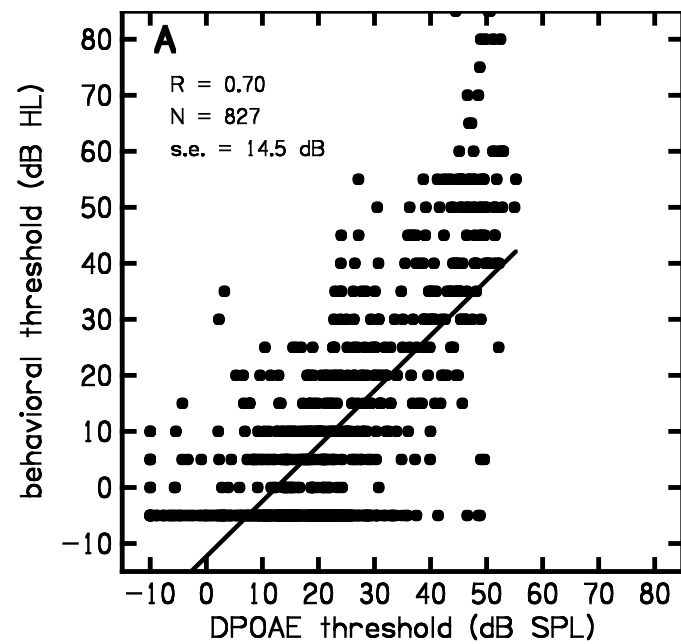- This threshold was then correlated with behavioral threshold.

The Consequences of Criteria Associated with SNR and with the Linear Fits

- There were many cases in which the SNR criterion was not met. These cases were eliminated from any further analyses in the Boege and Janssen (2002) approach.

- There also were cases in which the SNR criterion was met, but the criterion associated with the linear regression were not. These cases also were not considered further in the Boege and Janssen approach.

Replication of Boege and Janssen (2002)

Correlation between behavioral threshold
and DPOAE threshold (top panel)

Cumulative distributions of behavioral
thresholds for cases not meeting either the
SNR criterion or criteria associated with
the linear regression (bottom panel)

A
R = 0.70
N = 827
s.e. = 14.5 dB

behavioral threshold (dB HL)

DPOAE threshold (dB SPL)

B

cumulative proportion

failed L.R.
N = 406
mean = 13.6
s.d. = 27.3

failed SNR
N = 978
mean = 62.9
s.d. = 27.3

behavioral threshold (dB HL)

Applicability of the Boege and Janssen Approach

- Predictions of behavioral thresholds from DPOAE I/O functions were possible in 37% of cases.

- 44% of all I/O functions failed to meet the SNR criterion

- An additional 18% failed to meet the criteria associated with the linear regression.

Summary of Results of Initial Analyses

- Behavioral threshold correlates with DPOAE threshold
- The present correlation (0.70) agrees with the correlation observed by Boege and Janssen (2002)
- Majority of ears failing to meet the SNR criterion had hearing loss (mean threshold of 62.9 dB)
- Majority of ears failing to meet criteria associated with linear regression had normal hearing (mean threshold of 13.6 dB)
- There were more cases in which the SNR criterion was not met than there were cases in which criterion associated with linear regression were not met

Applicability of the Boege and Janssen Model as a Function of Frequency

- Results were collapsed across frequency in the Boege and Janssen study and in the first slide presented above. The effects of frequency, therefore, are not described.

- Is the correlation between behavioral and DPOAE threshold the same across frequency?

- Does frequency have an influence on the applicability of the model?

- Do similar percentages fail to meet SNR criterion and criteria associated with the linear regressions?

Behavioral Threshold as a Function of DPOAE Threshold

Each panel in the next figure represents data for a different _ octave frequency from 0.5 to 8 kHz. In all cases, DPOAE data at a specific f_2 frequency are compared to behavioral threshold data at the same frequency (i.e., f_2 = audiometric frequency).
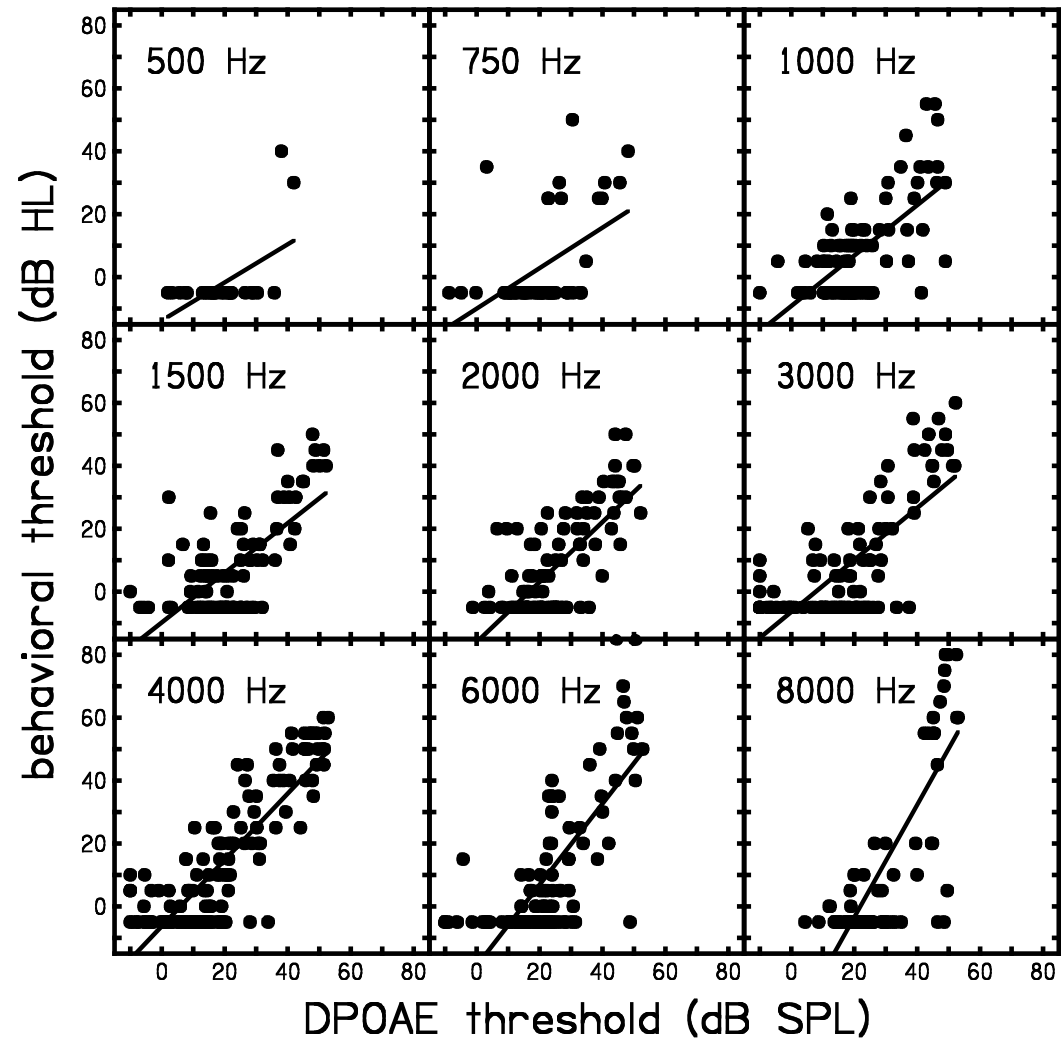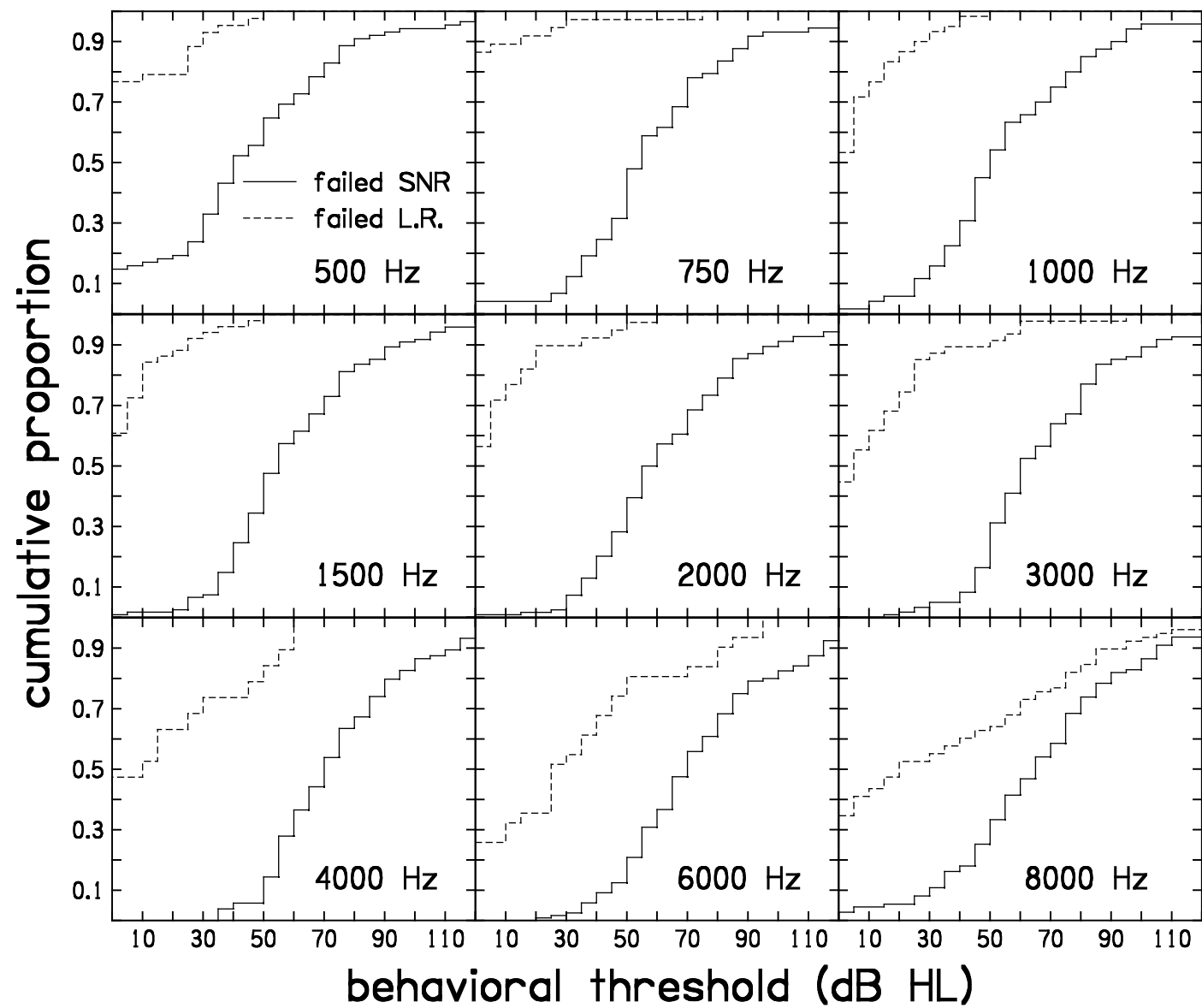
Frequency Effects on Correlations

- Best correlation between behavioral and DPOAE thresholds are observed at 4 kHz.

- Correlations decrease as frequency either increases or decreases from 4 kHz.

- These results are consistent with other observations in which DPOAEs are used to identify auditory status (i.e., dichotomously determine if hearing is normal or impaired). Best DPOAE test performance in these "screening" applications is always observed at 4 kHz.

Frequency Effects on Meeting Inclusion Criteria

- Did the percentage of cases meeting the SNR inclusion criterion depend on frequency?

- Did the percentage of cases meeting the criteria associated with the linear regression depend on frequency?

Cumulative Distributions

- Heavy solid lines: cumulative proportion of conditions not meeting the SNR criterion (at least 3 points on the DPOAE I/O function with SNR > 3 dB) as a function of behavioral threshold.

- Light dashed lines: cumulative proportions not meeting inclusion criteria associated with the linear regression.

- Each panel represents data for a different frequency.

Cumulative proportion as a function of behavioral threshold (dB HL) for failed SNR (solid) and failed L.R. (dashed) conditions across nine test frequencies: 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz, 6000 Hz, and 8000 Hz.

Superimposed Cumulative Distributions for Octave Frequencies from 0.5 to 4.0 kHz

- Line thickness increases as frequency increases.
- Note the low percentages of conditions in which the SNR criterion was not met and thresholds were less than 30 dB HL.
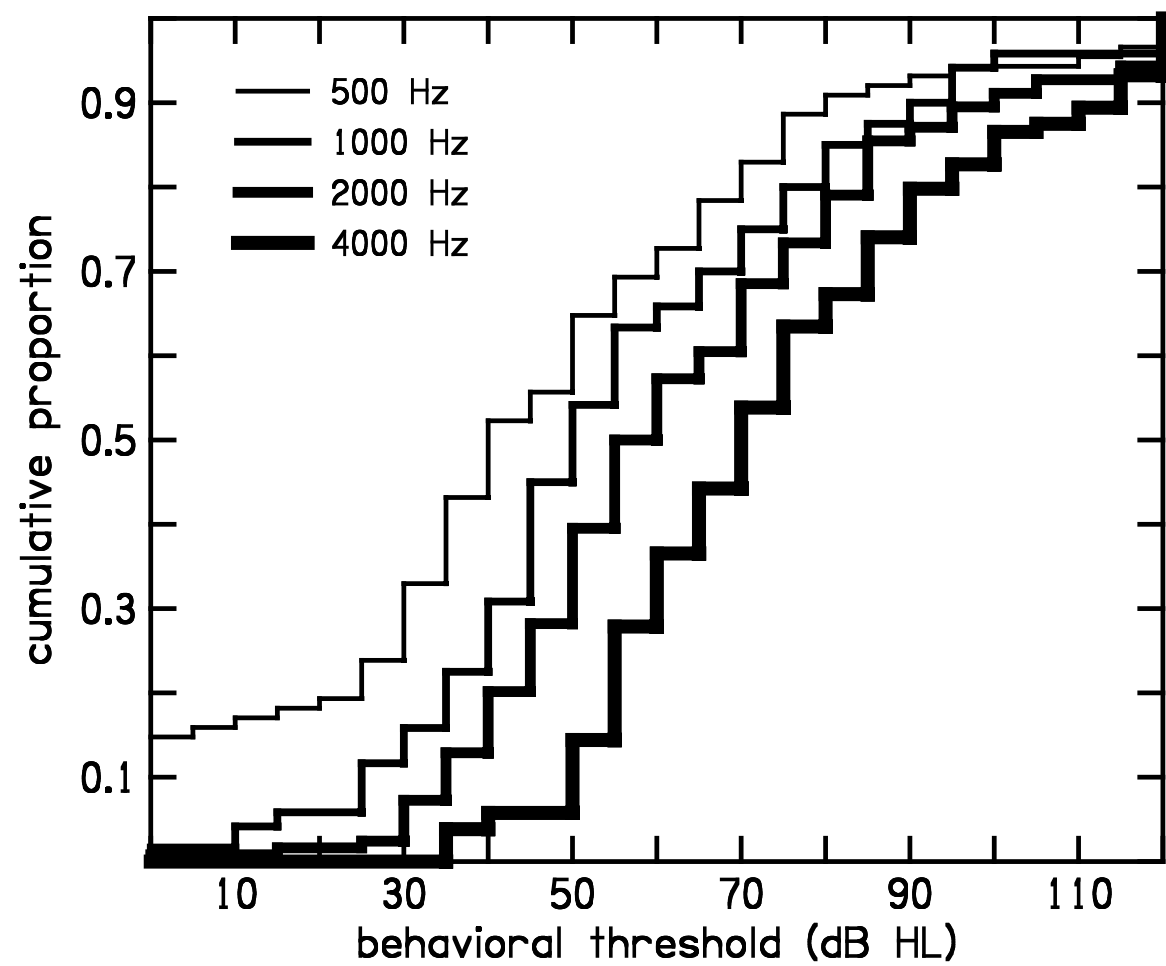
Frequency Effects on SNR Inclusion Criteria

- Majority of ears not meeting SNR criterion had hearing loss. At 4 kHz, every case not meeting the SNR criterion had hearing loss exceeding 30 dB.

- In contrast, 33% of the cases not meeting SNR criterion at 0.5 kHz had thresholds less than 30 dB.

- Intermediate values were observed at other frequencies.

- Although the percentage varied across frequency, these results mean that hearing loss was present for the majority of cases in which the SNR criterion was not met, even at 0.5 kHz.

- Thus, for those conditions in which predictions of behavioral thresholds were not possible (due to failing to meet the SNR criterion), clinical information about auditory status was still available.

Frequency Effects on Inclusion Criteria Associated with the Linear Regression

- The number of cases failing to meet the inclusion criteria associated with the linear regression was smaller than the corresponding number for the SNR criterion.
- The majority of these cases had normal hearing.
- Thus, one could conclude that it was likely that any condition meeting the SNR criterion but failing to meet the linear-regression criteria had normal hearing.

First Efforts to Optimize the Boege and Janssen Approach: Truncation of DPOAE and Behavioral Thresholds
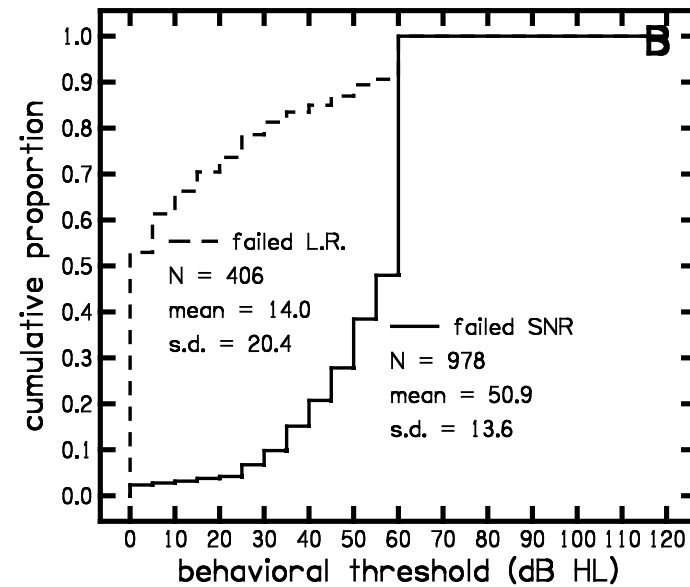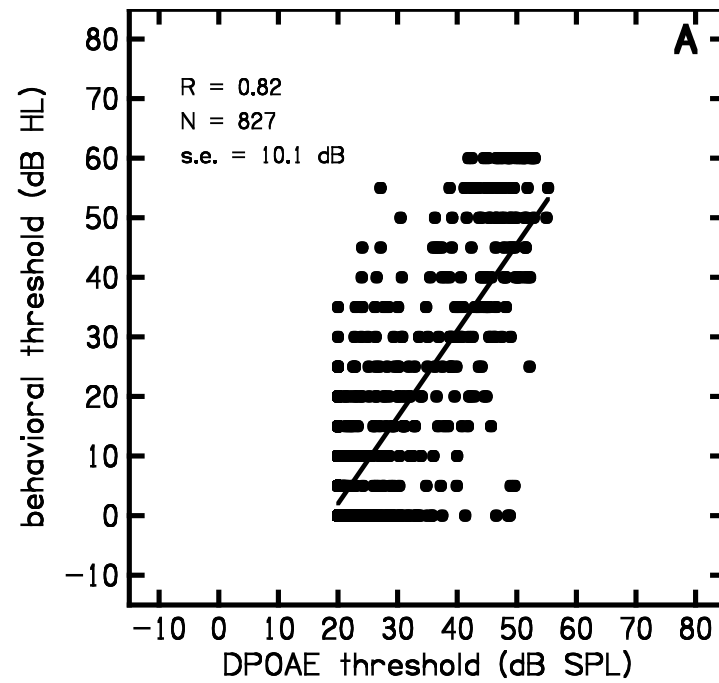
- Any DPOAE threshold less than 20 dB SPL was arbitrarily set to 20 dB SPL.

- Any behavioral threshold less than 0 dB HL was arbitrarily set to 0 dB HL.

- Any behavioral threshold greater than 60 dB HL was arbitrarily set to 60 dB HL

Rationale for These Changes

- DPOAEs are seldom measured for L_2 levels less than 20 dB SPL.

- Audiometric thresholds are seldom measured below 0 dB HL.

- DPOAEs are produced by nonlinear cochlear behavior thought to reflect outer hair cell (OHC) function. Since the first 60 dB of sensory hearing loss can be attributed to loss of OHC function, it is reasonable to truncate hearing loss at 60 dB.

First Efforts at Optimization

- Top panel: comparison of behavioral and DPOAE thresholds following truncation of both thresholds.

- Bottom Panel: cumulative distributions of conditions in which either the SNR (solid line) of linear-regression (dashed line) criteria were not met.

- Note: Data are collapsed across frequency.

A

R = 0.82
N = 827
s.e. = 10.1 dB

behavioral threshold (dB HL)

DPOAE threshold (dB SPL)

B

cumulative proportion

failed L.R.
N = 406
mean = 14.0
s.d. = 20.4

failed SNR
N = 978
mean = 50.9
s.d. = 13.6

behavioral threshold (dB HL)

# Results of Initial Efforts at Optimization

- Correlation between behavioral and DPOAE thresholds went up.

- Standard error of the estimate went down.

- These observations suggest that the predictive value of the Boege and Janssen approach might be improved upon by truncating the two threshold measurements.

Additional Modifications in Efforts to Optimize Predictions

- L_2 range was expanded to 20 to 85 dB SPL.

- Range of levels evaluated for any single I/O function was restricted to 40 dB.

- SNR inclusion criterion was increased to 10 dB.

Results Following Additional Changes to Optimize Performance

- Top Panel: Comparison of behavioral and DPOAE thresholds.

- Bottom Panel: Cumulative distributions of conditions in which either the SNR or linear-regression criteria were not met, following the convention used in the previous figure.

- Note: Data were collapsed across frequency.
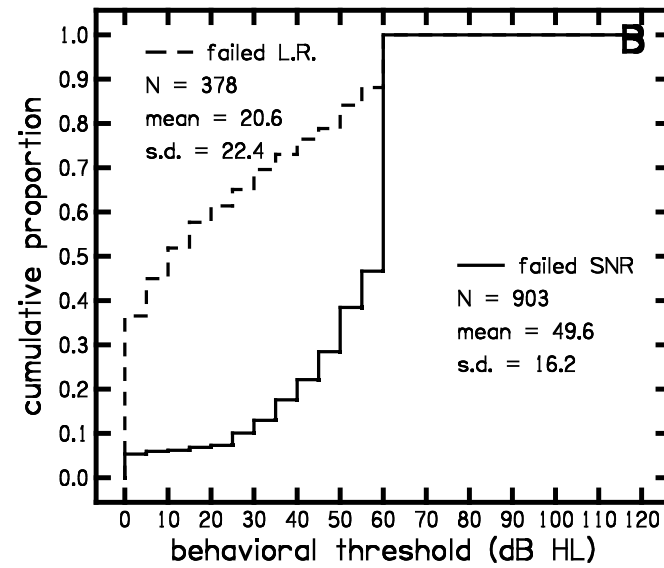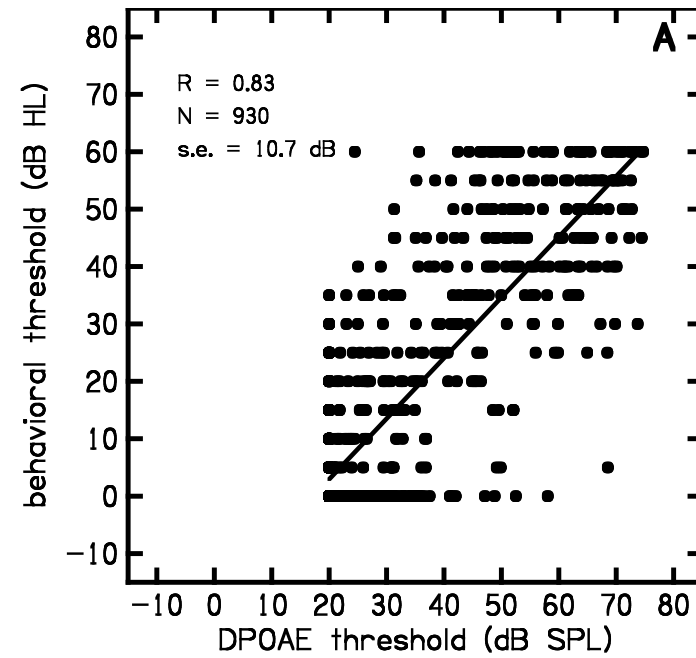
Results of Additional Efforts to Optimize Performance

- Correlation between behavioral and DPOAE thresholds went up slightly.

- Standard error went up slightly.

- Number of conditions failing to meet the SNR criterion went down.

- Number of conditions failing to meet criteria associated with the linear regressions went down.

- Results suggest that there may be value in applying other optimizations so that behavioral threshold predictions improve.

Overall Summary

- Behavioral thresholds can be predicted from DPOAE thresholds.

- Extent to which predictions can be made depends on frequency, being best at 4 kHz.

- Failing to meet SNR inclusion criterion does not allow one to predict behavioral thresholds, but suggests that hearing loss exists.

- Failing to meet criteria associated with the linear regressions does not allow one to use this approach to predict behavioral threshold, but suggests that hearing is normal.

Overall Summary Continued

- Truncation of both behavioral and DPOAE thresholds resulted in improvements in the predictive accuracy of the approach described by Boege and Janssen (2002).

- Increasing the range of stimulus levels increased the number of conditions for which their predictive model could be applied.

Overall Summary Continued

- There may be other optimizations that result in further improvements in the prediction of behavioral thresholds from DPOAE data. See Oswald & Janssen (2003), Z. Med. Phys. 13 (2), 93-98, "Weighted DPOAE input/output functions: A tool for automatic assessment of hearing loss in clinical applications" for more recent efforts to improve upon the prediction of behavioral thresholds from DPOAE I/O functions.