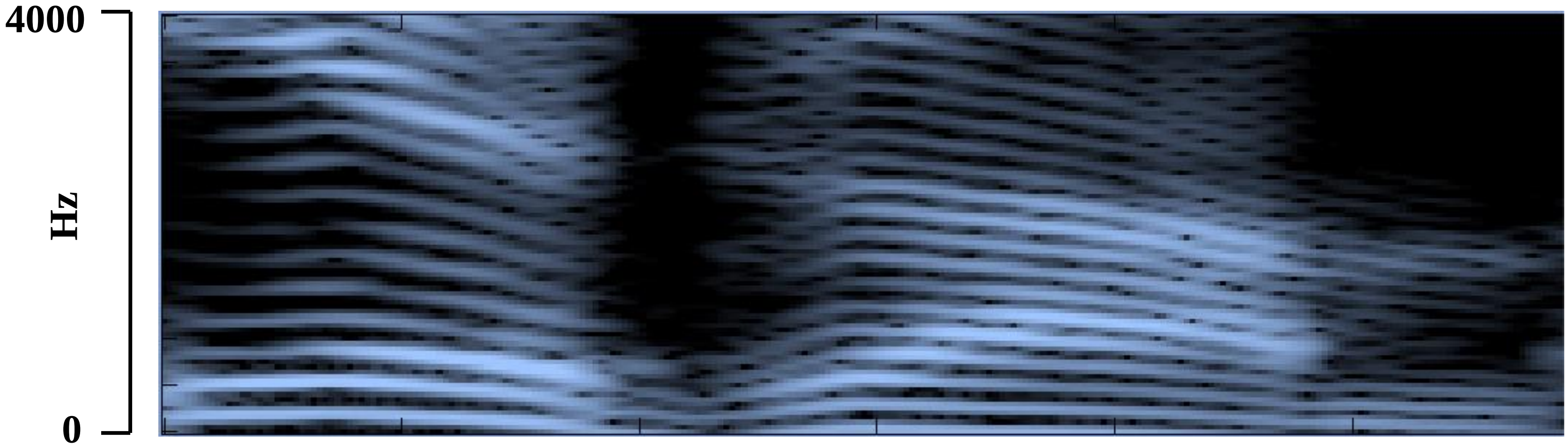
DALHOUSIE UNIVERSITY
Inspiring Minds
Faculty of Health Professions
School of Human Communication Disorders
Faculty of Science
Psychology & Neuroscience
Faculty of Medicine
Surgery

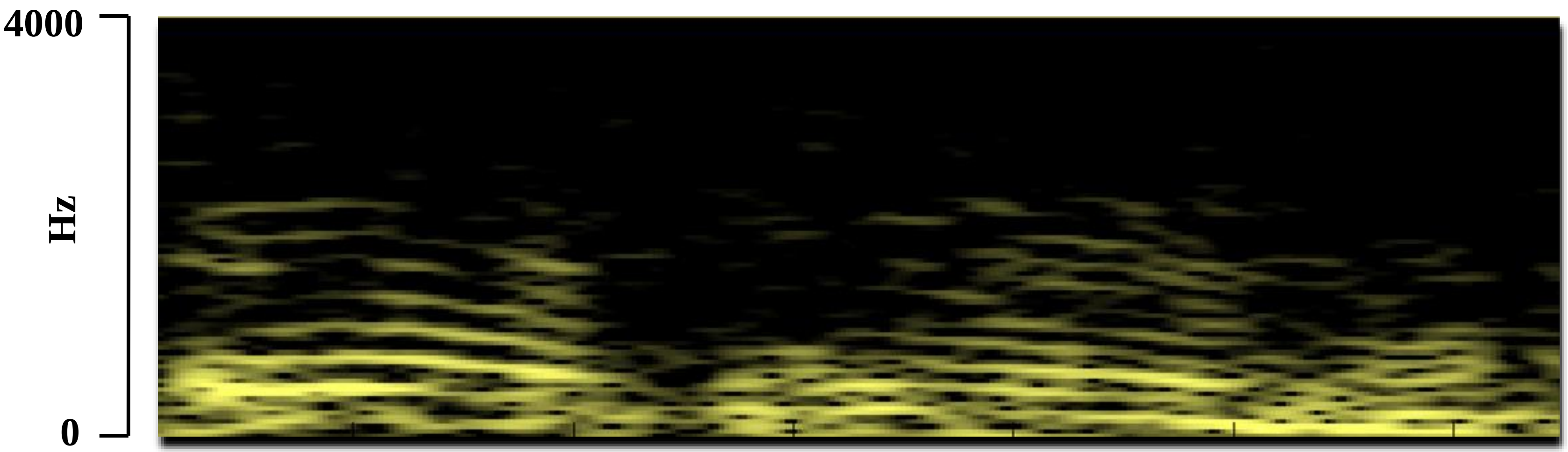
Unweaving the Rainbow—

Sensitivity to Stimulus Phase and Polarity in the Human Frequency Following Response

Dr. Steve J Aiken

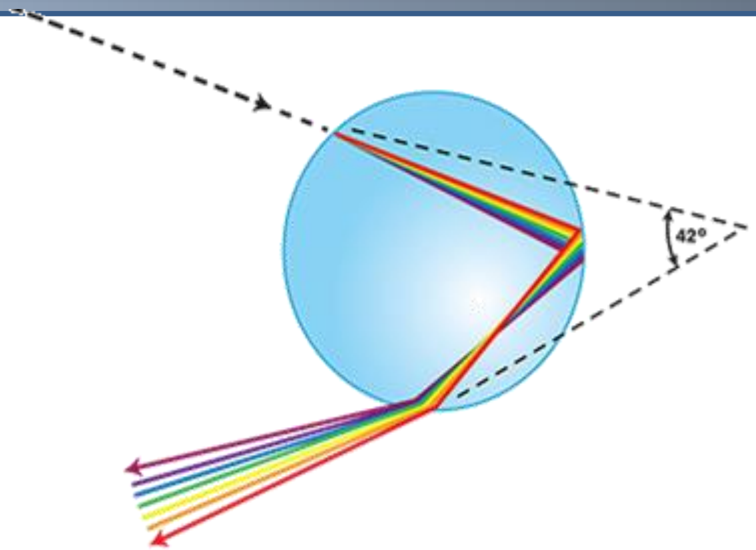
Beautiful in Form – Shows Spectrum





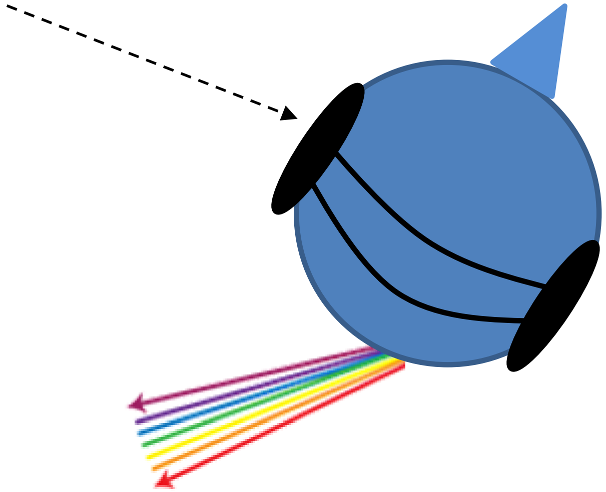
No Two People Ever See the Same Rainbow

- A rainbow is about a <u>relationship</u> between an observer and a light source, with a medium of diffraction

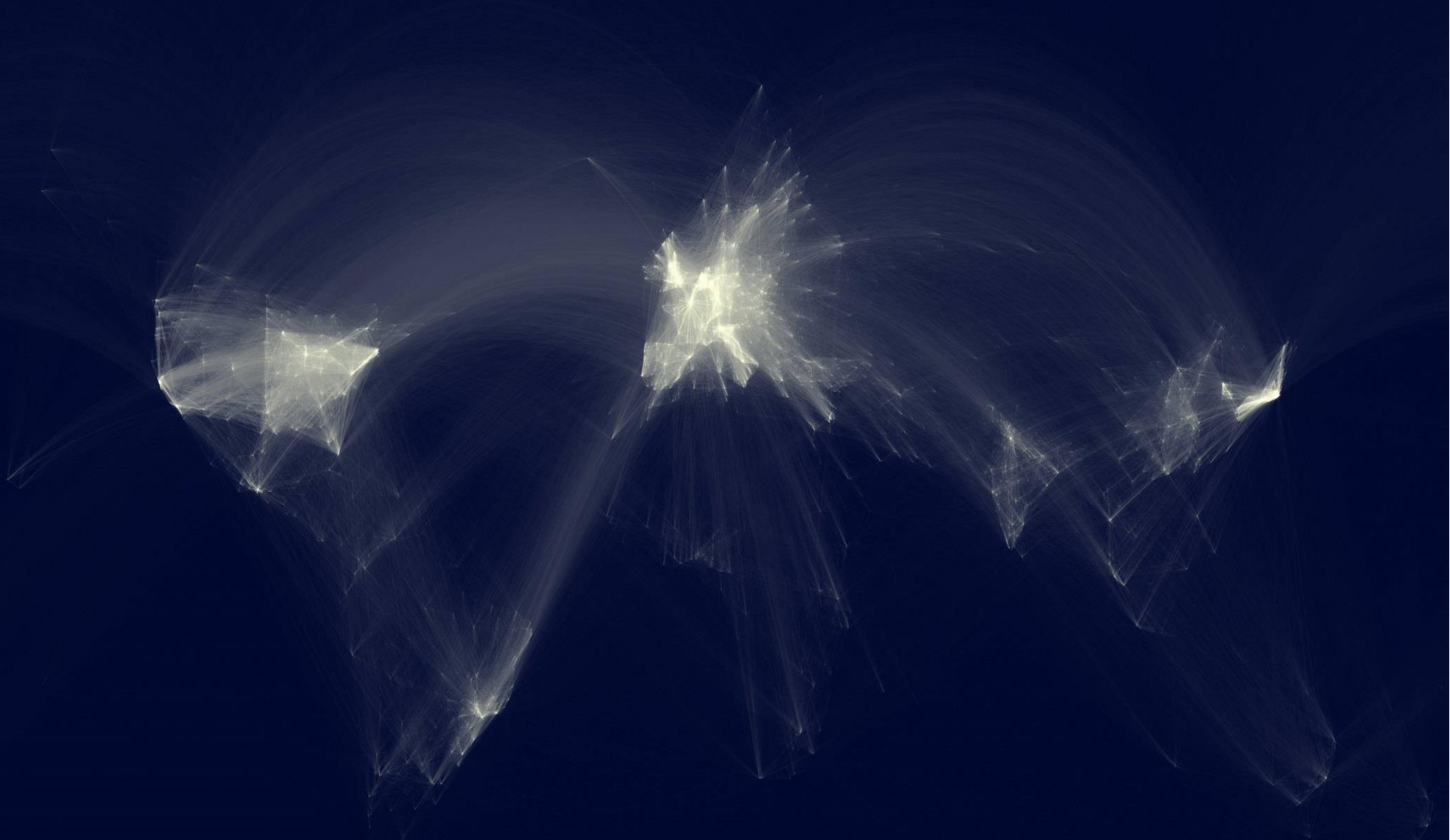


http://scijinks.jpl.nasa.gov/rainbow/

- The FFR is about a <u>relationship</u> between a voltage fluctuation and a sound source, with a medium of neural synchrony



Halifax in Relationship



Map of scientific collaborations from 2005 to 2009

Computed by Olivier H. Beauchesne @ Science-Metrix, Inc.

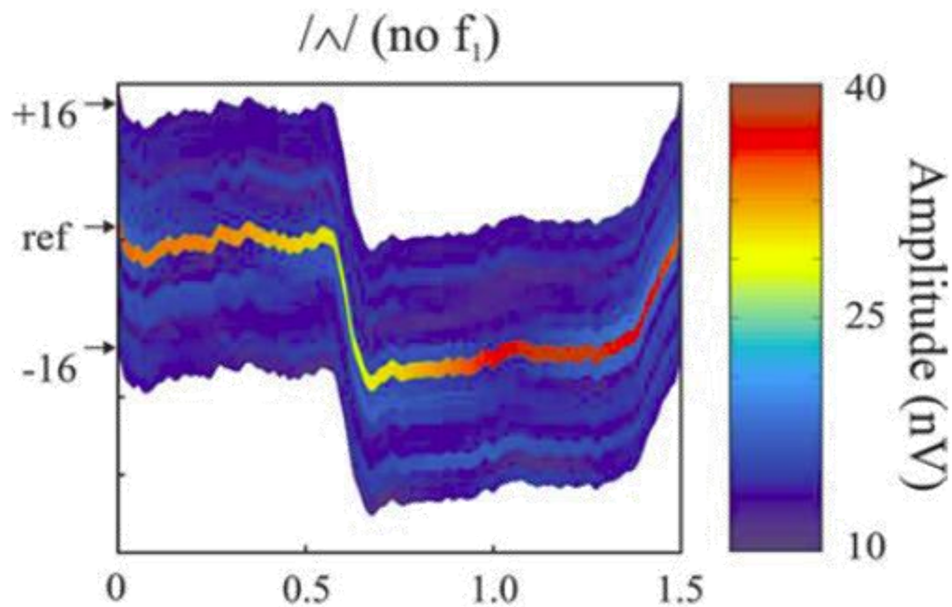
Data from Scopus, using books, trade journals and peer-reviewed journals

FFR Understood in Relationship to Stimulus 'Followed'

FFR in stimulus–independent view (voltage x time)

FFR amplitude in relationship to vocal f_0

→ synchrony understood via the stimulus-response relationship



Aiken & Picton, Audiol Neurotol, 2006

Why “Unweave the Rainbow” that is the FFR?

1. **Estimate speech audibility in infants wearing hearing aids**

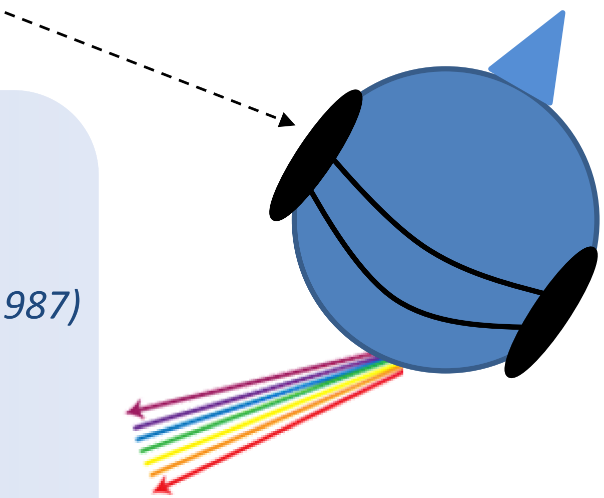
2. **Assess suprathreshold auditory processing**
   - suprathreshold distortion or “SNR Loss” often present with normal thresholds and no known lesions
     (Grant et al., Ear Hear, 2013, Plomp, J Speech Hear Res 1986, Strelcyk & Dau, 2009)
   - not entirely an auditory issue
     (Humes et al., J Am Acad Audiol, 2012; Moore et al., Int J Audiol, 2013)
   - but there are auditory factors found to be related to SNR loss, such as temporal fine-structure (TFS) processing
     (Buss et al., Ear Hear 2004; Hopkins & Moore, J Acoust Soc Am, 2009; Lorenzi et al., Proc Nat Acad Sci USA, 2006; Strelcyk & Dau, J Acoust Soc Am, 2009; Summers et al., Ear Hear 2013)

FFR and SNR Loss

- excitotoxic overstimulation damages ribbon synapses and AN fibers in mice *(Kujawa & Liberman, J Neurosci, 2009)* and guinea pigs *(Liu et al., PLoS One, 2012)*
  - may selectively damage low-SR fibers which are important for speech understanding in noise, and the FFR might be an ideal tool for assessing this *(Bharadjwaj et al, Front Sys Neurosci, 2014)*
- Brainstem responses phase-locked to speech fundamental frequency (f_0) have been found to be correlated with:
  - better speech-in-noise scores with competing speech—less SNR loss *(Anderson et al., Hear Res, 2010; Ruggles et al., Proc Nat Acad Sci, 2011; Song et al., J Cog Neurosci, 2011)*
  - musical experience *(Krishnan et al., Neuroreport, 2012),* which is also related to lower SNR loss *(Alain et al., Hear Res, 2013)*
  - short term auditory training *(Skoe et al., Neurobiol Learn Mem, 2014)*

Let’s get started: How does the FFR relate to Speech?

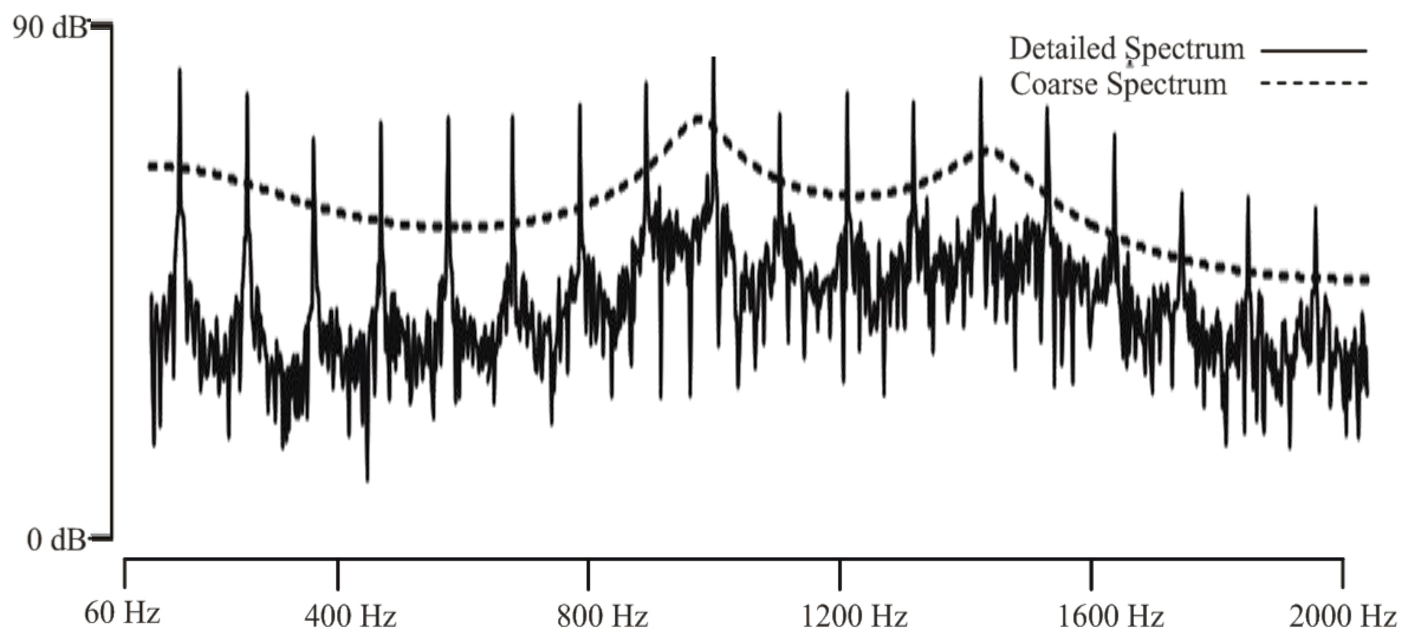
- **Speech is comprised of three types of temporal information** *(Rosen, Phil Trans Biol Sci, 1992)*
  1. low-frequency spectro-temporal ‘envelope’ (2-8 Hz)
  2. ‘periodicity’ information (100-400 Hz)
  3. temporal fine-structure (multiples of periodicity frequency)



- **The FFR can be decomposed into several types of information**
  (Aiken & Picton, Hear Res, 2008; Greenberg et al., Hear Res, 1987)
  1. a response to periodicity envelope
  2. a response to fine-structure

Formants (Envelope) Harmonics (TFS) in Speech

/a/ vowel



- Harmonics are inherently periodic—produced by the sawtooth-like vocal fold movement
- What role does each play?

Auditory Chimeras *(see Smith et al., Nature, 2002)*

TFS in Speech vs TFS Processing

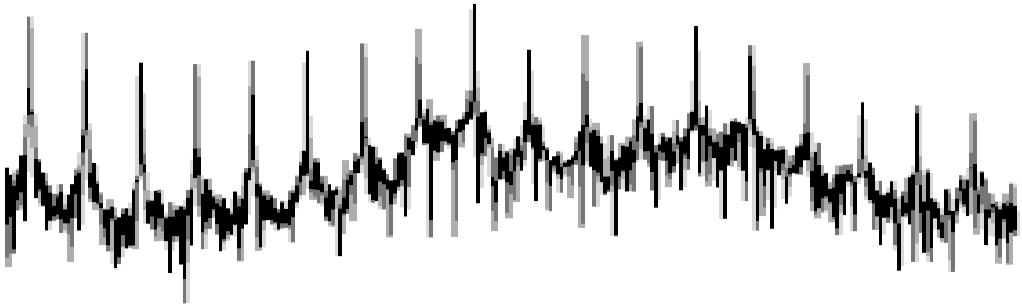
- Removing 'TFS' from speech doesn't test temporal FS processing, because resolved components also give rise to distinct excitation peaks

- The speech-FFR is an objective measure of temporal processing of the speech fine-structure and the periodicity envelope

- Behavioral Methods for TFS Processing Assessment:
  - low-rate FM detection, with superimposed random AM *(Moore & Sek, J Acoust Soc Am, 1996; Strelcyk & Dau, J Acoust Soc Am 2009; Summers et al., J Am Acad Audiol, 2013)*
  - lateralization *(Strelcyk & Dau, J Acoust Soc Am, 2009)*
  - binaural masked detection *(Strelcyk & Dau, J Acoust Soc Am, 2009)*
  - discrimination of frequency-shifted unresolved tone complexes *(Moore & Sek, J Acoust Soc Am, 2009ab)*

What about the periodicity envelope?

- Harmonic signals have components that are linearly spaced, but frequency spacing in the cochlea is logarithmic

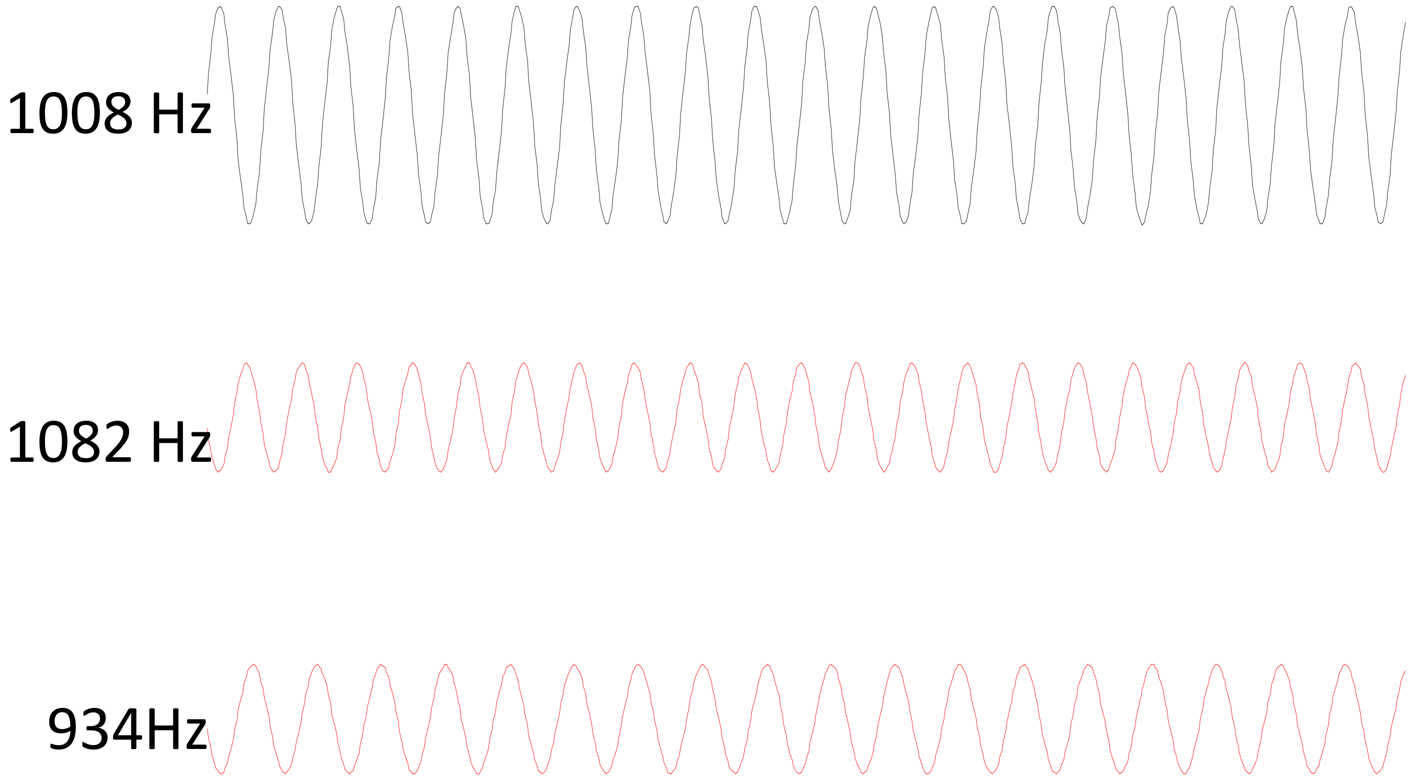


- the first 7/8 harmonics are fully resolved, giving rise to distinct peaks in the basilar membrane displacement pattern *(Oxenham et al., J Acoust Soc Am, 2009)*

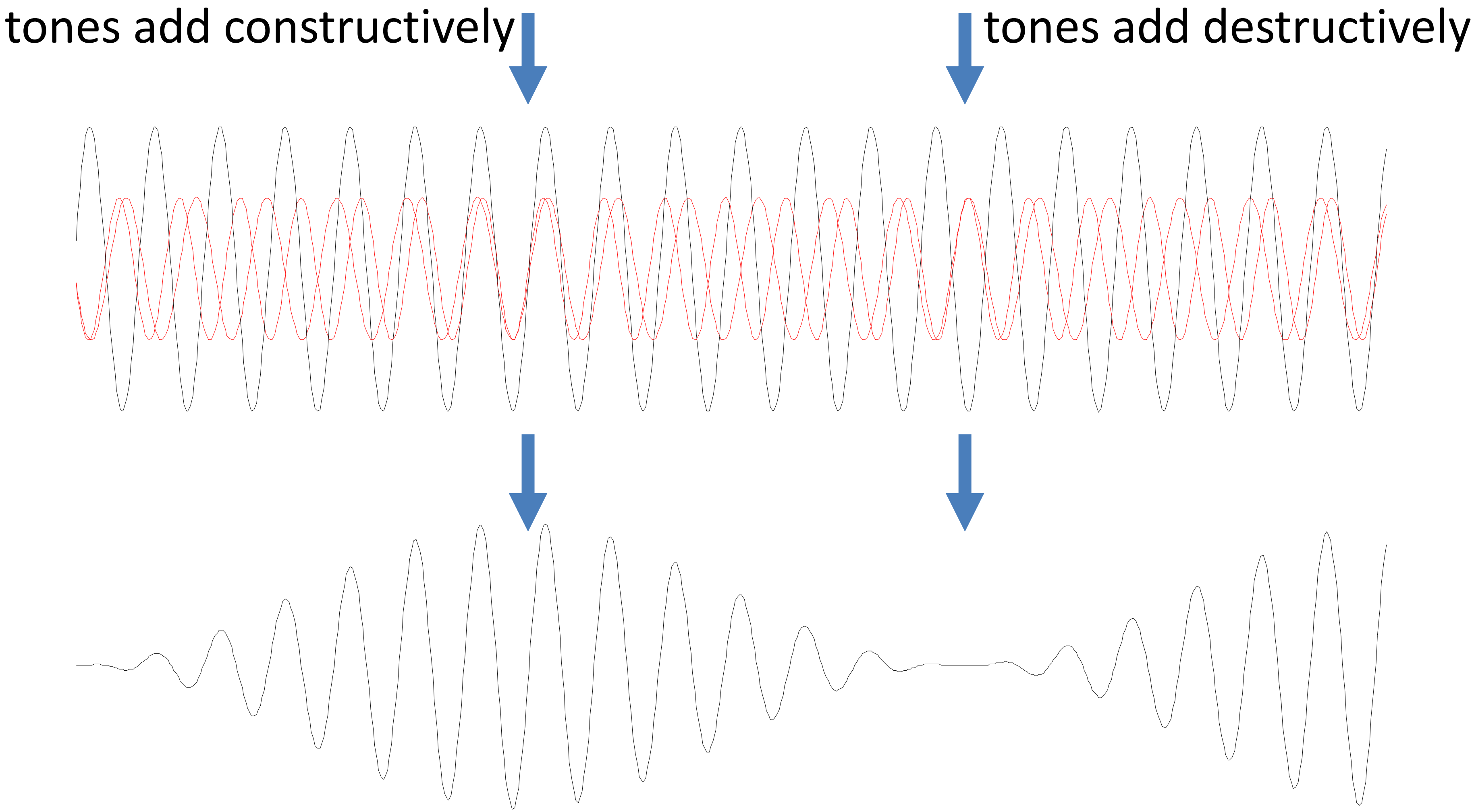
- harmonics > 7/8 will create overlapping displacement patterns on BM, **and these fine-structure interactions give rise to the 'periodicity envelope'**

Interactions Give Rise to Periodicity Envelope

- simple case: a sinusoidal amplitude modulation is a center ‘carrier’ frequency and two sidebands (e.g., 1008 Hz with 74 Hz AM)

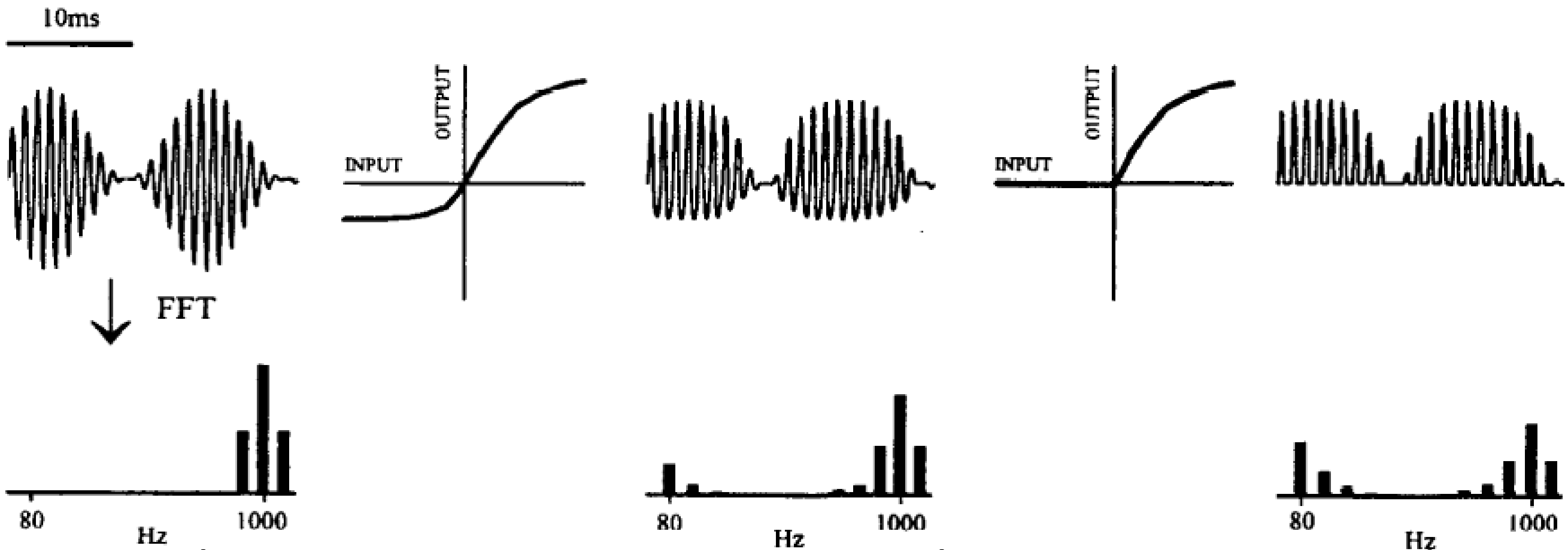


The Sum of the Components is Modulated



The sum is NOT present in the signal

What Underlies the Summation?



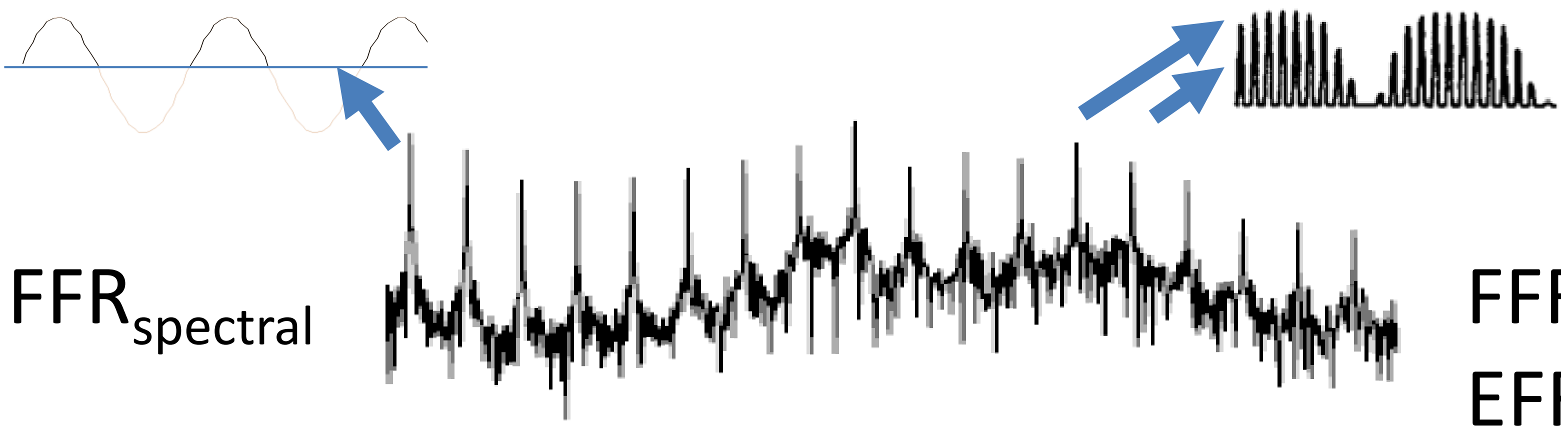
Stimulus IHC Potential Neural Firing

from Lins et al., J Acoust Soc Am, 1995

these non-linearities induce energy at the modulation frequency (<u>when they overlap at single inner hair cells / AN fibers</u>)

Responses to Fine Structure in Harmonic Signals

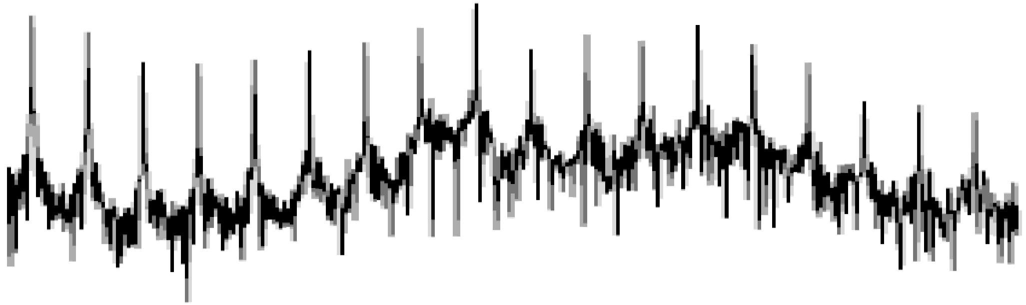
1. temporal information for fully resolved harmonics → phase-locking to resolved component
2. temporal information for unresolved harmonics → multiple frequencies and their sum (i.e., the periodicity envelope)



What is there to unweave?

- Harmonic signals like speech give rise to a variety of (often overlapping) responses to different things:

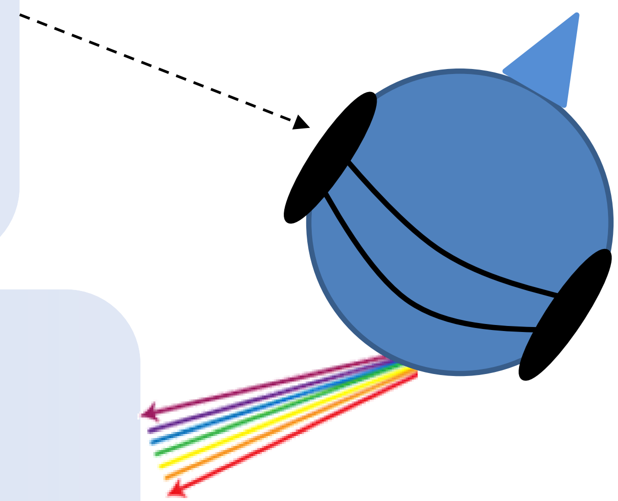
1. spectral FFR to resolved periodic components, esp. near formant peaks (e.g., a 200 Hz harmonic → 200 Hz response)
2. responses to cochlear distortion products, which occur at harmonic frequencies (e.g., 2f1-f2… 2(300)-400 = 200 Hz; *see Elsisy & Krishnan, 2008*)
3. responses to envelopes introduced by unresolved harmonics (e.g., envelope from 2200 and 2400 Hz = 200 Hz)
4. cochlear microphonic
5. signal artifact (current induced on electrode leads)



Tools

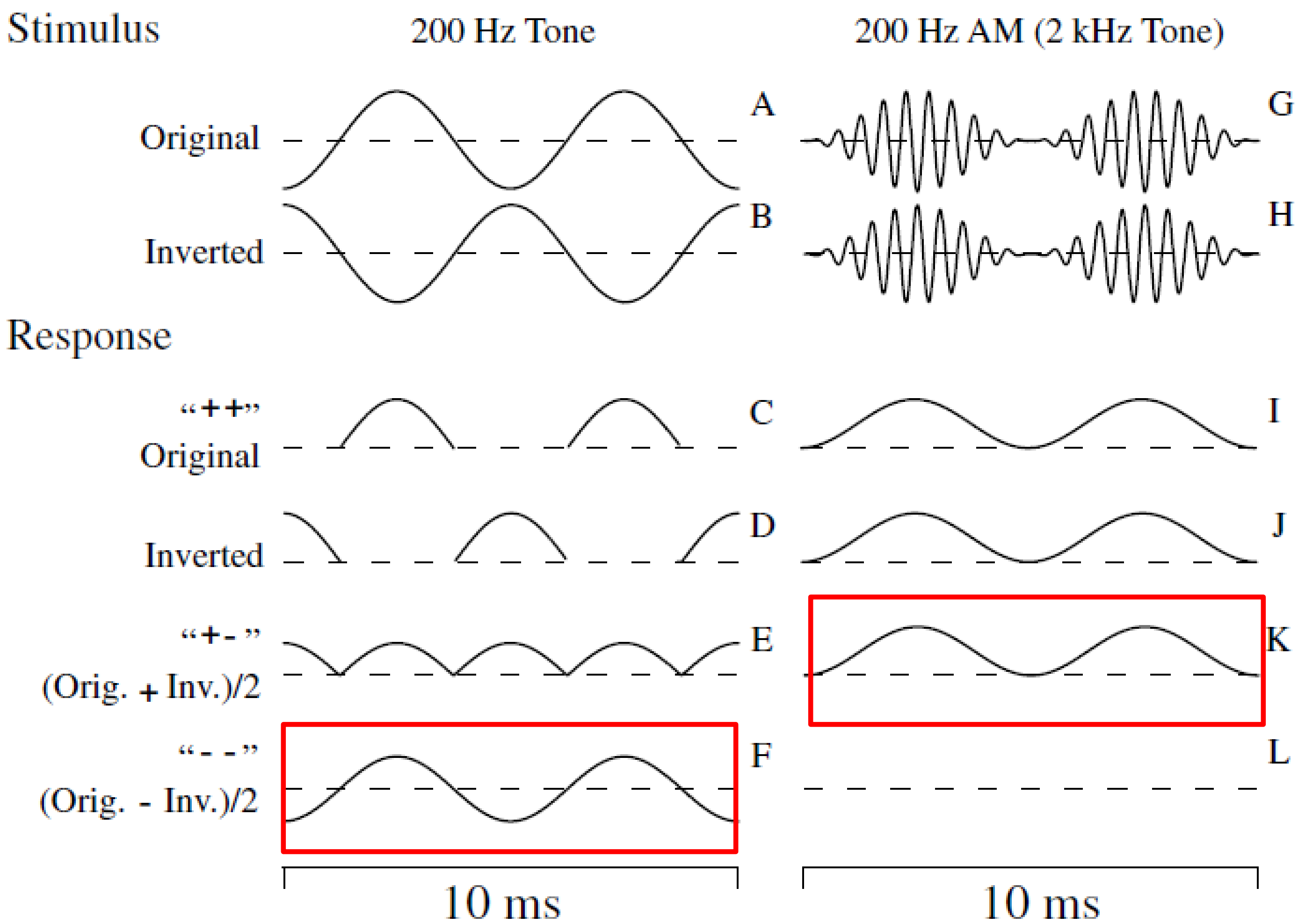
- How do we unweave the colours (wavelengths) of the FFR, especially with complex harmonic signals?

  – source tools
    - carrier and modulation frequencies
    - modulation depth and presentation level
    - **stimulus polarity**
    - **component phase**



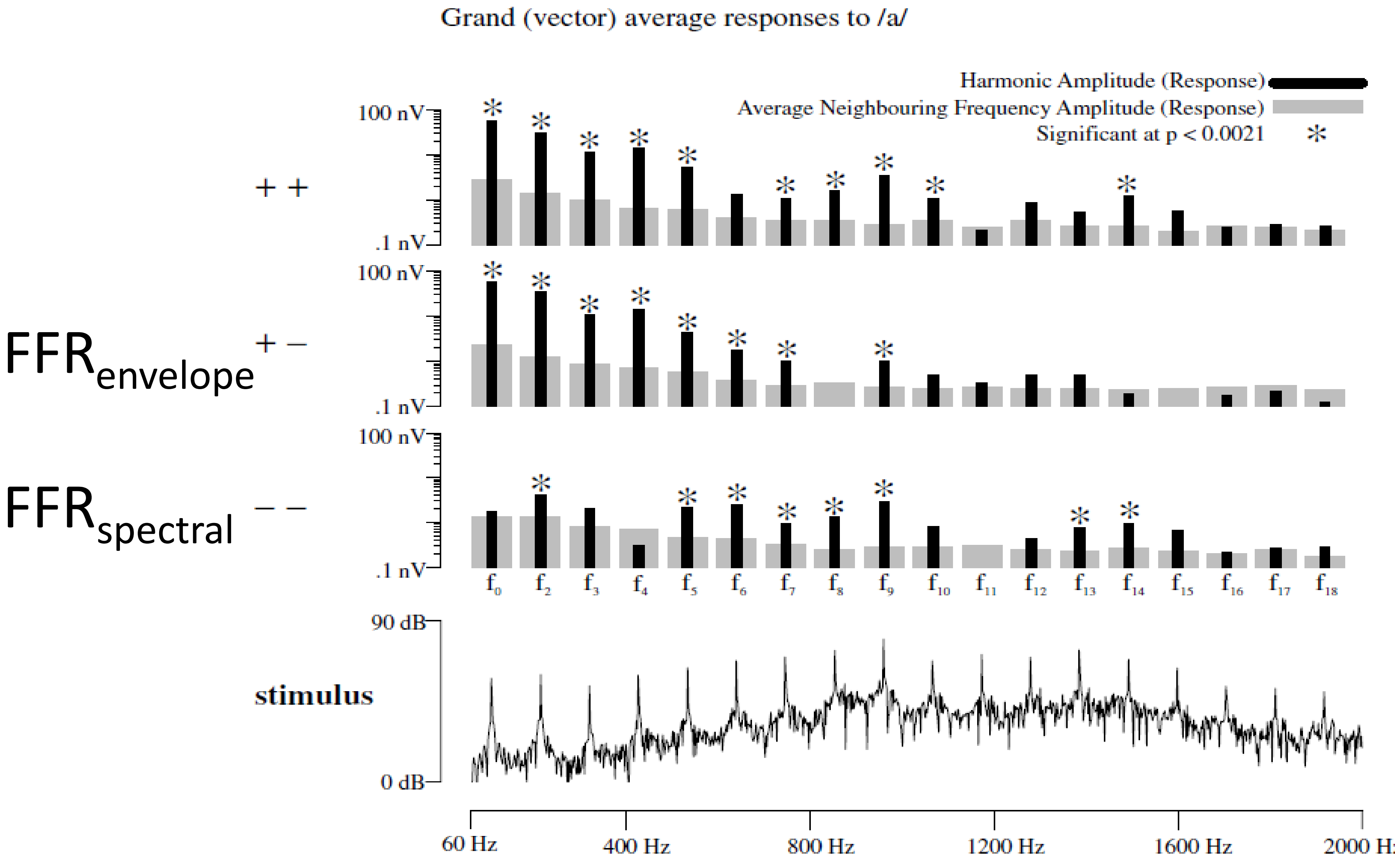
  – response tools
    - recording montage, filtering
    - amplitude, phase, PLV, autocorrelation
    - in relation to frequency or frequency trajectory

Using Polarity to Unweave Responses



Aiken & Picton, Hear Res, 2008

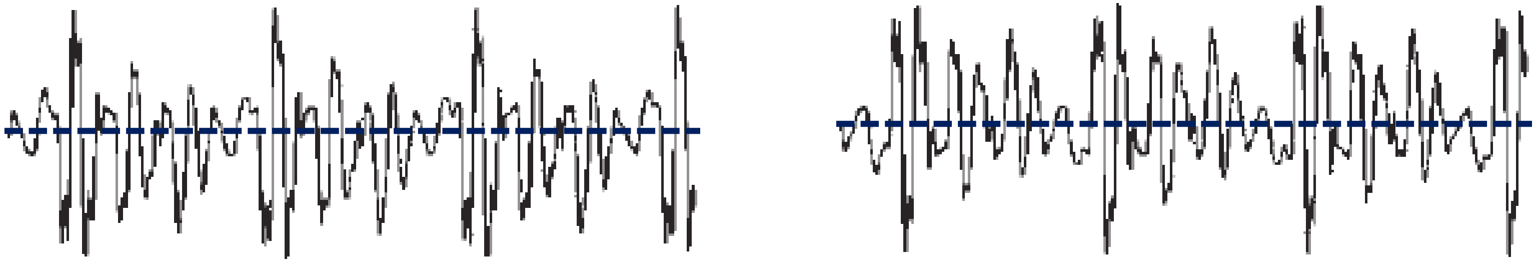
Responses to Speech After Polarity Manipulation



Aiken & Picton, Hear Res, 2008

How Effective is Polarity for Unweaving?

- Does the polarity manipulation work effectively for "unweaving" responses to asymmetric signals like speech?

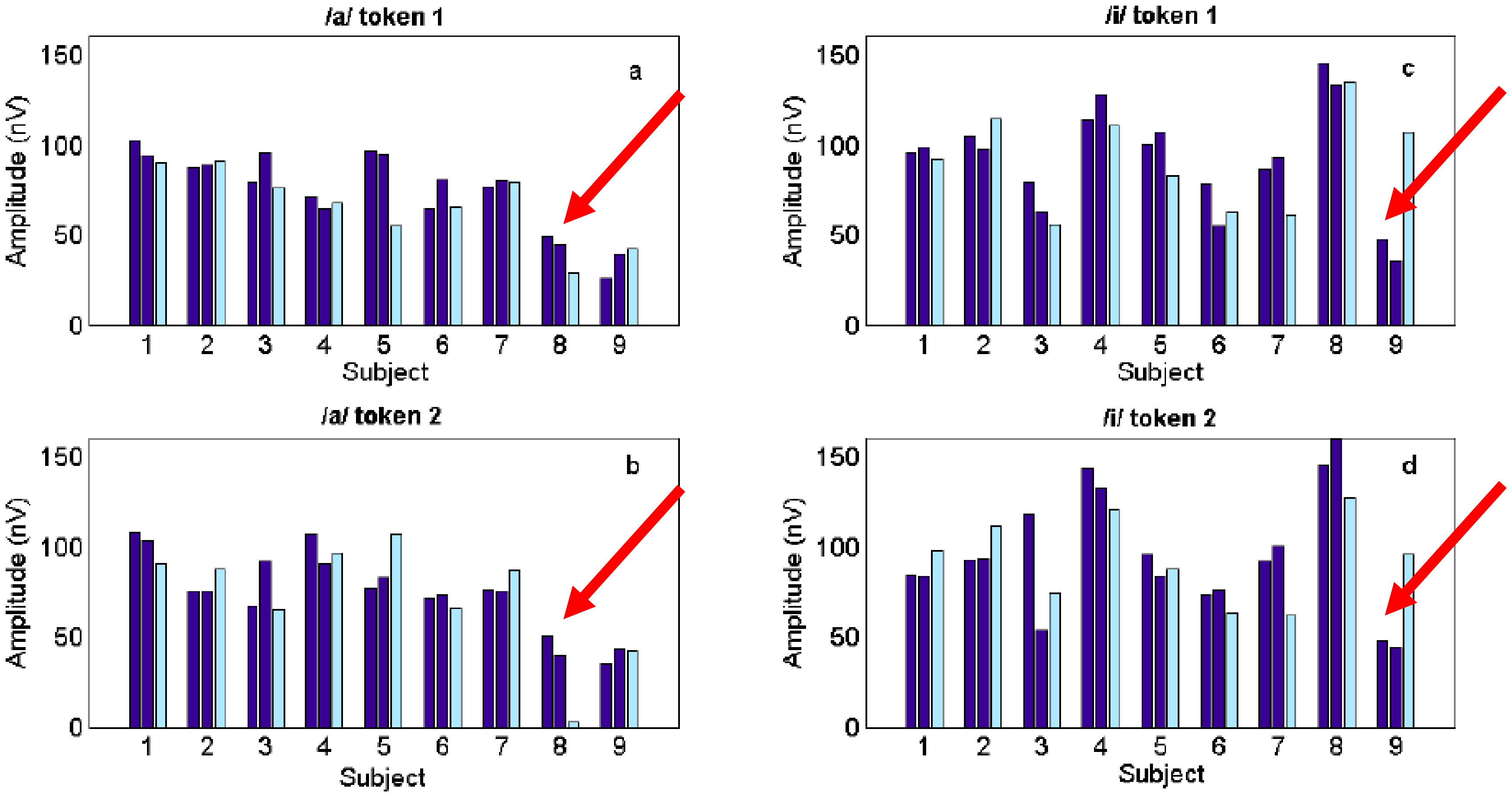


  - pseudo half-wave rectification in the AN response will be slightly different for each polarity *(Skoe & Kraus, Ear Hear, 2010)*
  - imperfect 'unweaving':
    - e.g., alternating polarity average may contain some spectral FFR and show attenuated envelope FFR

Aiken & Purcell, ICA-ASA, 2013

How Effective is Polarity for Unweaving?

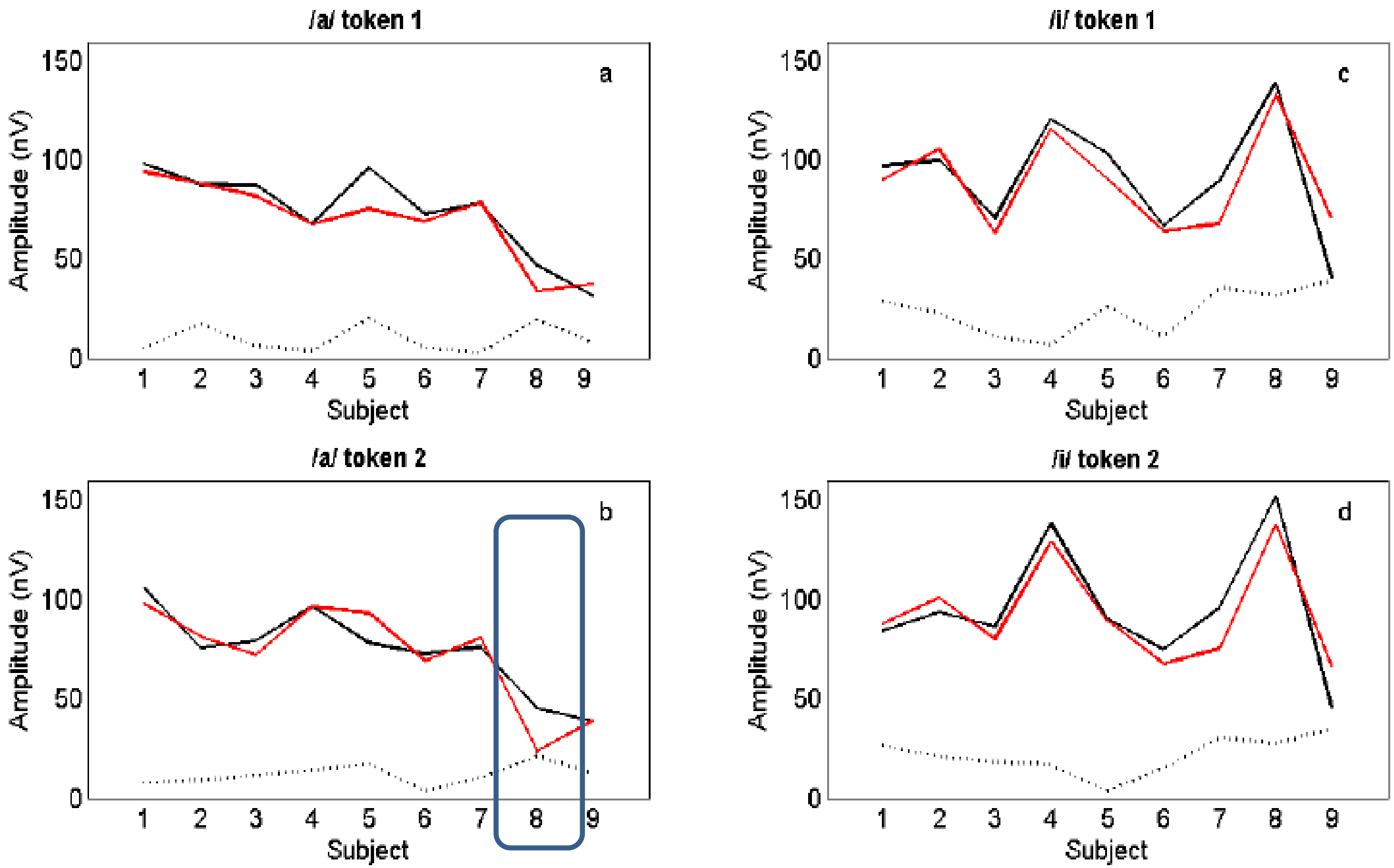
- responses to speech f_0 in individual subjects
- dark blue bars = polarity A; light blue bars = polarity B



Aiken & Purcell, ICA-ASA, 2013

How Effective is Polarity for Unweaving?

black = average (+ +); red = alt. polarity average (+ –)
dotted = alt. polarity difference average (– –)



Aiken & Purcell, ICA-ASA, 2013

How Effective is Polarity for Unweaving?

- successful in most cases, but individual polarities should be compared

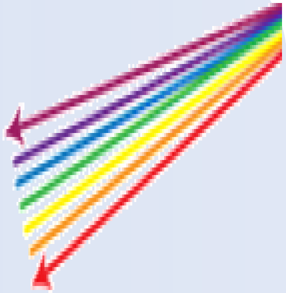
- continued work led by Dr. David Purcell and Viji Easwar at Western University
  - measured polarity effects for three vowels and two modulated consonants
  - measured separate responses to low and high harmonics
  - developed an envelope asymmetry index
  - asymmetry can be minimized

  → see the poster!

Using Polarity to Unweave Envelope and Spectral FFR

- Speech TFS supports:
  - phase-locked responses to resolved harmonic components (spectral FFR)
  - phase-locked responses to the periodicity envelope (envelope FFR)

- Combining polarities can help to unweave these two components:
  - adding responses to alternate polarities emphasizes envelope FFR (“+ –” average)
  - subtracting responses to alternate polarities emphasizes spectral FFR (“– –” average)
  - always check raw polarity responses



Envelope FFR is More Clinically Useful

Spectral FFR

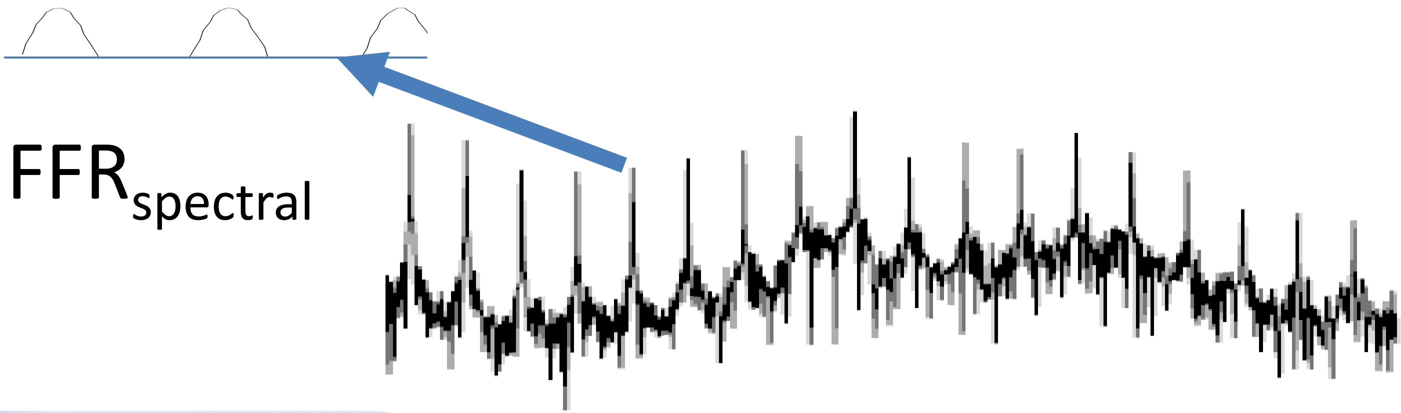
- cannot be recorded near threshold
- cannot be recorded above ≈ 1500 Hz
- difficult to distinguish from cochlear microphonic and signal artifact

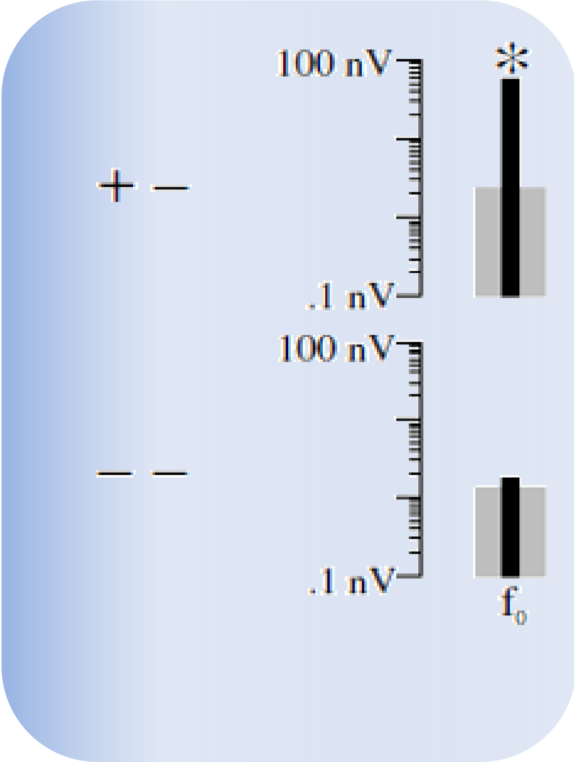
Envelope FFR

- can be recorded near threshold (see ASSR)
- carrier frequencies can be > 1500 Hz
- can be recorded with alternating polarities to reduce cochlear microphonic and artifact

Further Limitations of Spectral FFR

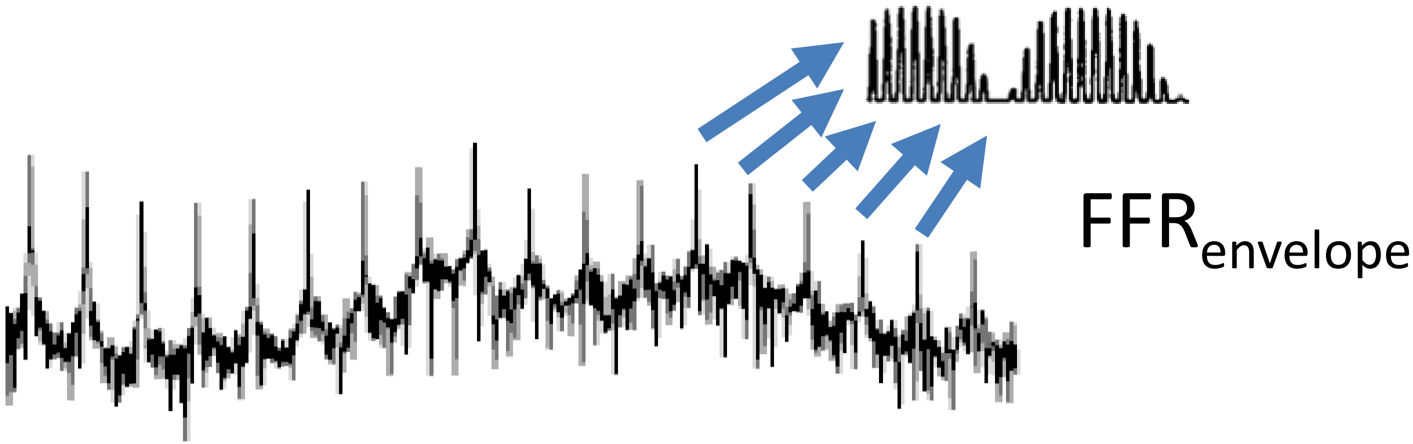
$FFR_{spectral}$





- response at f_0 usually does NOT reflect energy at first harmonic
- response to low-frequency tones is primarily mediated by low-frequency tails of higher-CF fibers *(Ananthanarayan & Durrant, Ear Hear, 1992; Dau, J Acoust Soc Am, 2003)*
  - better synchrony at base of cochlea
  - high-level response

Limitations of Envelope FFR for Speech

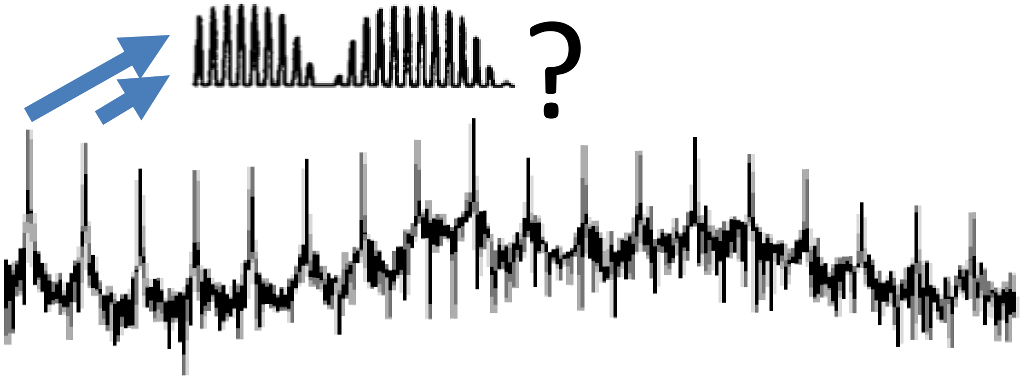


- FFR$_{envelope}$ not place specific – response at f_0 likely reflects interactions of many harmonics

- FFR$_{envelope}$ presumably arises from only unresolved harmonics

→ *Is there a clinically viable and objective way of assessing phase-locking to resolved harmonics?*

Does $\text{FFR}_{\text{envelope}}$ arise from resolved harmonics?



- these components do not overlap on BM at low-moderate levels

- this would likely require interaction of phase-locked neural activity from different AN fibers (<u>induced post-transduction</u>)
  - plausible given the existence of cells in CN with broad frequency tuning and excellent envelope encoding (e.g., 'onset' or stellate cells) *(Frisina, Hear Res, 1990; Palmer et al., J Neurophysiol , 1996; Rhode & Greenberg, J Neurophysiol, 1994)*
  - no neurophysiological evidence that this occurs *(Joris et al., Physiol Rev, 2004)*

- models suggest $\text{FFR}_{\text{envelope}}$ primarily from unresolved harmonics *(Shinn-Cunningham et al., Adv Exp Med Biol, 2013)*

Evidence to the Contrary

- TMTF models for broadband noise require a bandwidth of 2-4 kHz (much broader than peripheral channels) suggesting temporal information must be combined across frequency channels
  (Moore, An Introduction to the Psychology of Hearing, 1997; Viemeister & Plack, Human Psychophysics, 1993)

- $\text{FFR}_{\text{envelope}}$ at f_0 for resolved and unresolved harmonics not different in quiet; significantly **larger** for resolved harmonics in noise *(Laroche et al., Hear Res, 2012)*
  - i.e., $\text{FFR}_{\text{envelope}}$ at f_0 is larger in response to components that should not be interacting on the BM

Types of Responses to Harmonic Signals

1. $FFR_{spectral}$ to resolved stimulus frequencies and cochlear distortion products
   - most apparent in "– –" average
   - may be confused with cochlear microphonic and signal artifact

2. $FFR_{envelope}$ to unresolved stimulus frequencies
   - most apparent in "+ –" average
   - depends on phase-locking to modulation rate
   - can be largely eradicated with quadrature phase

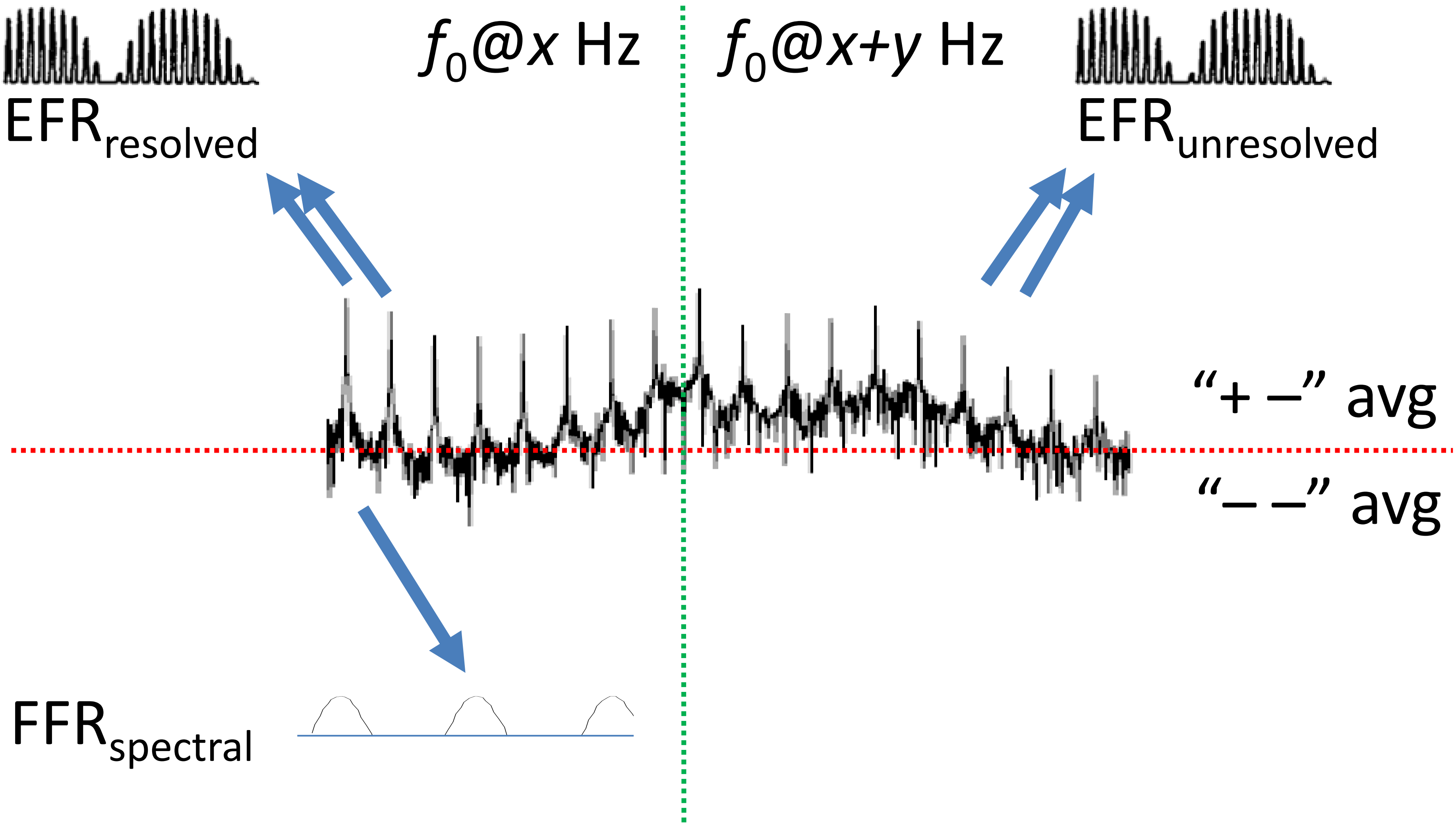
3. $FFR_{envelope}$ to resolved stimulus frequencies
   - most apparent in "+ –" average
   - appears to depend on phase-locking to carrier frequency and sidebands
   - is not eradicated with quadrature phase
   - might provide an estimate of phase-locking limits in auditory nerve
   - perhaps an ideal physiologic measure of TFS

Designing a Better Speech Stimulus

- Resolved and unresolved harmonics likely give rise to two types of activity
    - current research focused on isolating these with Allison MacEacheron at Dalhousie University

  - use quadrature phase to remove cochlear-induced envelope components
  - use different f_0s for low and high harmonics
    - response at each f_0 tells us about encoding of that set of harmonics
    - this also provides place specificity of responses
    - see work with David Purcell and Viji Easawar at Western University using multiple f_0s (poster)

Unweaving the Speech FFR




ARGYLE ST
CASINO
525

References

References

- Aiken, S.J., Purcell, D.P. (2013). Sensitivity to stimulus polarity in speech-evoked frequency-following responses. *Proc Meetings Acoust, ICA-ASA, Montreal, CA.*
- Aiken, S. J., Picton, T. W. (2006). Envelope following responses to natural vowels. *Audiol Neurootol, 11*, 213-232.
- Aiken, S. J., Picton, T. W. (2008). Envelope and spectral frequency-following responses to vowel sounds. *Hear Res, 245*, 35-47.
- Alain, C., Zendel, B. R., Hutka, S., et al. (2013). Turning Down the Noise: The Benefit of Musical Training on the Aging Auditory Brain. *Hearing Research*.
- Ananthanarayan, A. K., Durrant, J. D. (1992). The frequency-following response and the onset response: evaluation of frequency specificity using a forward-masking paradigm. *Ear Hear, 13*, 228-232.
- Anderson, S., Skoe, E., Chandrasekaran, B., et al. (2010). Brainstem correlates of speech-in-noise perception in children. *Hear Res, 270*, 151-157.
- Baker, R. J., Rosen, S. (2006). Auditory filter nonlinearity across frequency using simultaneous notched-noise masking. *J Acoust Soc Am, 119*, 454-462.

References

- Bharadwaj, H. M., Verhulst, S., Shaheen, L., et al. (2014). Cochlear neuropathy and the coding of supra-threshold sound. *Front Syst Neurosci, 8*, 26.
- Buss, E., Hall, J. W., 3rd, Grose, J. H. (2004). Temporal fine-structure cues to speech and pure tone modulation in observers with sensorineural hearing loss. *Ear Hear, 25*, 242-250.
- Dau, T. (2003). The importance of cochlear processing for the formation of auditory brainstem and frequency following responses. *J Acoust Soc Am, 113*, 936-950.
- Elsisy, H., Krishnan, A. (2008). Comparison of the acoustic and neural distortion product at 2f1-f2 in normal-hearing adults. *Int J Audiol, 47*, 431-438.
- Frisina, R. D., Smith, R. L., Chamberlain, S. C. (1990a). Encoding of amplitude modulation in the gerbil cochlear nucleus: I. A hierarchy of enhancement. *Hear Res, 44*, 99-122.
- Frisina, R. D., Smith, R. L., Chamberlain, S. C. (1990b). Encoding of amplitude modulation in the gerbil cochlear nucleus: II. Possible neural mechanisms. *Hear Res, 44*, 123-141.
- Grant, K. W., Walden, B. E., Summers, V., et al. (2013). Introduction: auditory models of suprathreshold distortion in persons with impaired hearing. *J Am Acad Audiol, 24*, 254-257.

References

- Greenberg, S., Marsh, J. T., Brown, W. S., et al. (1987). Neural temporal coding of low pitch. I. Human frequency-following responses to complex tones. *Hear Res, 25*, 91-114.
- Hopkins, K., Moore, B. C. (2009). The contribution of temporal fine structure to the intelligibility of speech in steady and modulated noise. *J Acoust Soc Am, 125*, 442-446.
- Humes, L. E., Dubno, J. R., Gordon-Salant, S., et al. (2012). Central presbycusis: a review and evaluation of the evidence. *J Am Acad Audiol, 23*, 635-666.
- Joris, P. X., Schreiner, C. E., Rees, A. (2004). Neural processing of amplitude-modulated sounds. *Physiol Rev, 84*, 541-577.
- Krishnan, A., Gandour, J. T., Bidelman, G. M. (2012). Experience-dependent plasticity in pitch encoding: from brainstem to auditory cortex. *Neuroreport, 23*, 498-502.
- Kujawa, S. G., Liberman, M. C. (2009). Adding insult to injury: cochlear nerve degeneration after "temporary" noise-induced hearing loss. *J Neurosci, 29*, 14077-14085.
- Laroche, M., Dajani, H. R., Prevost, F., et al. (2012). Brainstem Auditory Responses to Resolved and Unresolved Harmonics of a Synthetic Vowel in Quiet and Noise. *Ear Hear*.
- Lins, O. G., Picton, T. W., Boucher, B. L., et al. (1996). Frequency-specific audiometry using steady-state responses.

References

- Liu, L., Wang, H., Shi, L., et al. (2012). Silent damage of noise on cochlear afferent innervation in guinea pigs and the impact on temporal processing. *PLoS One, 7*, e49550.
- Lorenzi, C., Gilbert, G., Carn, H., et al. (2006). Speech perception problems of the hearing impaired reflect inability to use temporal fine structure. *Proc Natl Acad Sci U S A, 103*, 18866-18869.
- Moore, B. C., Sek, A. (2009a). Development of a fast method for determining sensitivity to temporal fine structure. *Int J Audiol, 48*, 161-171.
- Moore, B. C., Sek, A. (2009b). Sensitivity of the human auditory system to temporal fine structure at high frequencies. *J Acoust Soc Am, 125*, 3186-3193.
- Moore, B. C., Glasberg, B. R., Hopkins, K. (2006). Frequency discrimination of complex tones by hearing-impaired subjects: Evidence for loss of ability to use temporal fine structure. *Hear Res, 222*, 16-27.
- Moore, B. C., Moore, B. C. (2003). *An introduction to the psychology of hearing*. Academic press San Diego.
- Moore, B. C., Sek, A. (1996). Detection of frequency modulation at low modulation rates: evidence for a mechanism based on phase locking. *J Acoust Soc Am, 100*, 2320-2331.

References

- Moore, D. R., Rosen, S., Bamiou, D. E., et al. (2013). Evolving concepts of developmental auditory processing disorder (APD): a British Society of Audiology APD special interest group 'white paper'. *Int J Audiol, 52*, 3-13.
- Oxenham, A. J., Micheyl, C., Keebler, M. V. (2009). Can temporal fine structure represent the fundamental frequency of unresolved harmonics? *J Acoust Soc Am, 125*, 2189-2199.
- Palmer, A. R., Jiang, D., Marshall, D. H. (1996). Responses of ventral cochlear nucleus onset and chopper units as a function of signal bandwidth. *J Neurophysiol, 75*, 780-794.
- Plomp, R. (1986). A signal-to-noise ratio model for the speech-reception threshold of the hearing impaired. *J Speech Hear Res, 29*, 146-154.
- Rhode, W. S., Greenberg, S. (1994). Lateral suppression and inhibition in the cochlear nucleus of the cat. *J Neurophysiol, 71*, 493-514.
- Rosen, S. (1992). Temporal information in speech: acoustic, auditory and linguistic aspects. *Philos Trans R Soc Lond B Biol Sci, 336*, 367-373.
- Ruggles, D., Bharadwaj, H., Shinn-Cunningham, B. G. (2011). Normal hearing is not enough to guarantee robust encoding of suprathreshold features important in everyday communication. *Proc Natl Acad Sci U S A, 108*, 15516-15521.

References

- Schorer, E. (1986). Critical modulation frequency based on detection of AM versus FM tones. *J Acoust Soc Am, 79*, 1054-1057.
- Sek, A., Moore, B. C. (1994). The critical modulation frequency and its relationship to auditory filtering at low frequencies. *J Acoust Soc Am, 95*, 2606-2615.
- Shinn-Cunningham, B., Ruggles, D. R., Bharadwaj, H. (2013). How early aging and environment interact in everyday listening: from brainstem to behavior through modeling. *Adv Exp Med Biol, 787*, 501-510.
- Skoe, E., Chandrasekaran, B., Spitzer, E. R., et al. (2014). Human brainstem plasticity: the interaction of stimulus probability and auditory learning. *Neurobiol Learn Mem, 109*, 82-93.
- Smith, Z. M., Delgutte, B., Oxenham, A. J. (2002). Chimaeric sounds reveal dichotomies in auditory perception. *Nature, 416*, 87-90.
- Song, J. H., Skoe, E., Banai, K., et al. (2011). Perception of speech in noise: neural correlates. *J Cogn Neurosci, 23*, 2268-2279.
- Summers, V., Makashay, M. J., Theodoroff, S. M., et al. (2013). Suprathreshold auditory processing and speech perception in noise: hearing-impaired and normal-hearing listeners. *J Am Acad Audiol, 24*, 274-292.
- Viemeister, N. F., Plack, C. J. (1993). Time analysis. In *Human psychophysics* (pp. 116-154): Springer.