



Gravity dependent cortical control of sensation

FA9550-22-1-0346



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motivation

- vision, touch, smell, taste are *active senses*
 - sensations acquired via movements of the sensory organs
 - movements steered by cortical functions
 - closed loop perception
- audition & balance stand out
 - no overt sensor movements during perception
 - especially so in primates

is hearing, similar to other senses, is an active sense, with a cortico-cochlear loop at the core?

- beyond cochlea => cortico–inner-ear loop
- the inner ear = 〈 hearing organs & vestibular organs 〉
 - evolutionarily, they developed conjointly
 - share a common endolymphatic pool
 - important role of hair cells, in both

does active hearing depend on vestibular organs sensing?



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Objective

To examine the hypothesized function of cortico-cochlear control loop and to characterize the dependency of active hearing on vestibular conditions

Uniqueness

- We aim at determining if hearing, similar to other senses, is an active sense with a *cortico-cochlear loop* at the core
- We aim at characterizing the dependency of *active hearing* on vestibular conditions, in humans
- We aim at formulating a model of auditory perception in dynamic gravito-inertial conditions based on a cortico-inner-ear loop and cortical oscillations dynamics
- The concept should generalize to all sensory modalities

Technical Approach

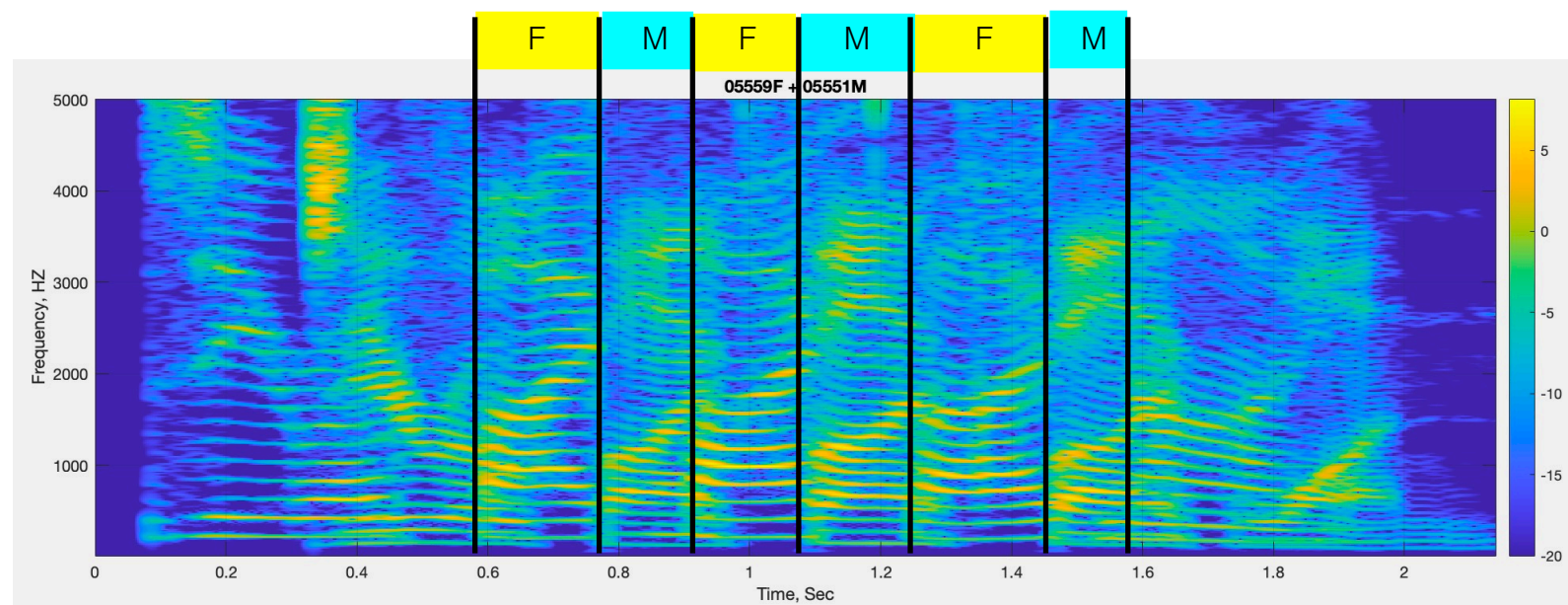
- Case study: speaker segregation, in upright and supine conditions
- We record electrocochleography (EcochG) in humans for naturally spoken sentences and analyze them in a search for cortical modulation of the Outer Hair Cells (OHC) response
- We measure the effect of the cortico-cochlear control on OHC responses as a function of body orientation with respect to gravity
- We model the cortico-cochlear loop as a dynamical motor-sensory-motor loop
- We determine the model parameters using our behavioral data
- We assess the potential benefit of the cortico-cochlear modulation by comparing the performances of the closed- versus an open-loop models

objective A

a cortico-cochlear loop?

- the case study is speaker segregation in the upright position
 - e.g., a female-male mixture

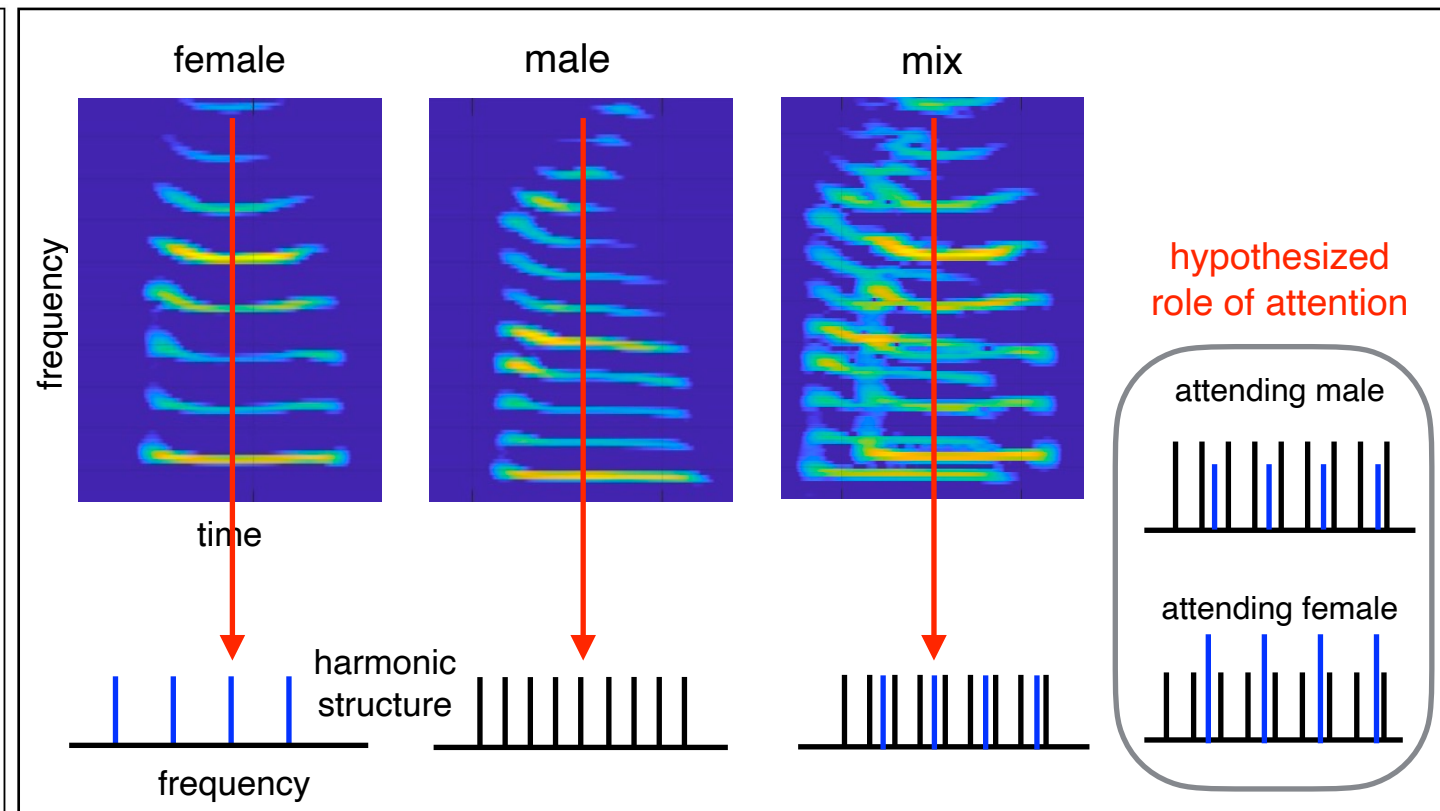
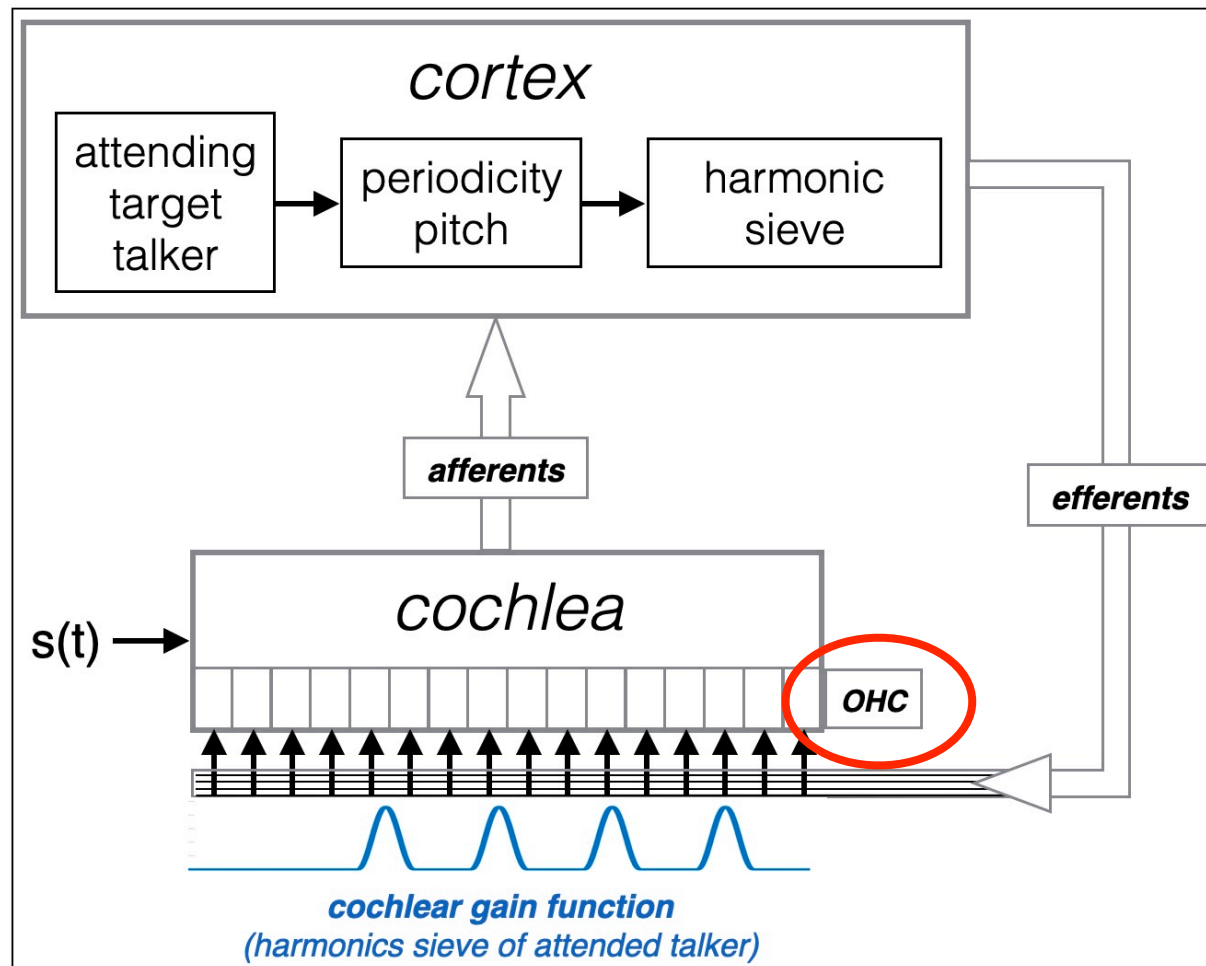
05551F & 05559M



objective A

a cortico-cochlear loop?

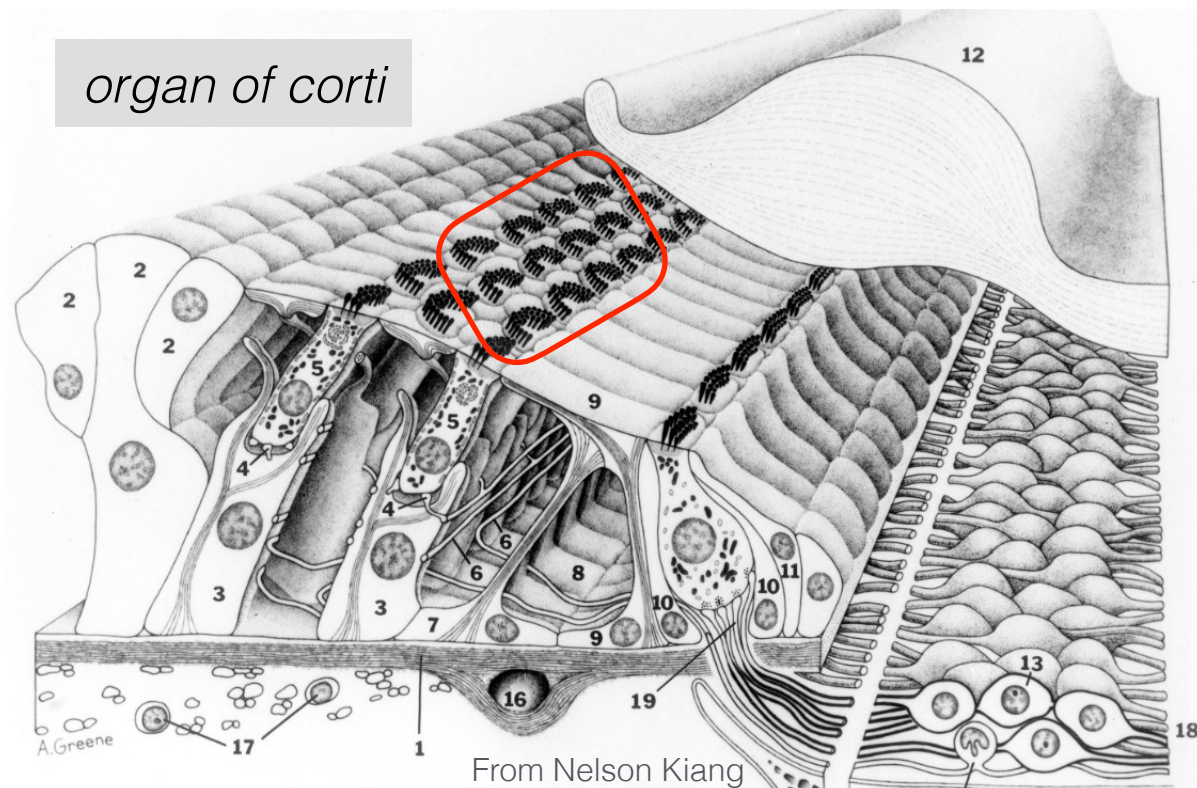
- we hypothesize an attention driven cortico-cochlear loop



in line with a psychophysical trend:

- the further apart the intonation of the individual speakers are the easier the segregation task is
 - e.g., a female-male mixture is much easier to segregate compared to a male-male mixture

about outer hair cells (OHC)



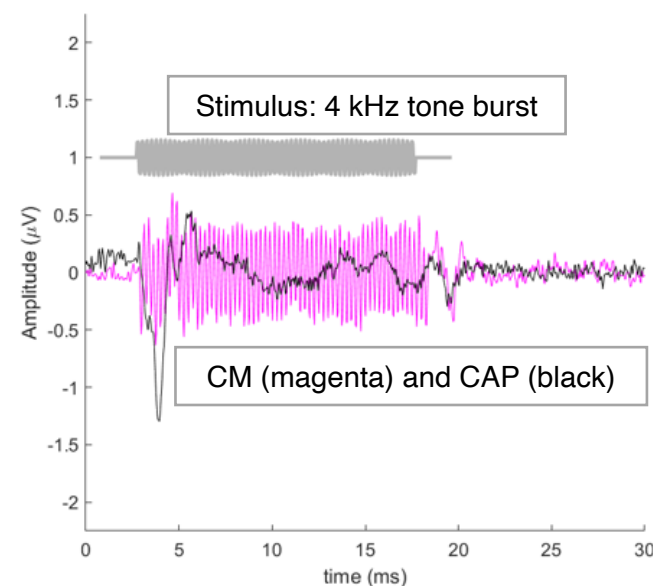
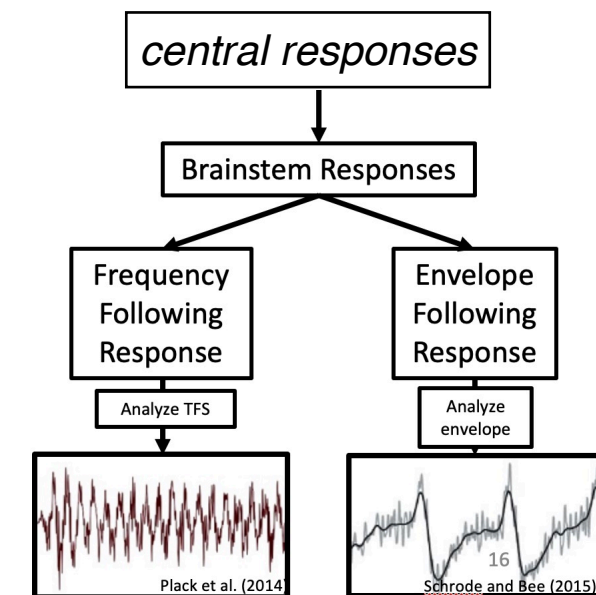
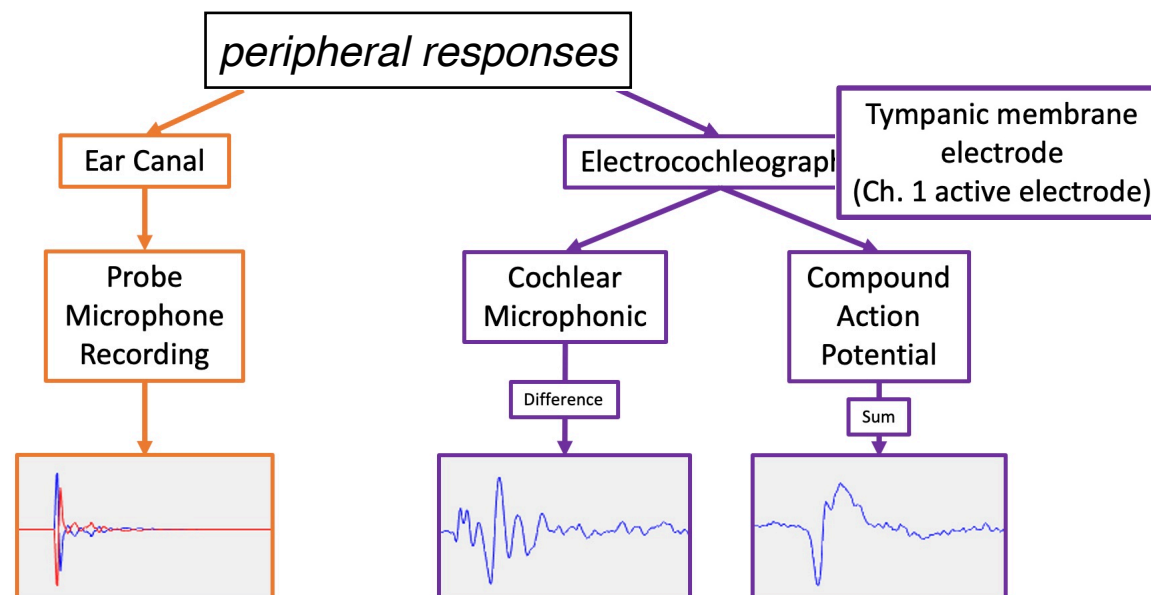
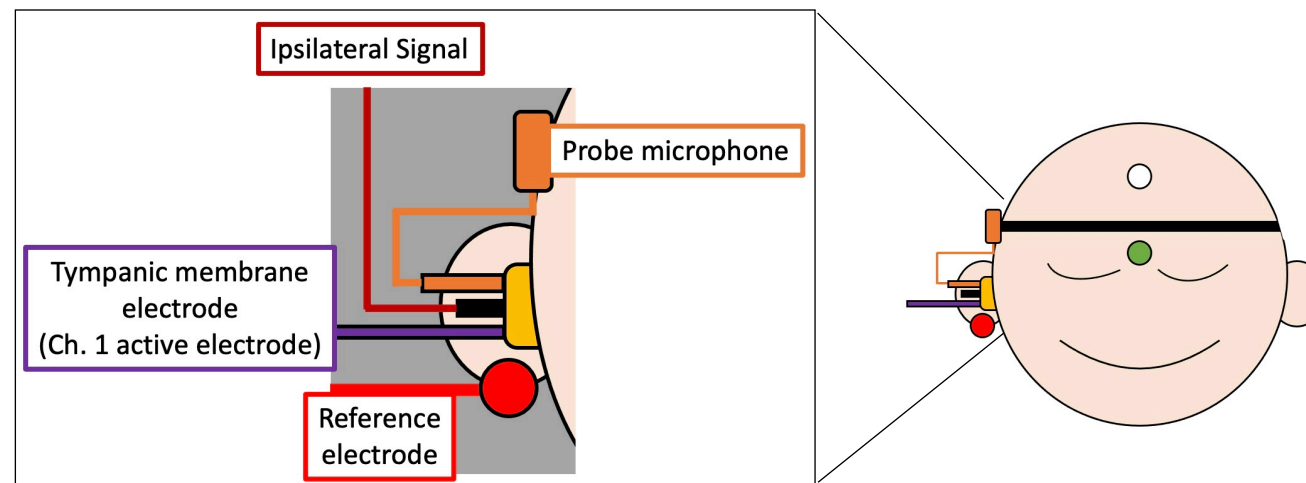
- OHCs change their axial dimensions in response to efferent stimulation
 - elongation via hyper-polarization
 - contraction via depolarizations
- locally (at a given place along the BM):
 - OHC motility results in changes in BM stiffness
 - hence changes in the local cochlear filter characteristics
 - gain, bandwidth
- globally:
 - efferent stimulation change the cochlear operating point
 - affects auditory nerve patterns

can cortico generated OHC response be observed?

- the CM signal is the result of nonlinear efferent-driven modulation of afferent cochlear processing
- *attention driven modulation effects are ever so delicate*
 - challenging signal pickup
 - challenging signal processing
- even more delicate effects
 - such as dynamic convergence towards cortico-cochlear attractors

measuring OHC response

ElectroCochleoGraphy (ECochG)



inherent challenges with ECochG

- signal magnitude and quality depend on electrode location w.r.t tympanic membrane
- a need to shield electromagnetic artifact from the transducer
- a need to reduce noise from the ongoing EEG (brain) signals
- workable SNR only for a limited bandwidth
 - workable CM bandwidth — [500 1400] Hz
- CM responses are dominated by OHCs located at the base of the cochlea
 - high CF filters

adjusting & tuning the experimental paradigm

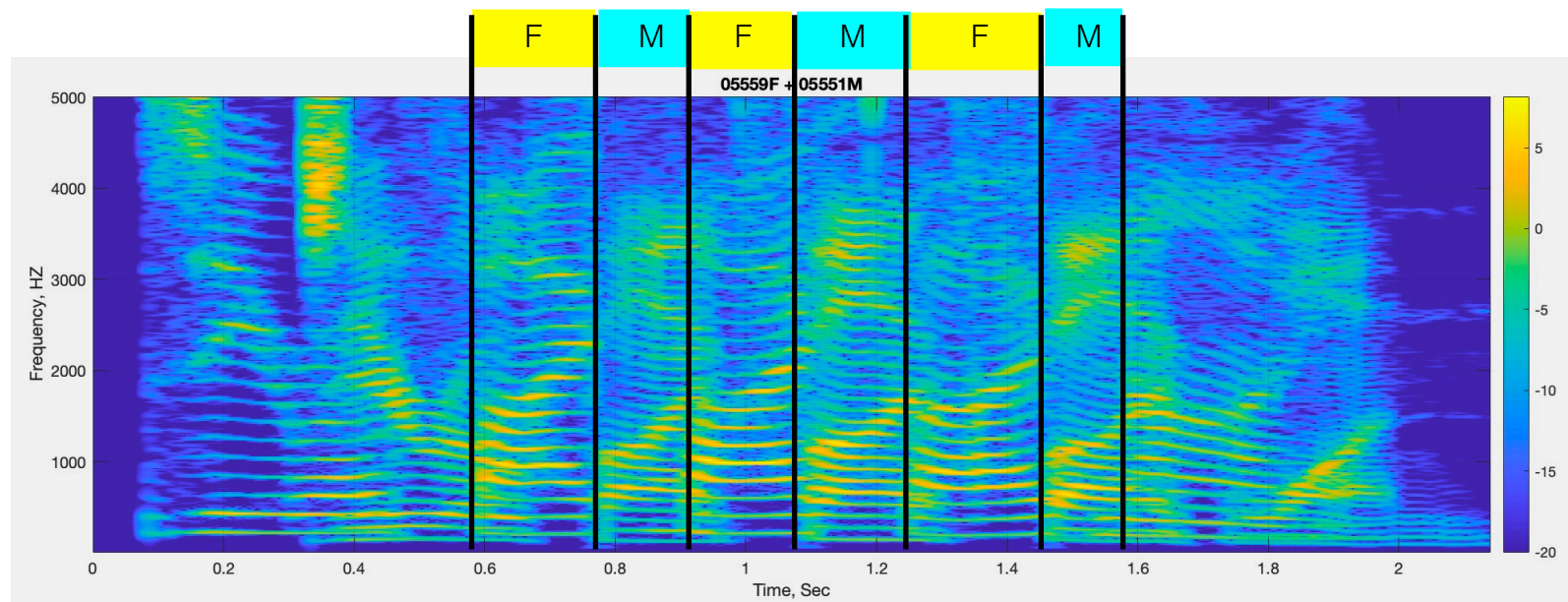
fall 2022 to summer 2024

- CM modulation elicited by harmonic complex with dynamic pitch — passive (N = 6)
 - stimuli: upgoing/downgoing chirps
 - conclusions: effects of dynamic pitch on cochlear hair cell responses can be assessed using the CM.
- effects of attention on the CM elicited by a harmonic complex with dynamic pitch (N = 5)
 - stimuli: upgoing/downgoing chirps
 - conclusions: no clear effect of attention
 - confound: attention instructions not well defined
- effects of attention on the CM elicited by speech (N = 5)
 - stimuli: a male-female mixture of single words (“shimmer,” “colored”)
 - conclusions: inconclusive enhanced CM signals in the presence of the speech
 - confound: voices were presented in an overlapping fashion, making it difficult to isolate the CM effects
- effects of attention on the CM elicited by speech mixtures (N = 5)
 - stimuli: a male-female mixture of the non-overlapping words “shimmer” and “colored”
 - instructions:
 - attend M in a “455M & 433F”
 - attend F in a “455F & 433M”
 - conclusions:
 - no significant difference in CM workable bandwidth
 - “3” vs “4” words
 - confound: the [500 – 1400] Hz band
- effect of CM elicited by mixtures with balance speech stimuli (N = 4)
 - stimuli: a male-female mixture of nonoverlapping “05551,” “05559”
 - conclusions:
 - participants found one speaker easier to attend to
 - the limited number of stimuli facilitated a workaround whereby participants could provide the “correct” response by attending to the “distractor”
 - next step: increase the number of stimuli to eliminate the workaround
- current: increased number of stimuli to eliminate the workaround (“0555x”) (N = 4)
 - results from one example subject provided in this presentation
 - conclusions: discussed in the following slides
- (note: the progress reported here was achieved despite a temporary relocation of the Jennings lab due to building updates mandated by the University of Utah. Relocation efforts resulted in a lack of recording for three months)

the bullets detail the evolving experiments, the paradigms, the results in each step, and the conclusions that led to the next stimuli sets and attention directive to the subjects

experiment

- mixtures of non-overlapping stimuli
 - 0555x & 0555y (x, y = 0, 1, ..., 9) spoken by F and M



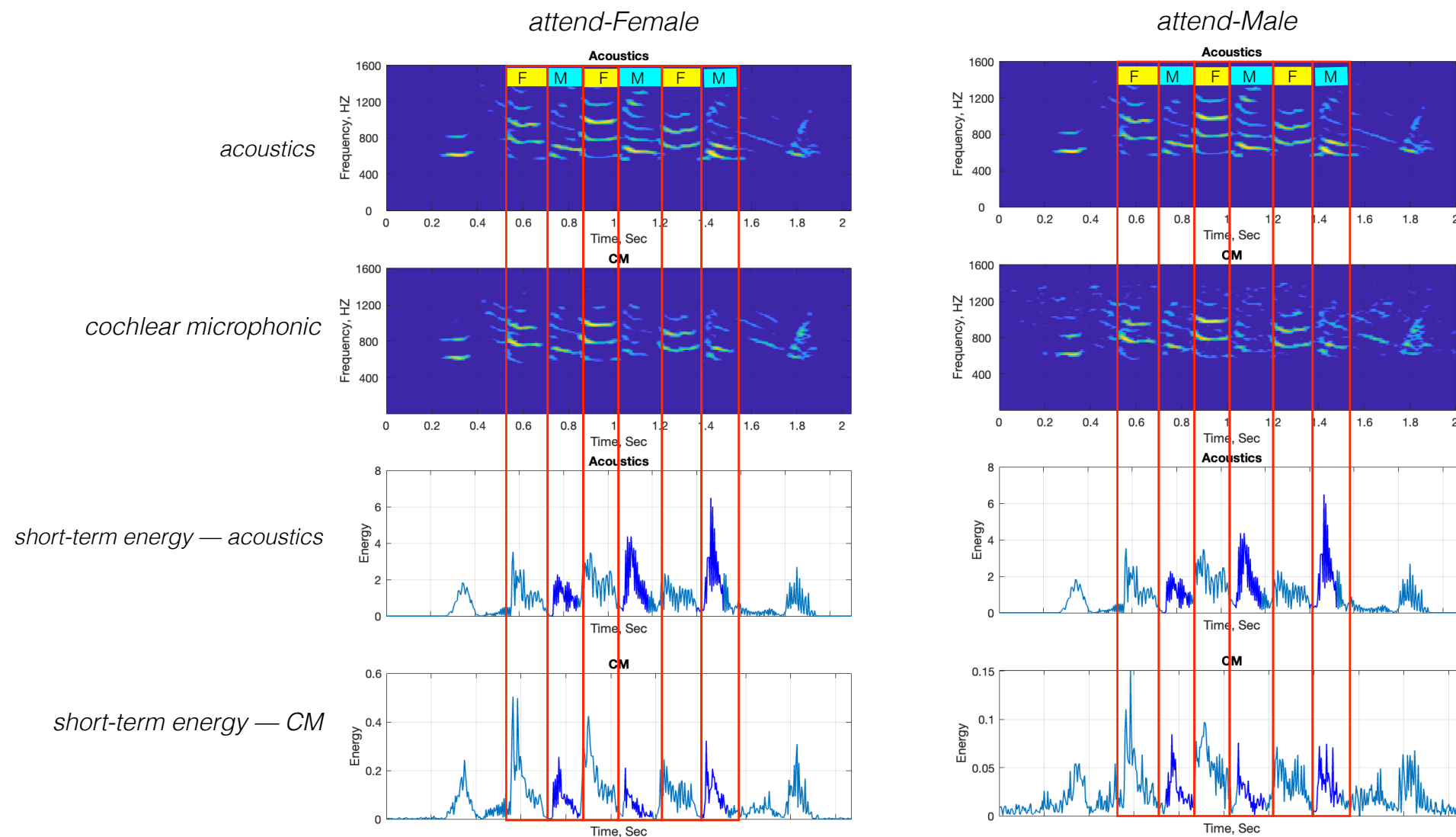
- attention:
 - 1st half of a session: press when F says 51
 - 2nd half of the session: press when M says 51
 - with such paradigm, the subject is covertly forced to attend the **gender of the speaker**, whether or not the target digit is present in the attended mixture.

next: preliminary result (one subject)

attend-Male vs attend-Female

short term Energy (4ms window)

- does CM energy enhanced within speech fragments of attended speaker (target)?

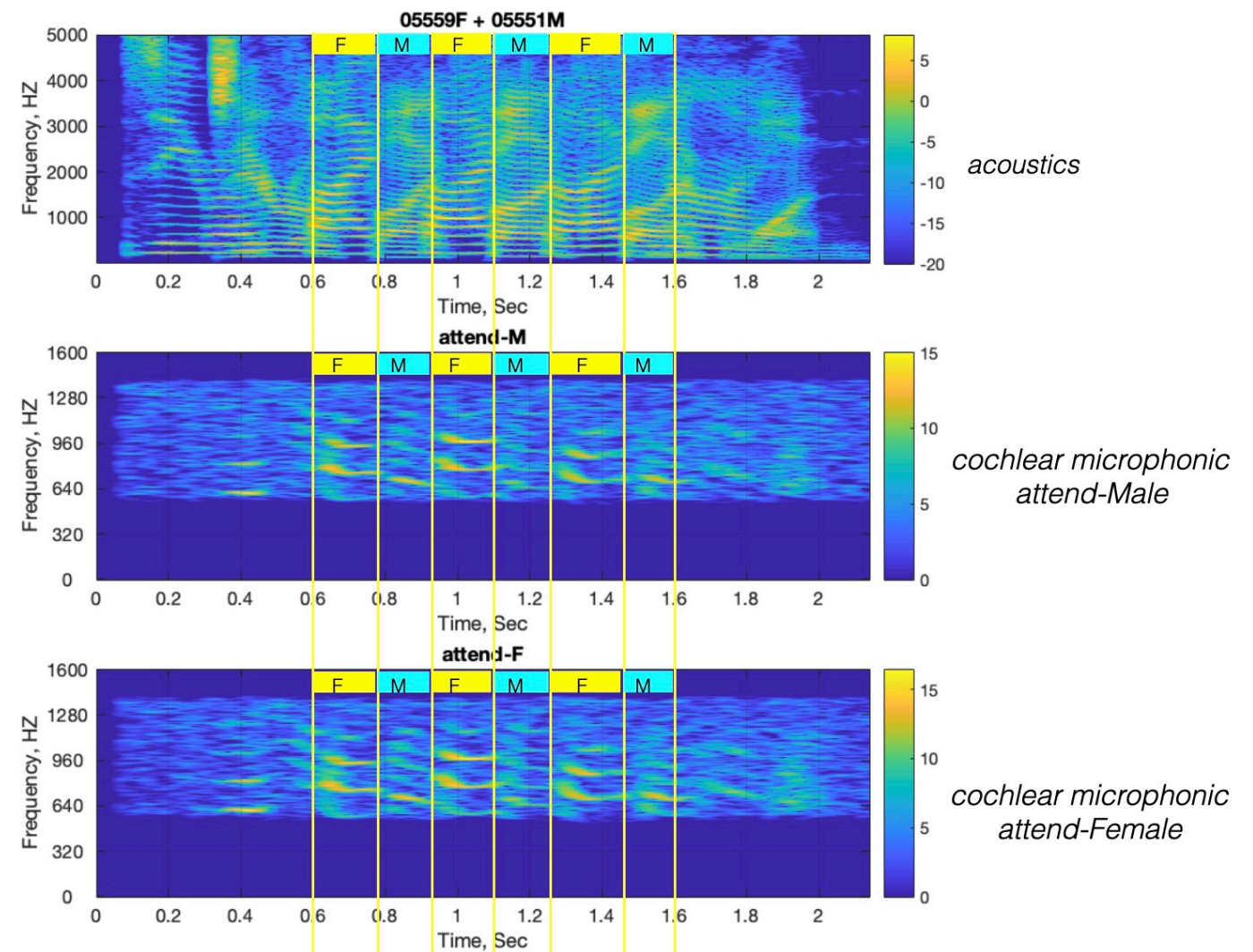


- For *attend-F*, enhanced energy of target speaker and attenuated energy of the distractor
- not so for *attend-M*, why?

attend-Male vs attend-Female

harmonic components

- data
 - attend-M & attend-F iterations
 - same session (same electrode location)
- analysis
 - CM signals – unscaled
 - classical (FFT) spectrograms
 - afferent processing assumed same for attend-M & attend-F
 - => **difference** flush out efferent driven modulations
 - signum operation on difference



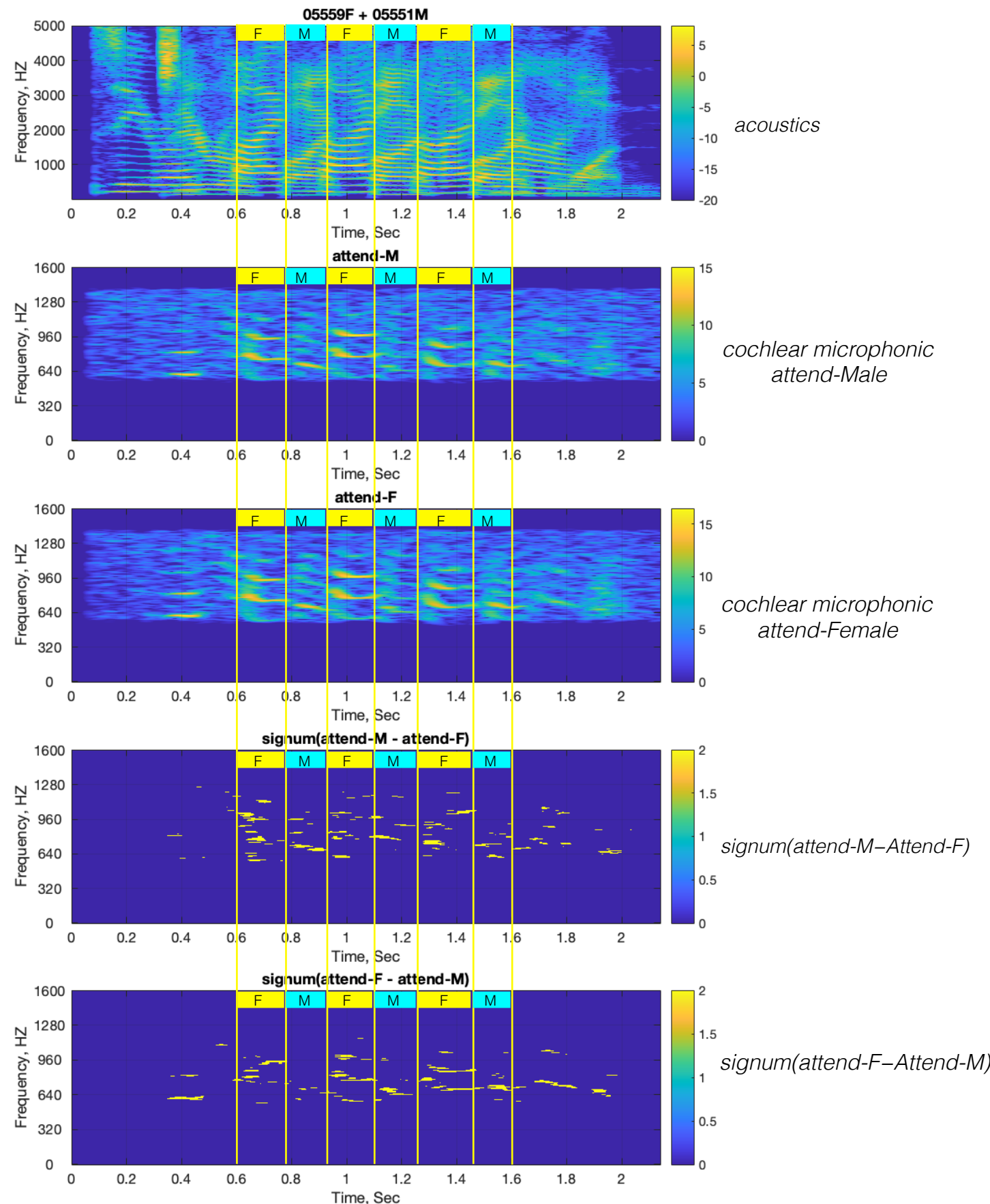
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harmonic components

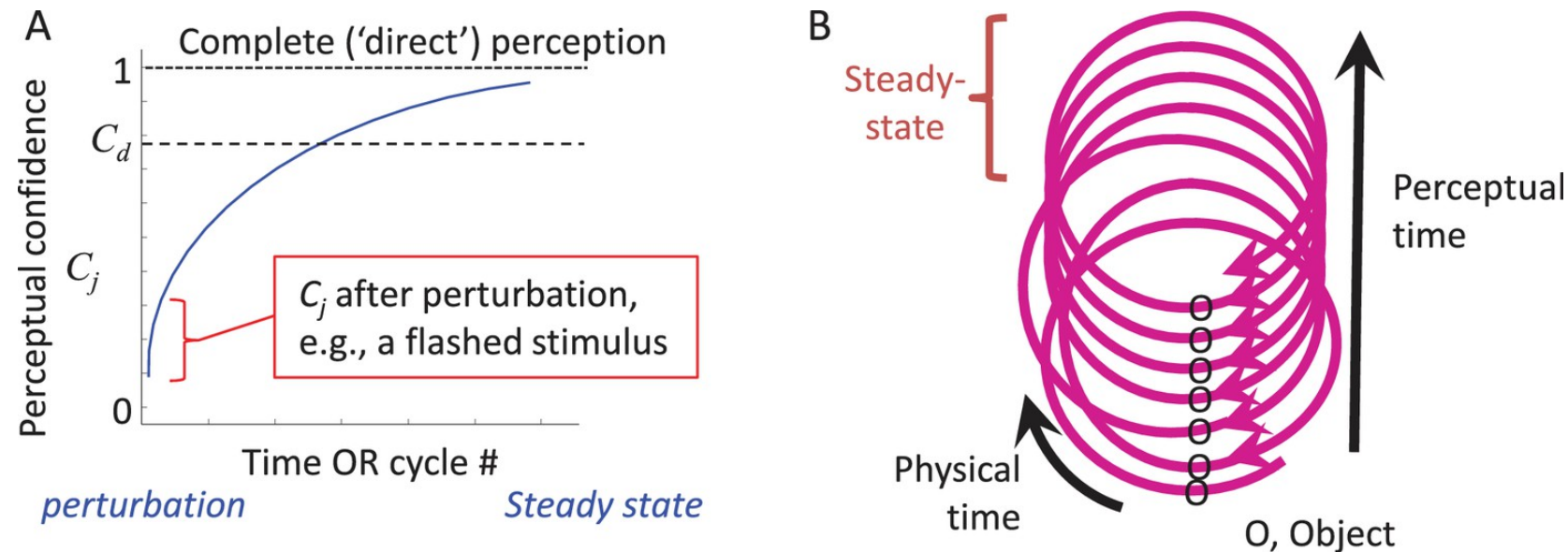
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for *attend-F*, a difference between the spectrograms reveals enhanced harmonics of the target speaker and attenuated harmonics of the distractor.

- as we speak:
 - more subjects



our closed-loop perception model

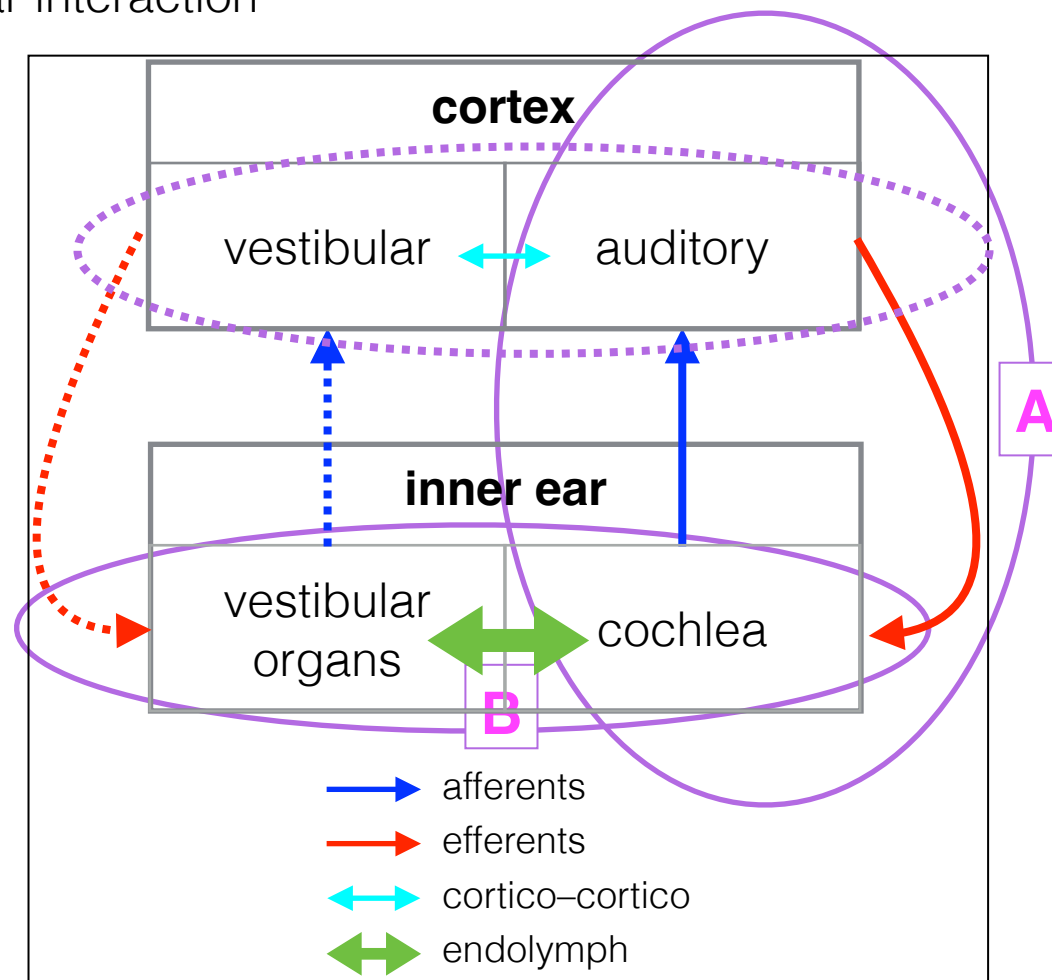


- according to our model, speech perception involves a closed-loop convergence process
- in our model, the cochlea-cortex-cochlea loop is modeled as a dynamical motor-sensory-motor loop, which includes:
 - efferent (motor) (\mathbf{m}) variables
 - (sensory) cochlear (\mathbf{s}) variables
 - neuronal (\mathbf{n}) variables
 - interactive differential “loop equations”: $\mathbf{s} = f(\mathbf{m}, u)$, $d\mathbf{n}/dt = g(\mathbf{n}, \mathbf{s})$, $d\mathbf{m}/dt = h(\mathbf{m}, \mathbf{n})$
 - we assume no memory of $\mathbf{s} \Rightarrow \mathbf{s}$ not differential and does not self-depend on \mathbf{s}
- function f encapsulates the physical laws governing the interactions within the inner ear
- the state of the system is defined by all the variables ($\mathbf{m}, \mathbf{s}, \mathbf{n}$) – the “msn-vector”
- the model assumes that speech perception is achieved through the convergence of the system to a steady state within this vector’s state space

objective B

active hearing dependency on vestibular organs sensing?

- outside the scope of this study:
 - binaural-hearing-vestibular interaction
 - visual-auditory-vestibular interaction



- the otolith organs are sensitive to body orientation
- there is endolymphatic continuity of the otoliths with the semicircular canals and the cochlea

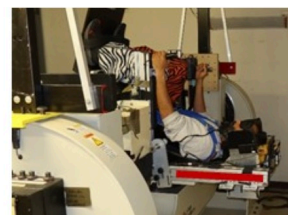
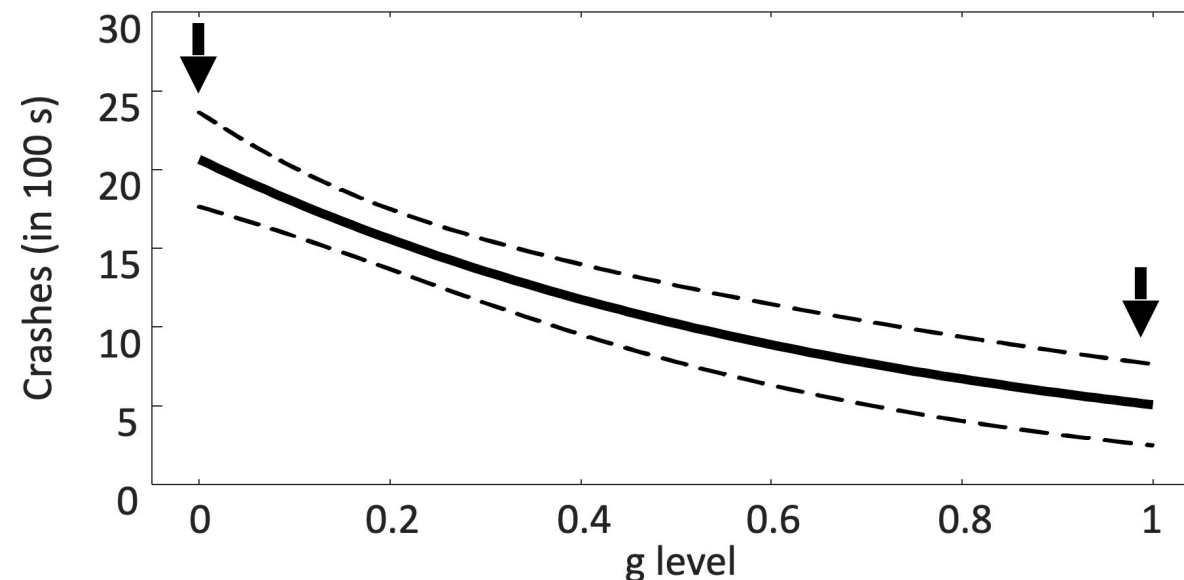
=> hypothesis:

vestibular organs interpretation linked to cortico-cochlear control circuit

- validating hypothesis B:
 - we thought to measure the OHC responses in the supine orientation
 - spatial disorientation in “0g” relative to 1g

meanwhile, at Lackner's lab (AGSOL)

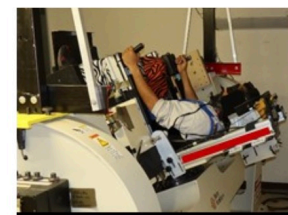
- a gradient of spatial disorientation between 1-g and 0-g
 - spatial disorientation increases in Analog Hypo-g conditions



"Space", 0g
(90°)



"Lunar", 0.16g
(80°)



"Mars", 0.38g
(68°)



Earth, 1g
(0°)

- => should we add "Mars" and "Lunar" conditions to "Space" condition?
- the significance of the gradient is in refining a priori predictions about tests in progress, as well as model interpretation:
 - g-dependency of performance **but no** g-dependency in CM
 - consistent with an open loop model where g-induced alteration in endolymphatic pressure modulates vestibular and cochlear biomechanics.
 - g-dependency of performance **and** in CM
 - favors cochlear loop model in which cortical processing of otolith afference modulates semicircular canals and cochlea.

Funded by a
research grant
from





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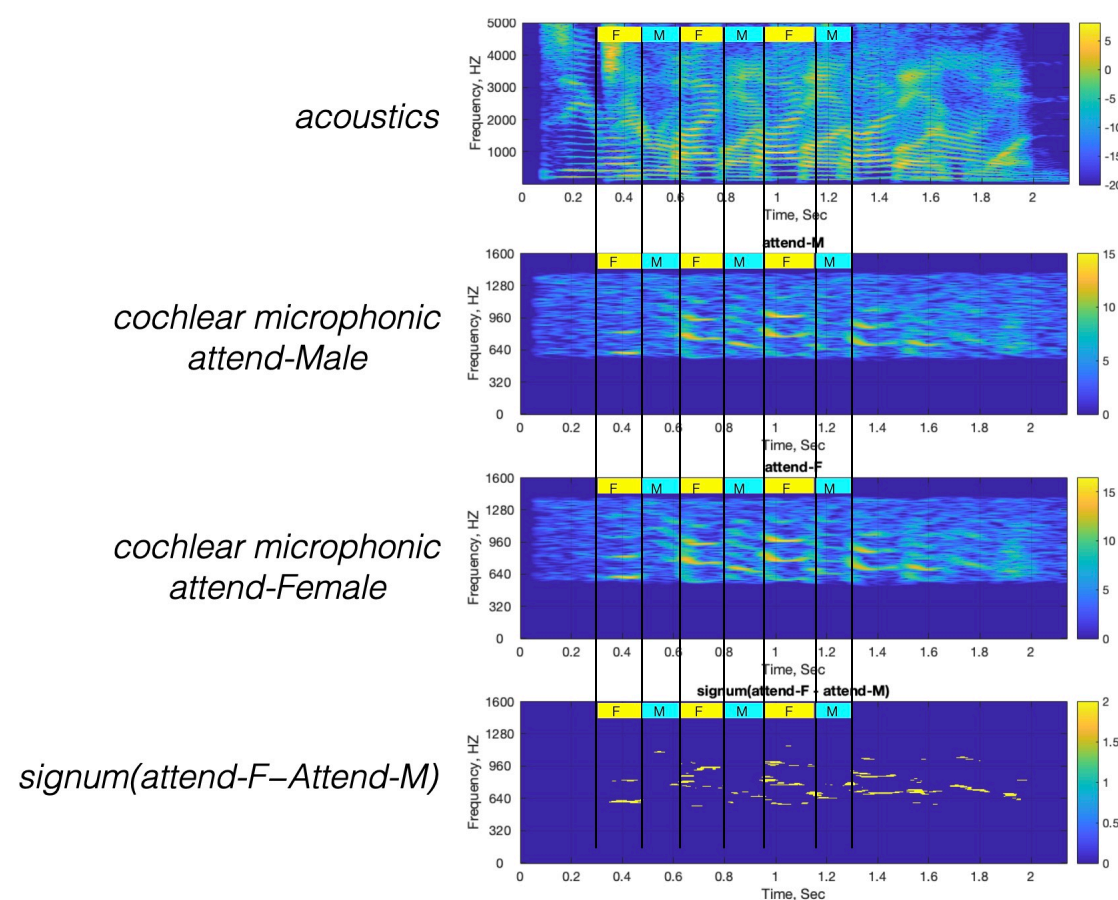
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The effect of cortico generated signals on OHC response

A difference between the spectrograms of an attend-Female and an attend-Male OHC responses to an acoustic mixture reveals enhanced harmonics of the target speaker and attenuated harmonics for the distractor.



DoD Benefits

- Given the general similarity in receptor transduction anatomy and closed-loop dynamics across all senses, a generic model of closed-loop perception will have a significant impact on the understanding sensory and sensorimotor computation principles in biological organisms, in all modalities
- Such knowledge will improve the understanding of human performance in dynamic gravito-inertial conditions
- It will improve the design of speech and non-speech cues to combat spatial disorientation with auditory cues

Acknowledgement

- Pat Bradshaw, AFOSR