Clinical Interpretation of Distortion Product Otoacoustic Emissions (DPOAEs)

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Otoacoustic Emissions

- First described by David Kemp, 1978
- Low level sounds that originate from the cochlea (outer hair cell activity); by-product of normal hearing process
- Propagate through the middle ear and external auditory ear canal
- Measured in the ear canal using a sensitive microphone

Otoacoustic Emissions

- Objective indirect measure of cochlear function, specifically outer hair cell (OHC) function
- Reflect nonlinear and sharply tuned micro-mechanics of the normal hearing process
- Preneural – do not require 8th nerve function

OAEs and Identification of Hearing Loss

- Normal cochlea behaves nonlinearly
  - Source of nonlinearity is the OHC system
  - Healthy, functioning OHCs required for normal hearing
- OAEs are byproducts of normal nonlinear function
  - Loss of OAEs indicates damage to the OHCs

The Clinical Link

Loss of OAEs → OHC damage

Loss of OAEs → Infer hearing loss is present

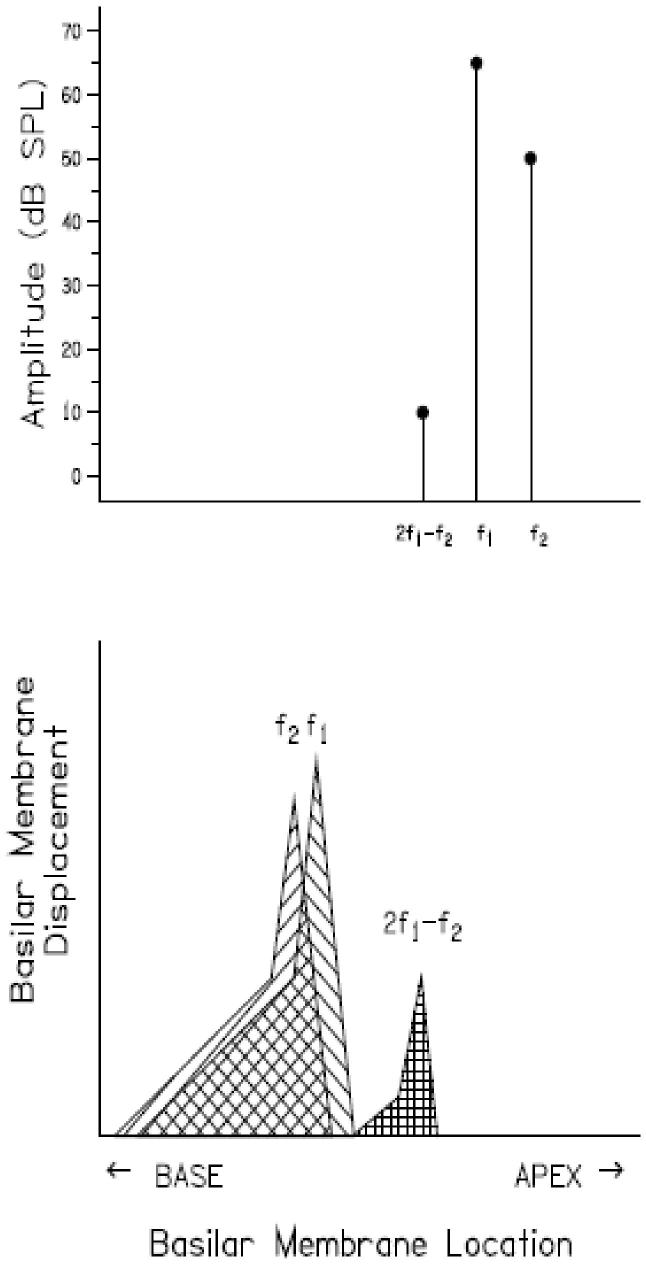
OAEs and Hearing Loss

- OAEs generally present at normal levels in ears with normal hearing, absent or present at reduced levels in ears with hearing loss
  - Many ears with mild hearing loss have OAEs, it is hard to distinguish normal from mild hearing loss.
  - Having present OAEs (for typical clinical protocols) generally suggests normal hearing or no more than a mild hearing loss
  - For typical clinical protocols the vast majority of ears with moderate to profound hearing loss have absent OAEs

Types of OAEs

- Spontaneous
- Evoked
  - Transient Evoked OAEs (TEOAEs)
  - Distortion Product OAEs (DPOAEs)
  - Stimulus Frequency OAEs (SFOAEs)

DPOAE Stimulus and Response



Typical clinical stimulus conditions

- Stimulus levels:
  - L1 = 65 dB SPL, L2 = 55 dB SPL
- Stimulus frequencies:
  - f2/f1 = 1.22
  - f2 often set equal to audiometric frequency. Why?

- Many studies suggest these conditions, particularly L1, L2 = 65, 55 dB SPL, are most accurate for identifying hearing loss (e.g., Stover et al., 1996; Johnson et al., 2007; 2010).

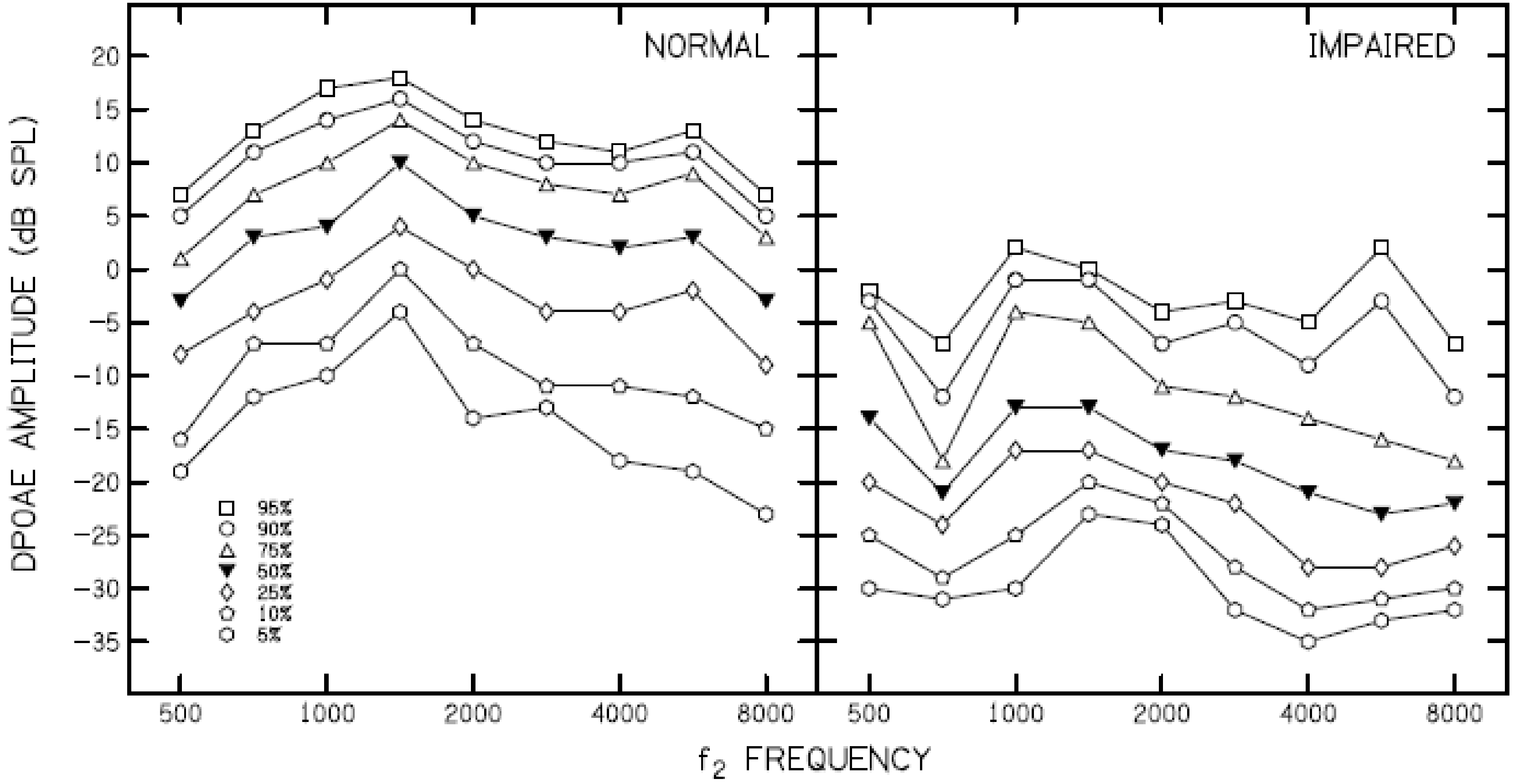
Clinical Interpretation of OAEs

- Goal: Identify Ears with Hearing Loss
- How does response from normal ears differ from impaired ears?

Next figure shows DPOAE levels for normal and impaired ears

- DPOAE level as a function of f_2
- Data from normal (left panel) and impaired (right panel) ears are shown
- Parameter is percentage, from 5^{th} to 95^{th} percentiles
- Filled symbols represent the DPOAE levels at the median (50^{th}) percentile

DPOAEs in Normal & Impaired Ears



Gorga et al. (1996)

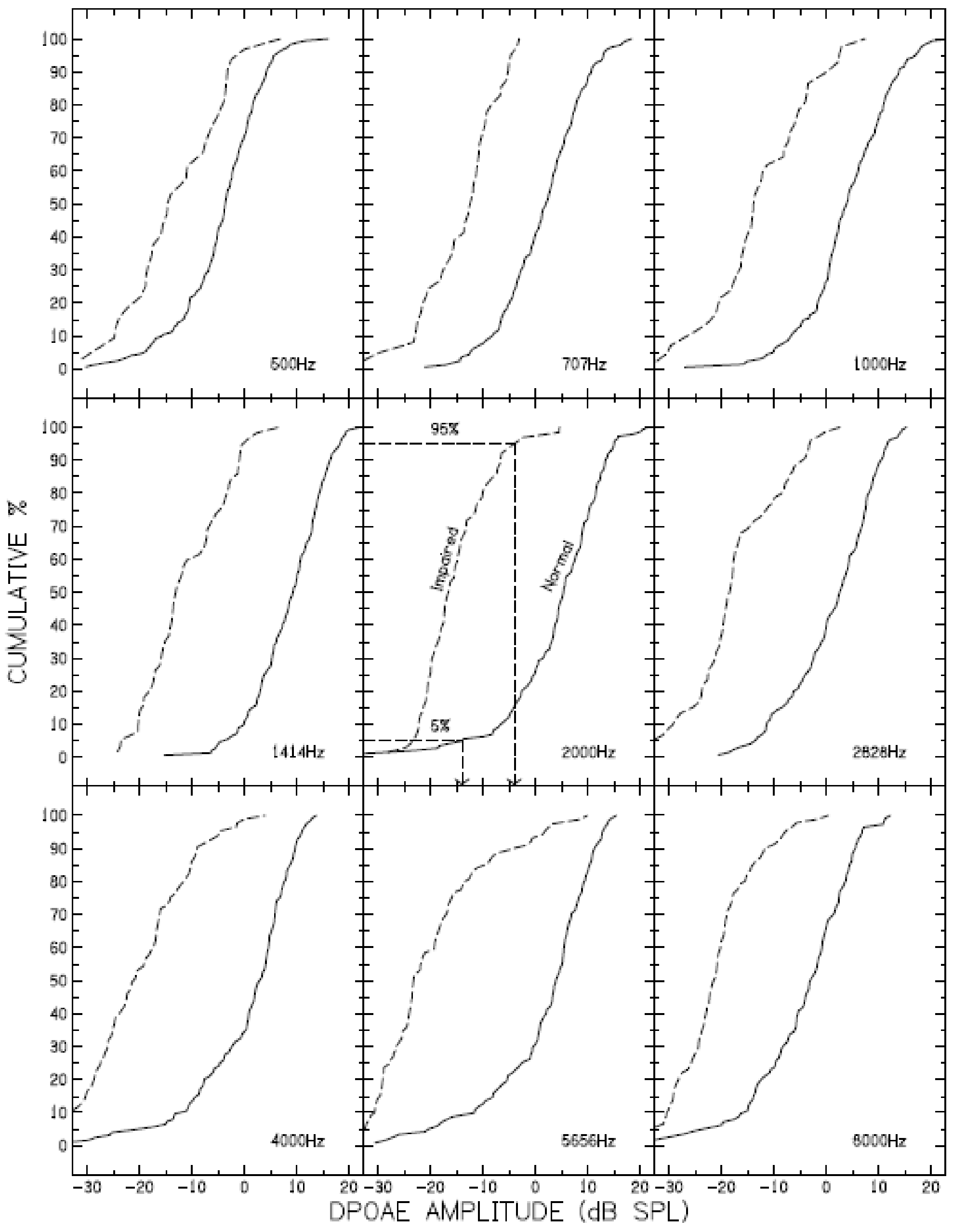
Overlap Between Normal and Impaired Responses

- No criterion can be selected that completely separates responses from the normal and impaired ears.
  - Some impaired ears produce bigger responses than some normal ears
  - *And*, some normal ears produce smaller responses than some impaired ears

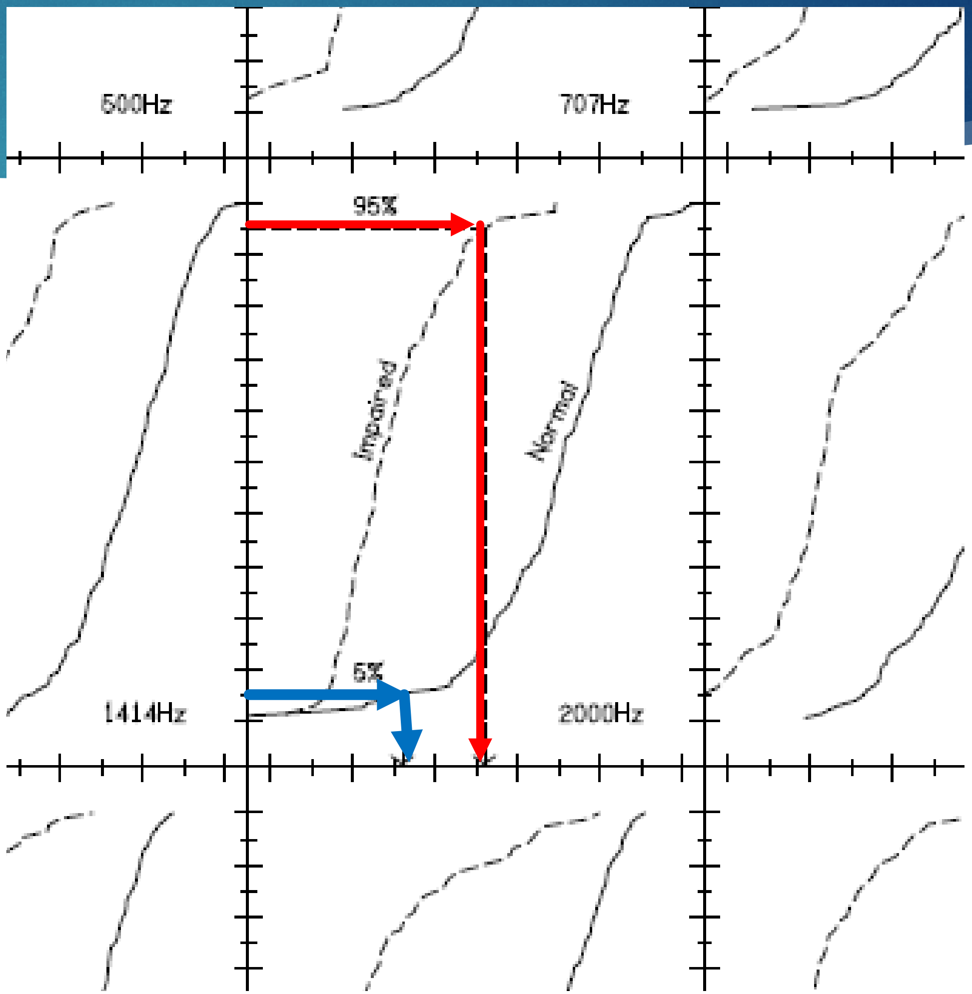
Development of Template

- Study: Gorga et al. (1997, E&H)
- Data from **1257** normal and impaired ears
- L_1/L_2 = 65/55 dB SPL
- All data collected under clinical conditions
- Constructed cumulative distributions

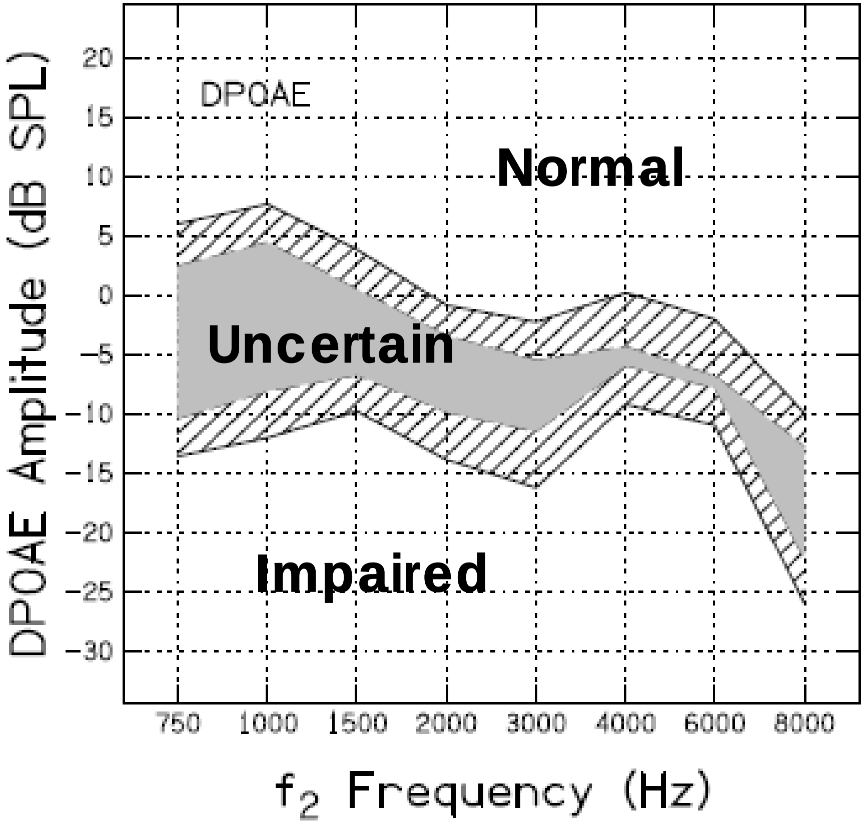
Cumulative distributions & Template Construction

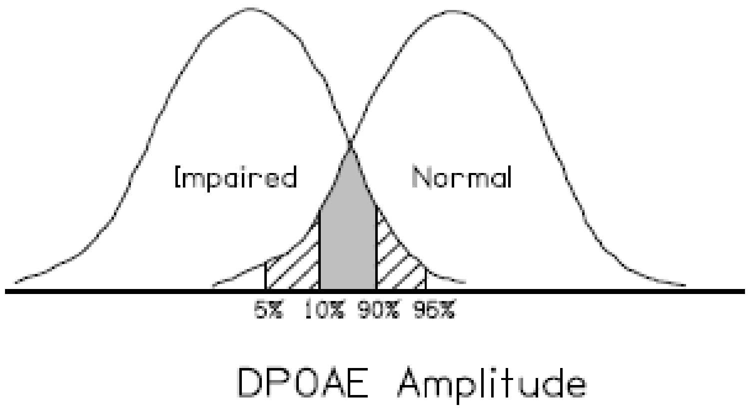


Cumulative distributions & Template Construction



BTNRH Template





Using the template

Must judge influence of noise

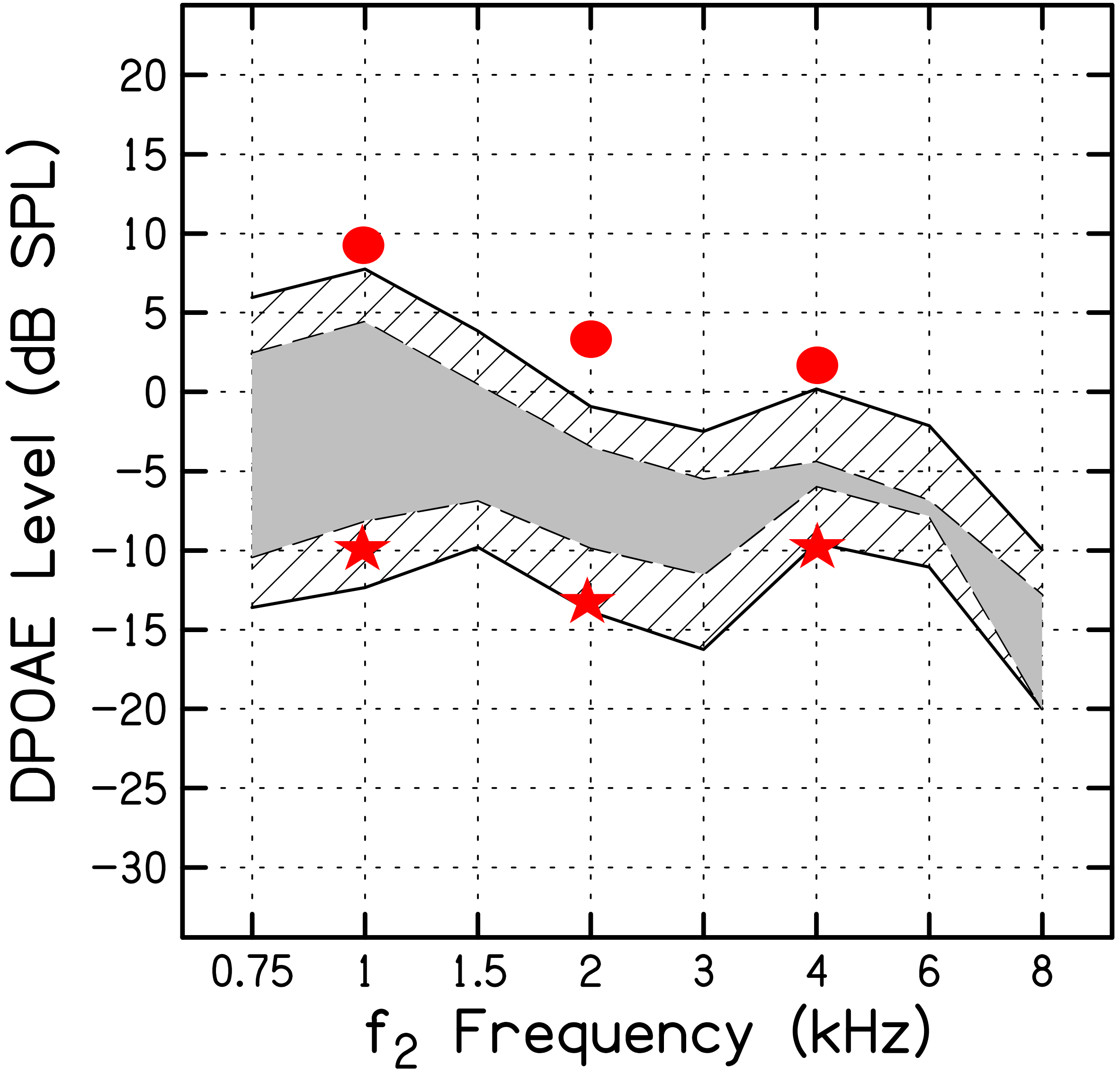
1. If SNR ≥ 6 dB, plot DPOAE level on template, interpret accordingly
2. If SNR ≤ 6, how noisy was the response?
   - If noise falls ***below*** the lower lines on the template (impaired region), plot and interpret accordingly
   - If noise falls ***above*** the lower lines on the template (impaired region) responses contaminated by noise and can't be interpreted

Uncertain region

- Diagnosis is **uncertain** for responses in the shaded region, even if SNR ≥ 6 dB, because responses here could be from either normal or impaired ears.

Example Case #1

f2 frequency	DPOAE level (dB SPL)	Noise level (dB SPL)	SNR (dB)
1000	8	-10	18
2000	3	-13	16
4000	2	-10	12


DPOAE Level (dB SPL)
20
15
10
5
0
−5
−10
−15
−20
−25
−30
0.75
1
1.5
2
3
4
6
8
f2 Frequency (kHz)

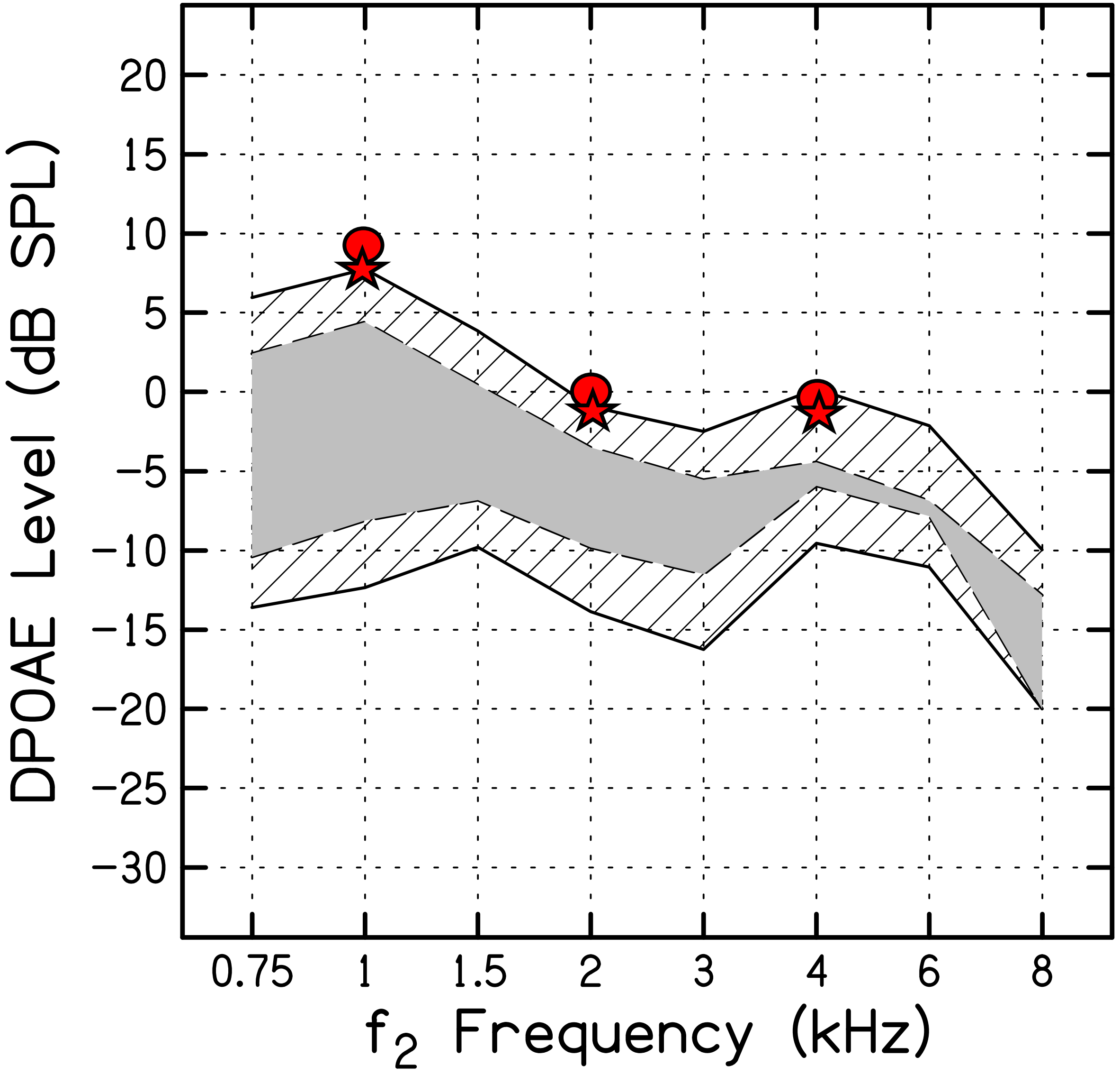
Case 1

Case 1: Results Consistent with Normal Hearing

- Low noise levels even for lower f_2's
- Large DPOAEs
- Positive SNRs at all f_2's
- Levels above 95^{th} percentile for impaired ears
- Results consistent with normal hearing because few impaired ears produce such large responses

Example Case #2

f2 frequency	DPOAE level (dB SPL)	Noise level (dB SPL)	SNR (dB)
1000	8	8	0
2000	0	-1	1
4000	0	0	0


20
15
10
5
0
−5
−10
−15
−20
−25
−30
DPOAE Level (dB SPL)
0.75
1
1.5
2
3
4
6
8
f2 Frequency (kHz)

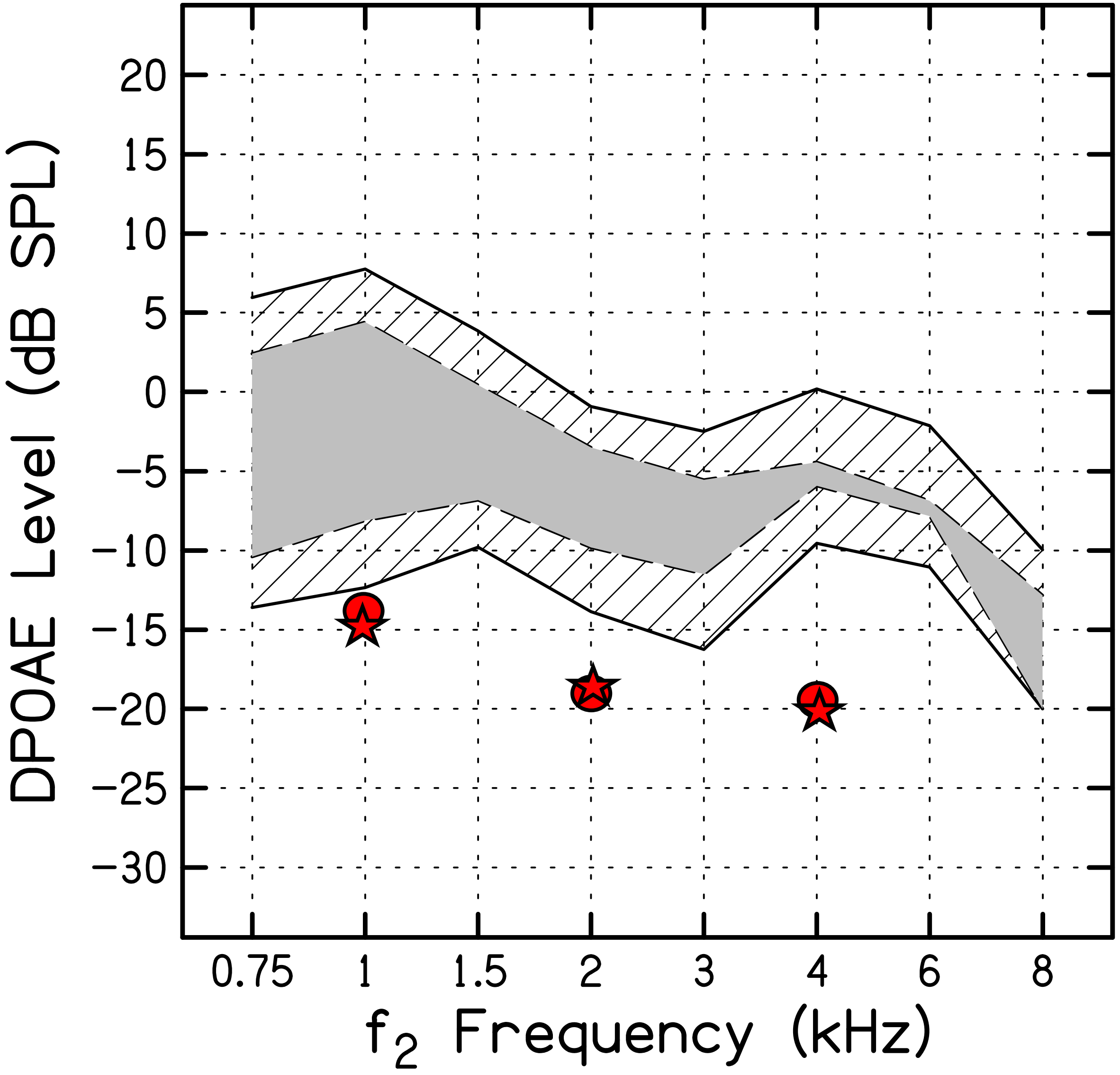
Case 2

Case #2: High Noise Levels = Uninterpretable Responses

- “Large” DPOAEs
- High noise levels
- Low SNRs
- Results are uninterpretable because “large” DPOAEs may be nothing more than noise
- Note that the DPOAE levels were similar to Case #1

Case #3

f2 frequency	DPOAE level (dB SPL)	Noise level (dB SPL)	SNR (dB)
1000	-14	-15	1
2000	-18	-17	-1
4000	-18	-20	2



DPOAE Level (dB SPL)
20
15
10
5
0
−5
−10
−15
−20
−25
−30
0.75
1
1.5
2
3
4
6
8
f2 Frequency (kHz)

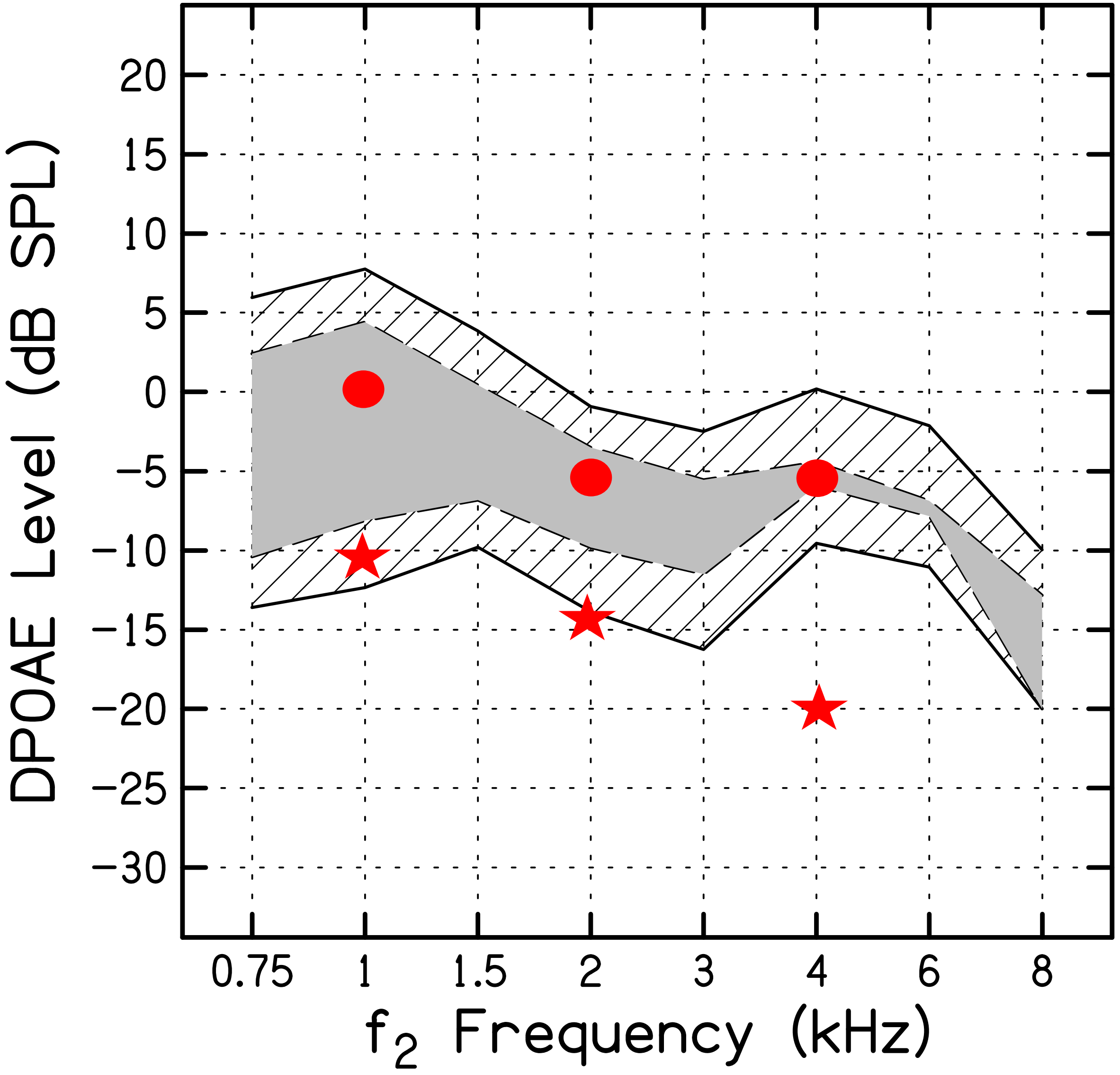
Case 3

Case #3: Low SNRs & Low Noise Levels can be Interpreted

- DPOAEs below the lower limits of graph
- Noise levels also are low
- Low SNRs (i.e., DPOAE level was not measured reliably)
- Results are consistent with hearing loss because the reason a response was not measured was NOT due to high levels of noise, but to low level of response.

Example Case #4

f2 frequency	DPOAE level (dB SPL)	Noise level (dB SPL)	SNR (dB)
1000	0	-11	11
2000	-6	-14	8
4000	-6	-20	14


DPOAE Level (dB SPL)
20
15
10
5
0
−5
−10
−15
−20
−25
−30
0.75
1
1.5
2
3
4
6
8
f_2 Frequency (kHz)

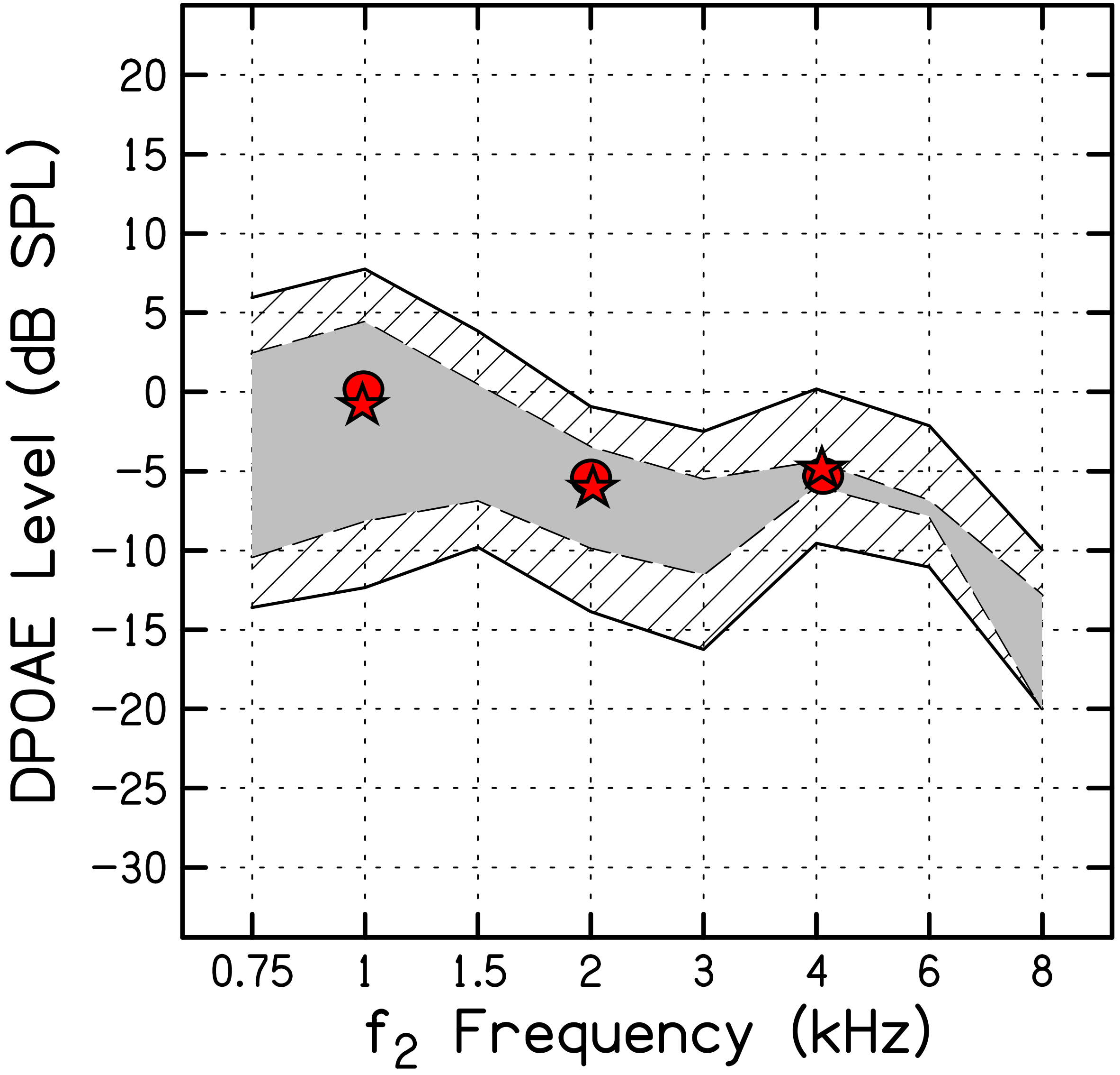
Case 4

Case #4: DPOAEs in the region of uncertainty

- DPOAE levels in shaded region
- Noise levels well below DPOAEs
- Positive SNRs, meaning DPOAEs were measured reliably
- Results cannot be assigned to normal or impaired distribution

Example Case #5

f2 frequency	DPOAE level (dB SPL)	Noise level (dB SPL)	SNR (dB)
1000	0	-2	2
2000	-5	-5	0
4000	-6	-5	-1


20
15
10
5
0
−5
−10
−15
−20
−25
−30
DPOAE Level (dB SPL)
0.75
1
1.5
2
3
4
6
8
f_2 Frequency (kHz)

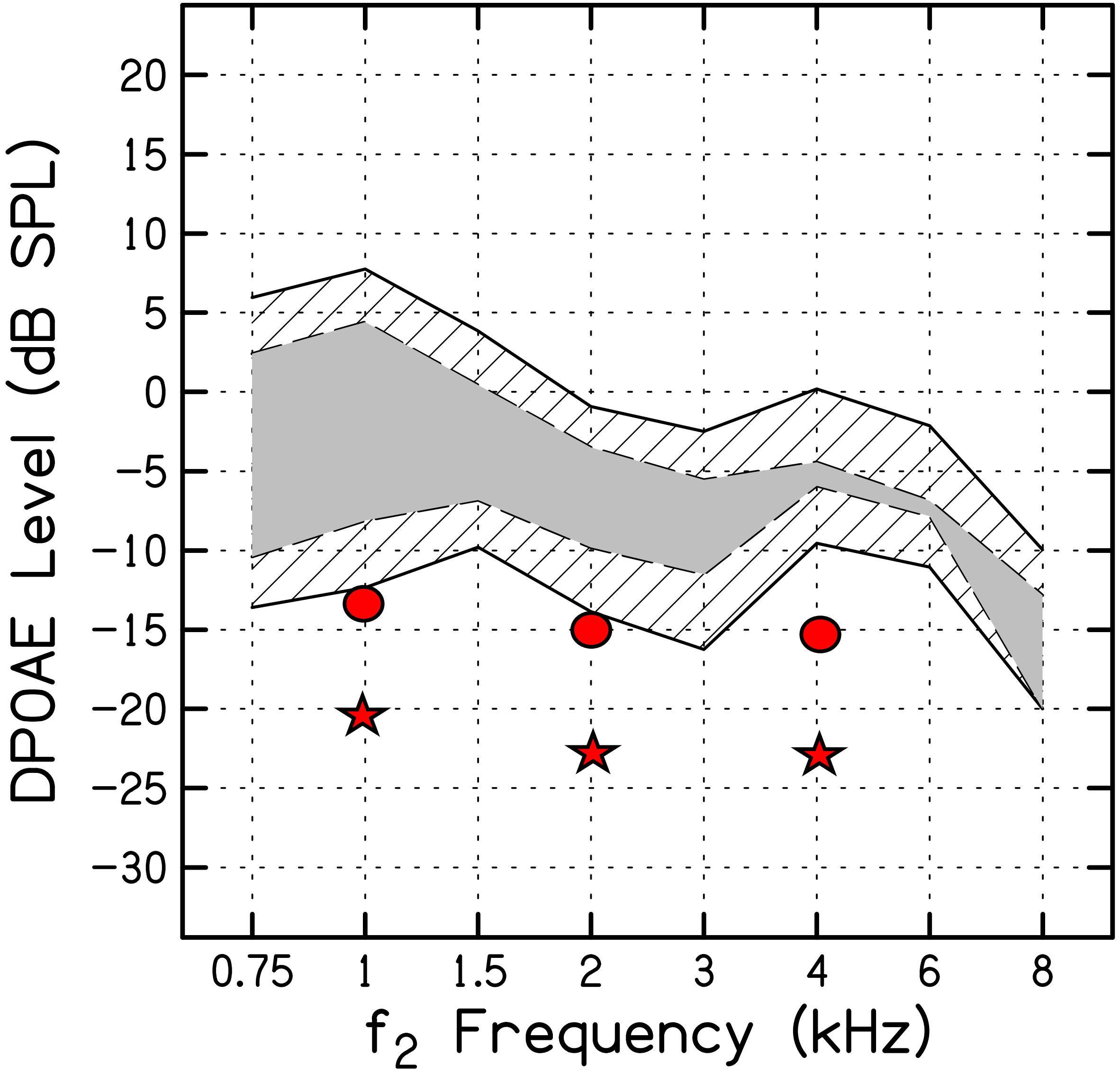
Case 5

Case #5: Uninterpretable DPOAEs in Region of Uncertainty

- DPOAEs in shaded region
- Noise levels = DPOAE level
- SNRs approximately = 0
- DPOAEs therefore are not reliable
- Results cannot be interpreted because measured “responses” may be just noise, but this cannot be known

Example Case #6

f2 frequency	DPOAE level (dB SPL)	Noise level (dB SPL)	SNR (dB)
1000	-14	-21	7
2000	-16	-23	7
4000	-16	-23	7


20
15
10
5
0
−5
−10
−15
−20
−25
−30
DPOAE Level (dB SPL)
0.75
1
1.5
2
3
4
6
8
f2 Frequency (kHz)

Case 6

Case #6: SNRs > 6 dB, Responses in Impaired Region

- Although SNRs all > 6 dB, the DPOAE ***Levels*** indicate impaired OHC function, consistent with hearing loss
- Important to evaluate both response level and noise independently, not just the SNR

Bad News - Good News

- Bad news:
  - Errors in diagnoses are inevitable when OAEs are used to identify hearing loss.
  - This is true for other tests, not just OAE tests.
- Good news:
  - When auditory status is uncertain, it is more likely that we are confusing normal and mild hearing loss.
  - It is much less likely that we are confusing normal hearing with moderate or greater losses.

Multivariate Approaches

Typical Goal of OAE Testing

- Identify *auditory status*
- Does this ear have normal hearing or impaired hearing?

Predicting Auditory Status: *Univariate* Approach

- Responses interpreted by looking at information from one frequency
- For example:
  - Is the SNR at 2kHz > 6 dB and was the DPOAE level at 2kHz consistent with normal or impaired hearing?

Predicting Auditory Status: *Univariate* Approach

- Performance is not perfect, responses from normal and impaired ears can look the same
- Uncertain region on clinical forms comes from this overlap

Predicting Auditory Status: *Multivariate* Approach

- Measurements (DP level, noise) made at several frequencies can be used to predict auditory status at a single frequency
- Why do this?
  - Normal at one frequency, likely normal at other frequencies.
  - Impaired at one frequency, likely impaired at other frequencies.

Predicting Auditory Status: *Multivariate* Approach

- Need to know which frequencies help most in prediction
- How?
  - Use logistic regression

Logistic Regression

- Specifies which variables and associated coefficients most accurately separate a normal from an impaired ear
  - Variables = DPOAE levels and noise values at different f_2 frequencies
  - Coefficients = multipliers for the variables
- Generates an equation that transforms DPOAE and noise levels in to LF score.
  - LF score can be used to predict auditory status.

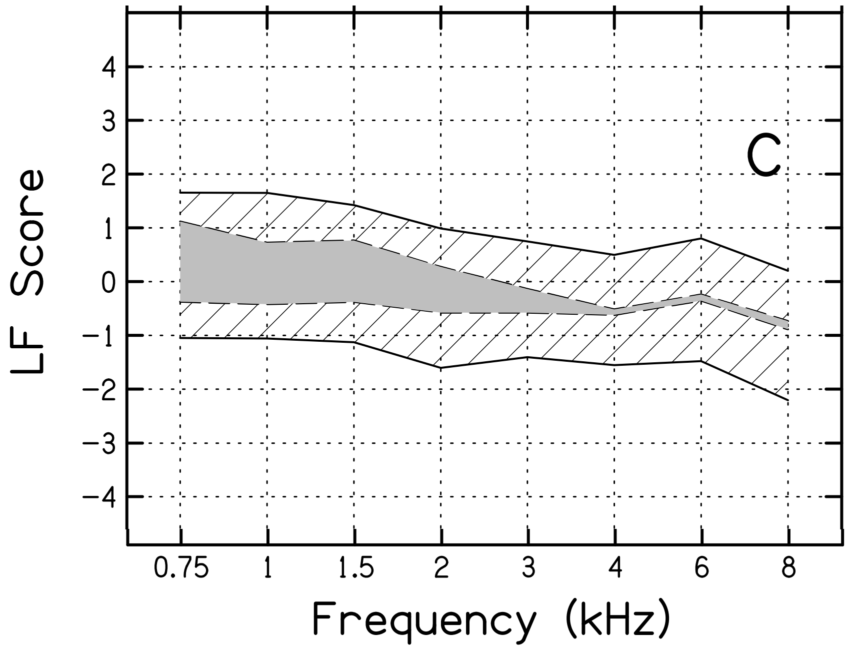
Simplified (!) example of LR equation

- $LF_{4000} = (0.068*DP_{2000} + 0.038*DP_{3000} + 0.172*DP_{4000}) + (-0.087*N_{3000} + -0.082*N_{4000} + -0.051*N_{6000})$

- LF score is not a physical variable like DP level or noise but can be used to make decisions about auditory status
- Use LF templates to make decisions.

LF Template

LF score (on ordinate) is a dimensionless number derived from logistic regression.



Gorga et al., 2005

Multivariate Approach

- Gorga et al. (1999, 2005)
  - First to use a multivariate analysis with DPOAEs
  - New approach improved test accuracy
    - Dependent on degree of hearing loss and frequency
    - Never produced more uncertainty
    - Improvements seen in two different studies with different subjects

Julie Bangert AuD Project

- Does the Gorga et al. multivariate approach translate to a different clinic, different equipment, and pediatric only data set?
- Tested this question using data from our clinic at KUMC.

Methods: Subjects & Inclusion Criteria

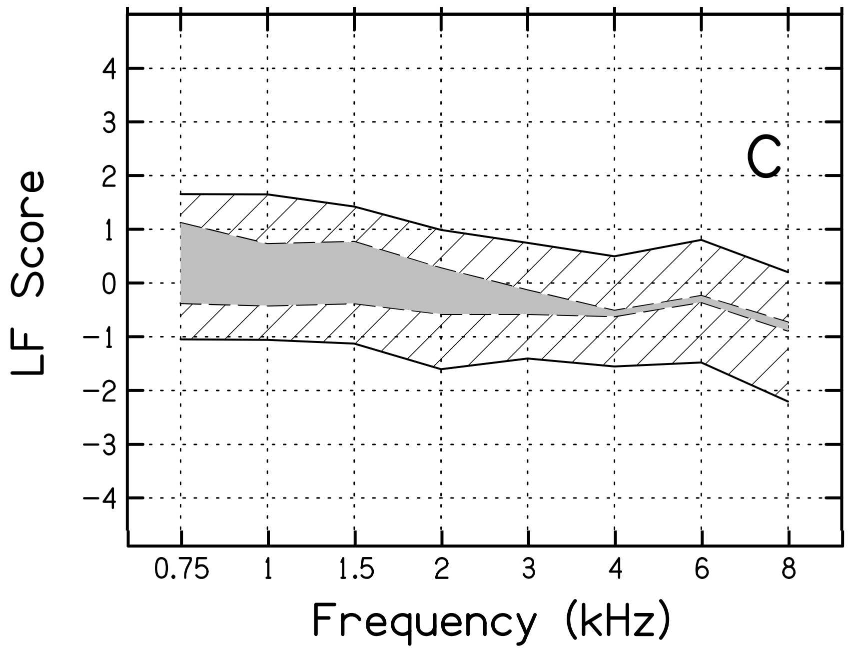
- Subjects selected from KUMC Audiology Clinic pediatric data
  - 24 subjects (n=47 ears)
  - Ages: 6 months to 16.5 years
- Inclusion criteria:
  - DPOAEs
  - Behavioral audiometric data (VRA, CPA, conventional)
  - Normal tympanometry

Methods: Behavioral & DPOAE Data

- Data extracted from our pediatric clinic records:
  - **Behavioral air conduction thresholds** from 1- 4 kHz (interpolated at 1.5 & 3 kHz)
    - Each threshold was classified as normal (≤ 20 dB HL) or impaired (>20 dB HL)
  - **DPOAE and noise levels** from 1-6 kHz
    - DPOAEs classified as normal, uncertain, or impaired using BTNRH template

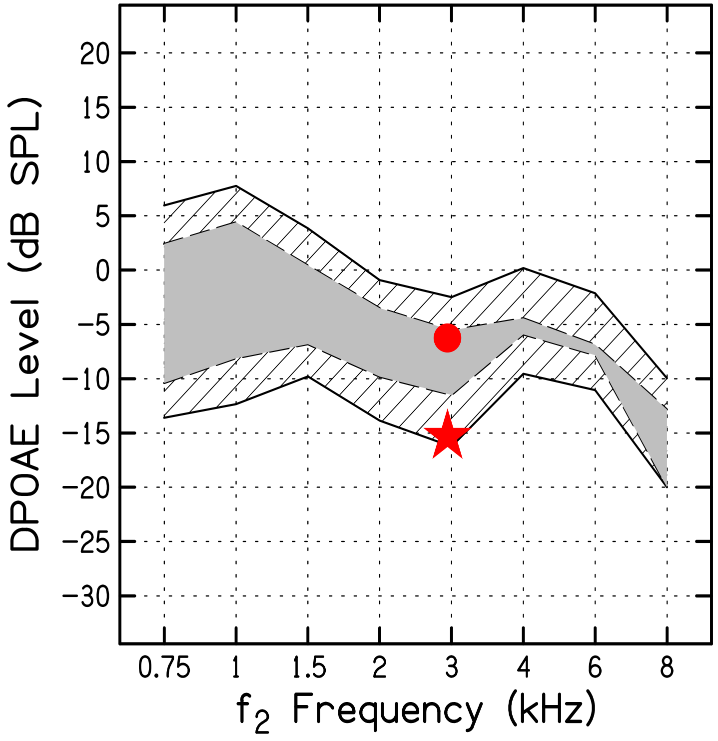
Methods: LF Scores

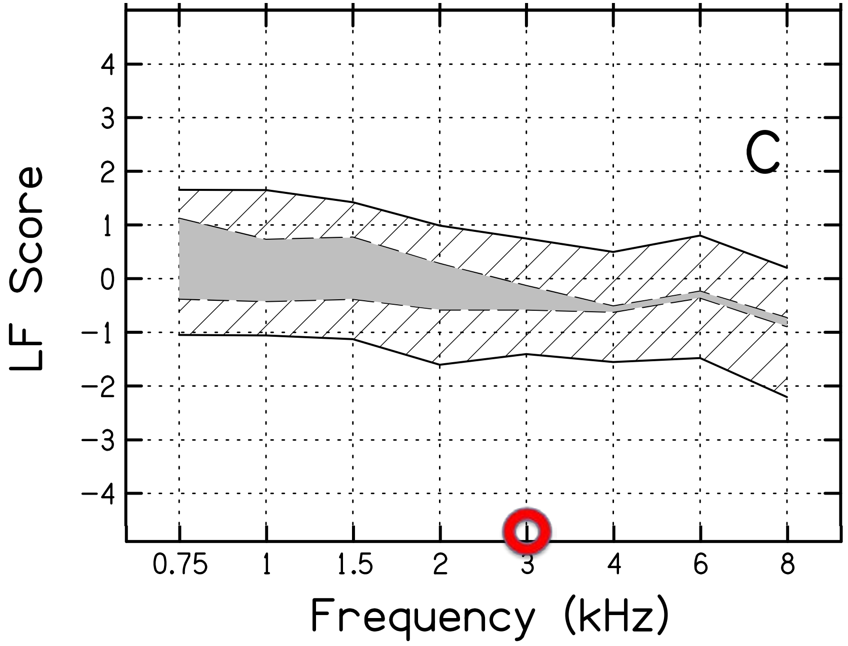
- DPOAE and noise levels were converted to LF scores using the Gorga et al (2005) equations.
- Example of the LF score computation at 4kHz:
  - LF_{4000} = (0.068*DP_{2000} + 0.038*DP_{3000} + 0.172*DP_{4000}) + (-0.087*N_{3000} + -0.082*N_{4000} + -0.051*N_{6000})
- LF score was classified as normal, uncertain, or impaired by comparing to template



Methods: Determining Accuracy

Truth (behavioral threshold) = Impaired

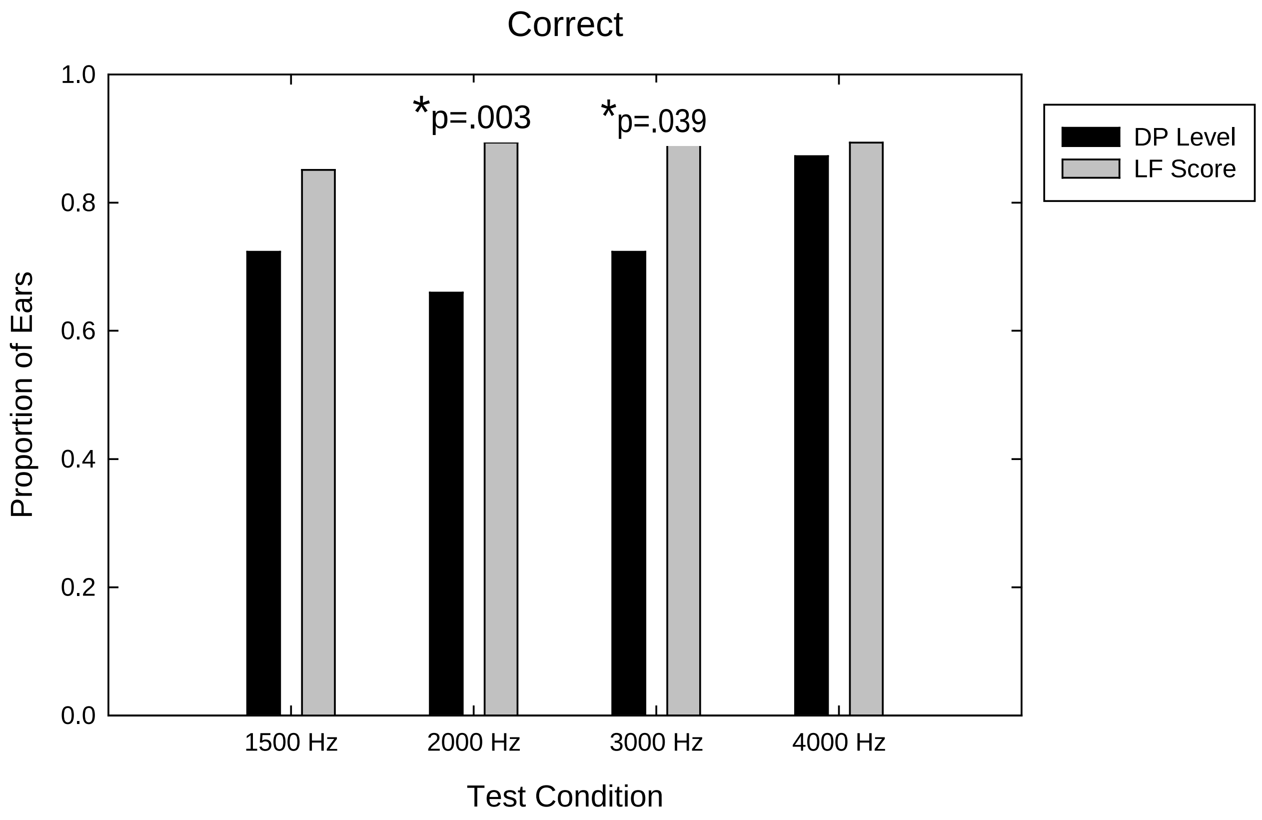


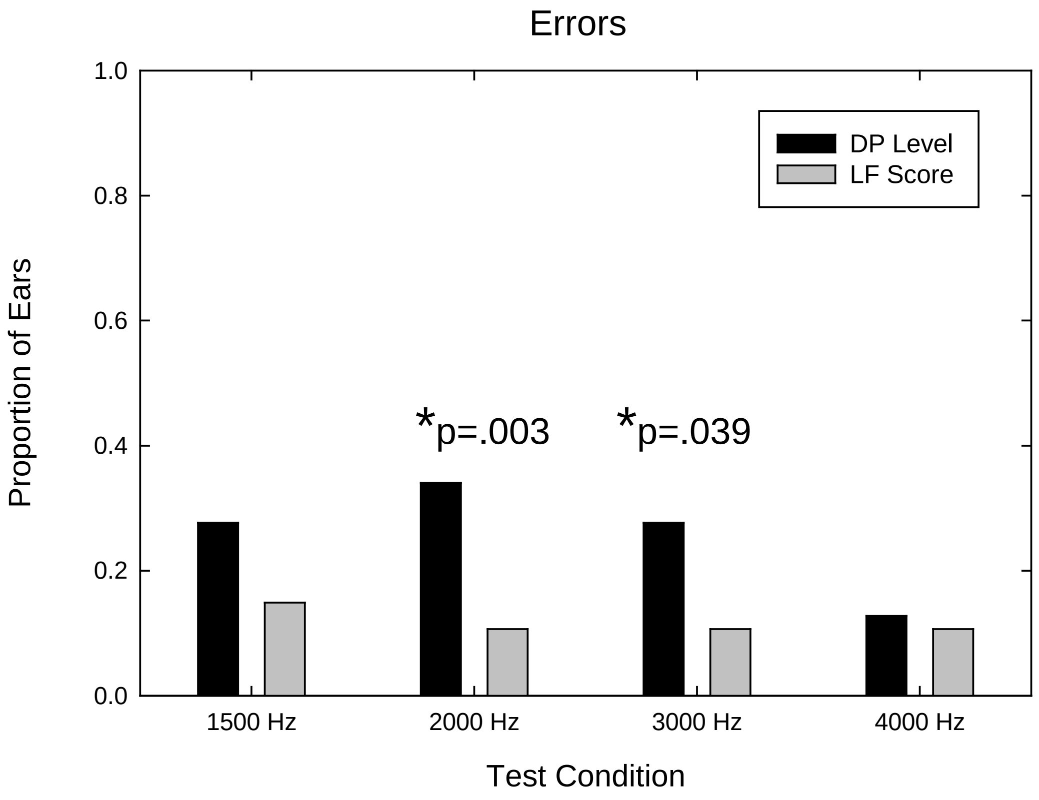


Methods: Determining Accuracy

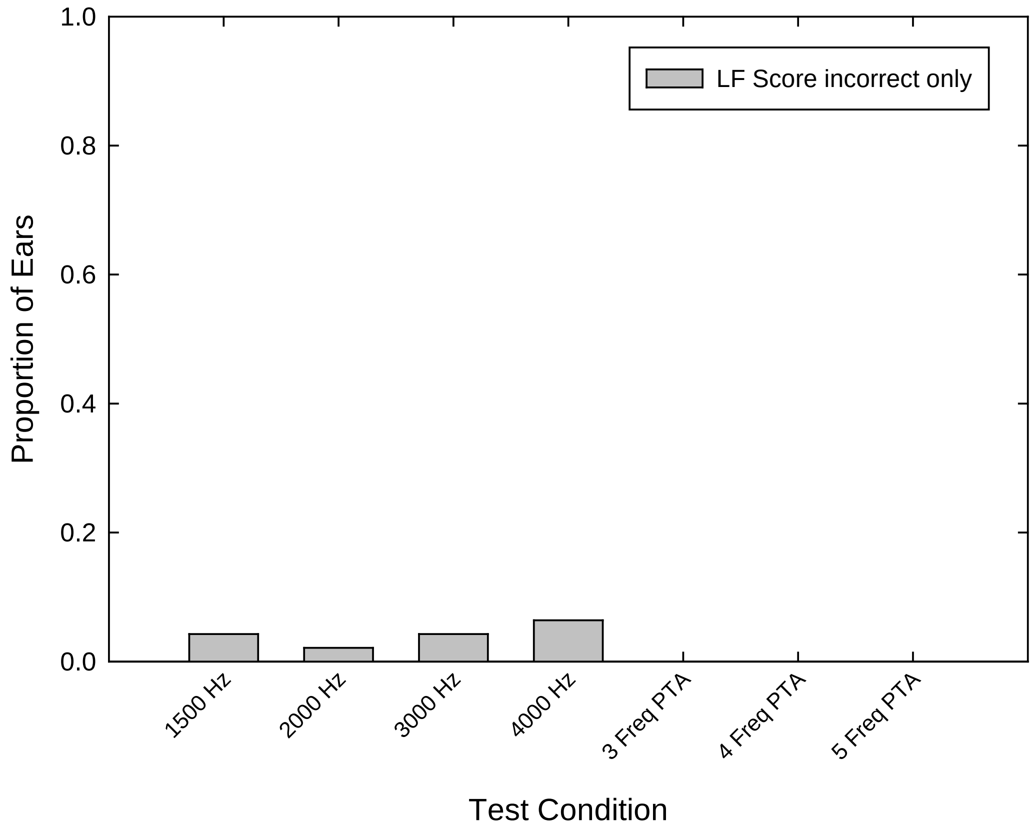
- What was considered an “error”?
  - If DPOAE decision differed from behavioral threshold decision
    - N vs. I, I vs. N, uncertain vs. N or I
  - If LF decision differed from behavioral threshold decision
    - N vs. I, I vs. N, uncertain vs. N or I
  - If DPOAE was uninterpretable due to high noise levels/poor SNR

Results: Decision Univariate DPOAEs vs. LF Score





Results: LF Only Errors



Rare for the LF score to make an error when univariate DPOAE had been correct

Discussion

- Increase in the number of correct decisions when using LF score vs. the univariate DPOAE
- Few cases where the LF score caused an error and the traditional approach did not
- Large contribution to improved decisions with LF scores was from cases where the univariate DPOAE was uninterpretable due to high noise levels and the LF score made a correct decision

Discussion

- Original formulas developed with the Biologic system generalized to the ILO system
- Multivariate approach does not require any more participation from the patient! It’s all data analysis after the fact.

Limitations

- Limited data for logit function equation
  - To compute all frequencies, you need DP emission and noise values for 750, 1000, 1500, 2000, 3000, 4000, 6000, and 8000 Hz
  - Do not typically collect DP_{8000} or N_{750}
    - Extrapolation of DP_{8000} from DP_{6000}
    - Did not use equations requiring N_{750}
- Small sample size (n=47 ears); but consistent with other larger studies

Overall Conclusions

- BTNRH templates provide an evidence-based approach to interpreting DPOAE data based on a very large data set
- It is important to look at both DPOAE level ***and*** noise levels when interpreting DPOAEs
- Multiple studies (BTNRH and KUMC) suggest that the multivariate approach improves DPOAE test accuracy.

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