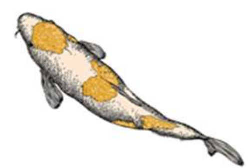
Sound and Signal: *How Fishes Hear and Communicate Through Sound*



Joseph A. Sisneros
Professor of Psychology (Animal Behavior / Neural Systems & Behavior)
University of Washington
www. sisneroslab.org

Sisneros Lab
University of Washington

Our lab has been exploring the underwater world of fish hearing and bioacoustics since 2004 (21 years).

Our lab is interested in the ***fish auditory system*** and changes in hearing related to influences of ontogeny, reproductive state, and steroid hormones.

We are also interested in ***sound source localization*** and how fishes detect and locate underwater sound sources in both relatively simple and complex acoustic environments.

How did I become a “Fish Psychologist?”

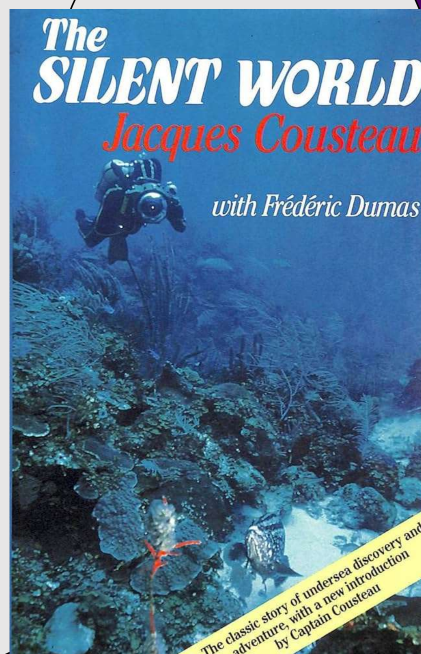
Early Influences

When I grow up, I want to be a marine biologist just like Jacques Cousteau!!

"The Undersea World of Jacques Cousteau“ (1966-1976)

How did I become a "Fish Psychologist?"

Early Influences



Cousteau's "Silent World"(1956)

BS Marine Biology (1988)
MS Biology (1993)

The underwater environment is not "silent" after all

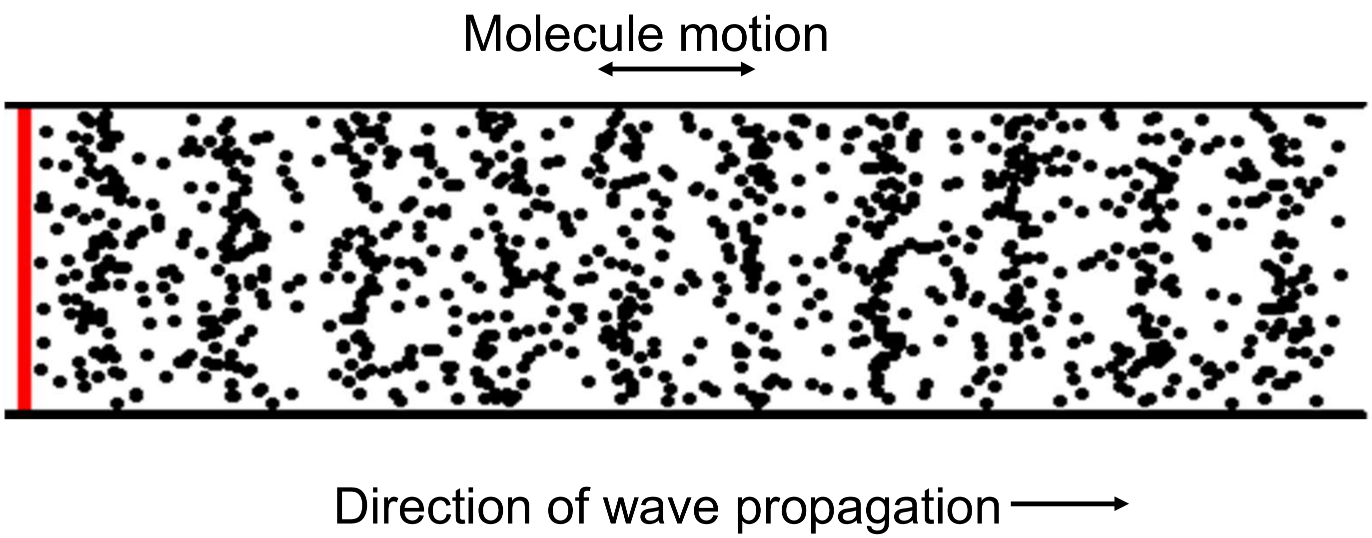
Sound in the aquatic environment can provide biologically relevant information for animals including fishes.

The ability of animals to ***hear and localize sound sources*** is a fundamental sensory function that supports many essential behaviors:

- ability to detect and track prey
- avoid predators
- navigate complex environments
- ***engage in social communication***
- ***locate potential mates***

What Is Sound??

Sound *is a mechanical disturbance that propagates as a longitudinal wave in air and water.*

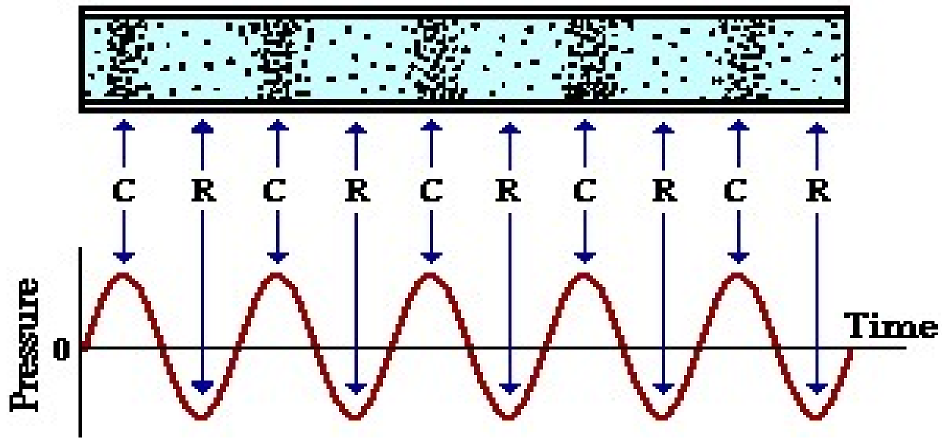


Acoustic Cues Available to Fish

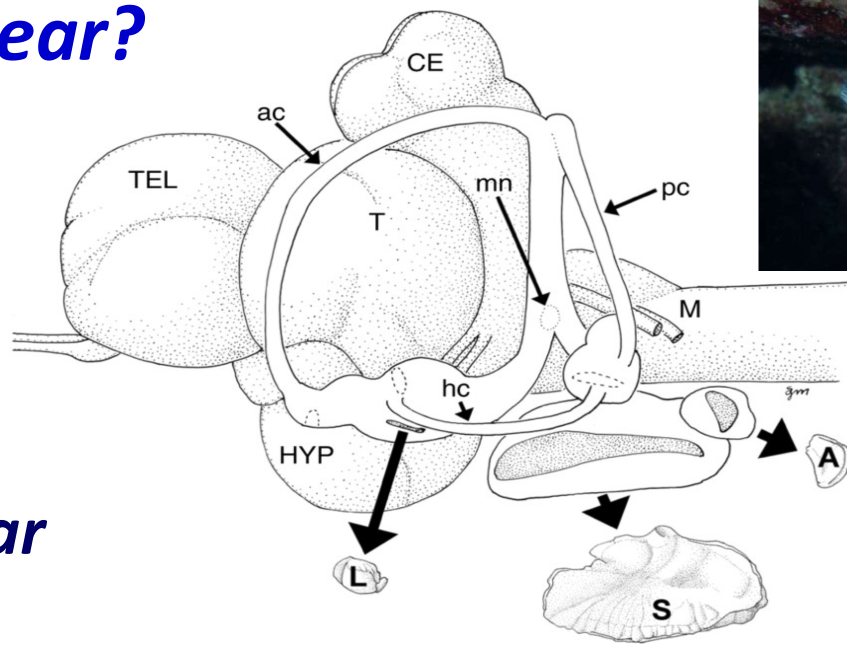
Sound can be described in terms of both ***pressure*** & ***particle motion***

Pressure = *fluctuation of the force per unit area* (pressure) above and below the ambient level.

Particle motion = *the movement of fluid particles* caused by the fluctuating forces of pressure.



How Do Fish Hear?



Maruska & Tricas 2009

Hawaiian sergeant fish
(*Abudefduf abdominalis)*

The Fish Inner Ear

consists of:

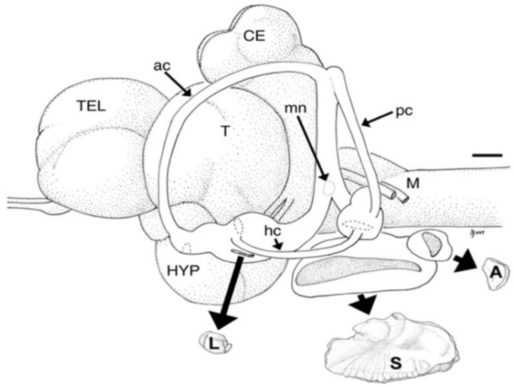
- **three semicircular canals** (ant., pos. & hor.)
- **utricle** * (otolithic end organ)

major vestibular parts of the ear

- **saccule** * (otolithic end organ)
- **lagena** (otolithic end organ)

major auditory parts of the ear

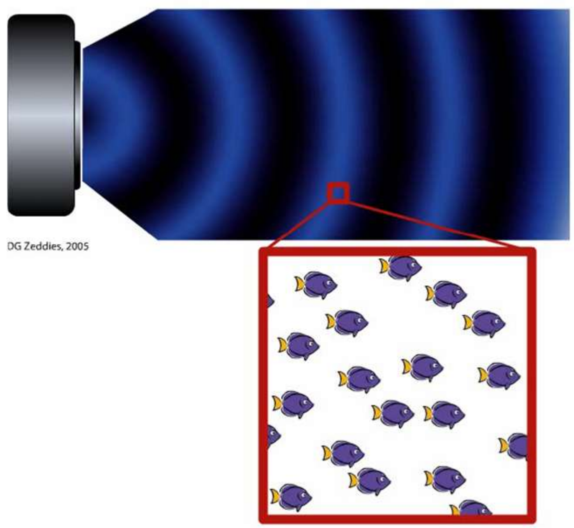
How Do Fish Hear?

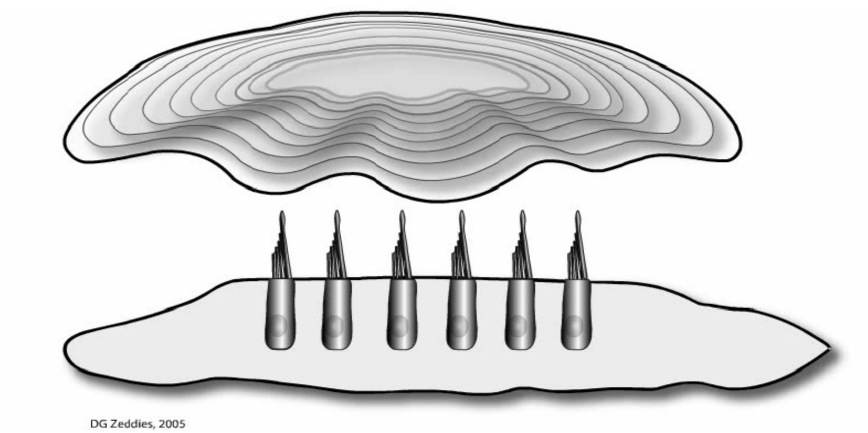


Two Modes of Fish Hearing

1) ***Inertial mode*** – otolith end organs are use to directly detect particle motion

Ancestral mode of hearing





Two Modes of Fish Hearing

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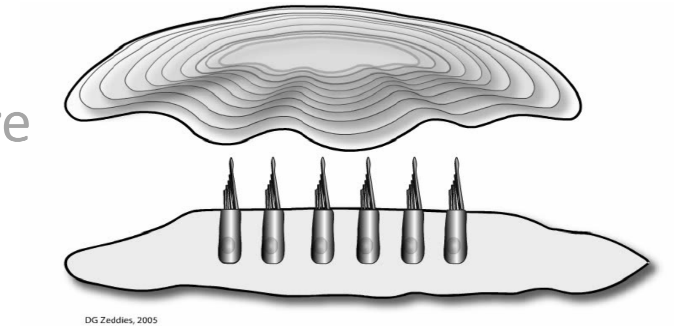
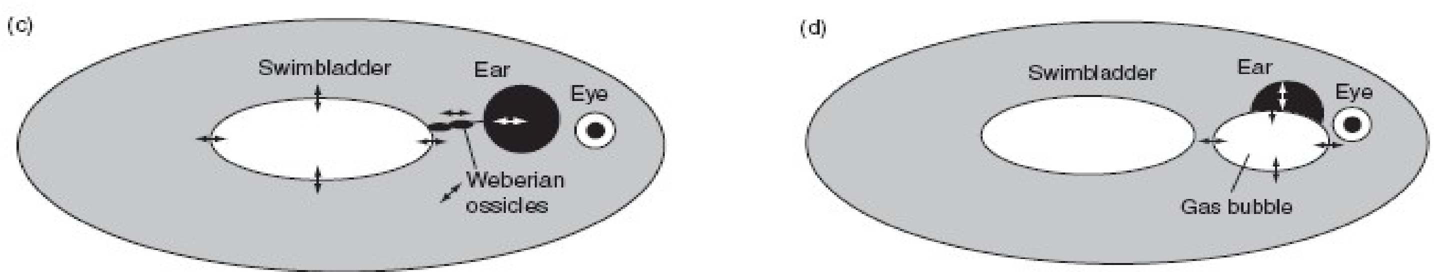


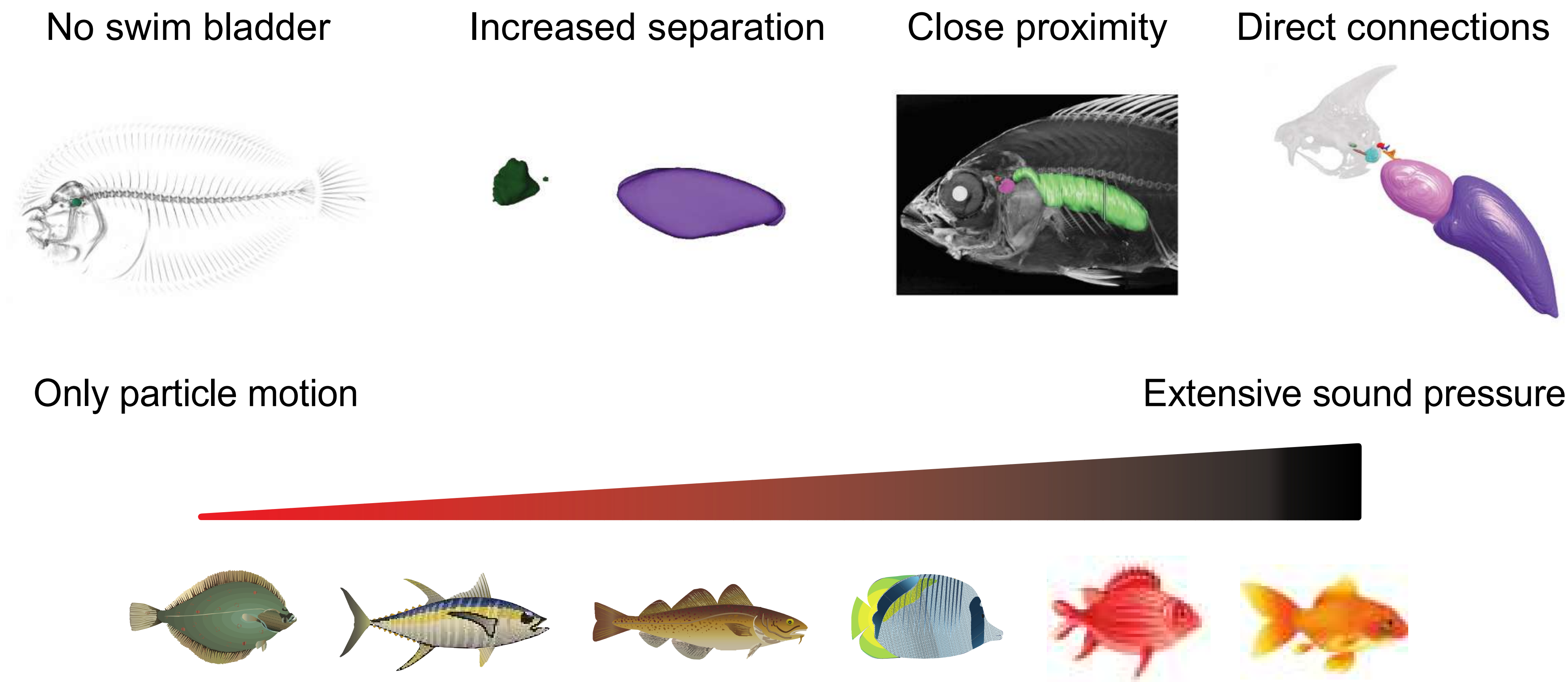
2) ***Pressure mode*** – otolith end organs are used to indirectly detect sound pressure via the particle motion created by the pressure fluctuations of a gas-filled organs.



Popper 2011

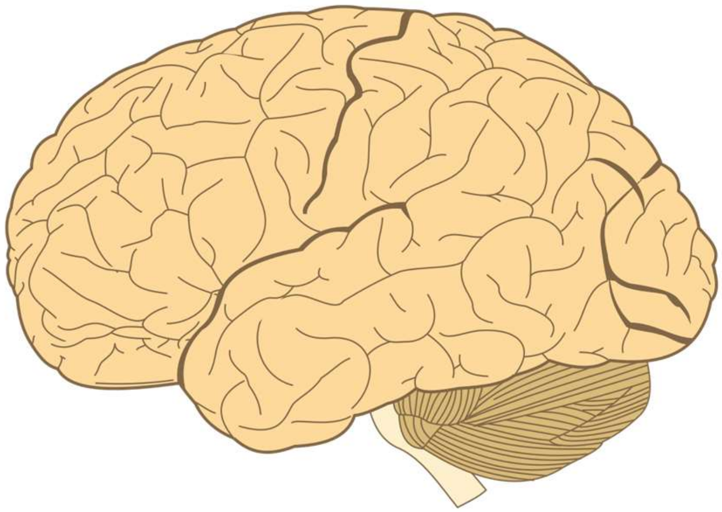
More recently derived

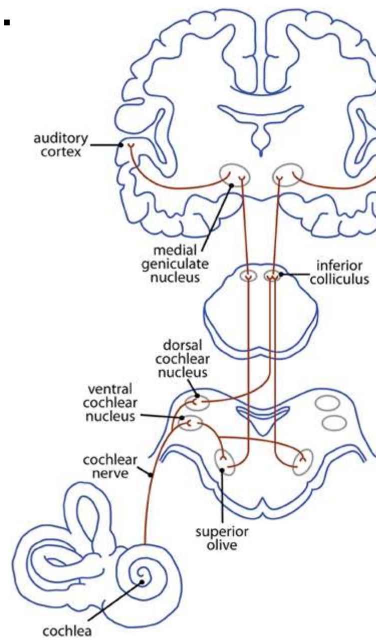
The Pressure Mode of Hearing is variable across fishes



Why Study the Auditory System?

A central goal in auditory neuroscience is to *identify how the vertebrate auditory system encodes social vocalizations* and …



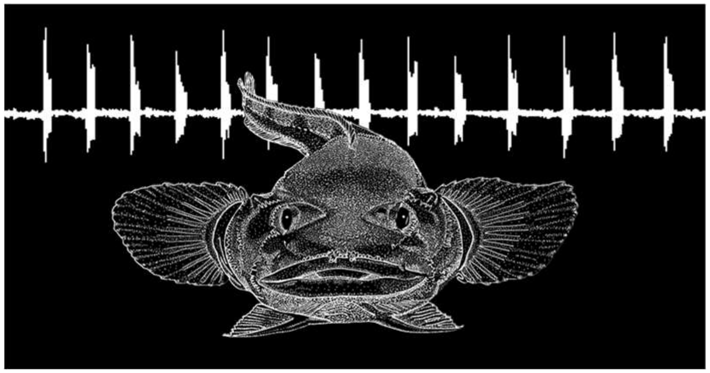


..to ultimately *understand how the human brain recognizes and interprets an enormous repertoire of vocal signals*.

Why Fish as Model Systems for Studying Audition?

Sound communication is not unique to humans, but rather it is a shared trait with most non-mammalian vertebrates including teleost (bony) fish.

Why Study Fish???



- *vocal species have a simple repertoire of acoustic communication signals*

- *they have auditory and vocal pathways organized like those of mammals*

- *they represent the simplest examples of how a vertebrate auditory system detects and identifies vocal communication signals.*

The ***Plainfin Midshipman fish*** as a model system for studying hearing and acoustic communication

Why Use the *Plainfin Midshipman* Fish as a Model System??

Krogh's Principle:

"***For a large number of problems (in biology) there will be some animal of choice, or a few, on which it can be most conveniently studied***."

August Krogh, The Progress of Physiology, The American Journal of Physiology, 1929. 90(2) pp. 243-251

August Krogh, *Professor of Zoology at the University of Copenhagen* (founded the first laboratory of animal physiology - 1910)
Nobel Prize 1920.
Discovery of the mechanism of capillary regulation in skeletal muscle

Why Use the Plainfin Midshipman Fish as a Model System??

Krogh's Principle: "***For a large number of problems (in biology) there will be some animal of choice, or a few, on which it can be most conveniently studied***."

Three Good Reasons for Midshipman:

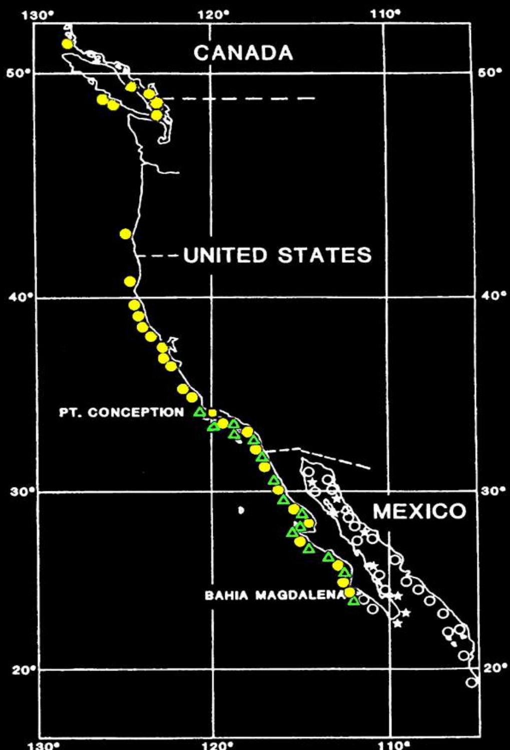
1) Very common & non-commercially important species of teleost fish

2) Adapted to the harsh environment (hypoxic conditions) of the intertidal zone where they are found during the breeding season

3) Acoustic communication is ***essential*** to the reproductive success of this species.

Plainfin Midshipman Fish (*Porichthys notatus*)

Geographic Range:



name derived from the pattern of photophores

found in deep water (50-300 m) most of the year, except during breeding season

Photos by M.A. Marchaterre

Plainfin Midshipman Fish (*Porichthys notatus*)

name derived from the pattern of photophores

found in deep water (50-300 m) most of the year, except during breeding season

Photos by M.A. Marchaterre

DURING LATE SPRING & SUMMER MIDSHIPMAN MIGRATE FROM OFFSHORE INTO THE ROCKY INTERTIDAL ZONE

Terry King

A.P.H. Bose

P.M. Forlano

Three Sexual Phenotypes: *Females and type I & II males*

Type I Males build nests in the intertidal zone under rocks

A.P.H. Bose

M.A. Marchaterre

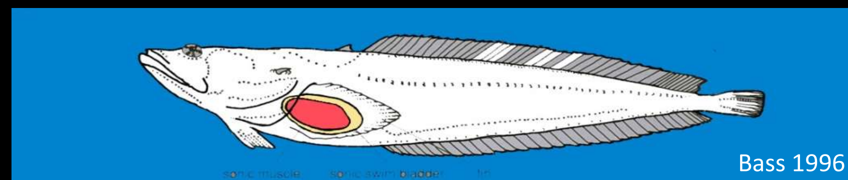
J.A. Sisneros

Type I males provide all the care of the eggs & larvae

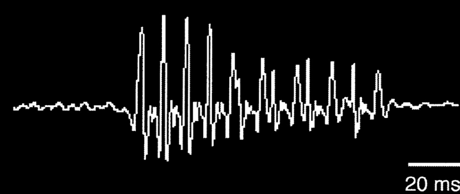
Photos by M.A. Marchaterre

Midshipman are Vocal Fish

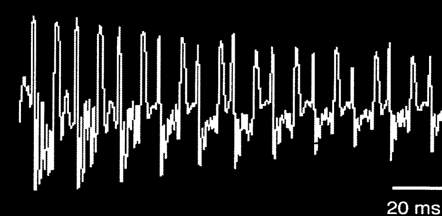
Midshipman generate acoustic signals for intraspecific communication during social and reproductive behaviors.



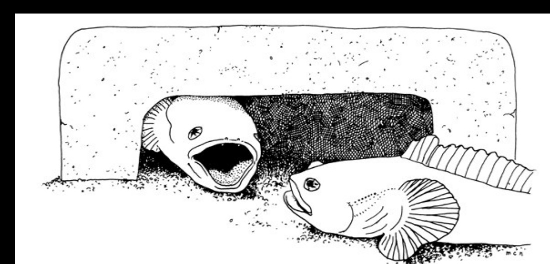
Grunt
(Agonistic)



Growl
(Agonistic)



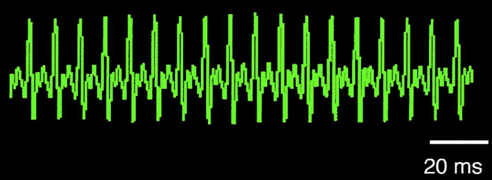
A.P.H. Bose

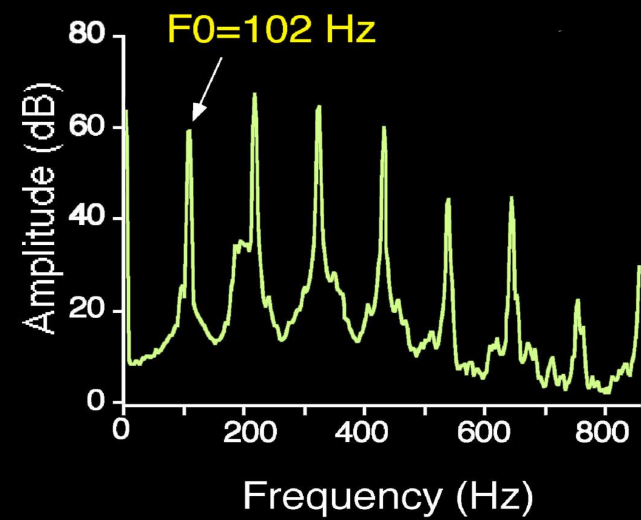


Bass 1996

“California Singing Fish”

Hum
(Mate Call)



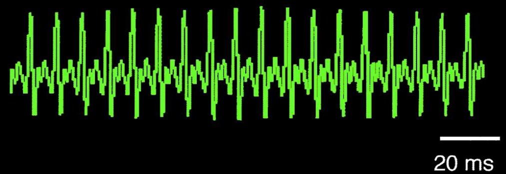


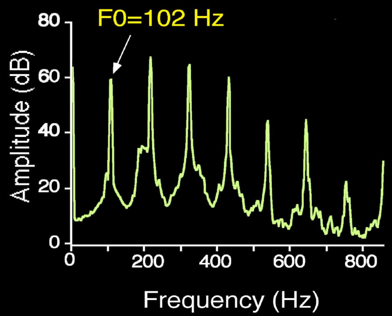
Video courtesy of A. Bass

Sound is very important: life history revolves around producing & detecting sound!

Why use the Plainfin Midshipman for Sound Source Localization Experiments?

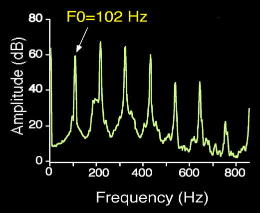
Gravid females exhibit phonotaxis to the playback of simulated male advertisement calls.





Pure tone similar to the call's ***F_0*** *is sufficient to evoke strong phonotaxis*

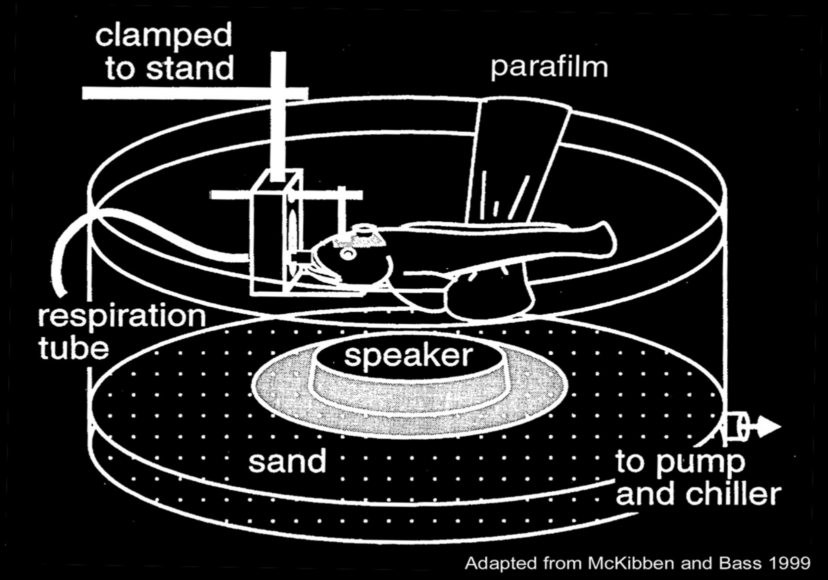
Female phonotaxic response to advertisement call



Best known example of sound source localization by fishes

Video courtesy of A. Bass

How is frequency encoded by the inner ear???



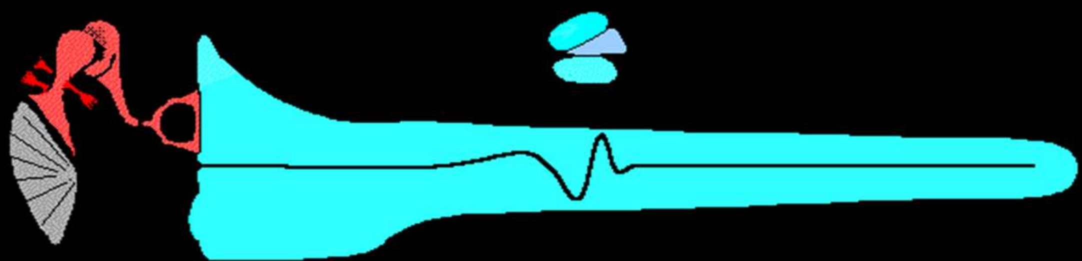
Extracellular single unit discharges were recorded from auditory saccular afferent neurons with glass microelectrodes using standard electrophysiological techniques.

Auditory stimuli: single tones (60-400 Hz) at an intensity of 130 dB (re: 1 μPa).

How is Frequency Coded by the Inner Ear??

1) Place Code

Basilar Membrane of the Cochlea



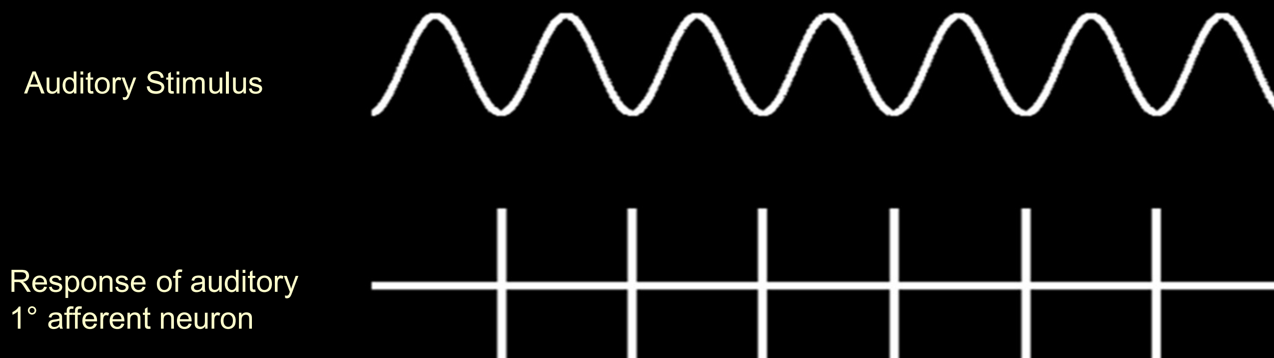
The basilar membrane vibrates in response to sound hitting the eardrum and *the frequency of the sound is encoded by the place on the basilar membrane that is maximally vibrated by the sound.*

2) Temporal Code

Q: How is Frequency Coded by the Inner Ear??

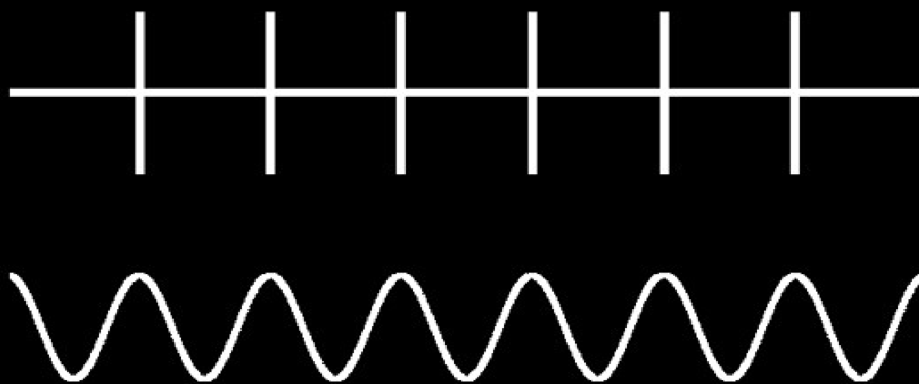
A: ***Temporal Code***

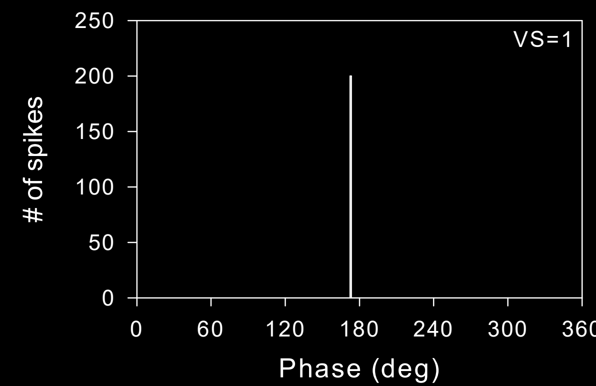
Neural activity was measured in terms of ***vector strength of synchronization*** *(VS)*



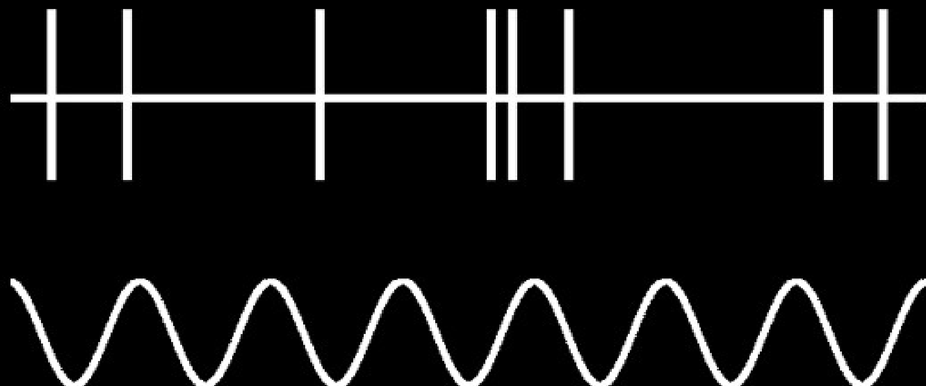
VS is the most accurate measure of frequency encoding among fishes, including midshipman (*Fay 1982, McKibben & Bass 1999*)

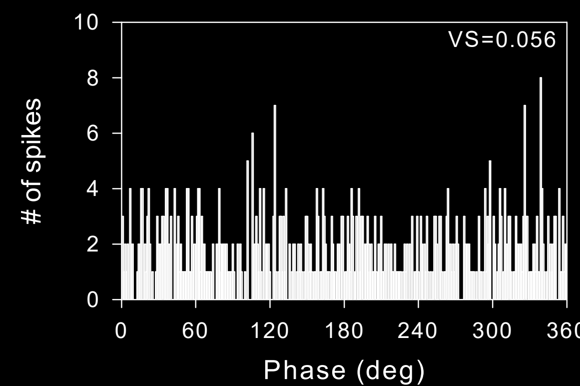
Strong phase locking, high VS





Weak phase locking, low VS

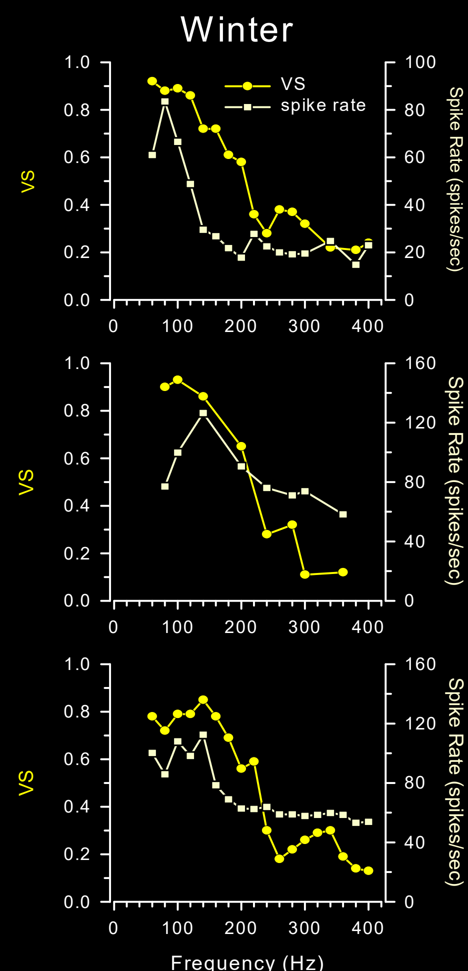


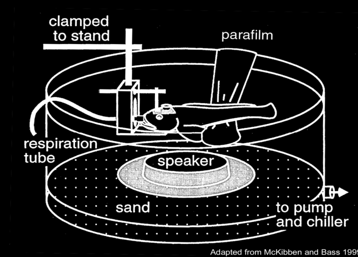


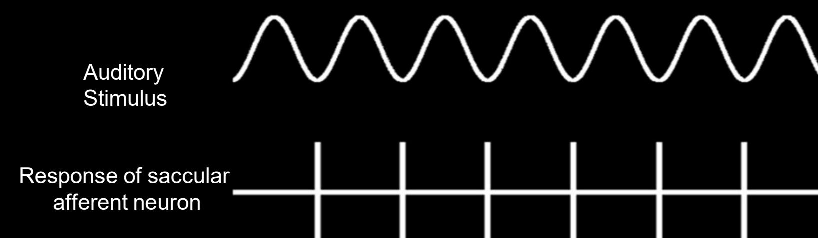
Frequency Response to Single Tone Stimuli (130 dB re: 1μPa)

Winter

non-gravid







Sisneros and Bass (2003)

Frequency Response to Single Tone Stimuli (130 dB re: 1μPa)

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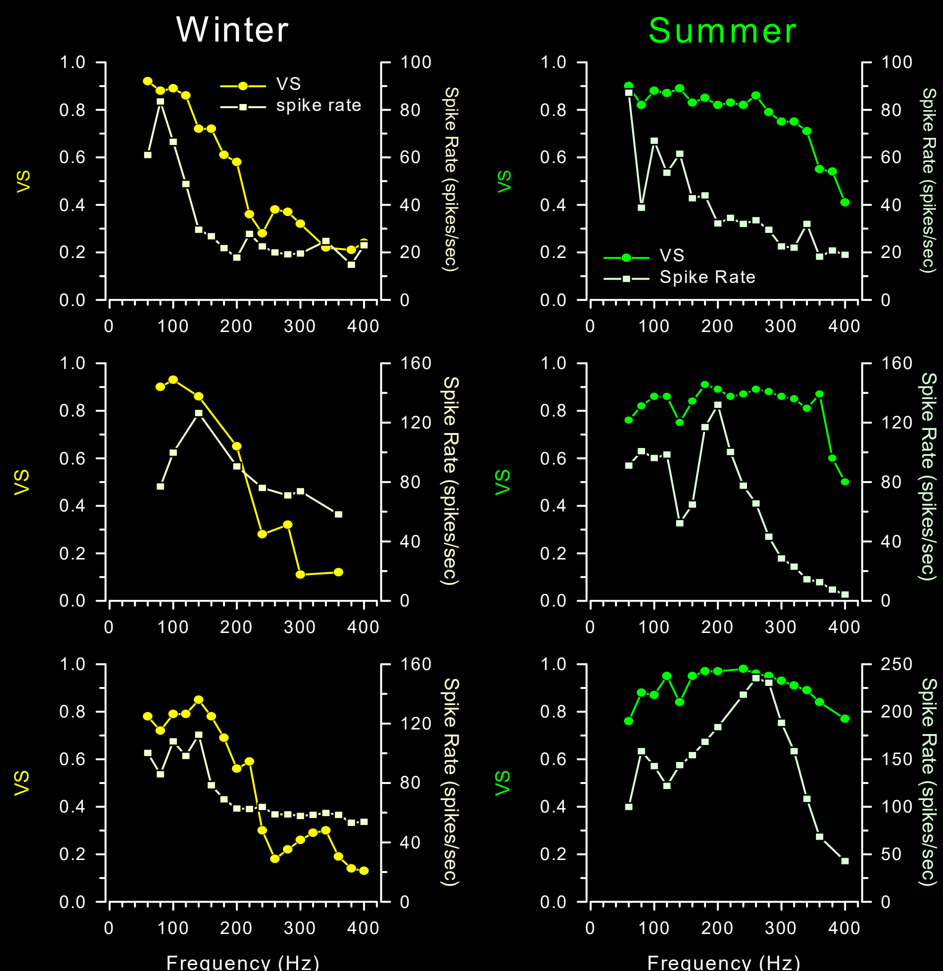
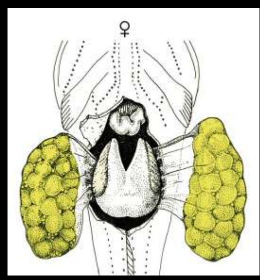


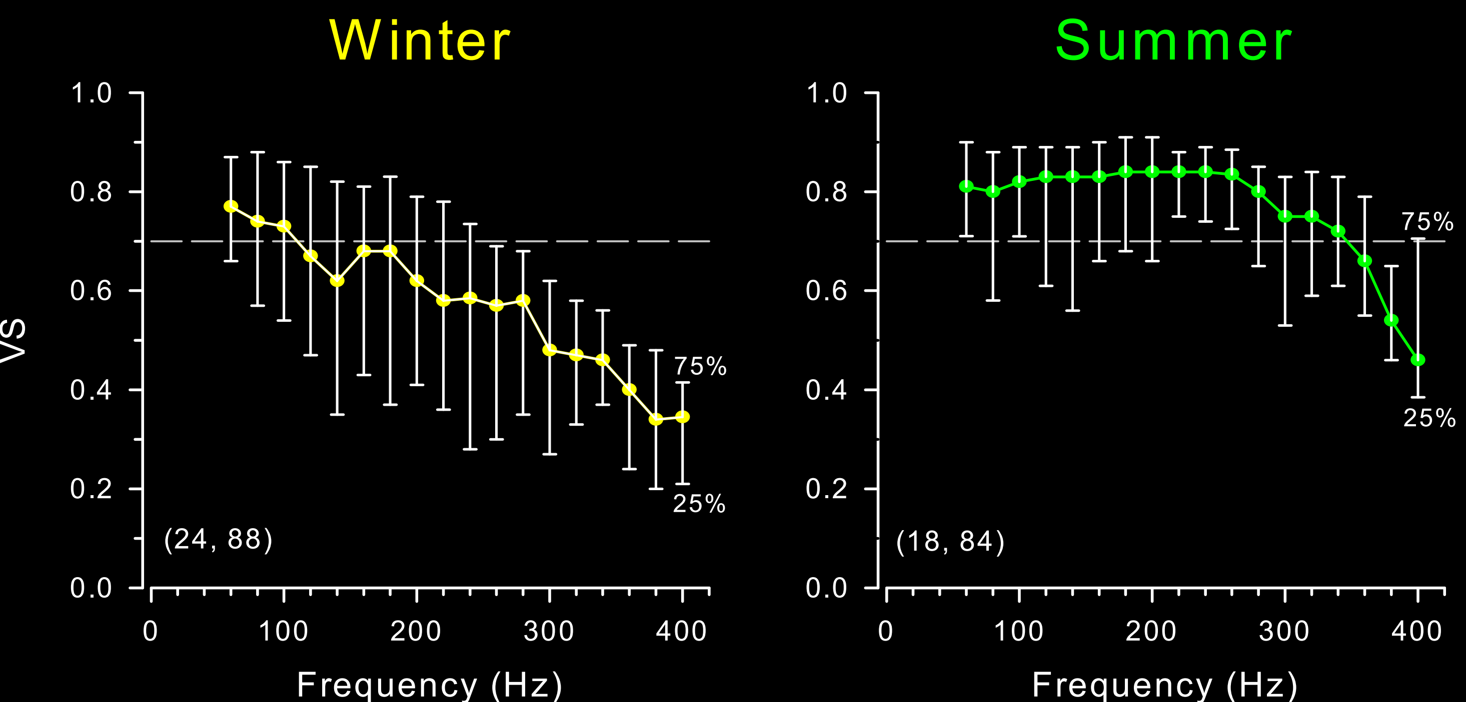
Summer



gravid

Sisneros and Bass (2003)

Auditory nerve: seasonal differences in frequency sensitivity

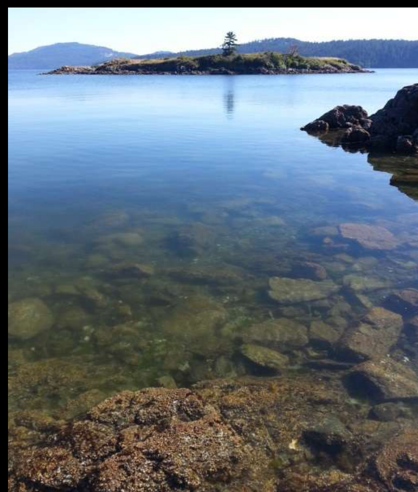


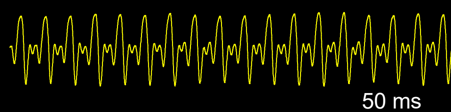
Sisneros and Bass (2003)

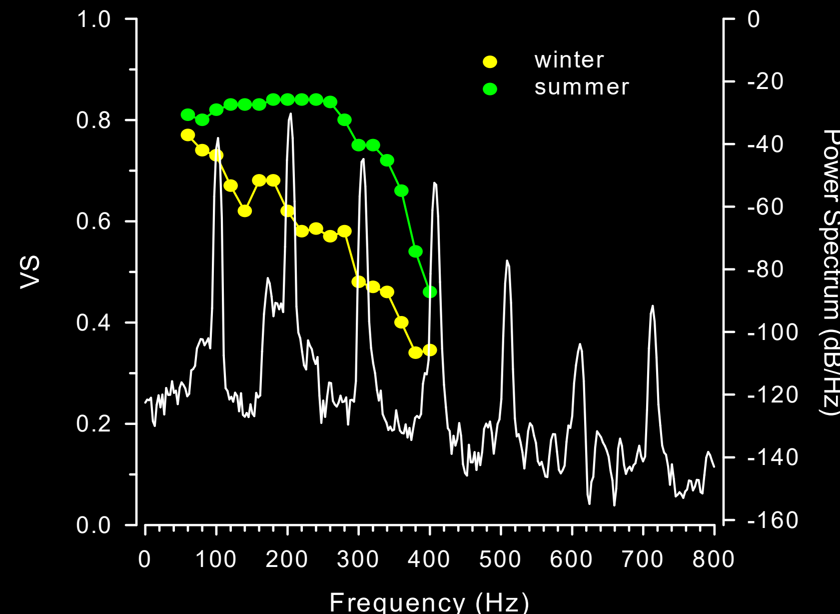
Summer females show robust temporal encoding (VS ≥ 0.70) up to 340 Hz, whereas winter females show comparable encoding only up to 100 Hz

What is the functional significance of this seasonal auditory plasticity???

Seasonal Plasticity May Function To Increase The Probability Of Mate Detection & Localization







Sisneros and Bass (2003)

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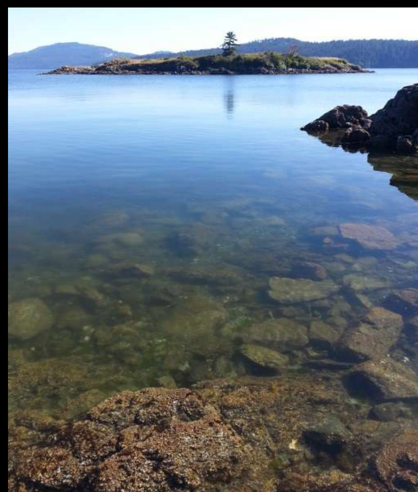
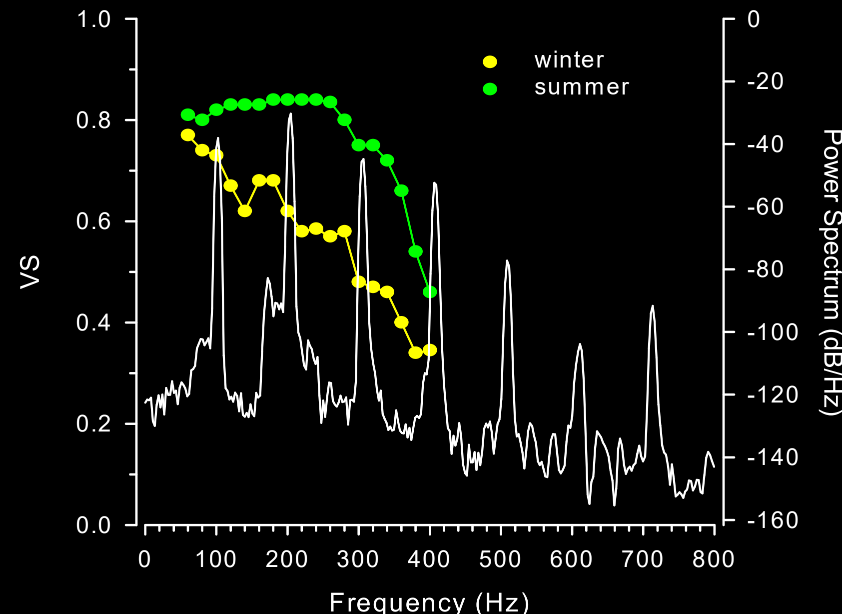


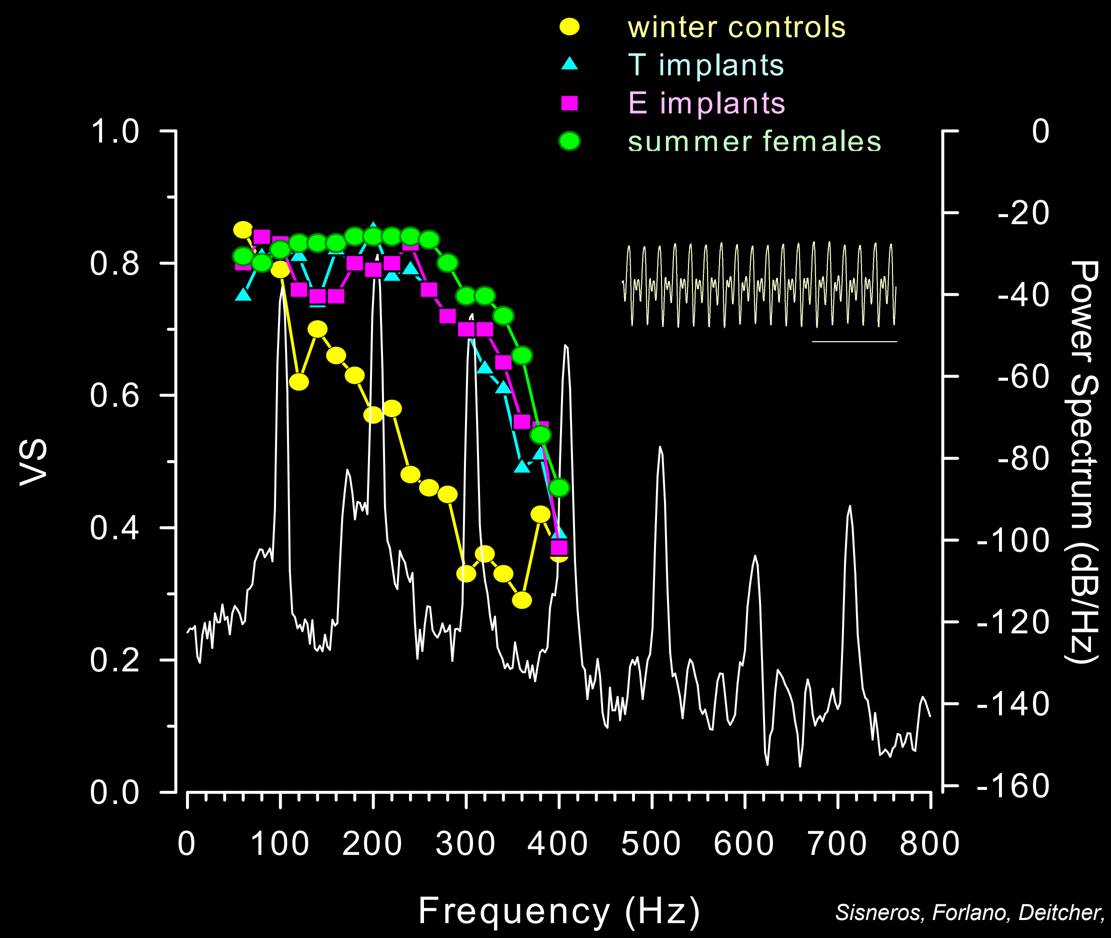


Sisneros and Bass (2003)

Reproductive females are better suited to detect the “hum” harmonics

Harmonics likely increase hum detection in shallow water

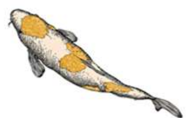
Adaptive Coupling of Sender and Receiver



Sisneros, Forlano, Deitcher, & Bass (2004)

Schuijf's Phase Model for Sound Localization by Fishes

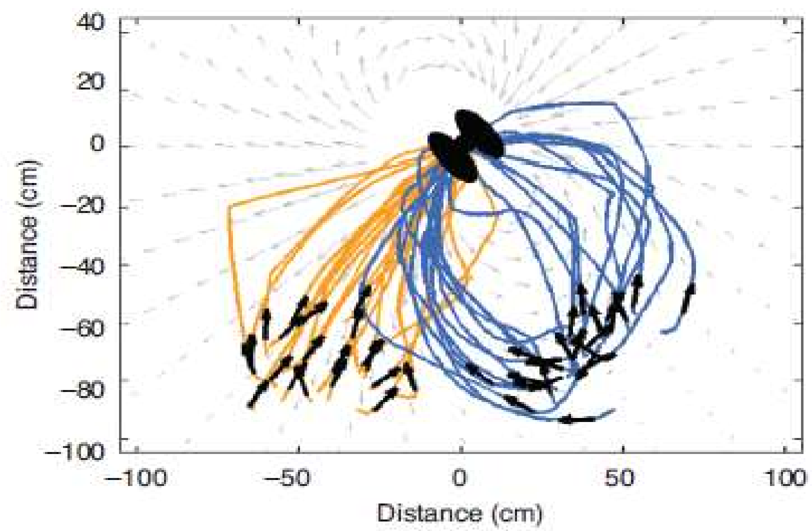
The dominant theory for fish sound localization *maintains that the detection and processing* of both **sound pressure** and **particle motion** are necessary for successful sound source localization.



What about the midshipman?

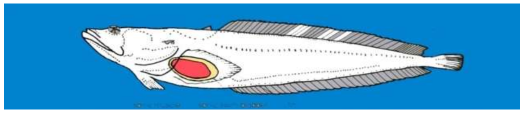
What acoustic cues are used for successful sound source localization?

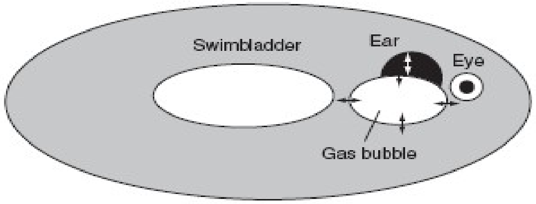
Previous dipole expts confirmed that midshipman use local acoustic particle motion cues to guide source localization behavior.



Zeddies, Fay, Gray, Alderks, Acob and Sisneros (2012) J Exp Biol 215:152-160

Expt: ***Is the swim bladder necessary for sound localization ?***

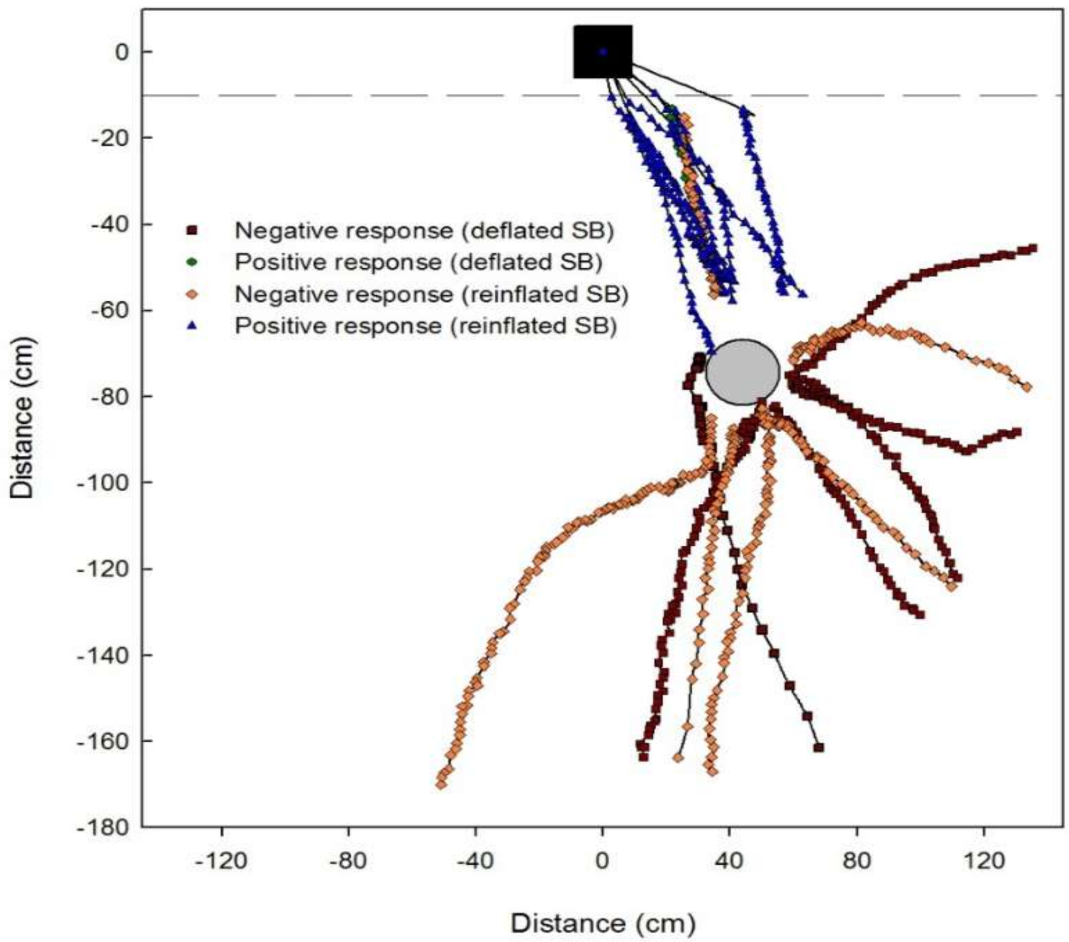




Is the pressure cue (in addition to particle motion) required to determine source direction?

In these expts, ***females underwent surgical deflation of the swim bladder.***

Swim bladder Deflation Experiments

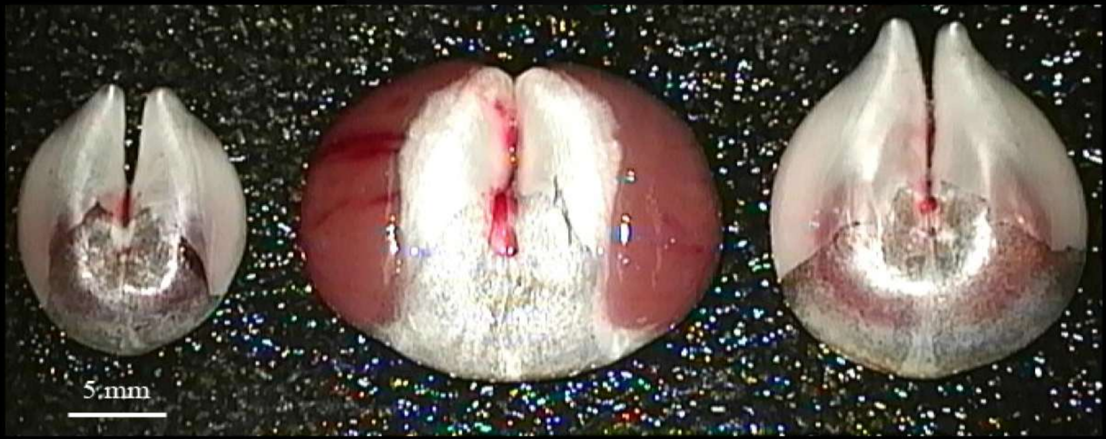


Results suggest that ***pressure reception*** *is likely required for sound source localization.*

Coffin, Zeddies, Fay, Brown, Alderks, Bhandiwad, Mohr, Gray, Rogers, & Sisneros (2014) JEB 217:2078-2088

Importance of Pressure Reception for Sound Localization

Swim Bladder Sexually Dimorphism



Type II Type I Female

WHOI Computerized Tomography (CT)

Darlene Ketten

Swim Bladder Sexually Dimorphism

Performed CT scans on Type I & II males and Females

Type II male Type I male Female

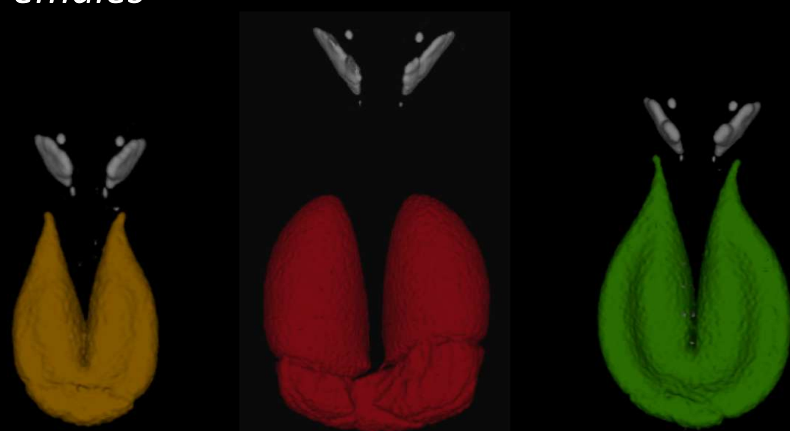
Females and type II males have anterior SB extension or 'horns'

WHOI Computerized Tomography (CT)

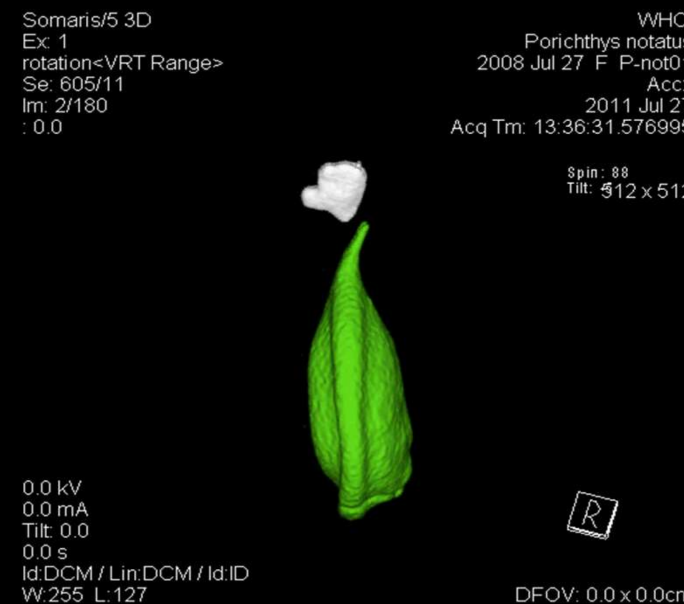
Darlene Ketten

Swim Bladder Sexually Dimorphism

Performed initial CT scans on Type I & II males and Females



Type II male Type I male Female



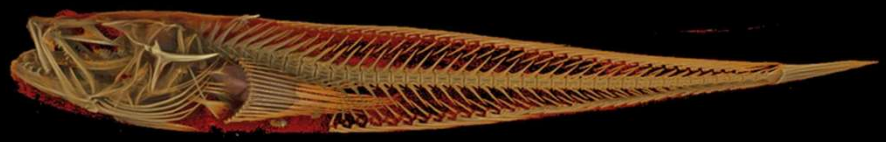
Females and type II males have anterior SB extension or 'horns'

MicroComputerized Tomography (CT)

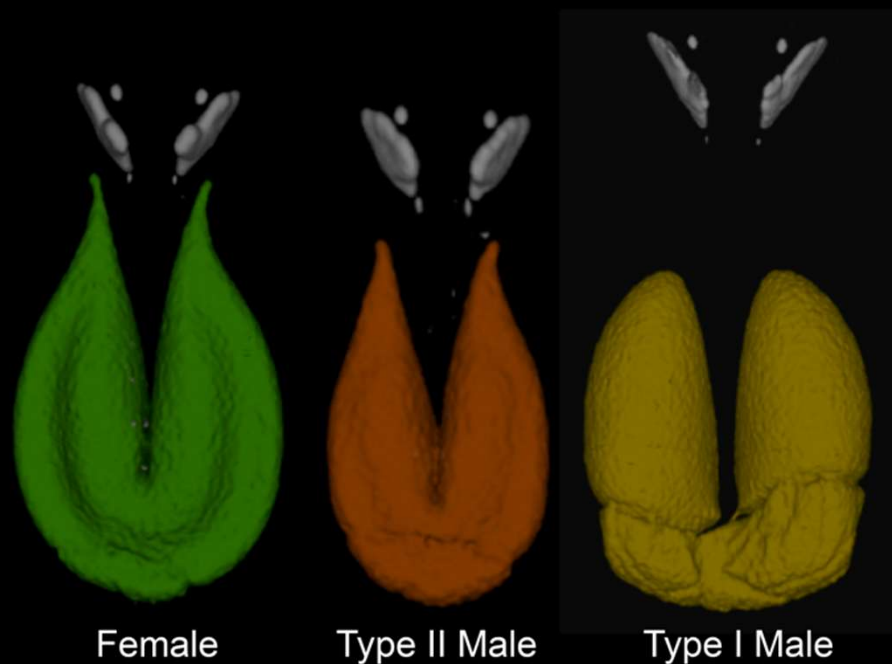
Swim Bladder Sexually Dimorphism

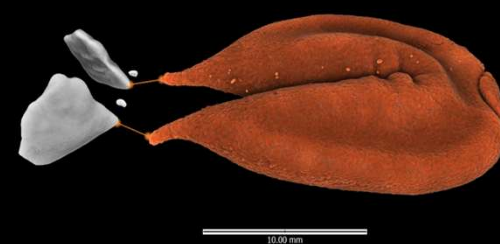
Tim Cox
Seattle Children's Hospital

Robert Mohr
UW Psychology

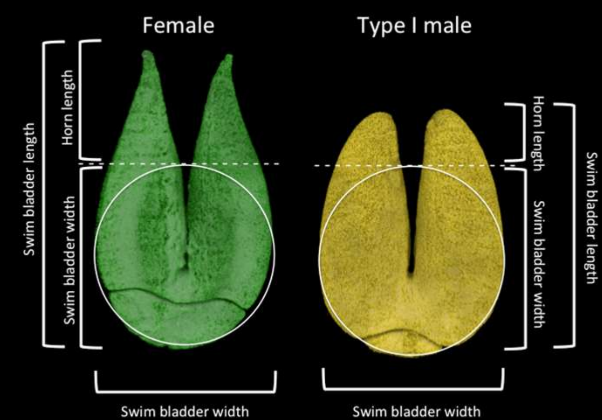


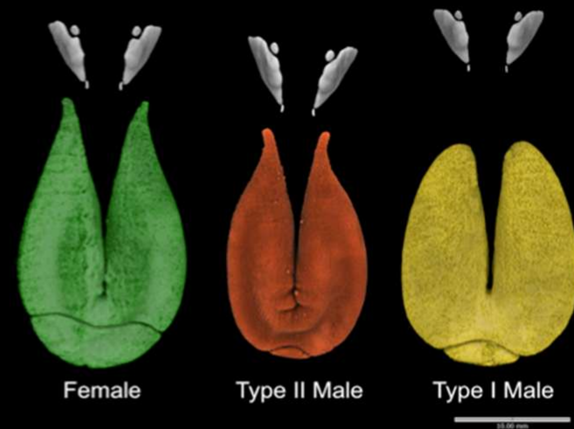
Females and Type II males have rostral SB extensions or 'horns' that project closer to the inner ear

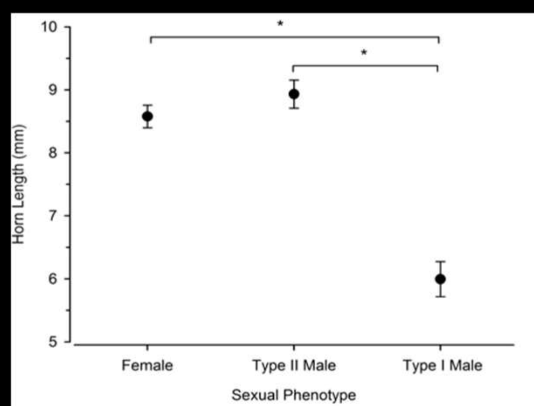




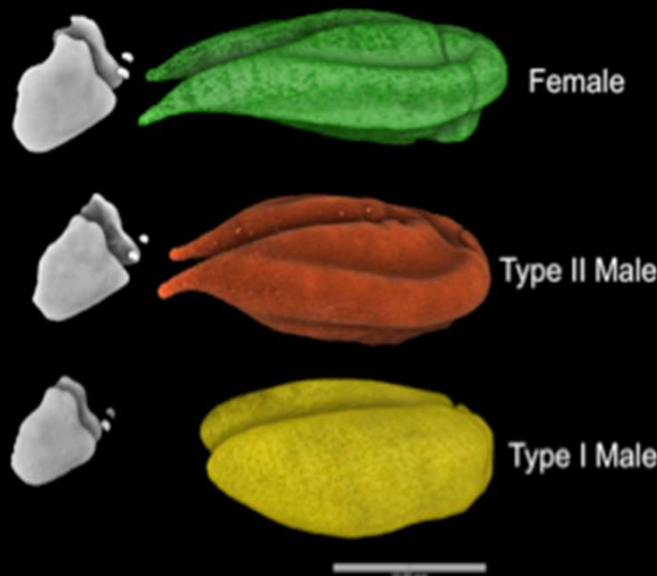
Females and *Type II* males have longer rostral SB extensions than *Type I males*

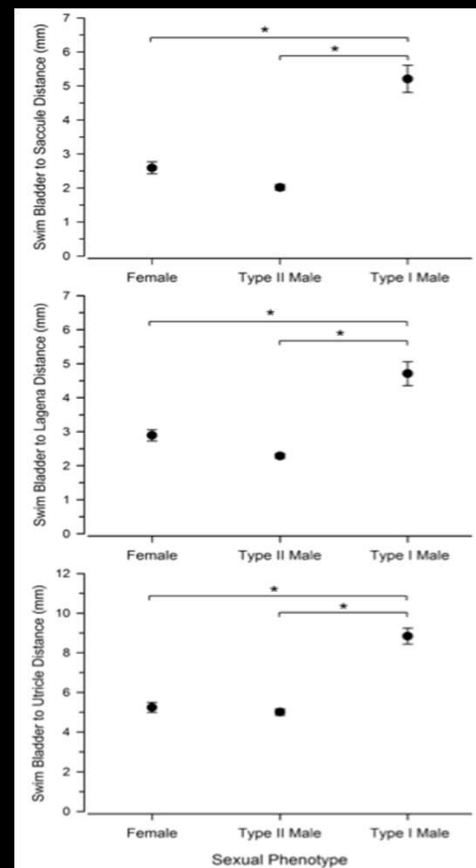






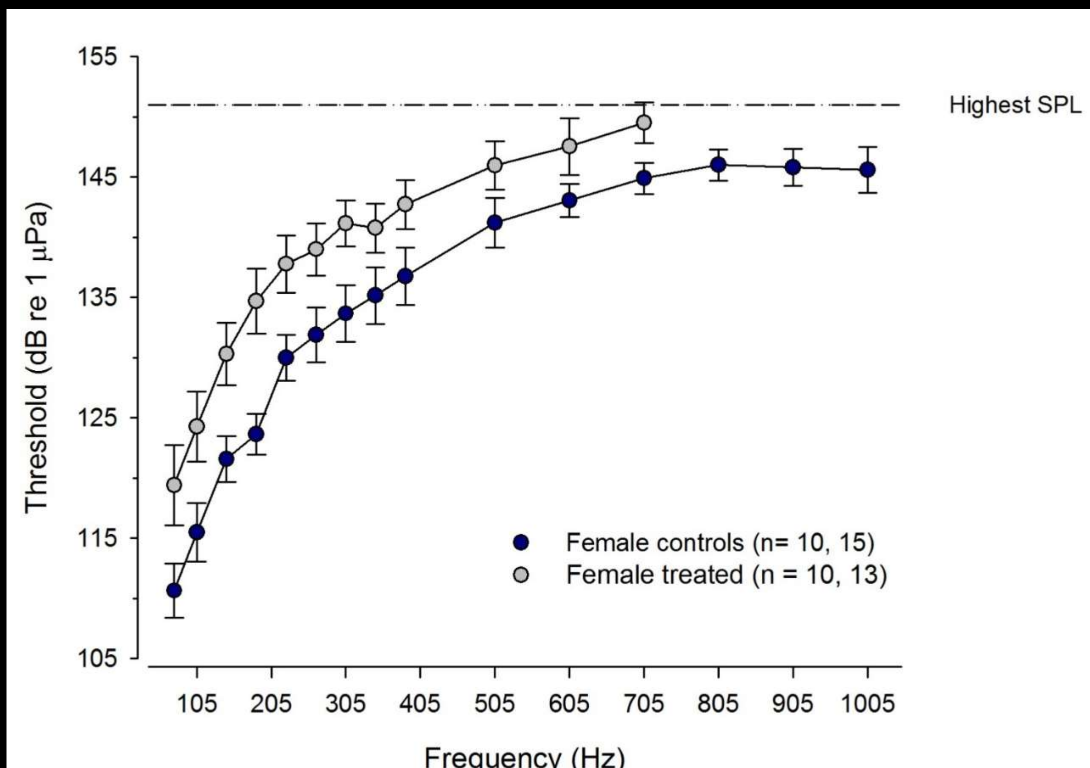
Females and Type II males have rostral SB extensions that extend closer to the saccule, lagena & utricle compared to Type I males

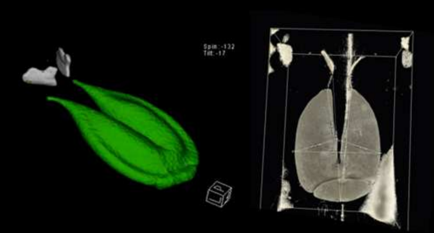


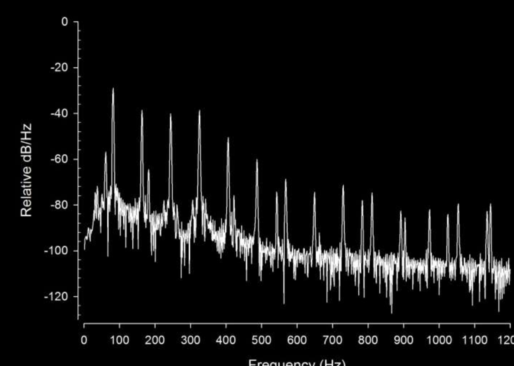


SB Increases Sound Pressure Sensitivity and the detection of higher freqs in social acoustic signals

Orphal Colleye







Summary and Conclusions:

- Fish auditory systems provide fundamental insights into vertebrate hearing and bioacoustics.

- The midshipman demonstrates how sound can be important for social and reproductive behaviors of fishes.

- Comparative models in fish can illuminate general auditory mechanisms relevant to mammals, including humans, and provide insights into mechanisms such as seasonal and hormone-dependent auditory plasticity and the evolution of spatial hearing in vertebrates.

Thank You! DOSITS

Sisneros Lab
University of Washington

Lab Members:
Loranzie Rogers
Sujay Balebail
Sofia Gray
Aoi Hunsaker

Collaborators:
Dick Fay
Paul Forlano
Peter Rogers
Jim Martin
David Zeddies
Michael Gray
Art Popper

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