How the ear really works?

A summary of Jim Fulton's work

By Dr. Rodney Staples

Current Understanding — The ear

- For over 70 years, we have come to understand something of how the ear works. Unfortunately, much of what we "know" may be wrong
- This presentation explores the work of Jim Fulton, and how this work illuminates the function of the inner ear and neural processing.

James Fulton – Wikipedia Entry

- **James T. Fulton** (born December 6, 1935) is a neuroscience researcher who publishes much of his research on the Internet.
- Before his retirement from the industrial community in 1989, he was an executive with Hughes Aircraft Company holding the positions of Vice President of Hughes Optical Products, Inc. and Assistant Division Manager of the Microelectronics Division of the parent company in Carlsbad, California.

Who is Jim Fulton - Education

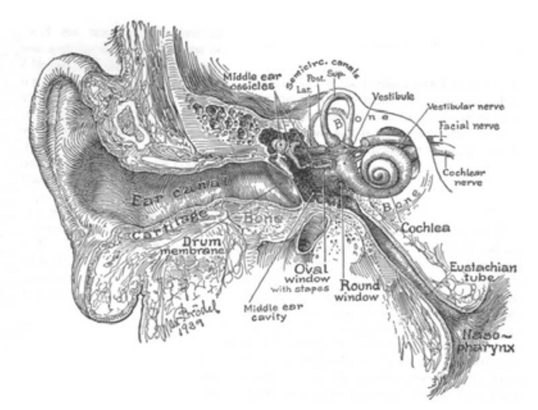
- MEE Rensselaer Polytechnic Institute (Radar/Communications)
- BEE Rensselaer Polytechnic Institute (TV and Servomechanisms)
- MBA Ohio State University (course work only)
- Patents in Bio-physics, Lasers, Optics, Cryogenics, Microcircuits & Large Astronomical Structures
- Self-published books on vision, audition and the neural system, available at: http://www .neuronresearch.net

Who is Jim Fulton - Résumé

- 1995- VISION CONCEPTS--Director of Research--Vision systems design, prototyping and verification services
- 1990-1995 Consultant to;
  - US State Dept. Agency for International Development
  - Russian Ministry of Research, Technology & Education
  - Soviet Academy of Science
  - PR China Bureau of Foreign Experts
- 1985-89 Hughes Aircraft Co. Asst. Division Manager--Microcircuit manufacturer
- 1983-85 Hughes Optical Products Co--Vice Pres. Eng.--Optics manufacturer
- 1979-85 Hughes Aircraft Co. Laboratory Manager--Optics design
- 1971-79 Grumman Aerospace Co. Program Manager--Imaging satellites
- 1967-71 CBS Laboratories, Inc. Laboratory manager--Vision & Imaging Tech.

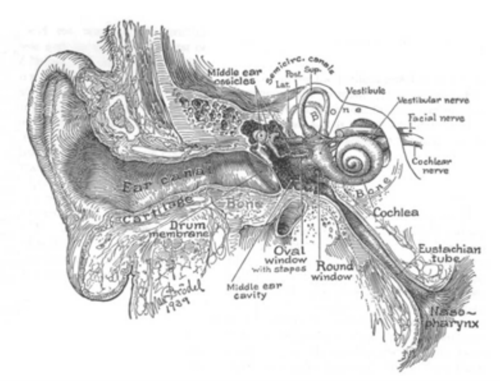
The ear physical structure

- The outer ear and the middle ear are well understood mechanical systems, amenable to physical intervention.
- The inner ear, centring on the cochlea, on the other hand, is something of a mystery.



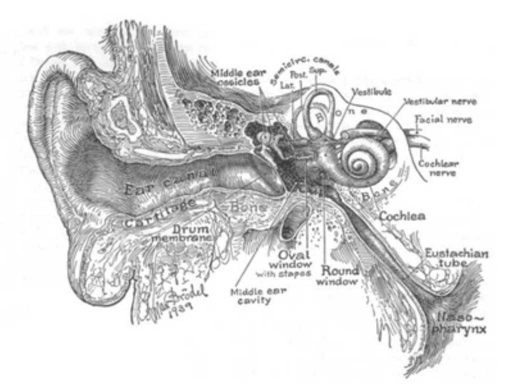
The ear physical structure

- In the outer ear, the pinae modify the characteristics of sound coming from different directions, so assist in providing directional localisation.
- The ear canal is essentially an acoustical transformer coupling the external sound pressure to the ear drum



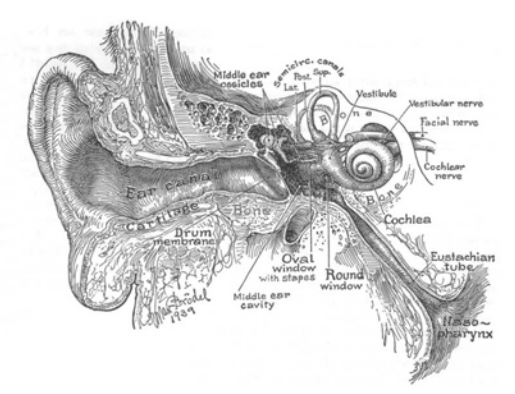
The ear physical structure

- The middle ear, between the ear drum and the round window of the cochlea, consists of a mechanical system with a small mechanical gain, connecting the two diaphragms and forming another impedance transformer
- Additionally, muscles connected to the ossicles can reduce transmission in the presence of sustained high sound levels – they are both a compressor and a protection mechanism

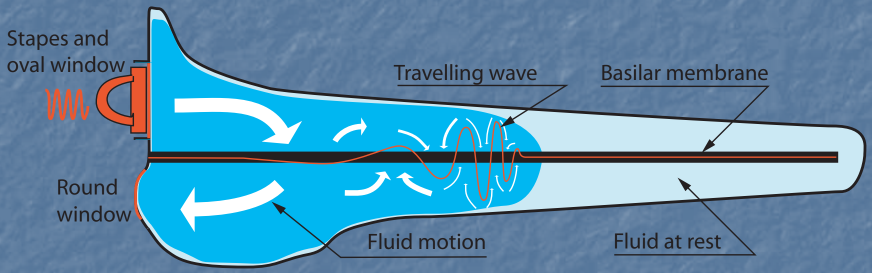


The ear physical structure

- The inner ear consists of the cochlea (a spiral shaped void in the bone) and the nerves connecting the transducers to the Cochlea Nerve
- The operation of the cochlea is the main subject of this presentation



Cochlea physical construction – Traditional View



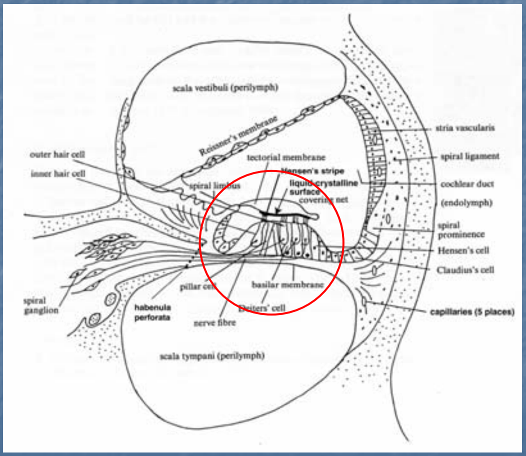
- The cochlea in the traditional (textbook) view, works by transmitting sound waves mechanically coupled via the oval window through the fluid in the space.
- The slow travelling wave in the fluid excites resonance in the basilar membrane at the critical frequency, whereupon the hair cells sense the motion and turn it into electrical impulses (no such slow travelling wave has ever been theoretically described)
- The selectivity is enhanced by an unexplained mechanical amplifier that sharpens the resonance produced at the hair cells.

Problems with traditional view

- The “dispersive longitudinal pressure wave in fluid” theory relies on approaching a discontinuity at the point of sensing a particular frequency. No such discontinuity has been found or explained.
- A “transverse pressure wave” applied differentially along the length of the basilar membrane as a function of frequency can not be satisfactorily modelled or explained.
- Transverse vibration of the Basilar Membrane alone is said to be used to excite the sensory neurons… The vibration is caused by a broadband signal in this theory, yet the response is said to be a resonance phenomenon at particular distances along the membrane.

Cochlea cross section

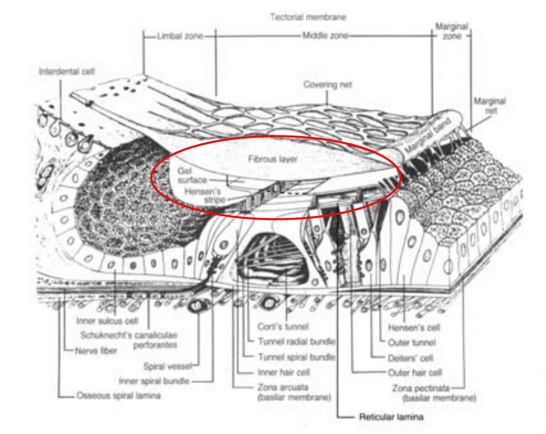
- In this cross section of the Cochlea, the basilar membrane is seen to be fixed at both edges, and is attached to a bony trapezoidal-shaped structure, called Corti’s Tunnel, increasing both transverse and longitudinal rigidity.



More problems

- The Basilar Membrane and the Organ of Corti near it are quite rigid structures at sound frequencies
- The propagation velocity of the acoustic wave in the fluids in the cochlea does not accord with the observed delays in sensing the sound
- There is no evidence supporting the concept of mechanical "resonance amplifiers" claimed to raise the "Q" of the resonance of the sensing mechanism.

Cochlea section detail



- The upper structure, the Tectorial Membrane is also quite rigid and not amenable to vibration of the surrounding fluid.
- Corti's Tunnel is also clearly shown as a rigid trapezoidal structure
- Both the inner and outer hair cells are mounted on the lower rigid structure, the Basilar Membrane, but are also touching the gel-like surface on the underside of the tectorial membrane of Henson's stripe and its associated gel layer, circled in red.

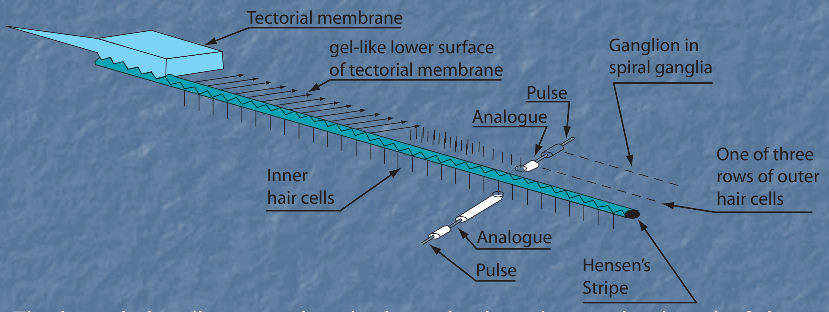
Sound Propagation

- The traditional view of sound in the cochlea propagating in the liquid (Newtonian fluid) is flawed
- Dispersion of sound in a Newtonian fluid is characterised by frequency dependent dispersion of the energy
- liquid crystals like the gel-like material on the underside of the tectorial membrane support retention of the broadband energy in a waveguide like structure (Henson's stripe) and a transverse wave on the surface between the gel and the fluid in the cochlea
- The waveguide is formed by the variable density at the boundary formed by the gel and the fluid surrounding it

The function of Henson's Stripe

- Henson's stripe is a strip of a gel-like (liquid-crystalline) substance on the underside of the Tectorial Membrane.
- Henson's stripe supports surface acoustic waves that are contained within the stripe by a waveguide action unless allowed to escape the waveguide because a "critical angle" of incidence against the variable density at the boundary is reached.
- Hair cells are in contact with Henson's Stripe and the attached gel
- The sound wave launched from the oval window into the fluid of the ear is coupled to Henson's stripe as a slowly travelling surface acoustic wave along the surface and in contact with the cillia (hairs) rigidly mounted on the basilar membrane

Schematic sensor array



- The inner hair cells respond to the intensity (envelope or loudness) of the applied sound
- The outer hair cells respond to the specific frequency at that point on the stripe due to the release of the sound energy from the curved waveguide as described by the waveguide models of Marcatili
- The cochlea model here is unwound, making in non-functional

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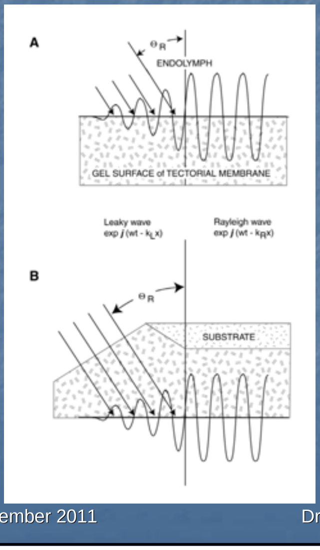
Propagation velocity

- The propagation velocity of the SAW in the liquid-crystal gel which carries the audio in Henson's Stripe is consistent with the observed delay in sensing the onset of a sound
- The velocity of sound in the fluid of the inner ear is around 1500 m/s, where the propagation velocity in the SAW of Henson's stripe is in the order of 6 m/s. The 6 m/s velocity accords well with the up to 10mS delay before awareness after the onset of a signal.

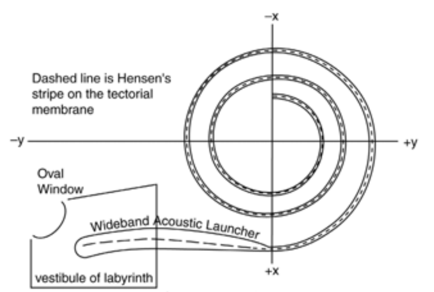
Launching a SAW



- There are typically two types of excitation of a SAW in materials
- “First surface” excitation, typical of waves excited by the wind, is where the excitation is in the first surface receiving the energy (a “capillary wave”)
- “Second surface” excitation, typically found in earthquakes, is where the excitation is normal to the launching surface, but causes the SAW in the opposite surface

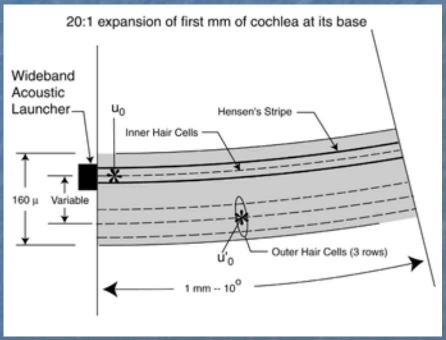
Launching the SAW

- Henson’s stripe on the tectorial membrane is about 2.5 turns of a helical logarithmic spiral
- The “tail” of the logarithmic helix constitutes a broadband acoustic-wave launcher
- The logarithmic helix forms a curved waveguide for the SAW
- The launcher is the tail accessing the vestibule of labrynth, receiving the rapidly moving sound energy from the oval window propagating through the Newtonian endolymph fluid



Curvature of a nominal cochlea

Critical Angle



- Henson's stripe is the waveguide containing the SAW
- When the frequency reaches the "critical angle", the wave is no longer constrained within the guide and is refracted at an angle to the guide to be absorbed by the outer hair cells (The theory of waveform escape from a curved transmission line is established by Marcatili in conjunction with WDM in optical fibres)
- This arrangement is a sharply selective "dispersive" filter, without the need for resonant elements or mechanical sharpening of the selectivity function

The curvature function

- The helix closely resembles a slightly modified mathematical form called a "Hankel Function"
- A Hankel function is described by two orthogonal Bessel functions
- The modification increases the curvature after about 720 degrees, impacting on the low frequency part of the spectrum

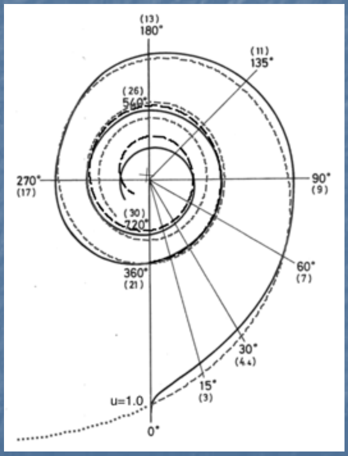
Hankel Function Formula

$$HS = 7.5 \bullet H_0^1(u) \bullet \left(1-\left(\frac{u}{22}\right)^4\right)$$

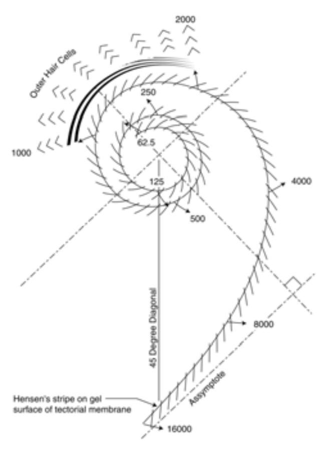
- *HS* is in mm from the centre of the helix
- *u* is the distance from the launcher at *u=1*
- H^1_0 is the Hankel function of the first kind of order zero
- The term $(1-(u/22)^4)$ is the modification to increase the curvature beyond 720 degrees to better match the observed helix in-vivo.

Observed vs. Expected

- The observed curvature (reflected into 2D) of a cochlea – solid line
- Simple Hankel function – light dotted line
- Modified Hankel function – heavy dotted line
- Cross is the centre of the helix



Critical Frequency



- The curved waveguide constrains the energy within the guide by total internal reflection up to a critical frequency which depends on the radius of curvature
- The critical frequency can be described by:
$$\alpha_\tau = c_1 \bullet \exp(-c_2 R / R_C(f))$$
- Where α_τ is the attenuation, R_C is the critical radius, and c_1 and c_2 are constants
- Mathematics of the waveguide properties are fully described by Marcatili in the context of optical fibre waveguides

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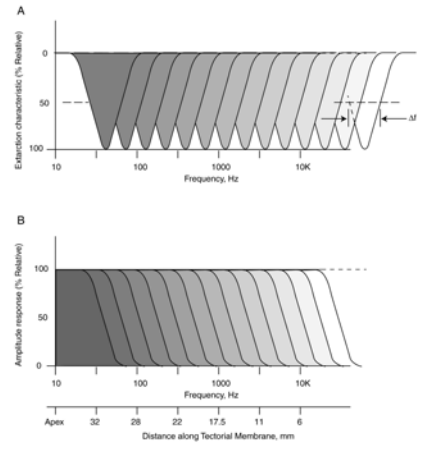
Resulting dispersive filter

- Image A shows conceptually the constant Q frequency selectivity of the outer hair cells
- Image B shows the frequency and energy density of the broadband energy in Henson's stripe (in the waveguide) as a function of distance from the launcher
- In practice, these curves are much sharper than is achievable with a resonant circuit, with very high Q and edge slope in the order of 180dB/decade – only achievable with a Marcatili filter : measured slopes as high as 1000dB/decade



Inner and Outer Hair Cell Function

- The inner hair cells (IHC), those in contact with Henson's stripe, are involved in evaluating the temporal properties of a broadband signal, low-pass filtered according to position along the cochlea
- The outer hair cells (OHC) evaluate the tonal qualities of the frequencies presented to them. They have no frequency selectivity inherently
- Frequency selectivity is achieved as the frequency reaches the critical angle and the SAW is released to those particular hair cells

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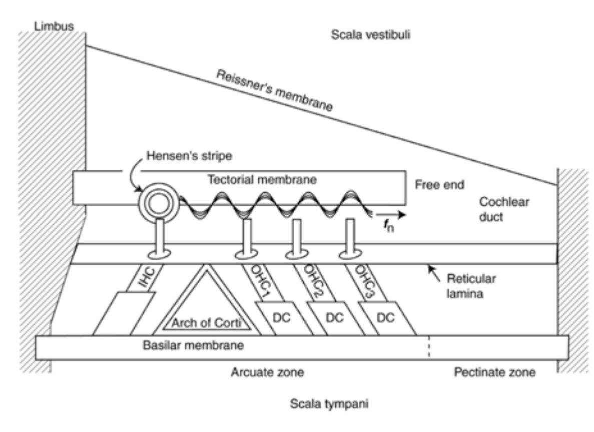
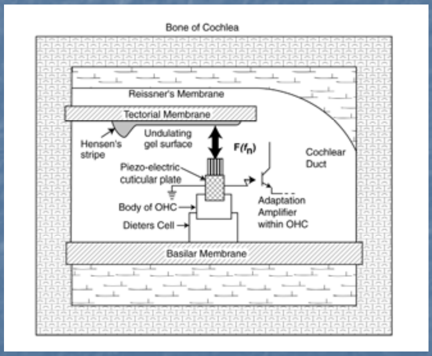
Simplified mechanical model of transducer

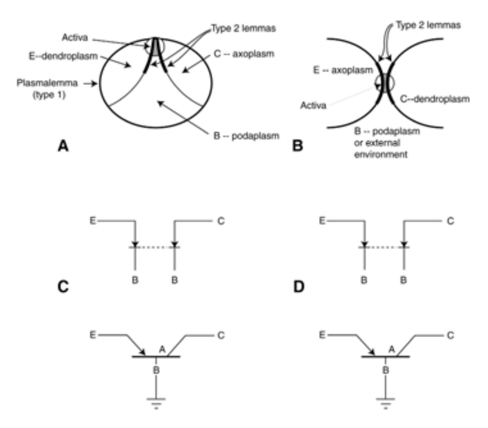


Mechanical model of OHC

- The hair cell has a piezo-electric cuticular plate in contact with the gel SAW carrier
- Movement of the plate in response to the SAW causes electrons to be freed and circulated within the cuticular plate of the cell
- This current in the cuticular plate is capacitively-coupled to the "adaptation amplifier"



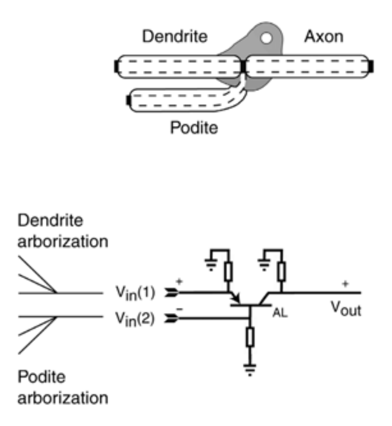
Realisation of an "Activa"



A. Single Neuron
B. Junction of two neurons
C. Diode junctions behave like a transistor when the junction is within 200 Angstroms
D. Diode junctions between two neurons

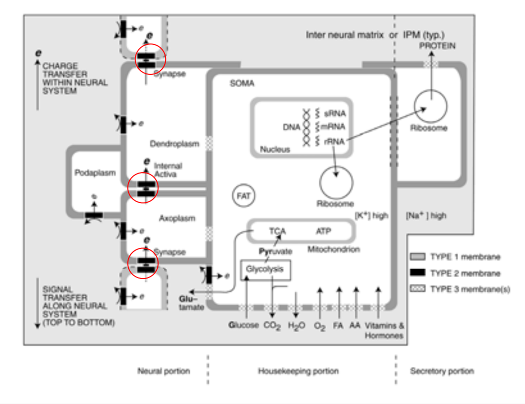
Adding complexity

- The simple model appears to be more complex in realisation
- The activa incorporates resistance and sometimes includes some electrolytic sources of voltage

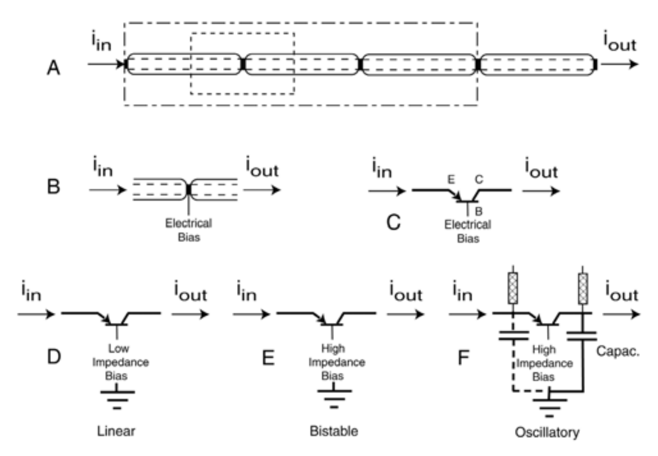


Activas in cells

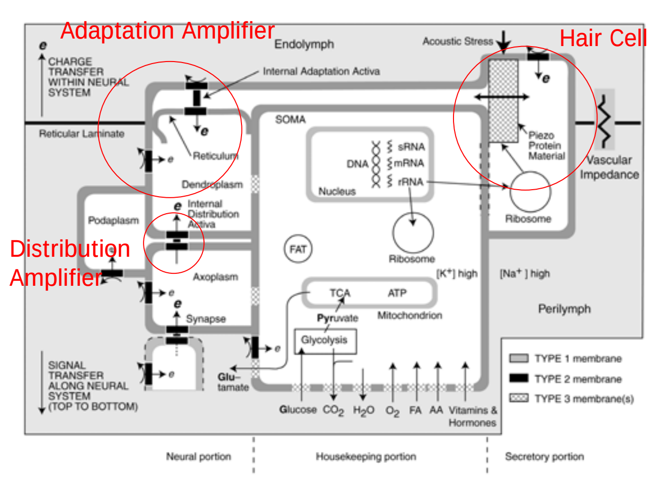
- Model showing how the activas relate to cellular structure and to membranes and electrolytes that produce the necessary bias voltages
- Red circles highlight activas

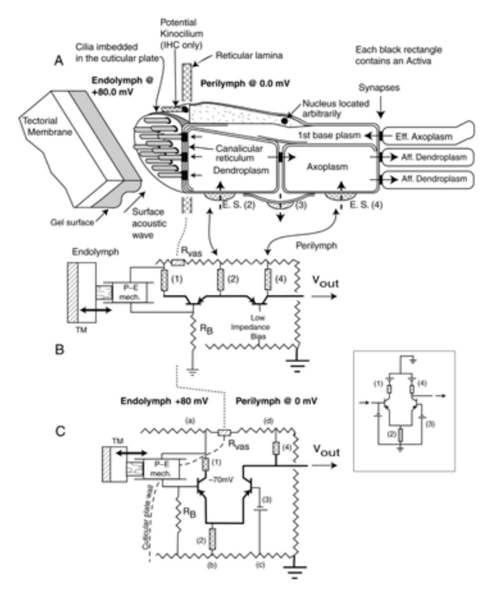


Circuit variants



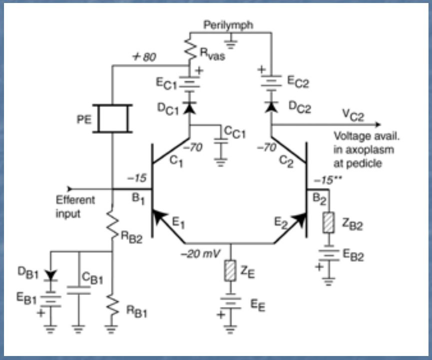
Realising the transducer



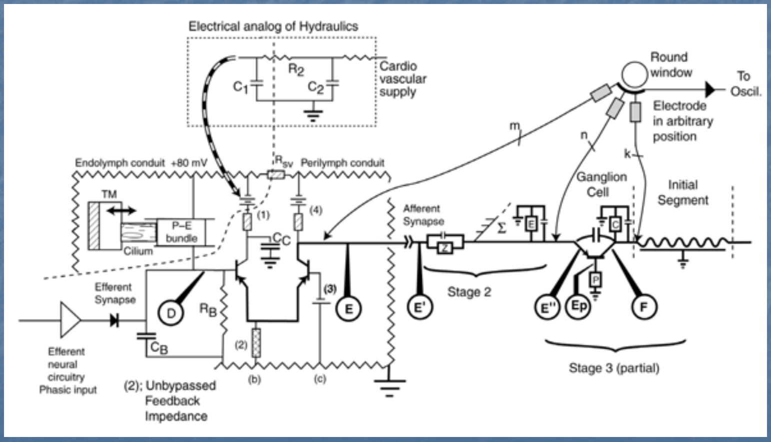


Probable bias sources

- Bias for the activas comes from the electrostenolytic potentials produced by the electrolytes in the various parts of the cells and the surrounds
- The suggested voltages are estimated, not measured directly



Theoretical Complete analogue neural circuit



Proof of concept

- While it is not possible to effectively model the activa with currently readily available software modelling tools, it is possible to model the suggested circuits with standard BJT devices with “conventional” bias arrangements
- This model is “not the territory”: it is basically proof that the circuit topology works and is consistent with the theory

Model Limitations

- The model is based on the physics of silicon semiconductors, not on the biological version with Angstrom-width barriers
- The biasing uses external bias, not electrostenolytic bias voltages in the millivolt range local to each device
- For convenience, it uses NPN transistors instead of the PNP activas posited in the theory
- Because of the physics of the silicon devices, the model does not provide evidence of the gain-adaptive behaviour posited in the theory
- The model does not include the integrating capacitor in the third stage that limits the channel bandwidth (LPF) to about 600Hz in humans

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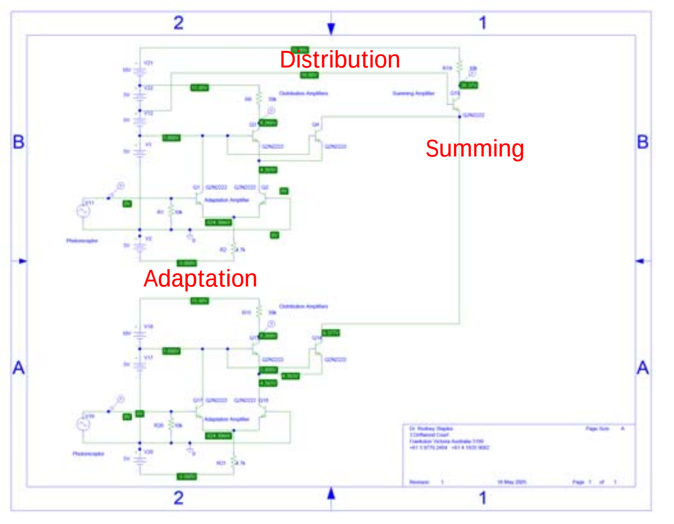
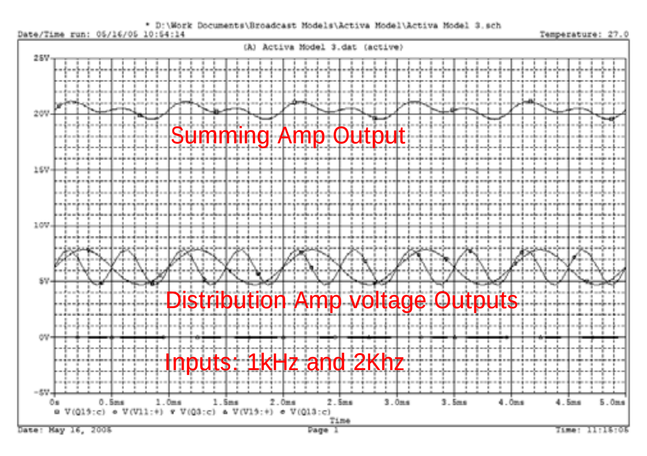
Proof of concept model



Transient solution: model

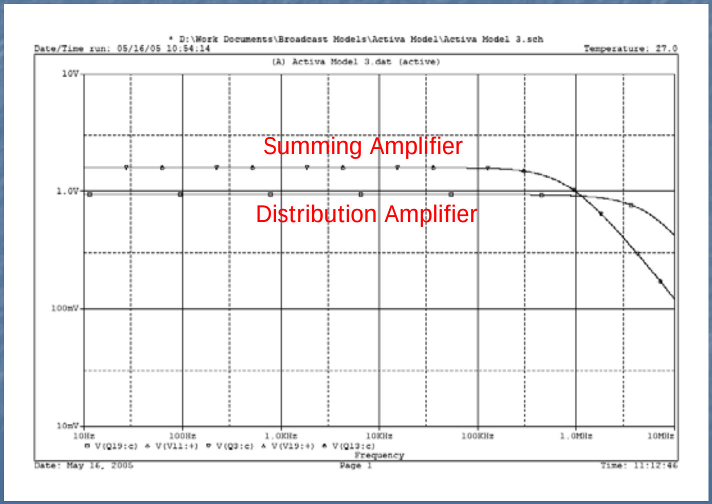


Summing Amp Output

Distribution Amp voltage Outputs

Inputs: 1kHz and 2Khz

Frequency Response: model



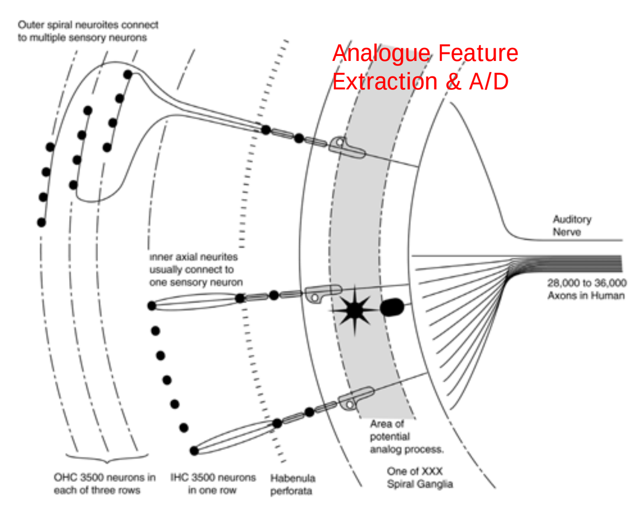
Summing Amplifier

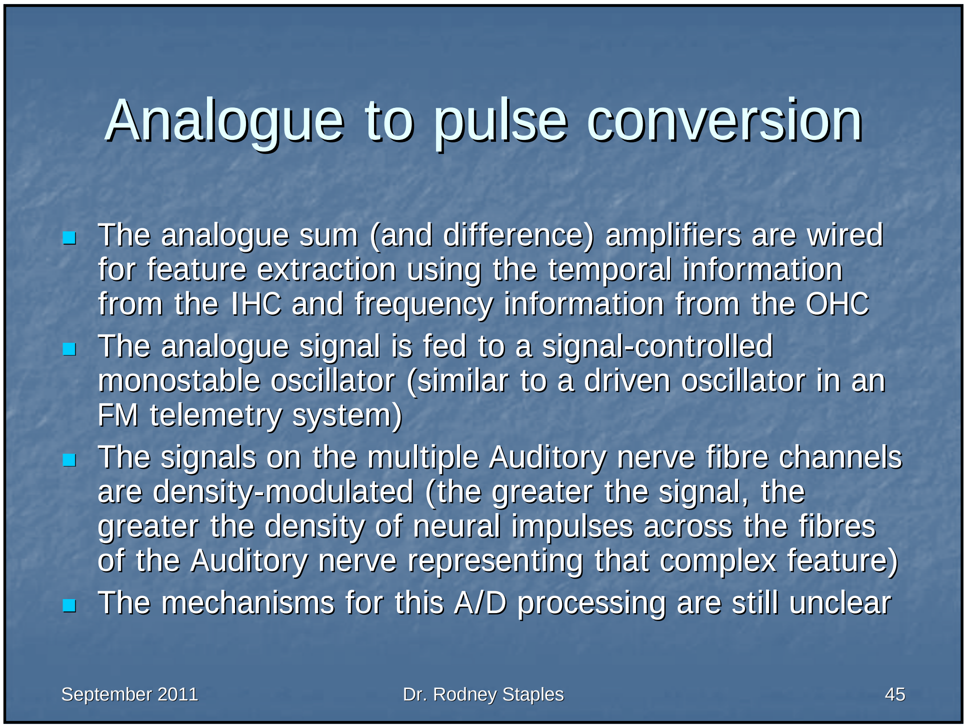
Distribution Amplifier

Commentary on model

- Clearly Fulton's posited model for the analogue electronics immediately behind the audio transducer is a viable topology, based on the observations from a conventional circuit with a similar topology
- The model needs to be refined to account for the individual electrostenolytic bias in the cells, and to account for the gain adaptation mechanism which the simplified model does not satisfactorily address
- Fulton claims that the actual micro- and millivolt voltages in the cell have been difficult for biologists to measure in the past (P 214)

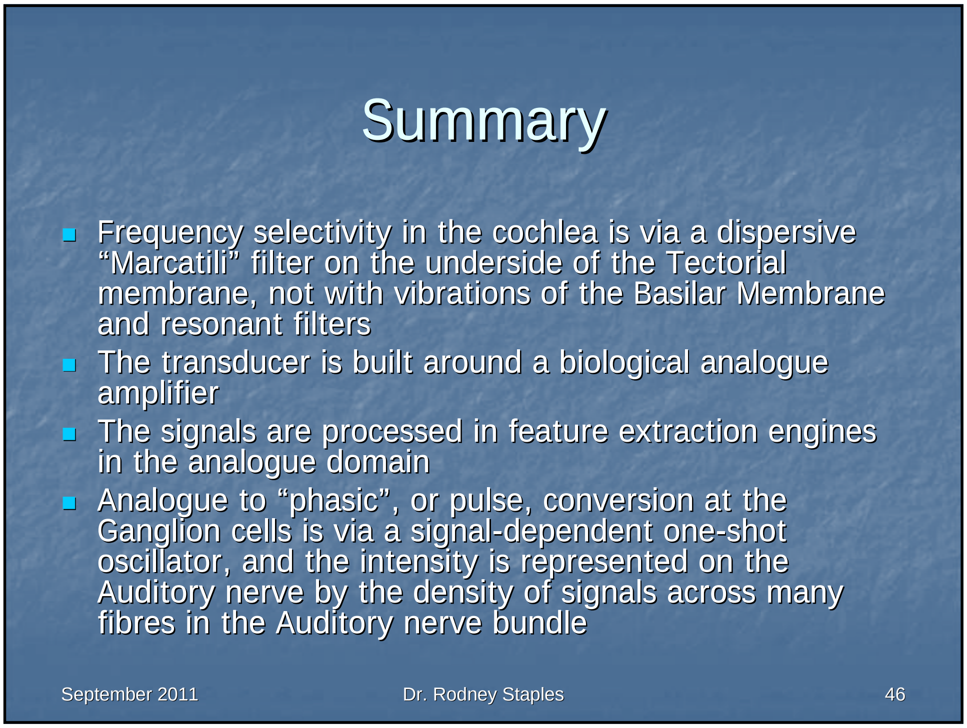
Connection between analogue circuits and the Auditory Nerve





Analogue to pulse conversion

- The analogue sum (and difference) amplifiers are wired for feature extraction using the temporal information from the IHC and frequency information from the OHC
- The analogue signal is fed to a signal-controlled monostable oscillator (similar to a driven oscillator in an FM telemetry system)
- The signals on the multiple Auditory nerve fibre channels are density-modulated (the greater the signal, the greater the density of neural impulses across the fibres of the Auditory nerve representing that complex feature)
- The mechanisms for this A/D processing are still unclear



Summary

- Frequency selectivity in the cochlea is via a dispersive “Marcatili” filter on the underside of the Tectorial membrane, not with vibrations of the Basilar Membrane and resonant filters
- The transducer is built around a biological analogue amplifier
- The signals are processed in feature extraction engines in the analogue domain
- Analogue to “phasic”, or pulse, conversion at the Ganglion cells is via a signal-dependent one-shot oscillator, and the intensity is represented on the Auditory nerve by the density of signals across many fibres in the Auditory nerve bundle

More information

- http://www.neuronresearch.net/hearing
- http://www.hearingresearch.net
- http://www.neuronresearch.net
- Fulton, J. (2008) *Hearing: A 21st Century Paradigm.* Corona Del Mar, California, Self Published.