Are basilar-membrane traveling waves necessary for *long* OAE delays?

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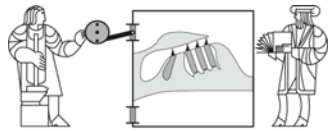
(worked performed with Christopher Shera and Dennis Freeman)



MIT Micromechanics Group
EPL Auditory Physics Group

OSU Workshop *June 2007*

QUESTION

Are BM traveling waves necessary for *long* OAE delays?

MOTIVATION

How is energy propagated through the mammalian cochlea? If BM traveling waves are absent, would delays be smaller?

Comparative Approach

Systematic examination in wide range of ears where anatomy & physiology vary significantly

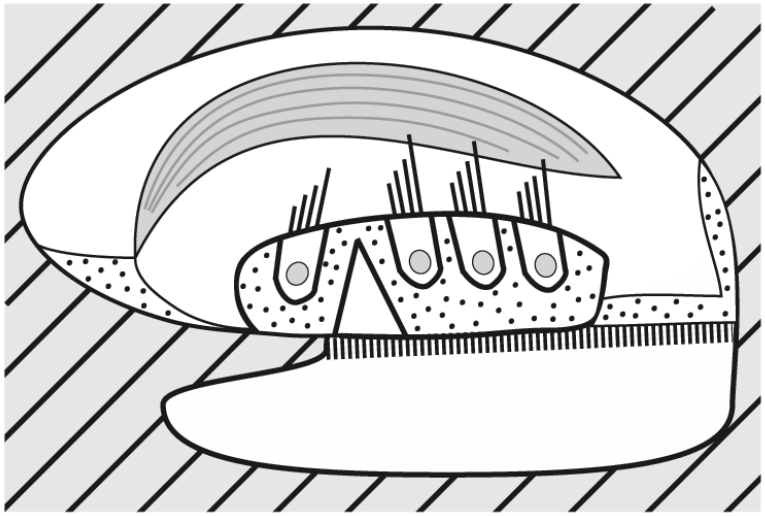
HUMANS

CHICKENS

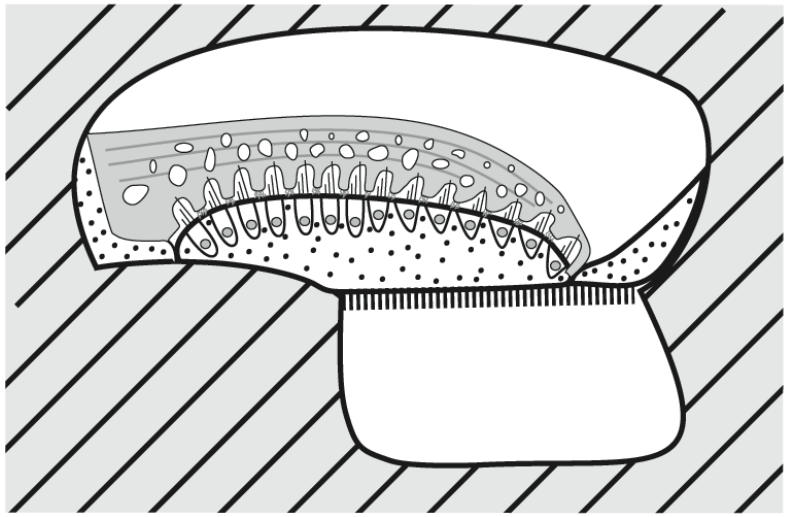
GECKOS
(two species)

FROGS

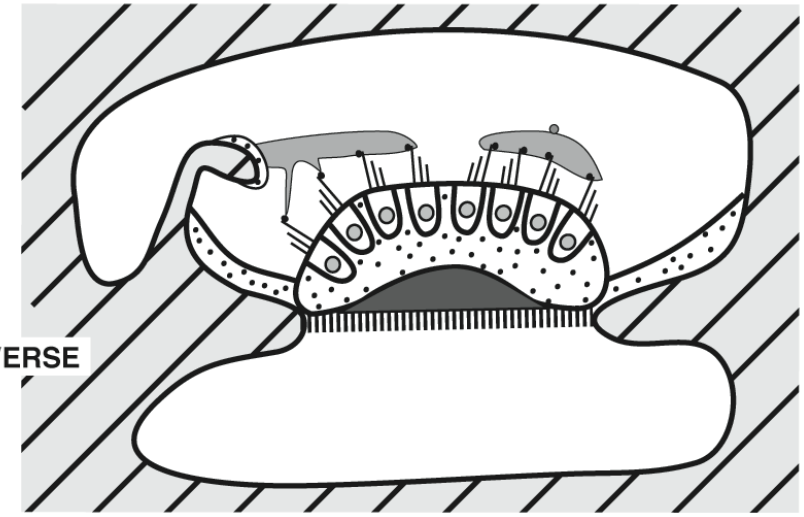
HUMAN



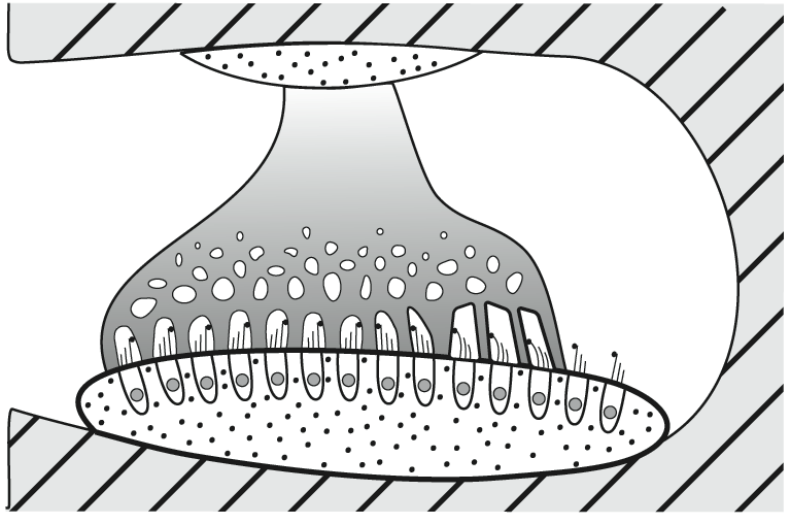
CHICKEN



GECKO



FROG



[Frog has two papillae]

COMPARING ACROSS SPECIES

SIMILARITIES: hair cells, tectorial membrane, ossicular/tympanic middle ear

DIFFERENCES: tuned/flexible membrane, somatic motility, different sizes, fewer HCs

HEARING ACUITY:

- low thresholds (at least 20 dB SPL)
- tuned responses
- poor high frequency hearing

How long is *long*?

Middle ear delays: ~ 0.05-0.1 ms

(possibly shorter in non-mammals)

Inner ear: ~ 1500 m/s (speed of sound in water)

~ 0.001-0.03 m (range of inner ear dimensions)

$\Rightarrow$ 0.001-0.02 ms

ballpark: ~0.1 ms (excluding traveling waves)

METHODS

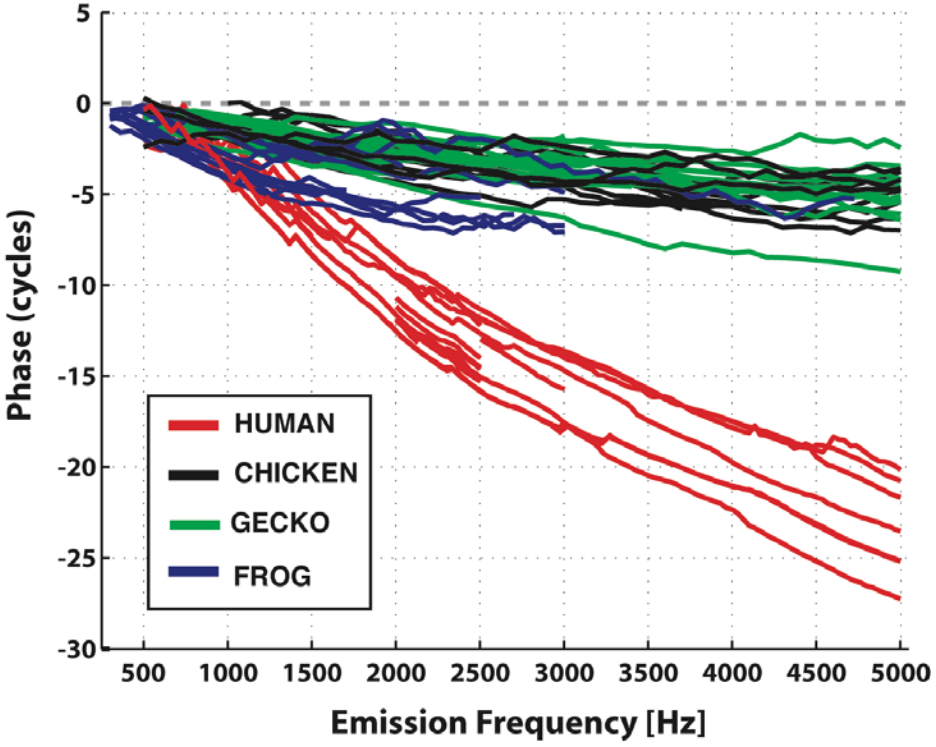
- **Stimulus frequency otoacoustic emissions (SFOAEs) (suppression paradigm)**

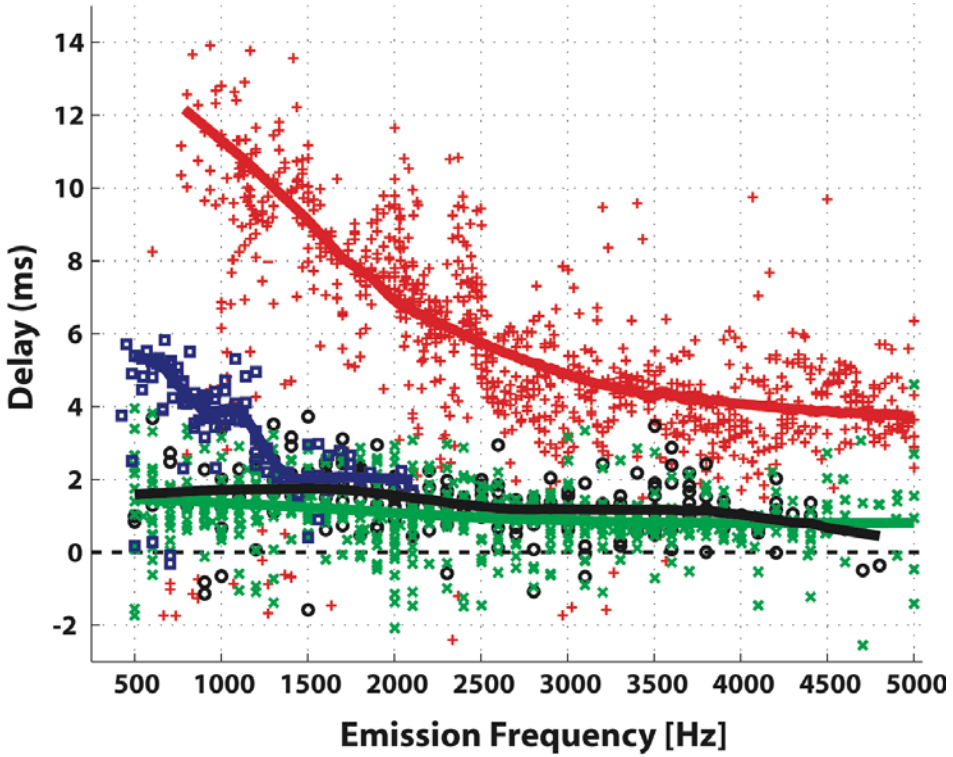
- **Phase response (frequency gradients) in steady-state used to determine delays**

- **‘*Low-Level*’ stimuli used: L_p=40 dB SPL, L_s=55 dB SPL**

SFOAEs

Lp=40 dB SPL, Ls=55 dB, fs=fp+40 Hz





SUMMARY

Long **delays (>1 ms) observed in all species**

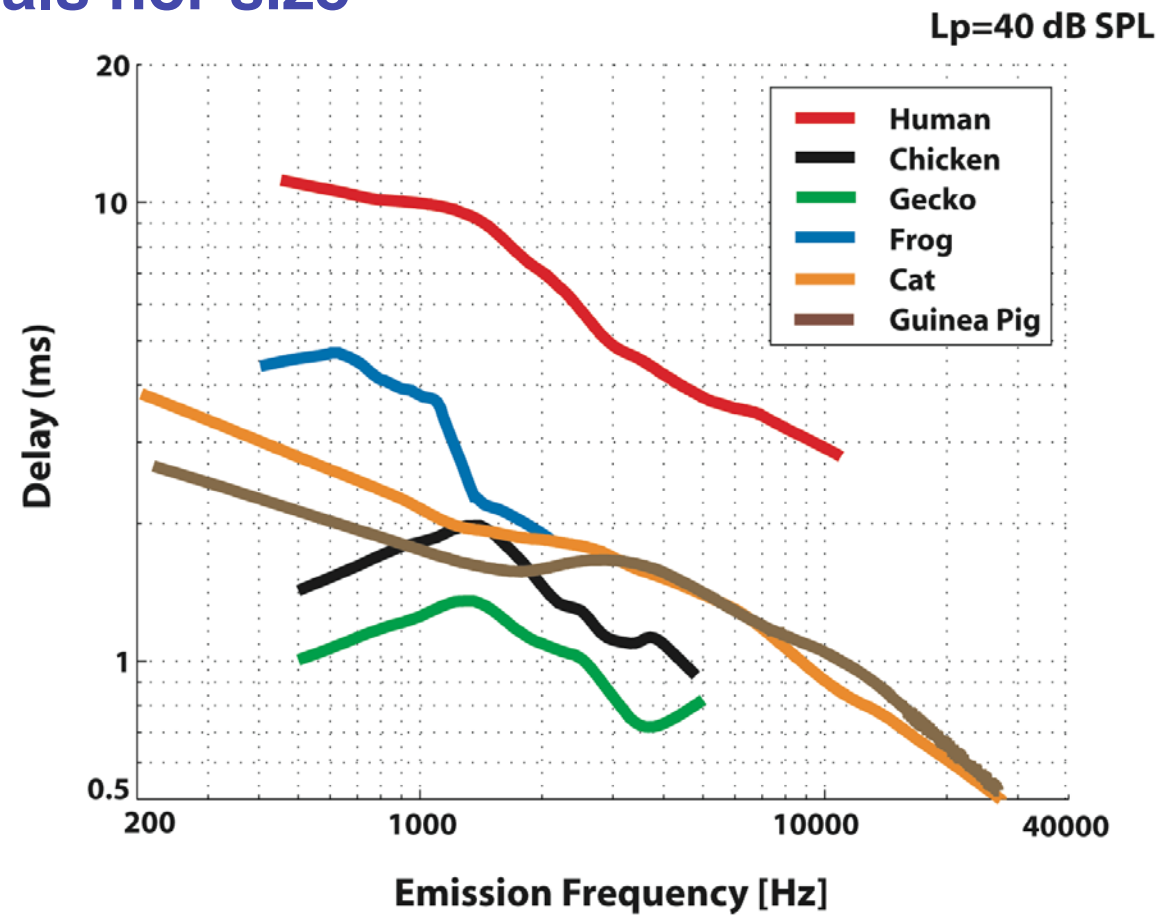
(being significantly largest in human)

QUESTION: Are BM traveling waves necessary for *long* OAE delays?

ANSWER: NO, *long* delays (~1 ms or longer >> 0.1 ms) arise in species lacking a tuned/flexible BM

Extending Further

Not due to differences between mammals and non-mammals nor size



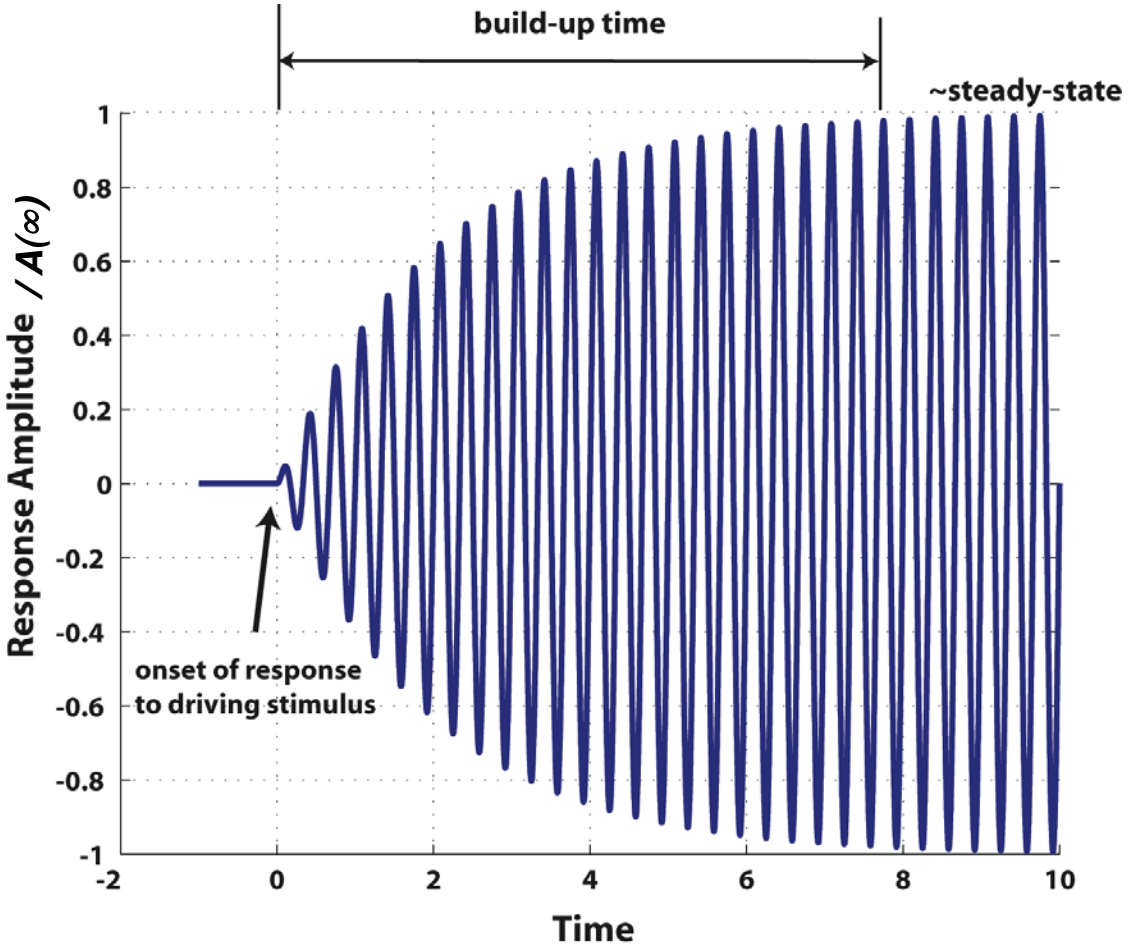
[cat and guinea pig data from Shera and Guinan, 2003]

Extending Further

⟹ So where does the additional delay come from?

TUNING

Tuned Responses Take Time



Second Order System
(resonant frequency ω_o)

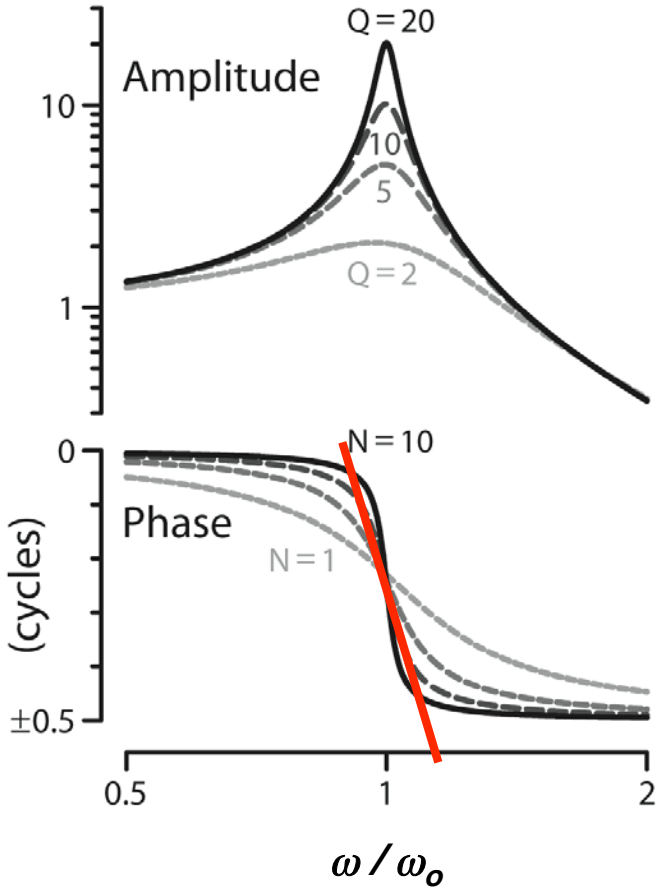
⇒ External driving force at frequency ω

$$x(t) = A(\infty)\,[1-e^{(-t/\tau)}]$$

$$\tau = Q / \omega_o$$

Q and Phase Gradients Co-vary

Second Order System
(resonant frequency ω_o)



$Q = \omega_o / (2\pi \times \text{BANDWIDTH})$

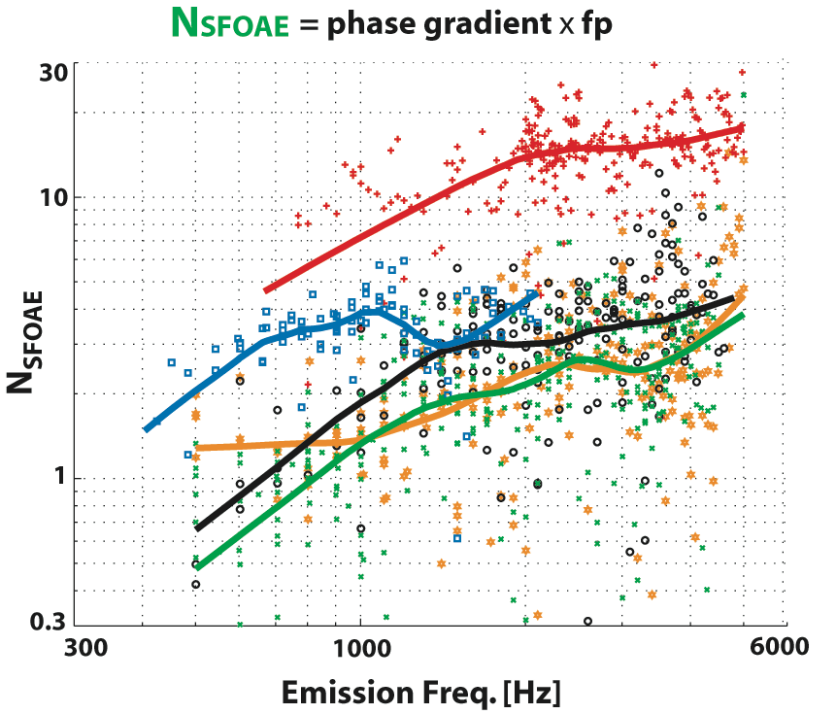
$N = \omega_o \times \text{Phase Gradient} / 2\pi$
(at ω_o)

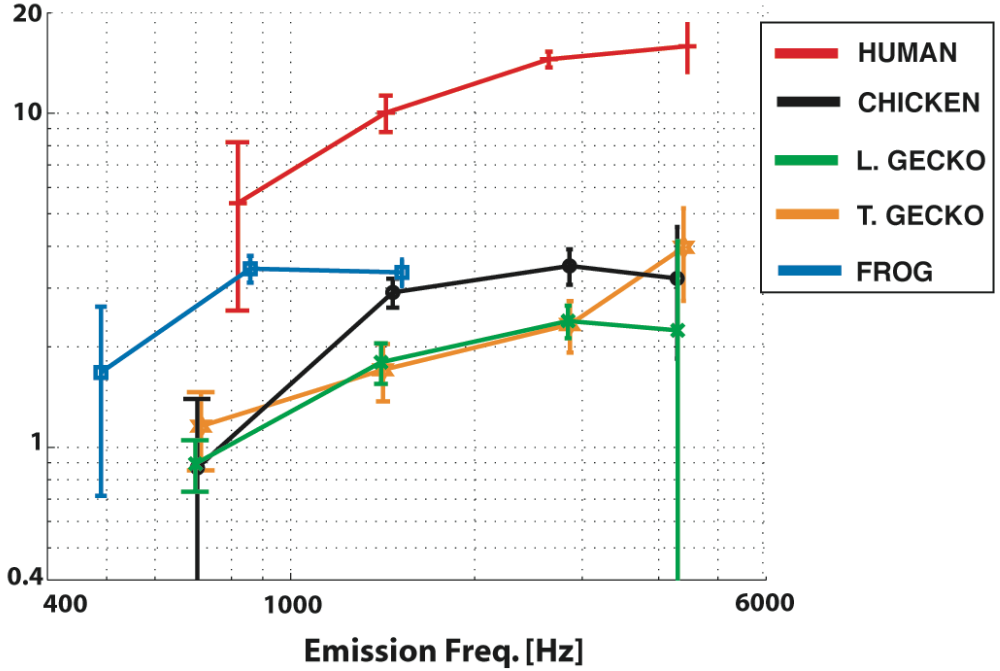
$Q \propto N$

(Shera, Oxenham and Guinan, 2007)

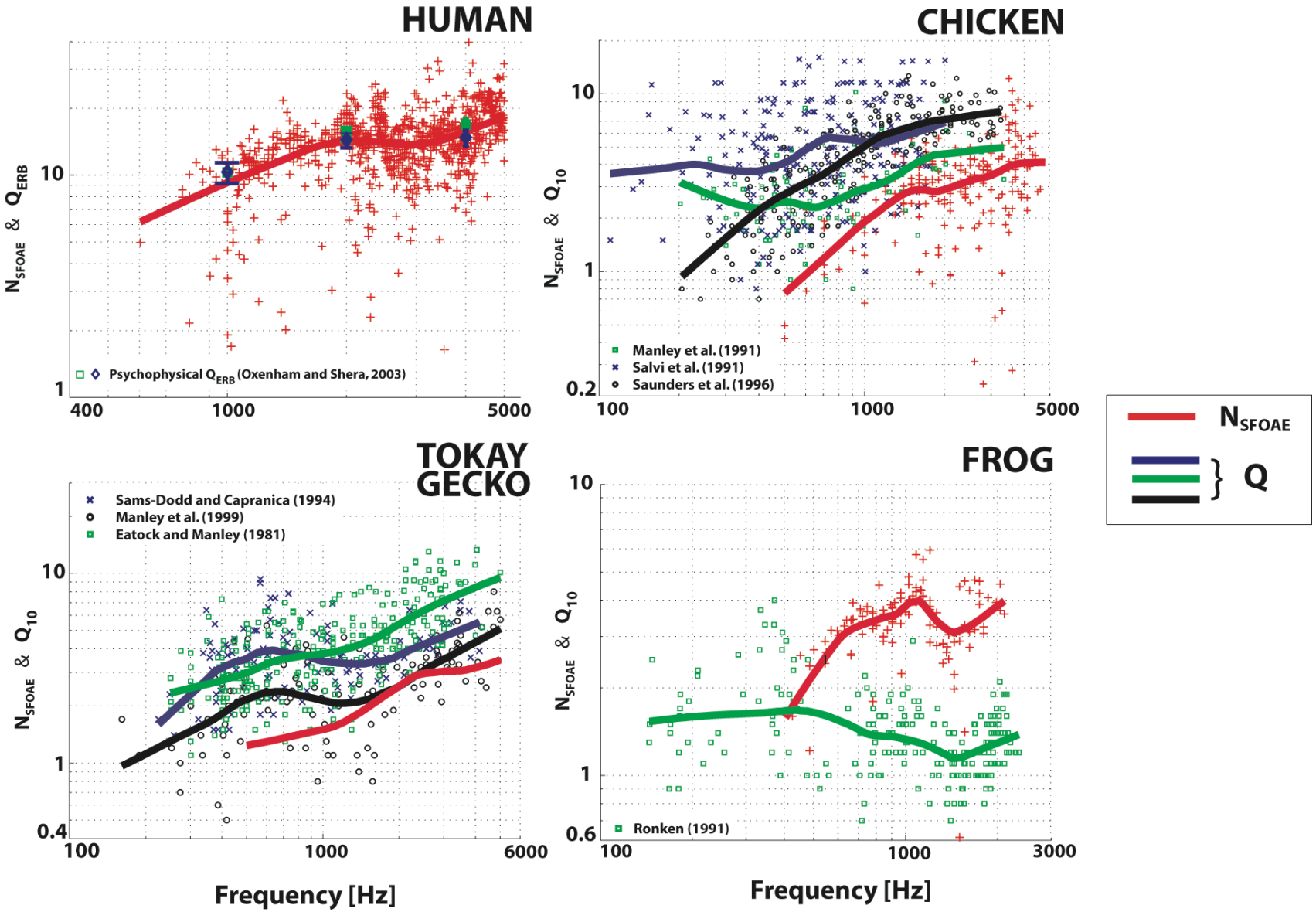
Plot Delay in Dimension-less Form as N

Lp=40 dB SPL, Ls=55 dB, fs=fp+40 Hz





Comparison of N (SFOAE) to Q-value (ANF)



SUMMARY (II)

Similar frequency dependence between N and Q

[for human, chicken and gecko]

Sharper tuning in human would account for differences

[N-values relative to other species]

Additional delay not associated with tuning in frog

⇒ Due to unique anatomy (‘*tectorial curtain*’)?

Connection between tuning and traveling waves?

CONCLUSIONS

What has the comparative approach revealed?

BM traveling waves not needed for *long* OAE delays

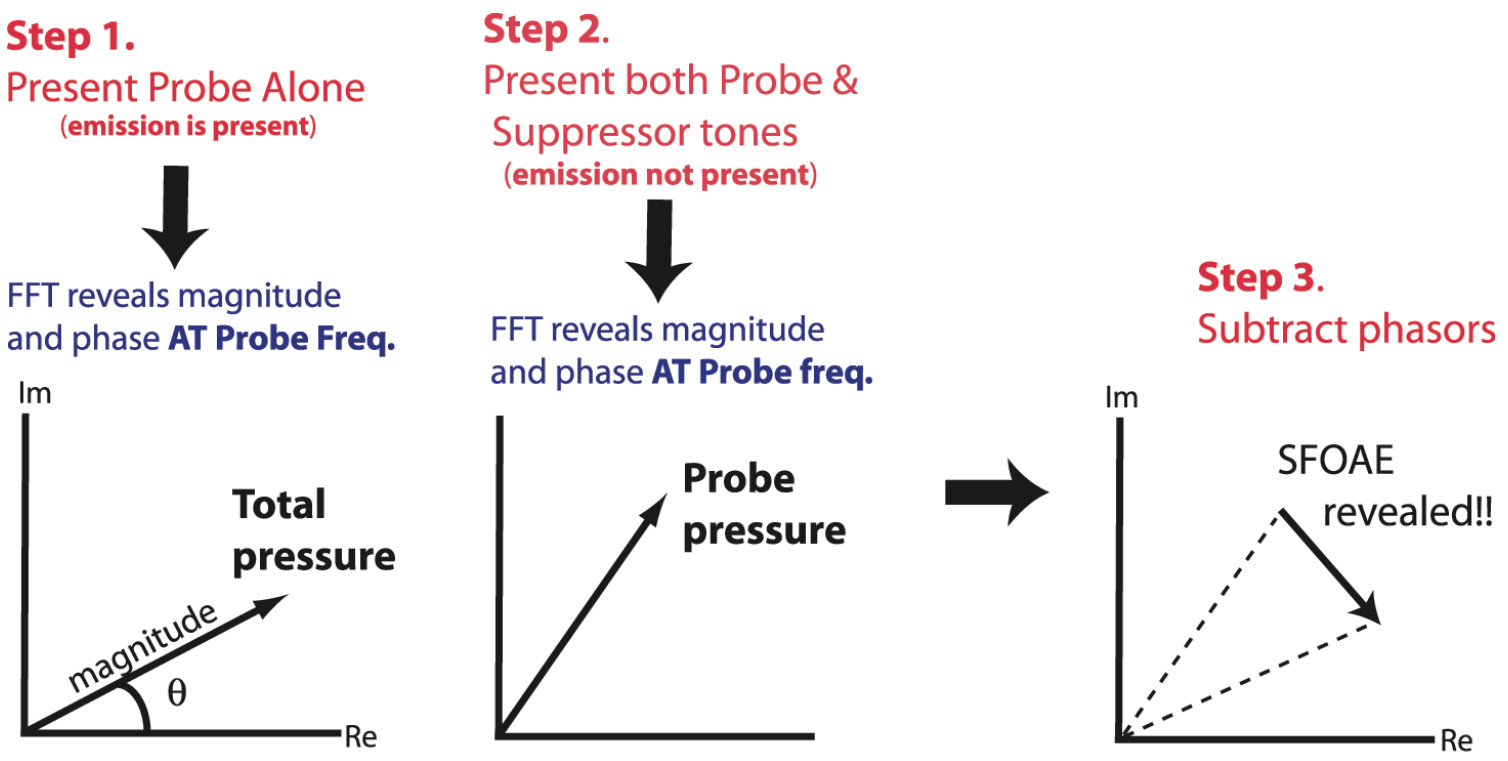
Similarity in frequency dependence between OAE phase gradients and Q-values suggest tuning can account for delays in most species

Fini

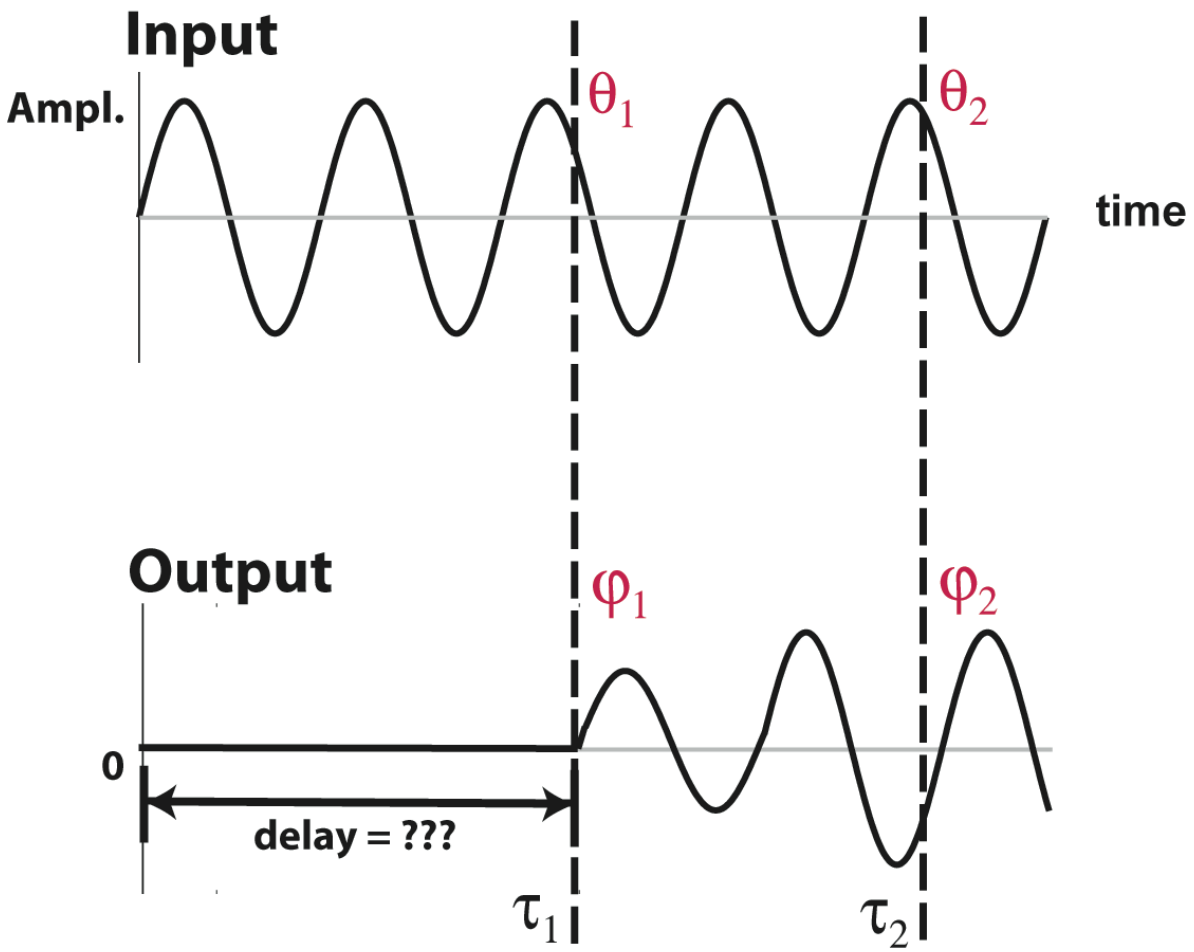
Supported by NIH grants T3200038, DC0023821 (DMF) and DC03687 (CAS)

QUESTION 1

SFOAEs: Nonlinear suppression paradigm

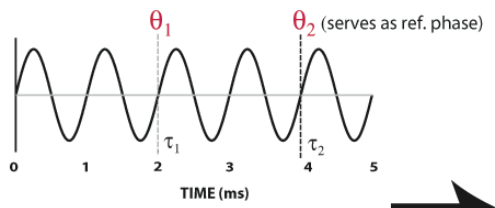


Phase can reveal time delays



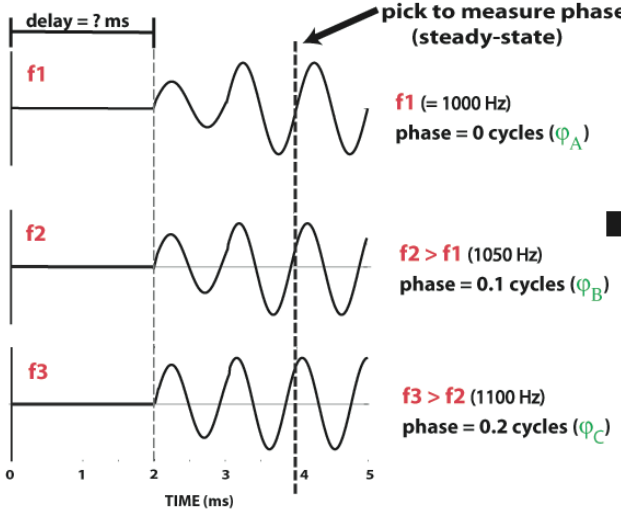
Phase Gradient

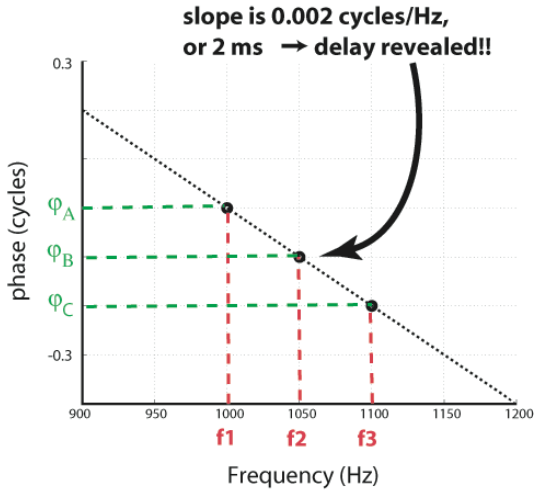
Input (stimulus we present)

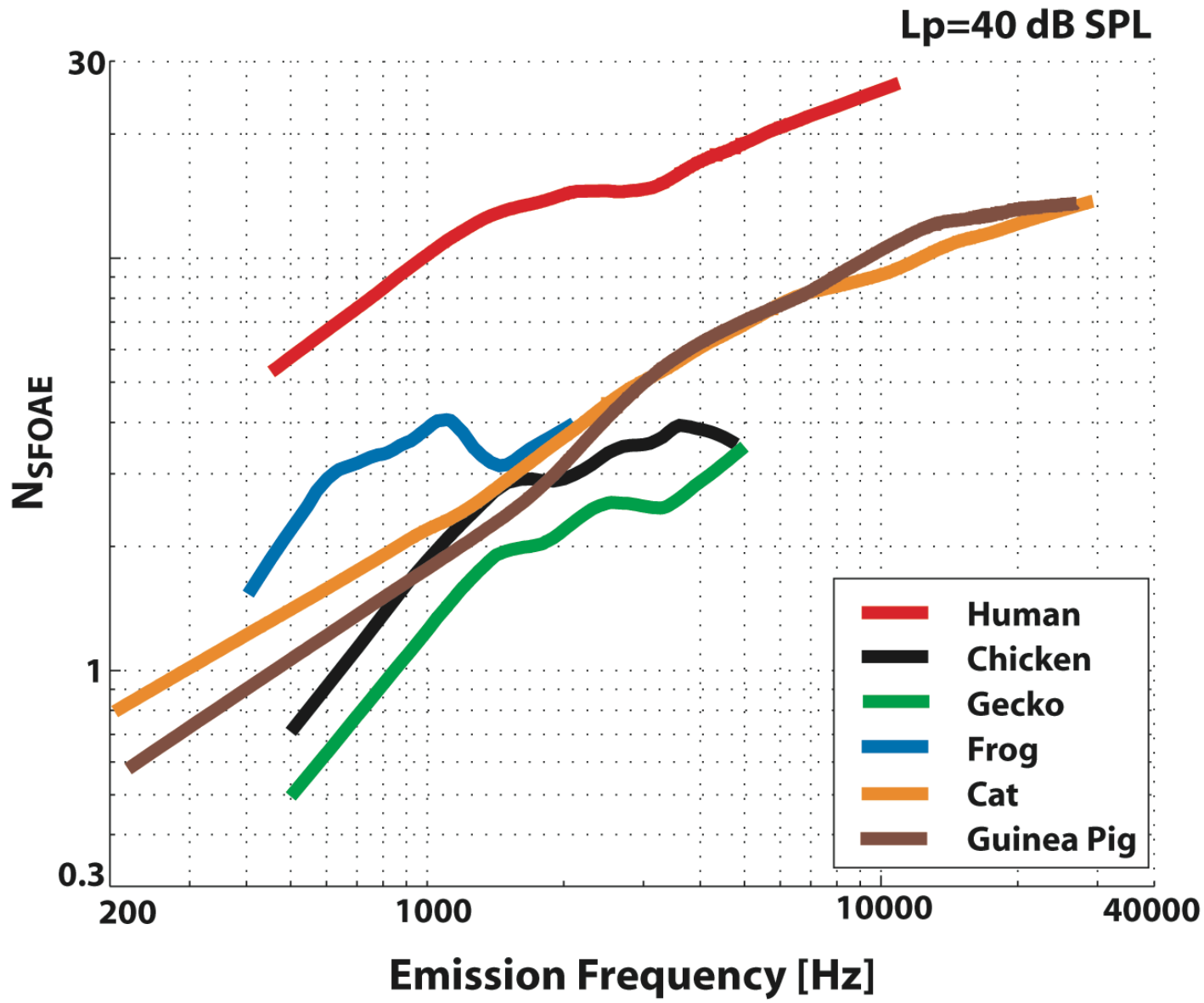


- vary frequency of stimulus
- stimulus phase is ALWAYS 0 at t = 0

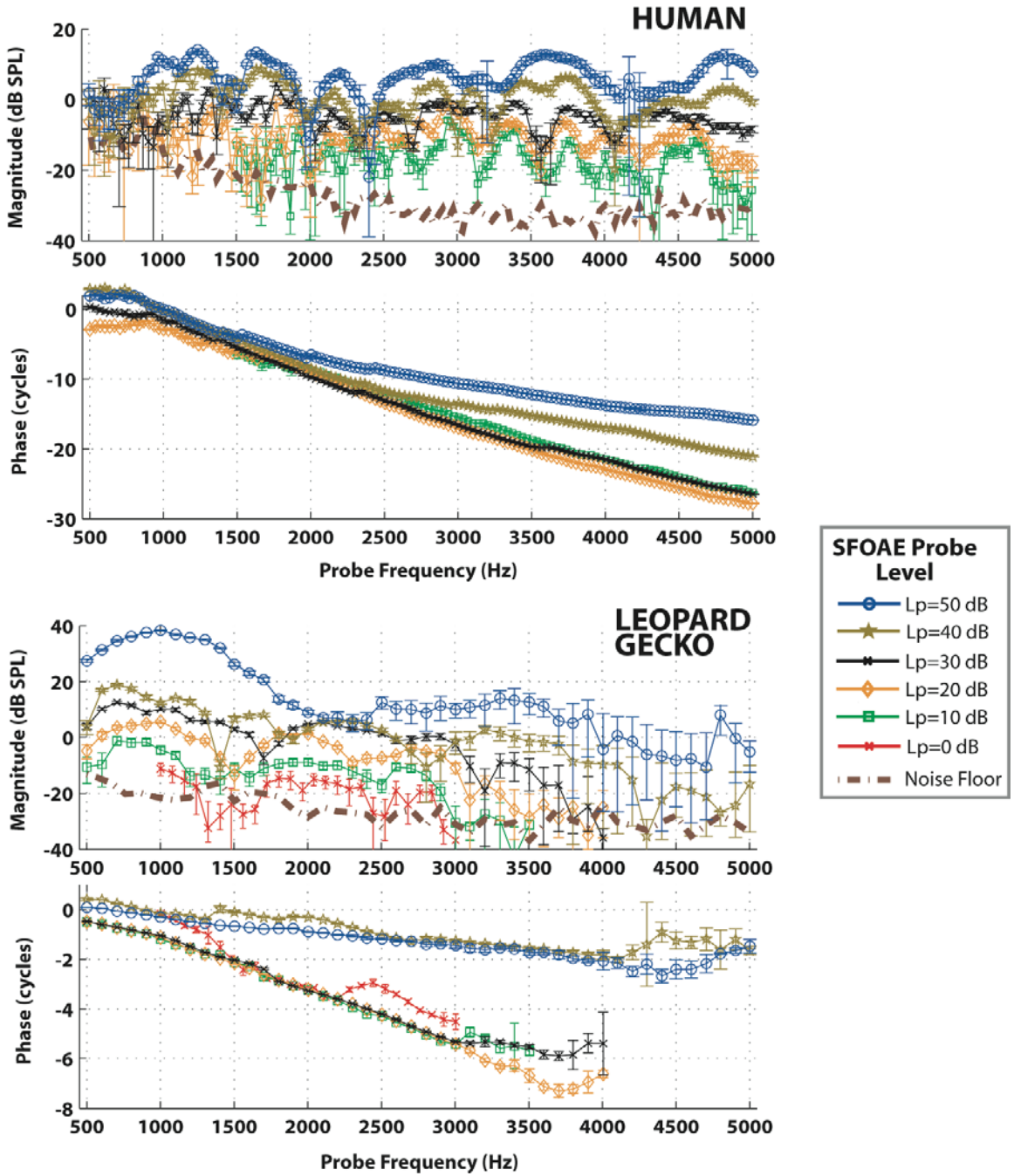
Output (response we measure)

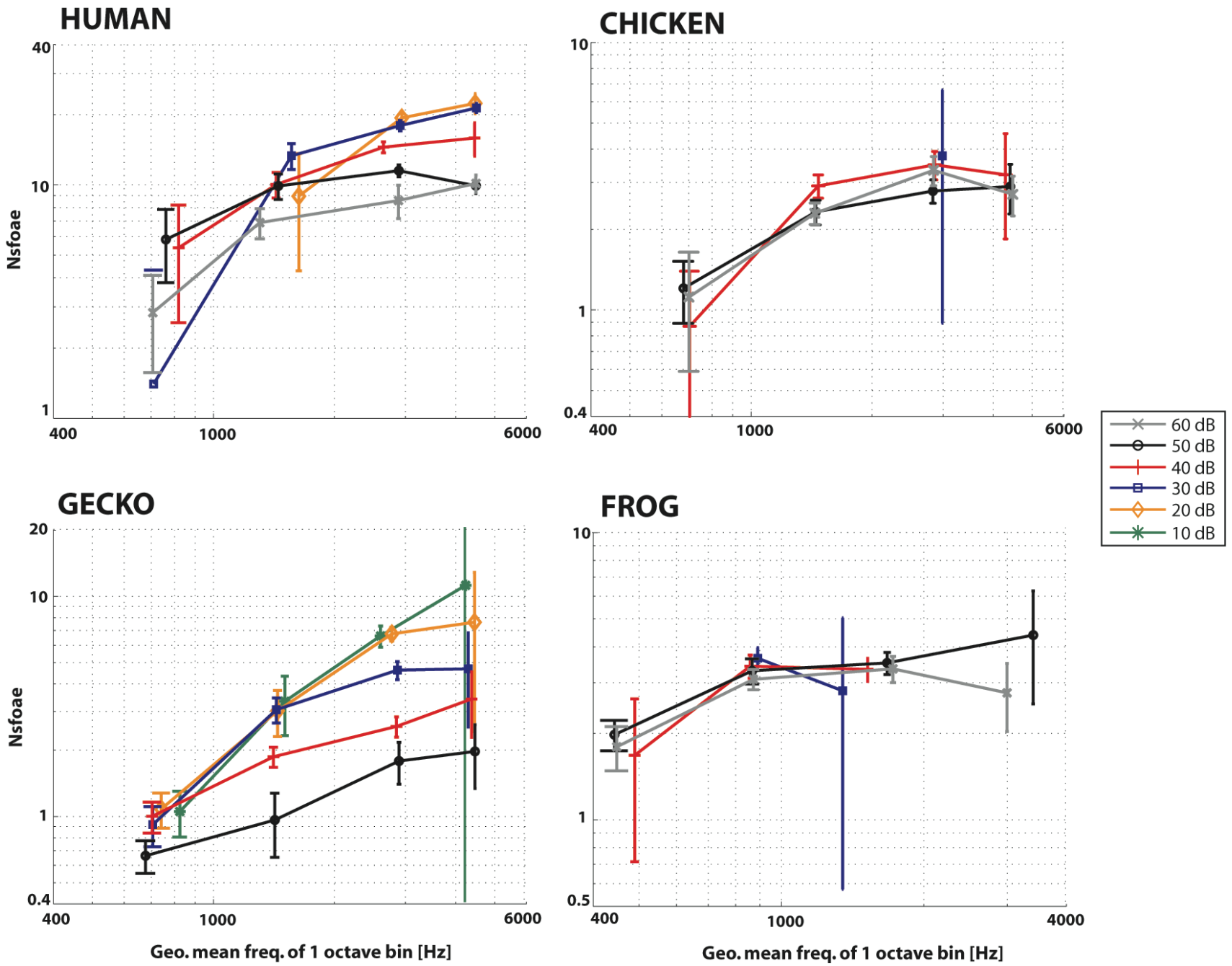






[cat and guinea pig data from Shera and Guinan, 2003]


HUMAN
Magnitude (dB SPL)
20
0
-20
-40
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Phase (cycles)
0
-10
-20
-30
Probe Frequency (Hz)
LEOPARD GECKO
Magnitude (dB SPL)
40
20
0
-20
-40
Phase (cycles)
0
-2
-4
-6
-8
Probe Frequency (Hz)
SFOAE Probe Level
Lp=50 dB
Lp=40 dB
Lp=30 dB
Lp=20 dB
Lp=10 dB
Lp=0 dB
Noise Floor


HUMAN
CHICKEN
GECKO
FROG
Nsfoae
Geo. mean freq. of 1 octave bin [Hz]
60 dB
50 dB
40 dB
30 dB
20 dB
10 dB