

Efferent Control of Synchronization in Systems of Coupled Hair Cells

AFOSR Human Performance and Biosystems
Program Review
Arlington, Virginia
October 23rd, 2024

Dolores Bozovic
Dept. of Physics and Astronomy and
California NanoSystems Institute
University of California Los Angeles

Characteristics of the auditory response

sensitivity in the presence of noise

0.3 nm displacements

temporal resolution

10 μ s inter-aural time difference

dynamic range

6 orders of magnitude in
pressure



M. Konishi, California Institute of Technology

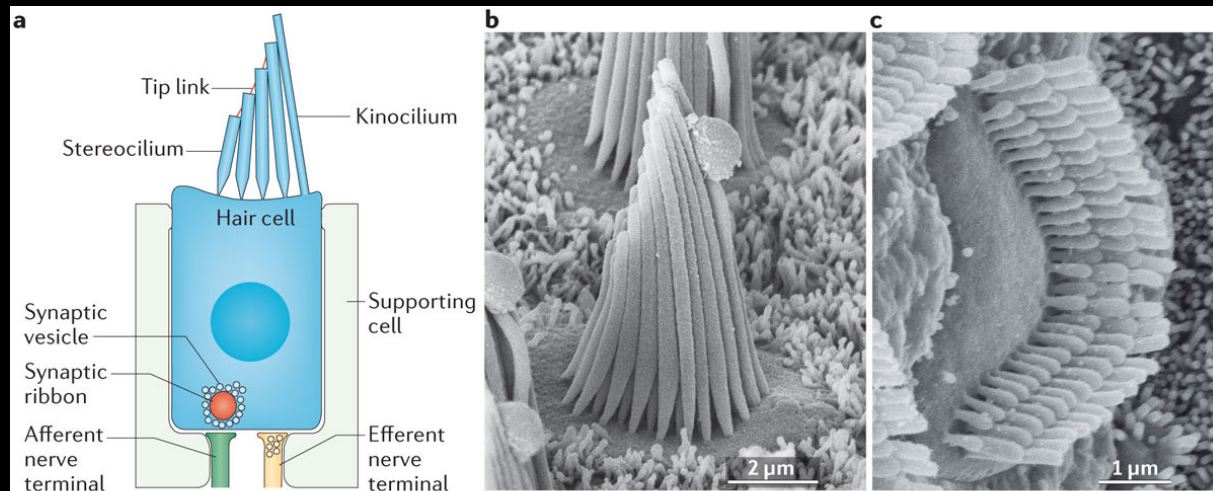
Physics of hearing: open problems

How does the auditory system detect sub-nanometer vibrations? How is this achieved in the presence of noise?

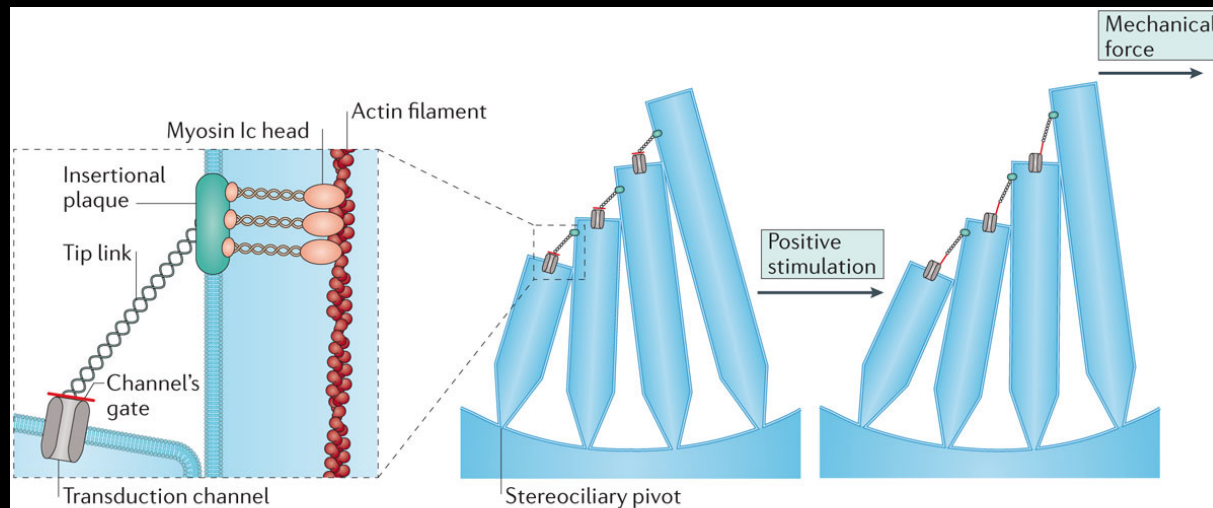
What are the internal self-tuning mechanisms that allow for the broad dynamic range?

How is the information about the acoustic signal extracted by systems of coupled oscillators?

Hair cells



Nature Reviews | Neuroscience

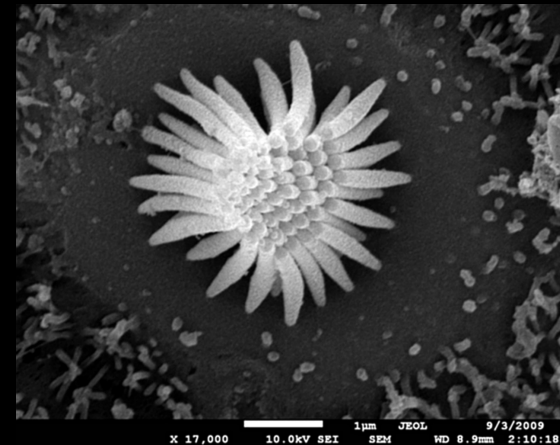
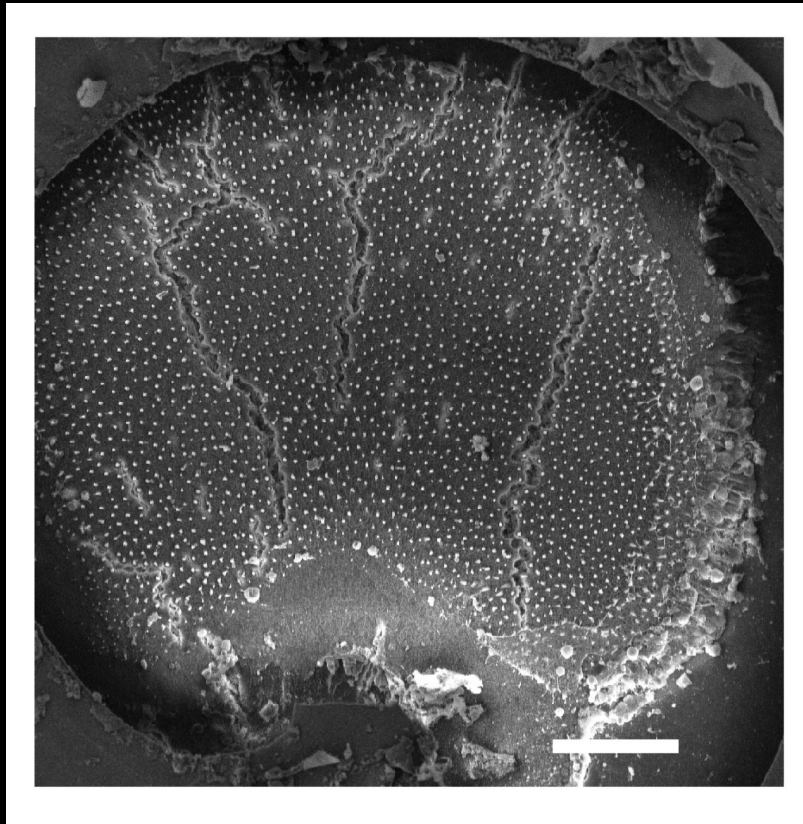


Nature Reviews | Neuroscience

Hudspeth, A. J., *Nat. Rev. Neurosci.*, 15 (2014).

Experimental techniques

Experimental techniques



in vitro preparation of the sacculus from *Rana catesbeiana*



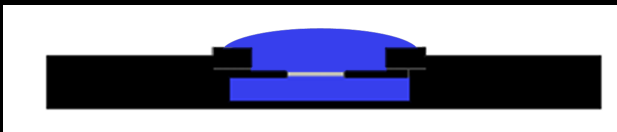
Acoustic isolation
booth



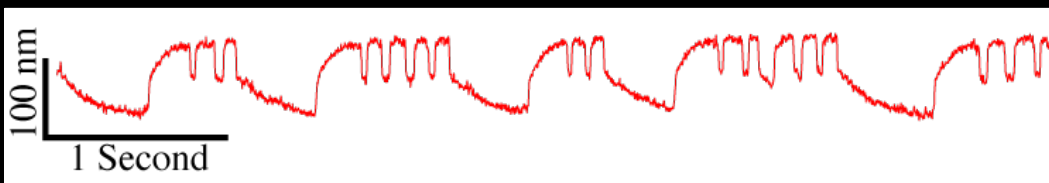
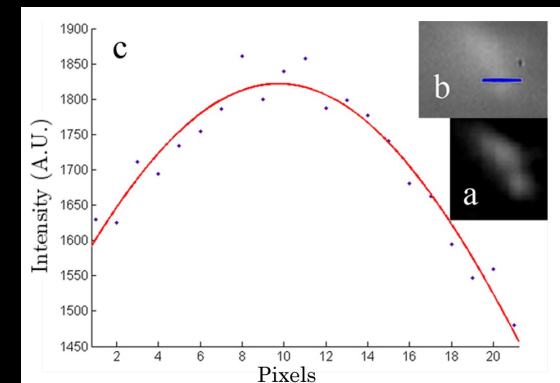
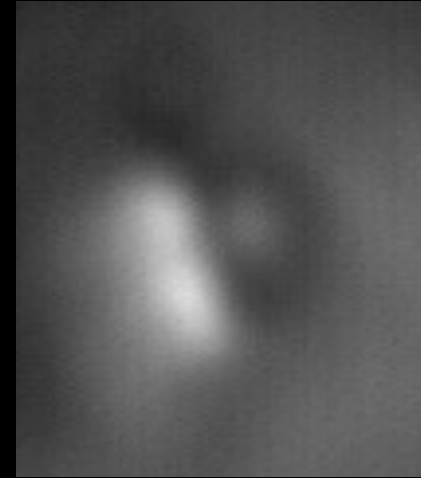
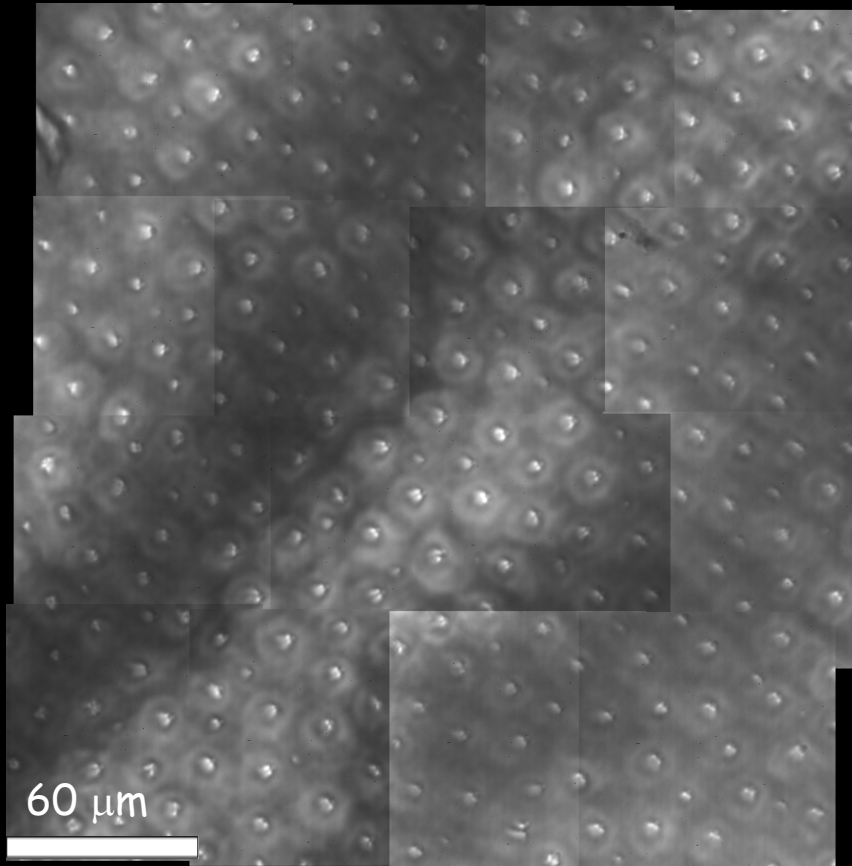
Olympus optical
microscope



Photron FASTCAM SA1.1
1024 x 1024 pixels
5400 fps

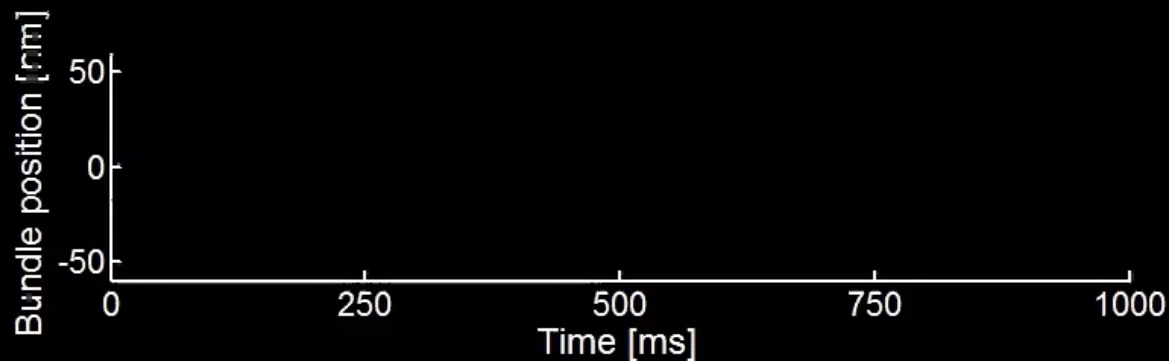
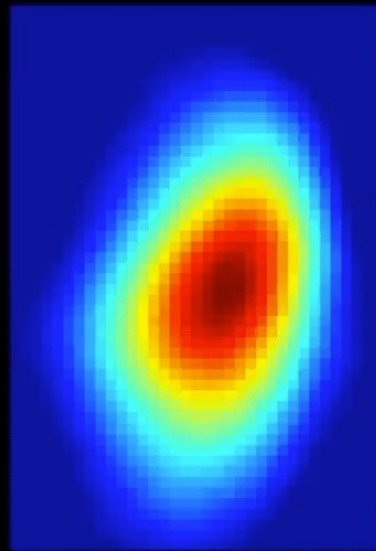


2-compartment chamber
artificial perilymph and endolymph

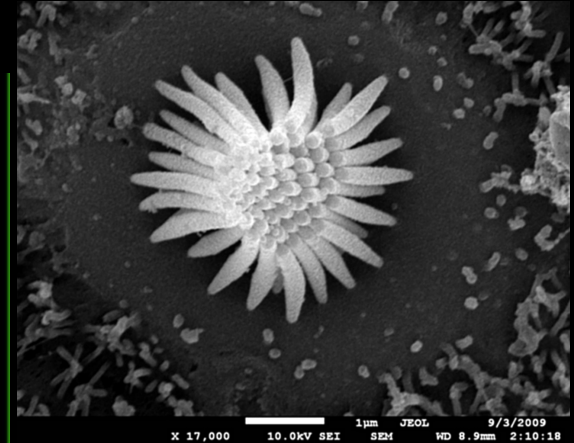


tracking hair
bundle movement

Hair cells follow nonequilibrium and nonlinear dynamics



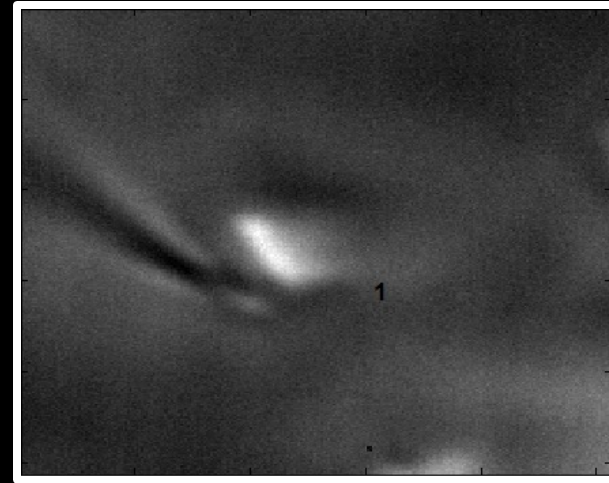
Recorded by S.W.F. Meenderink



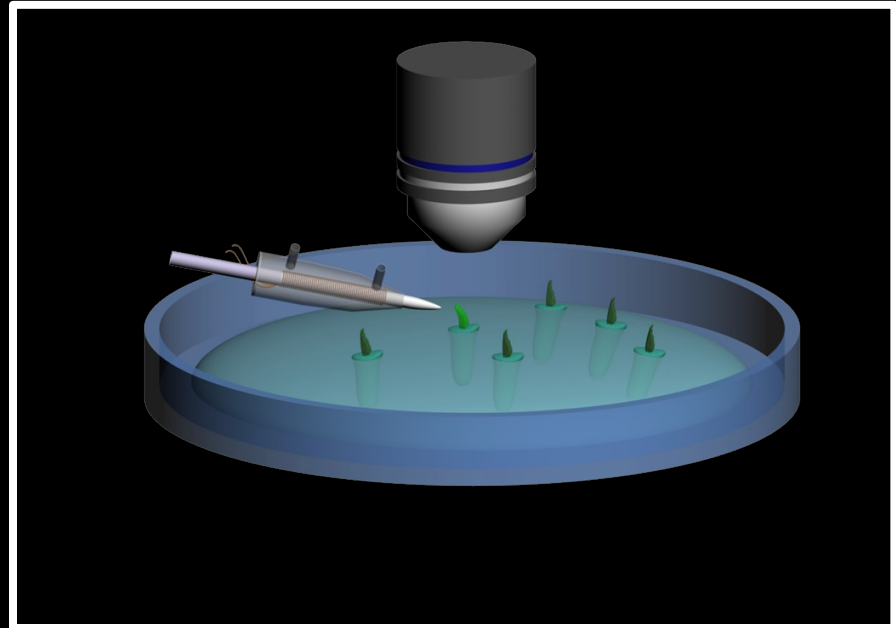
active innate
oscillations of the
hair bundle

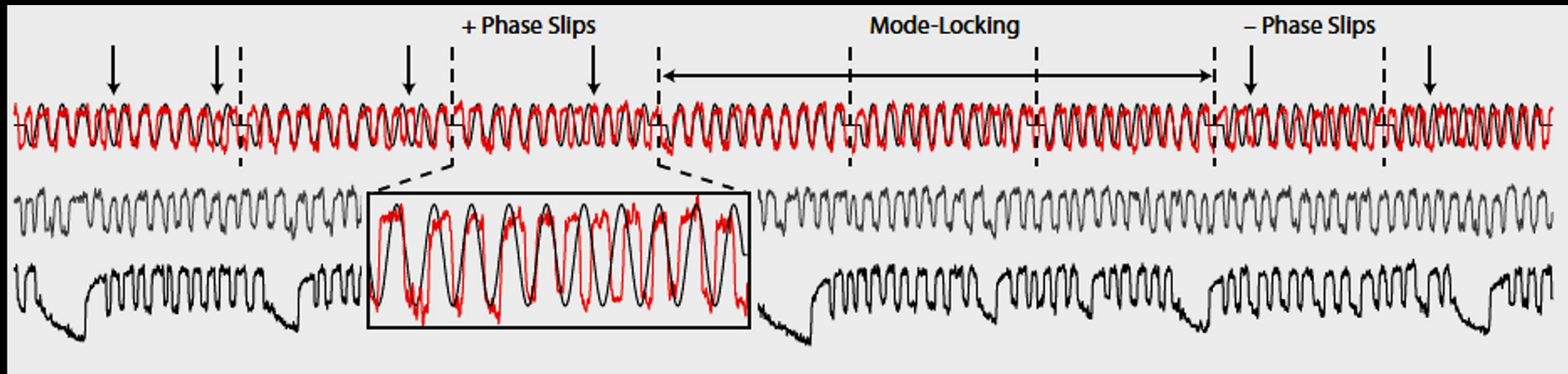
Mechanical stimulation

Glass probes
mounted on a
piezoelectric
actuator



Magnetic
nanoparticles
deflected by an
electromagnet

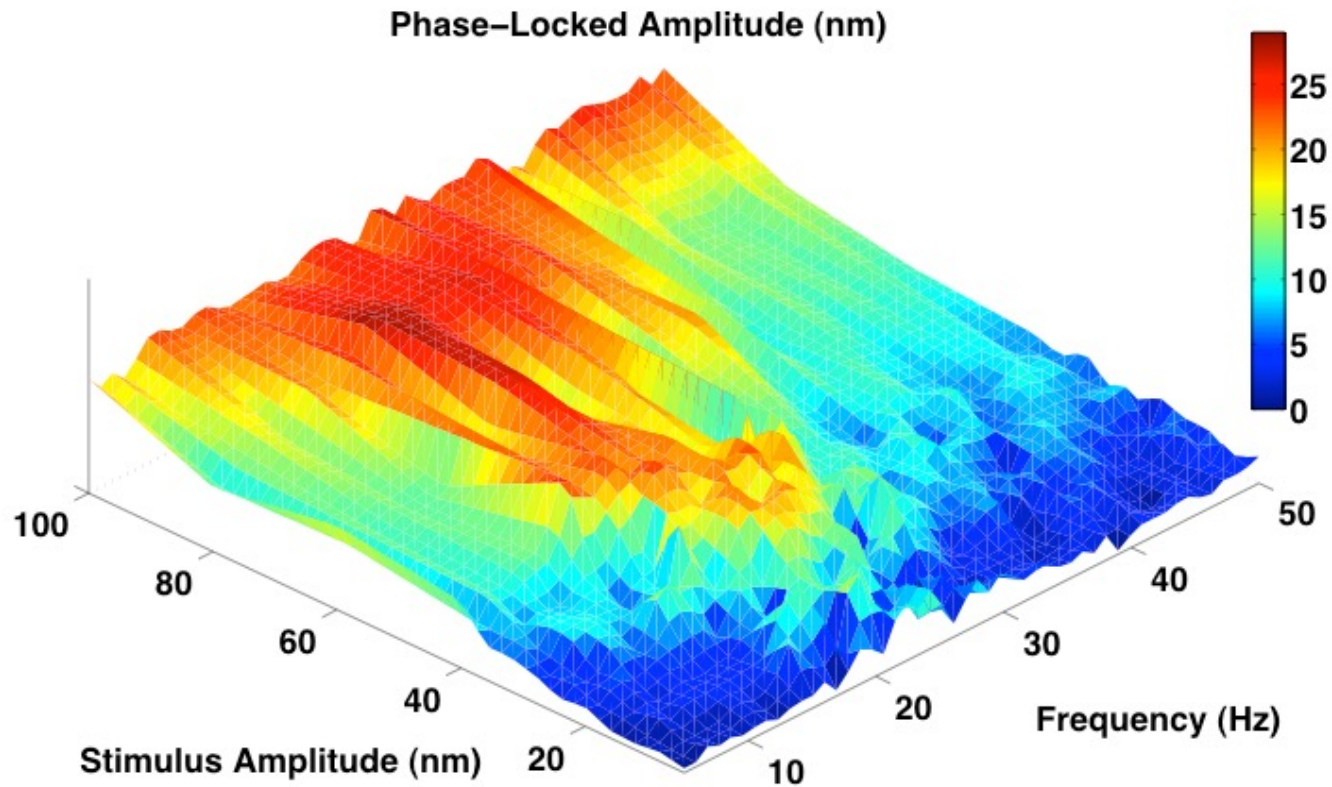




Applied stimuli entrain the innate oscillations of the bundle.

Phase-locking depends on both the frequency and amplitude of the applied signal.

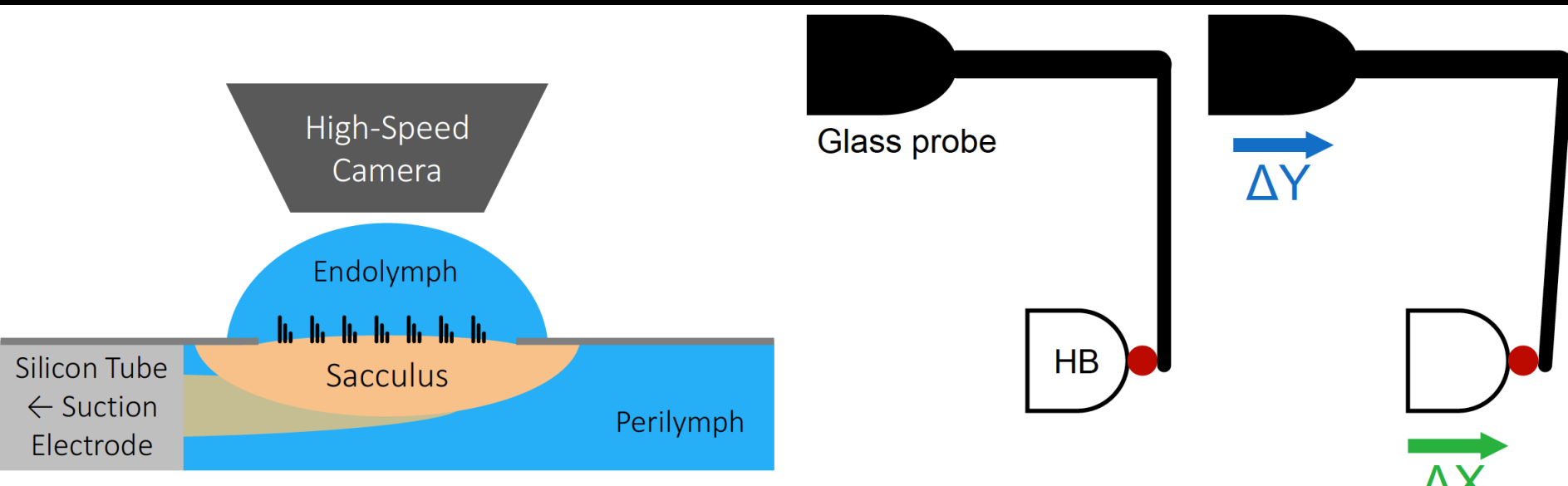
Response over the physiological range



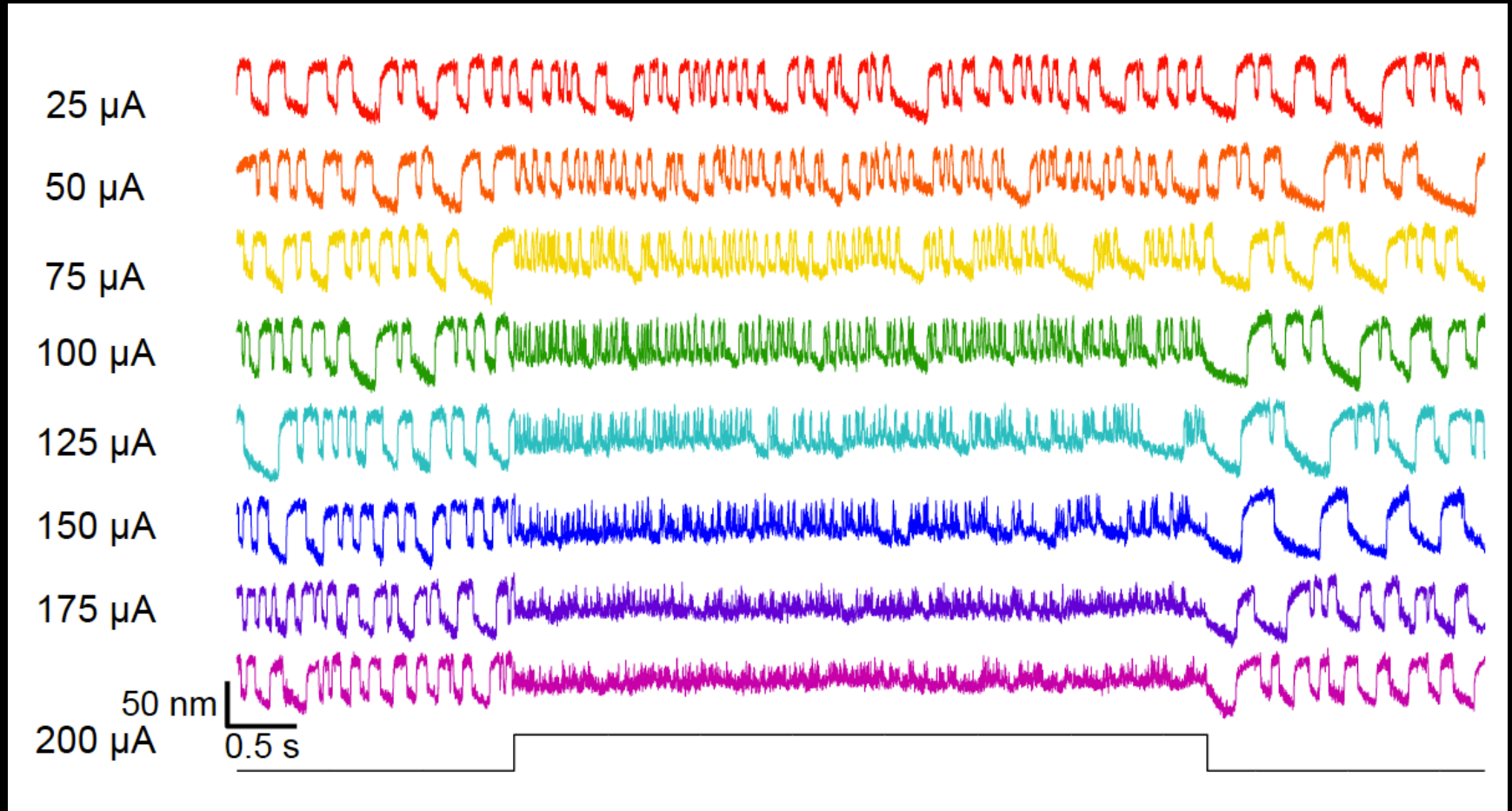
Fredrickson-Hemsing, L.M. et al, *Phys. Rev. E*, 86, 21915 (2012).

Neural control of auditory detection

Experimental setup for efferent stimulation

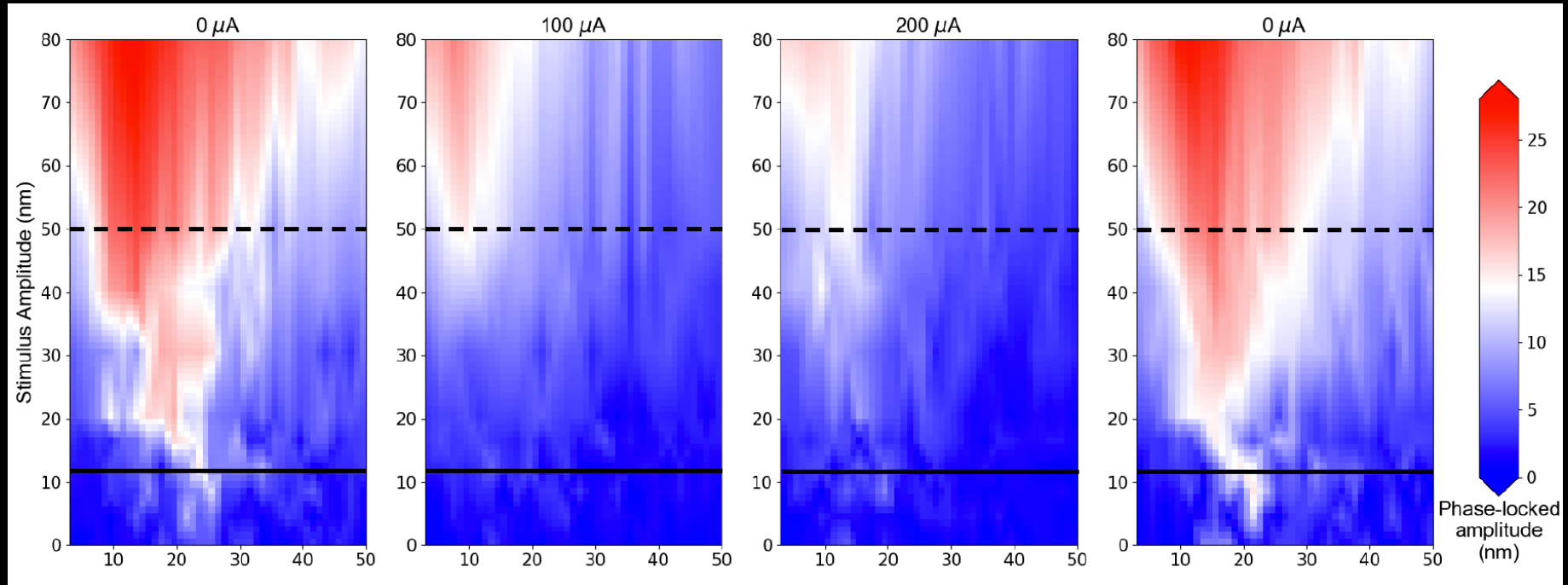


Efferent control of underlying dynamics



Lin, C. H. et al, *J. Neurosci.*, 40, 2390 (2020).

Reduction of sensitivity by efferent stimulation



control

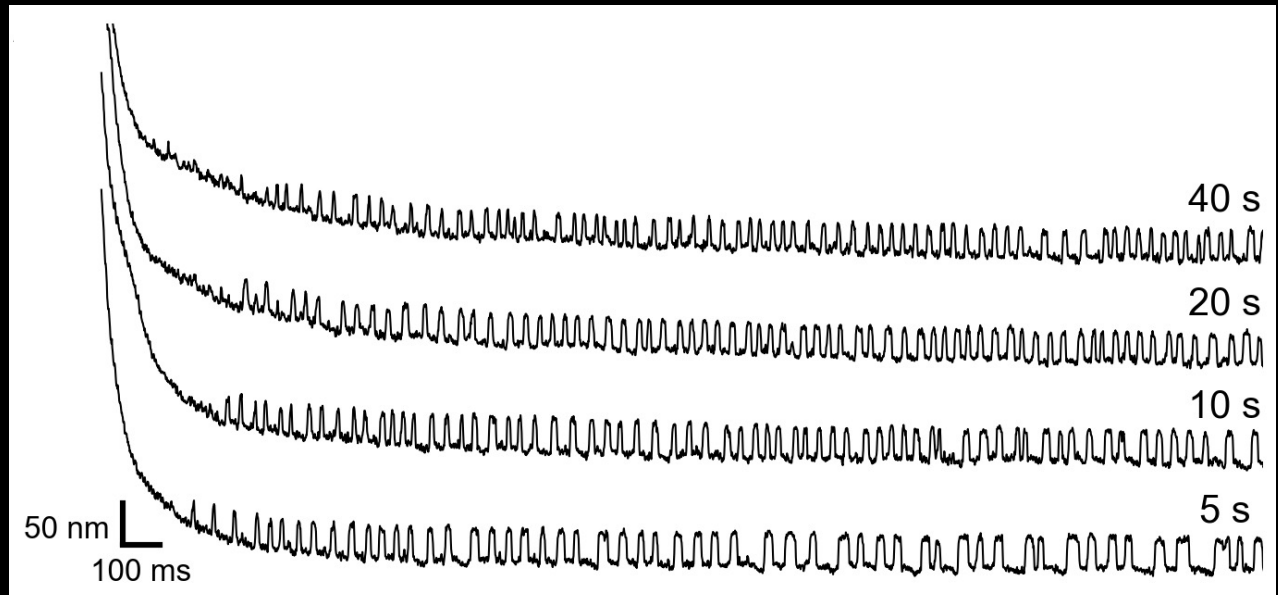
with
efferent
stimulus

with
efferent
stimulus

control

Effects of mechanical overstimulation

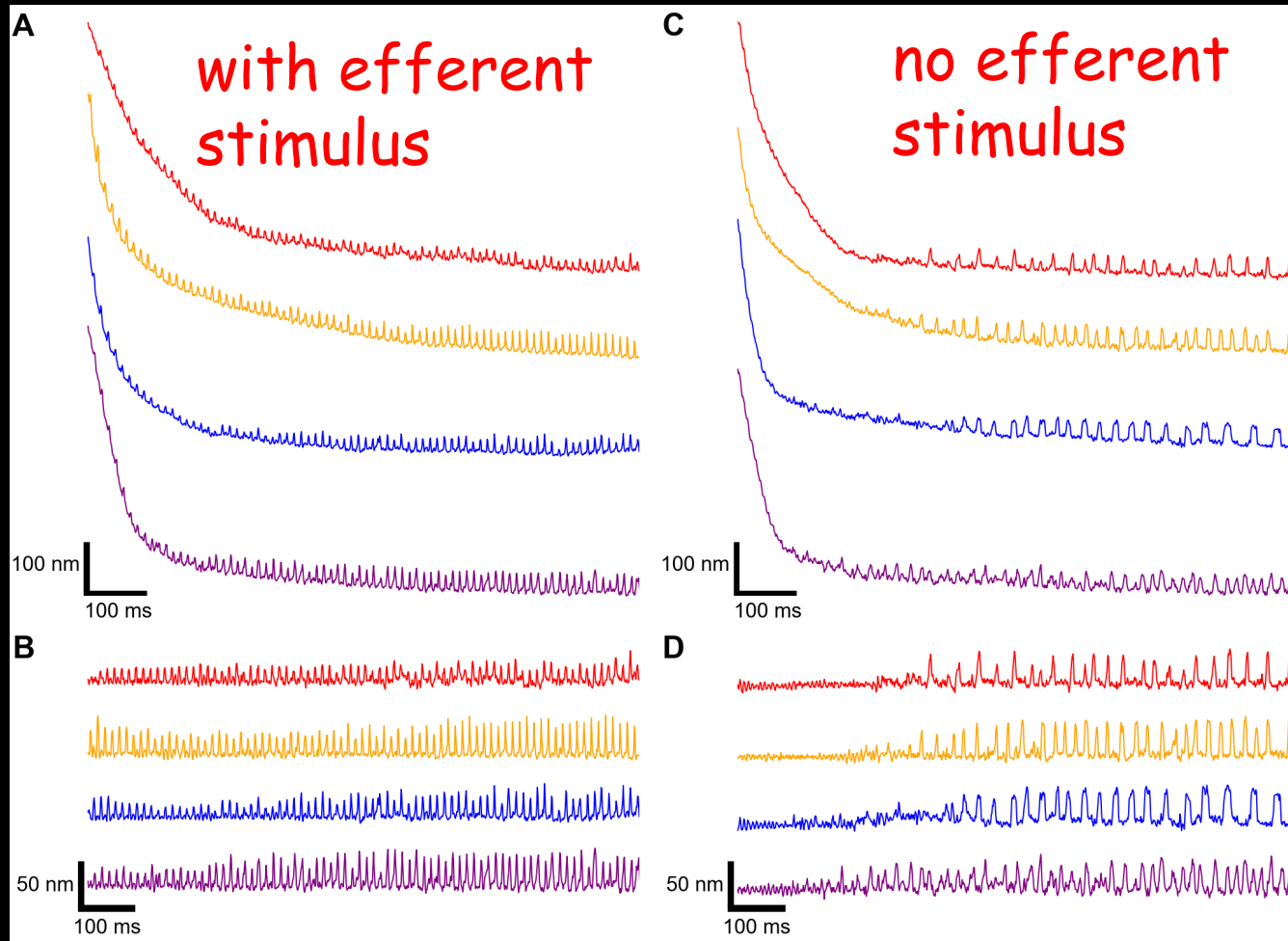
accrued offset



Lin, C.H. et al, *eNeuro*, 9, 0198 (2022).

temporary suppression of innate oscillation

Efferent effects on recovery from overstimulus

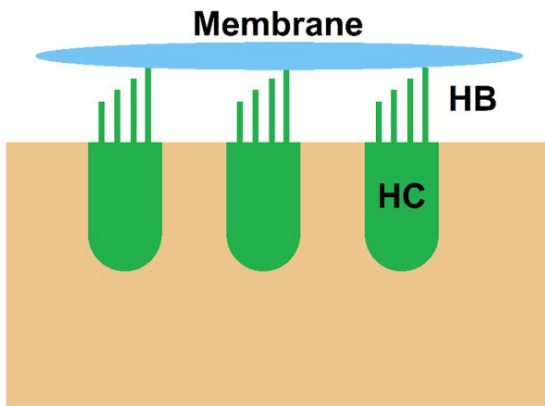


Neural activation induces a qualitative shift in the hair bundle dynamics.

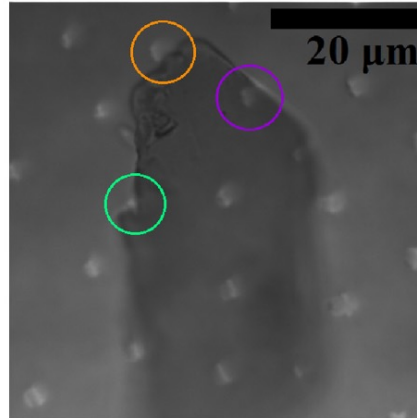
Coupling between hair cells

Hybrid preparation: artificial coupling interfaced with biological cells

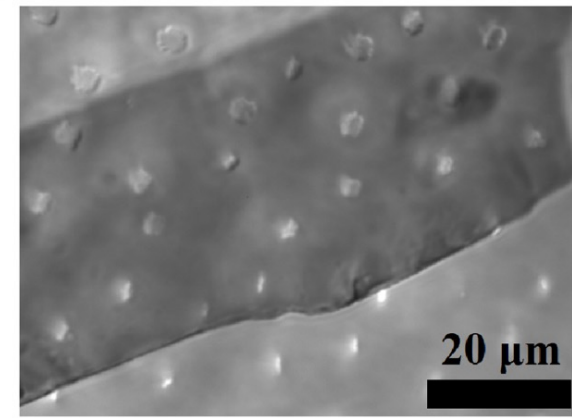
(a)



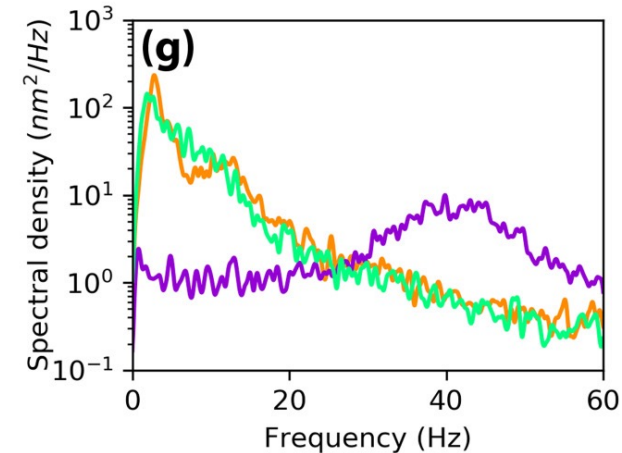
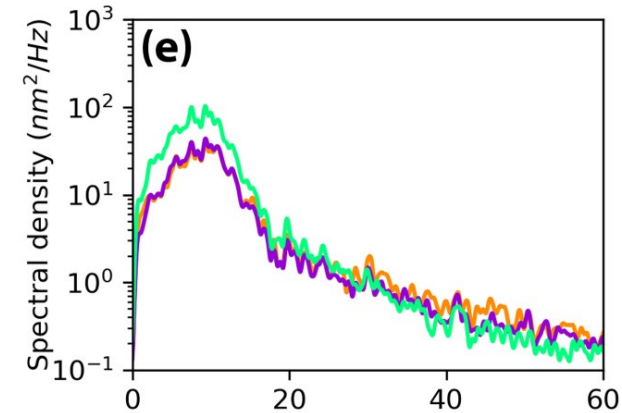
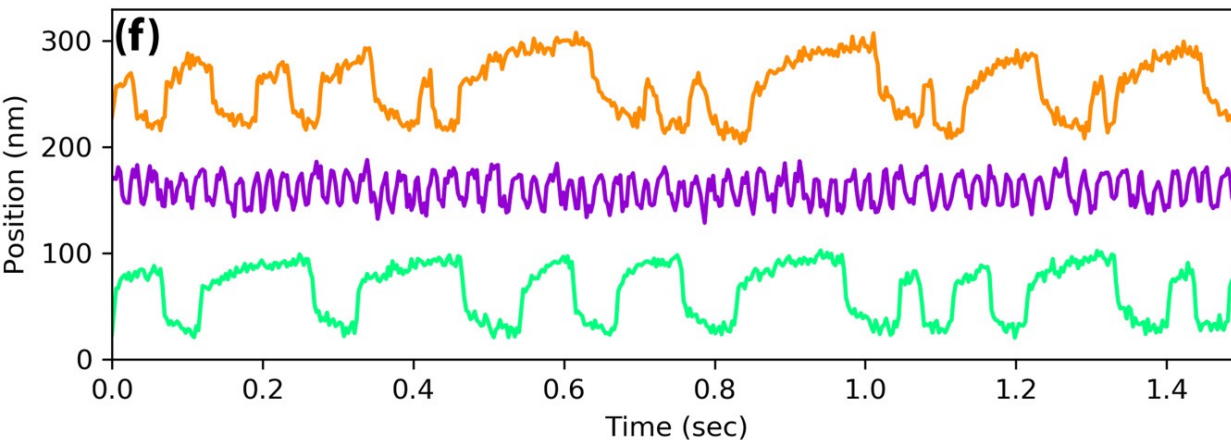
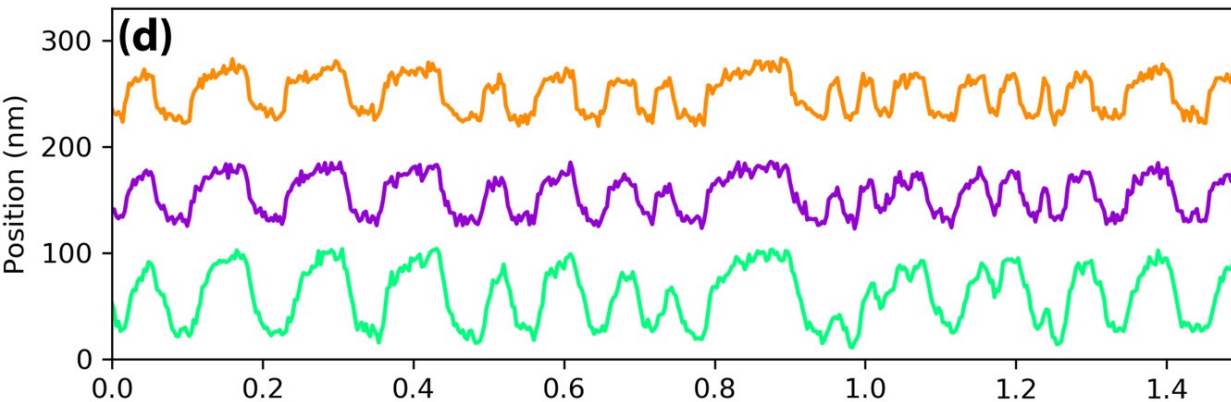
(b)



(c)

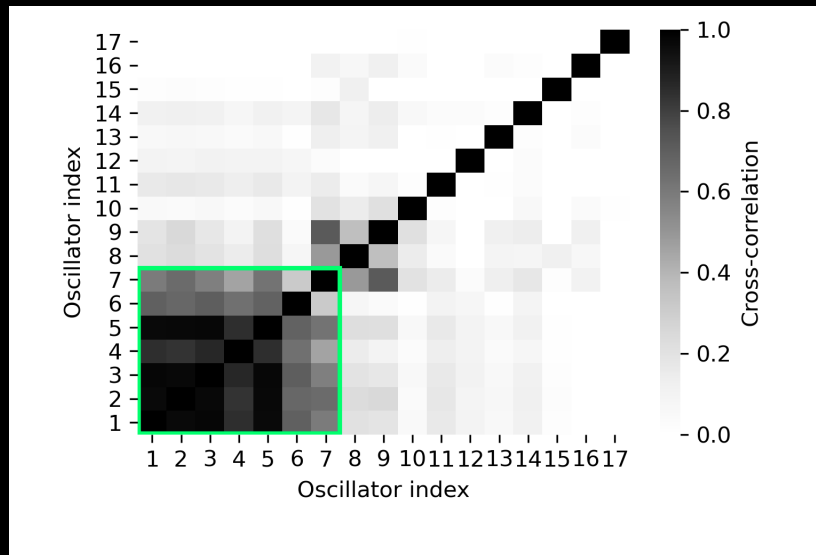


Coupled bundles

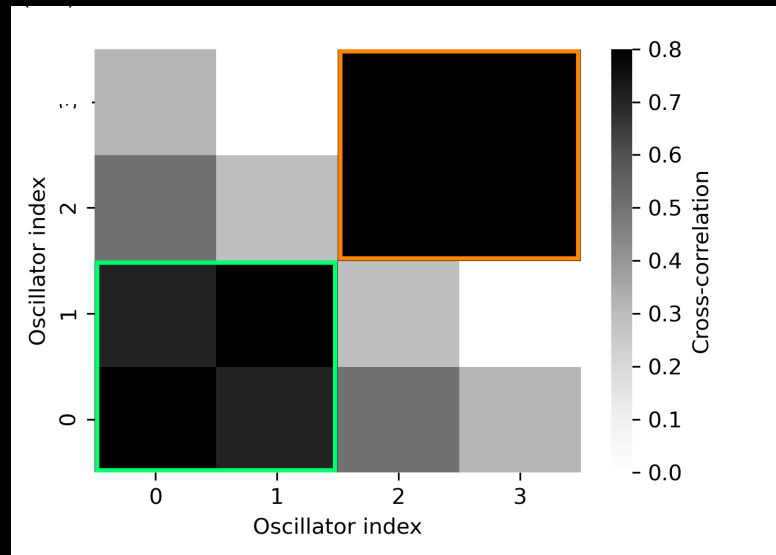


Artificial membrane removed

Large frequency dispersion renders full synchronization difficult.



chimera states

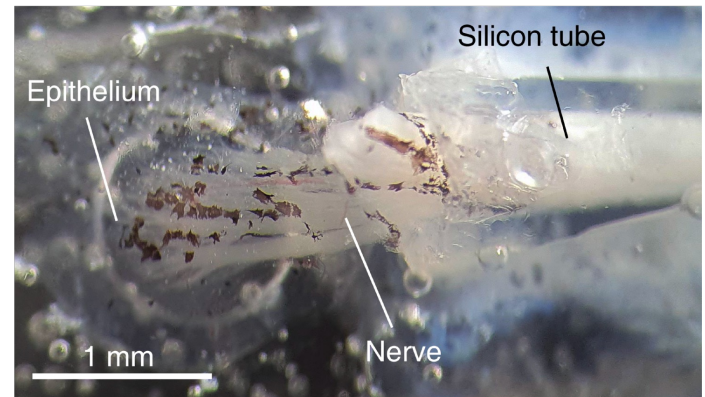
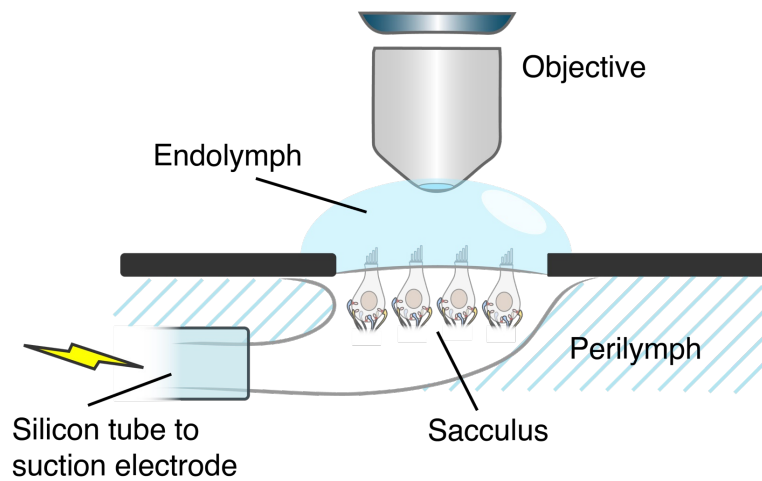


frequency clustering

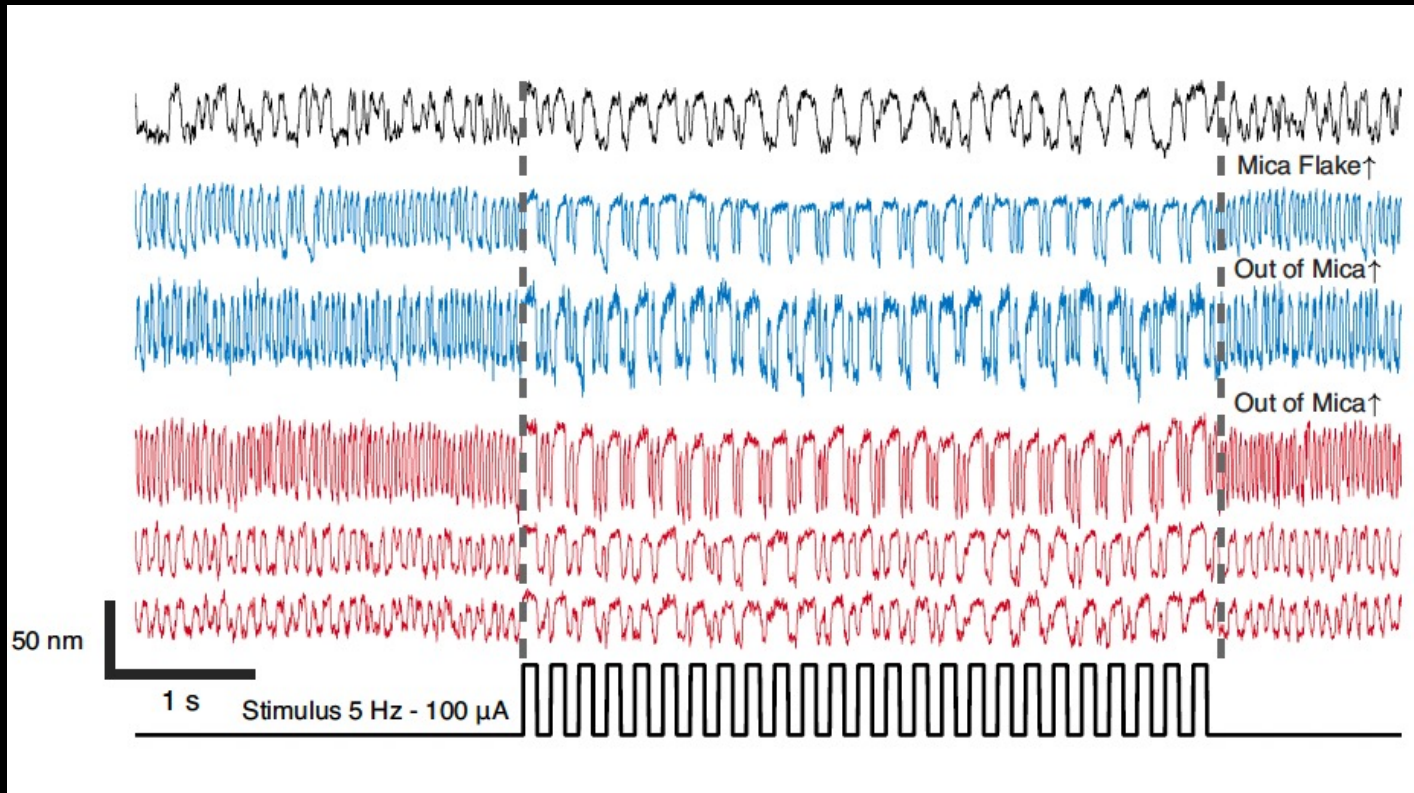
Partial synchronization can lead to high sensitivity.

Efferent control and the coupled system

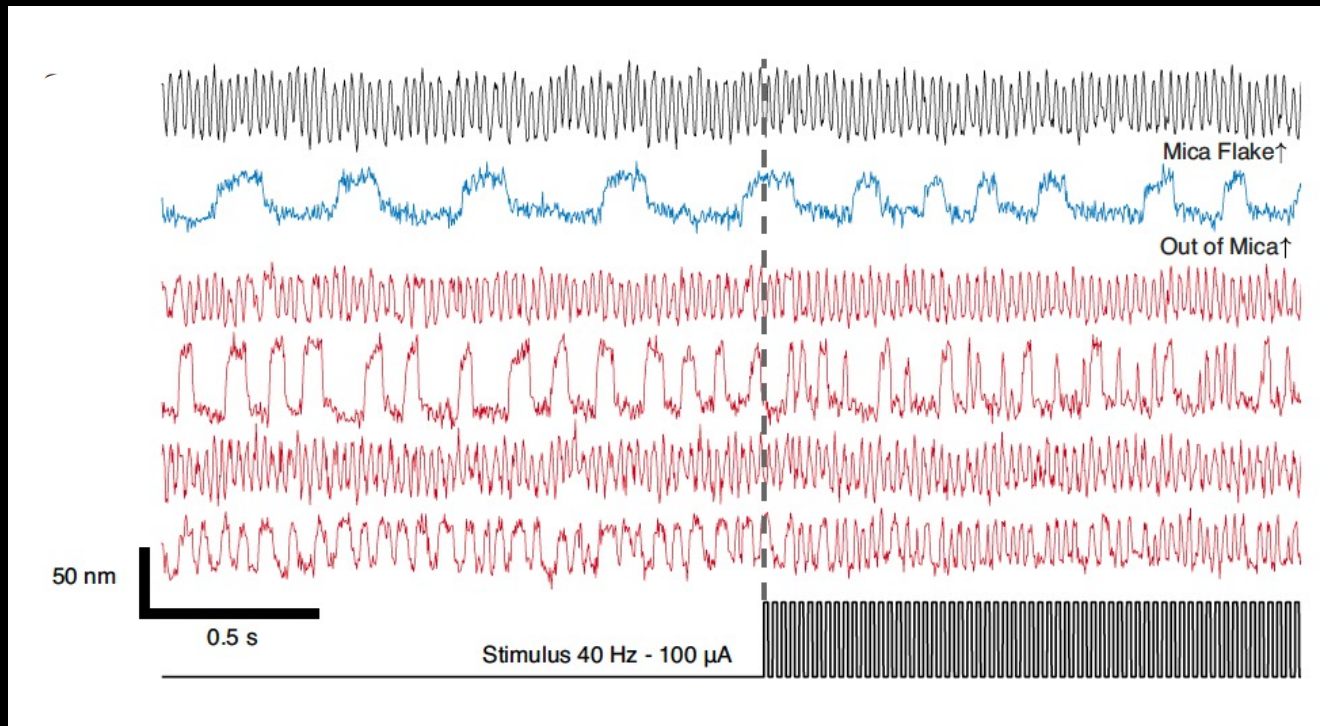
Experimental setup



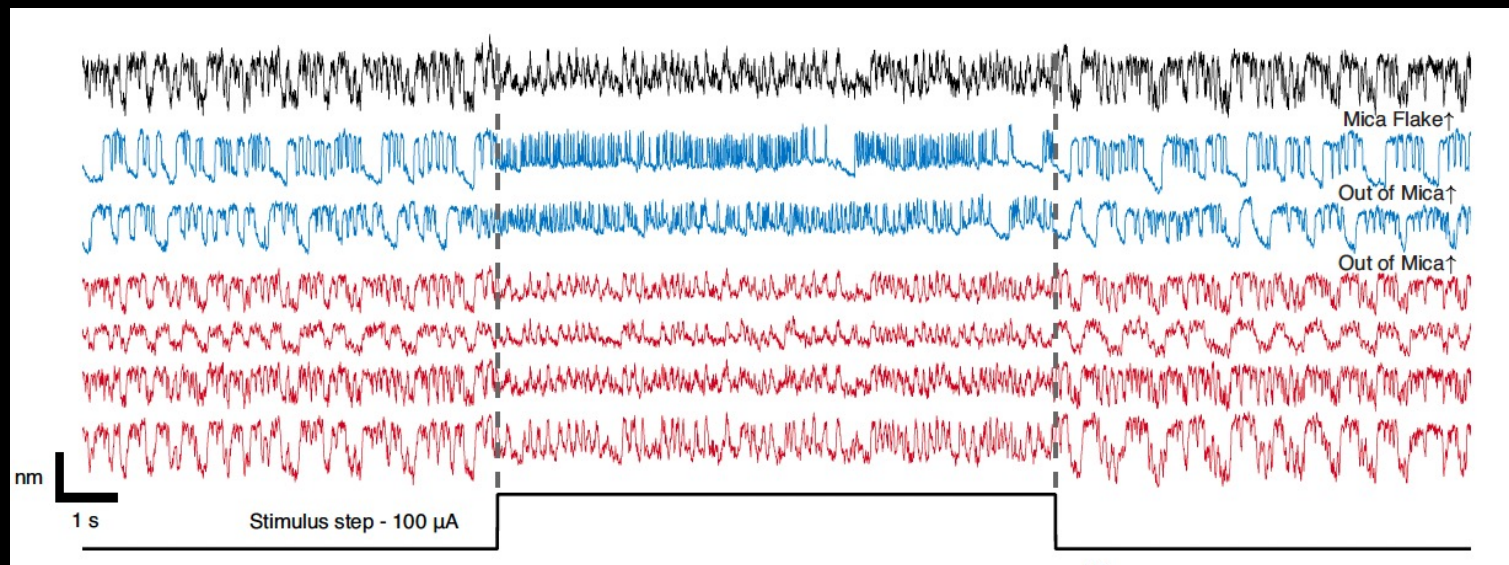
Efferent stimulus: pulsed train



Efferent stimulus: pulsed train at higher frequencies



Efferent stimulus: continuous step



Summary of observations

Activation of efferent neurons exerts a strong effect on hair bundle mechanics, both in individual bundles and in systems of coupled hair bundles.

Efferent stimulus applied at a fixed frequency entrains the hair bundle oscillations. Preliminary results indicate that the effect is more prominent in the coupled system.

Inter-cell coupling reduces the inhibitory effect of efferent stimulus, as evidenced by a reduction in the oscillation amplitude.

Future directions

Efferent effects on partial synchronization states

Sensitivity of the coupled system under efferent stimulus - comparison to individual cells

Extension to the amphibian papilla

Nonlinear dynamics model of the effect

Acknowledgements

Dr. Martin Toderi
Dr. Justin Faber

Joseph Marcinik
Dima Vaido
Gabriela Munoz
Charles Winslow-Metzner
Kate Holwick
Jacob McConley

Funding

Air Force Office of Research