FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG
FACULTY OF ENGINEERING

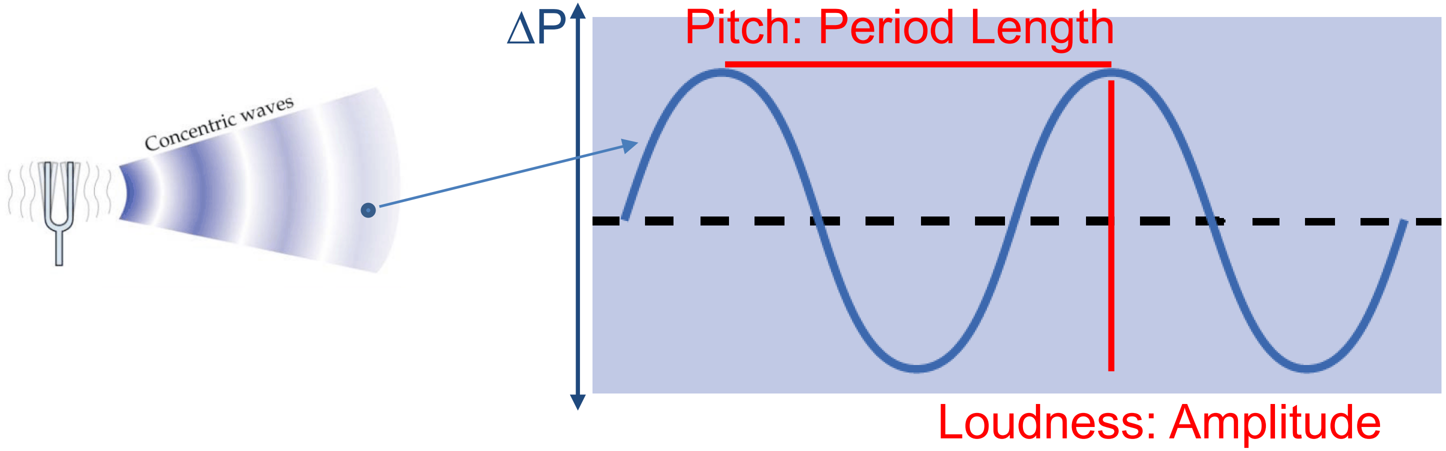
Cognitive Neuroscience for AI Developers

Week 8b – Sensation and Perception: The Auditory System

Overview over auditory system

The Auditory System – Overview

- The auditory system transforms and processes sound
- Sound: Longitudinal wave (pressure fluctuations)

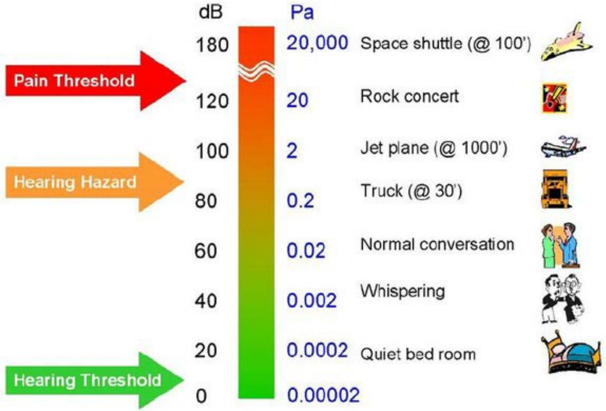


The Auditory System – Overview

- **Weber-Fechner Law (specific)**

$$L = 20 \cdot \log\left(\frac{P}{P_0}\right)$$

L = Loudness
P = Sound Pressure
$P_0 = 2 \cdot 10^{-5}$ Pa Threshold

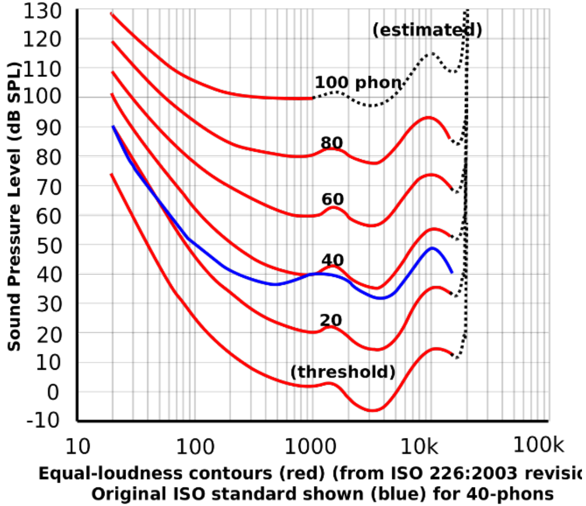


- Subjective Loudness rises logarithmic with sound pressure
- Thus loudness is measured in dB
- Loudness logarithmic with pressure

Shatnawi, S., Stroup-Gardiner, M., & Stubstad, R. (2009, April). California's perspective on concrete pavement preservation. In *National conference on preservation, repair, and rehabilitation of concrete pavements, St. Louis, Missouri* (pp. 71-86).

The Auditory System – Overview

- Contour lines of equal subjective loudness
- Best hearing at approx. 3.4 kHz

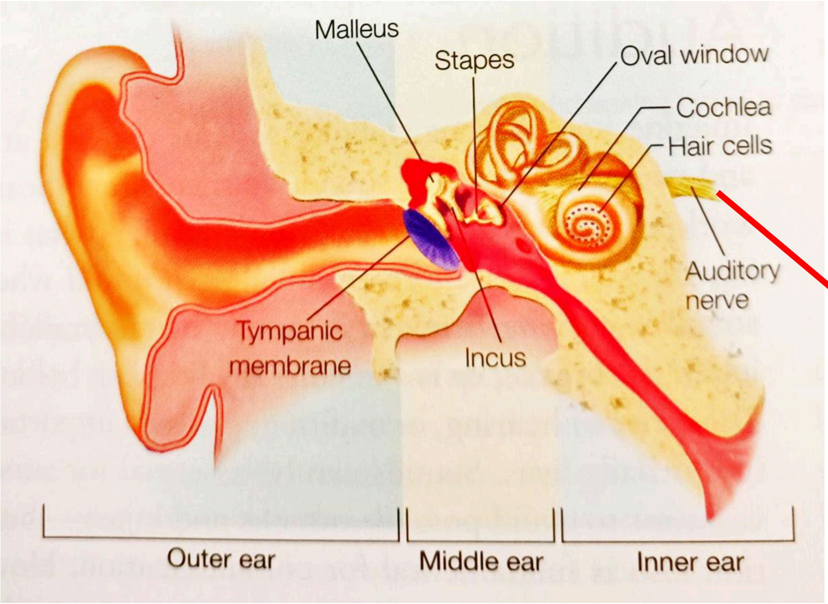


https://en.wikipedia.org/wiki/Sound_pressure

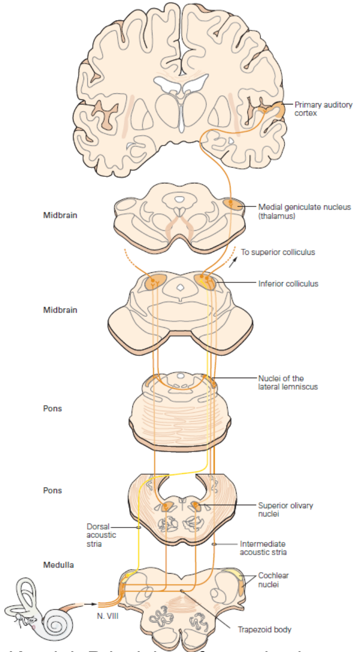
The Auditory System – Overview

- sensory system for the sense of hearing

-> includes the sensory organs (the ears) and the auditory parts of the sensory system



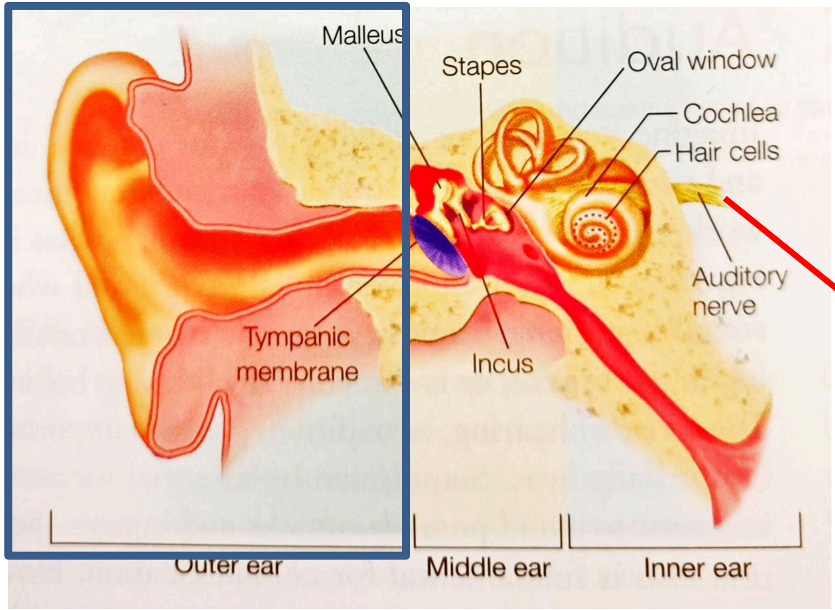
Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014



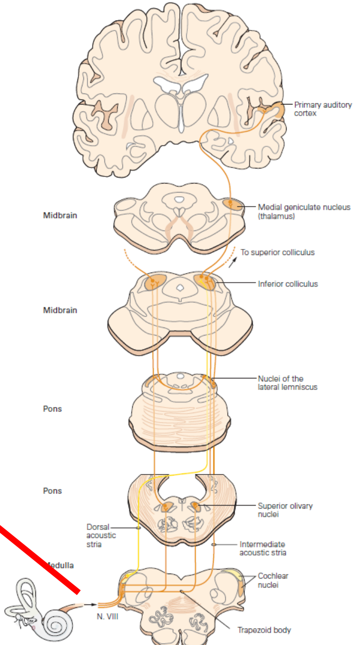
Kandel, Principles of neural science

The auditory System: Outer Ear

The Auditory System – The outer ear



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014



Kandel, Principles of neural science

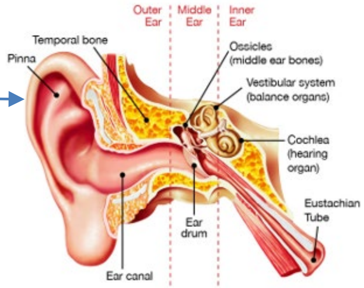
The Auditory System – The outer ear

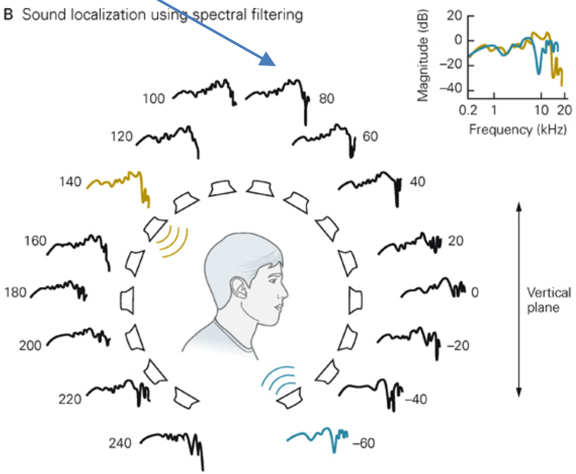
- Funnel
- Pinna: Directional Hearing
- Transmission from pinna to tympanic membrane is not linear:

-> Resonance frequency at 3.4 kHz

-> frequency of best hearing

https://eyeandear.org.au/patients-visitors/fact-sheets/middle-ear-fluid/





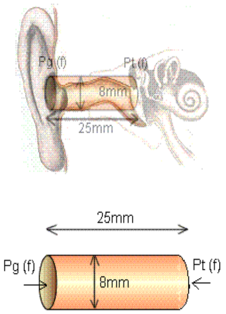
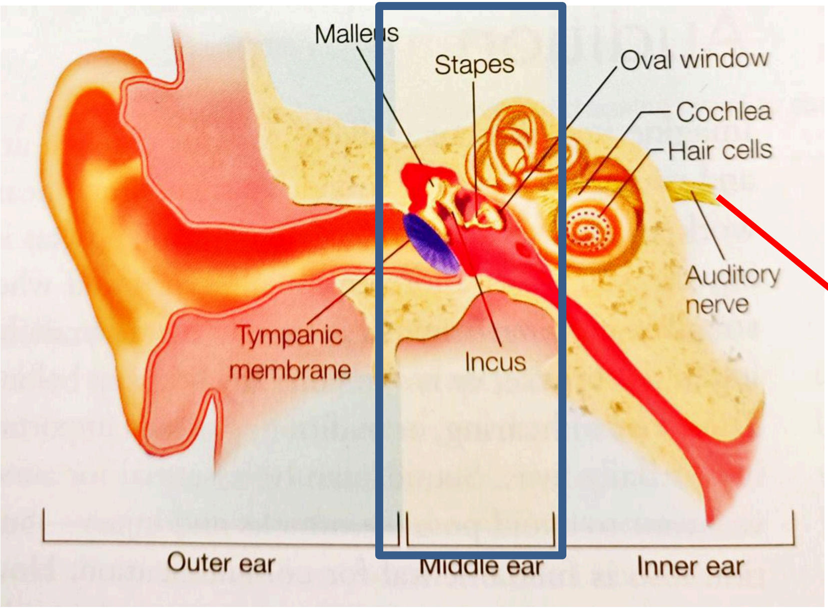


Abb: web.fbe.uni-wuppertal.de/fbe0014/ars_auditus

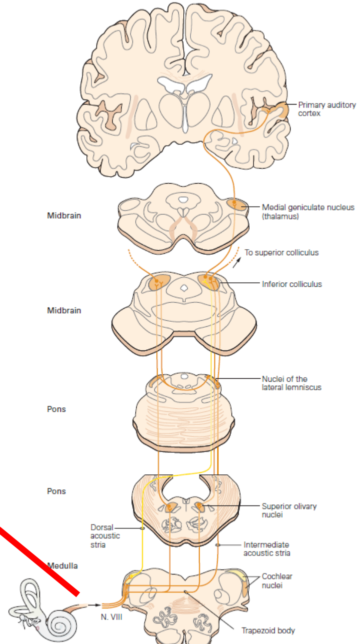
The auditory System: Middle Ear

The Auditory System – The middle ear

3 ossicles

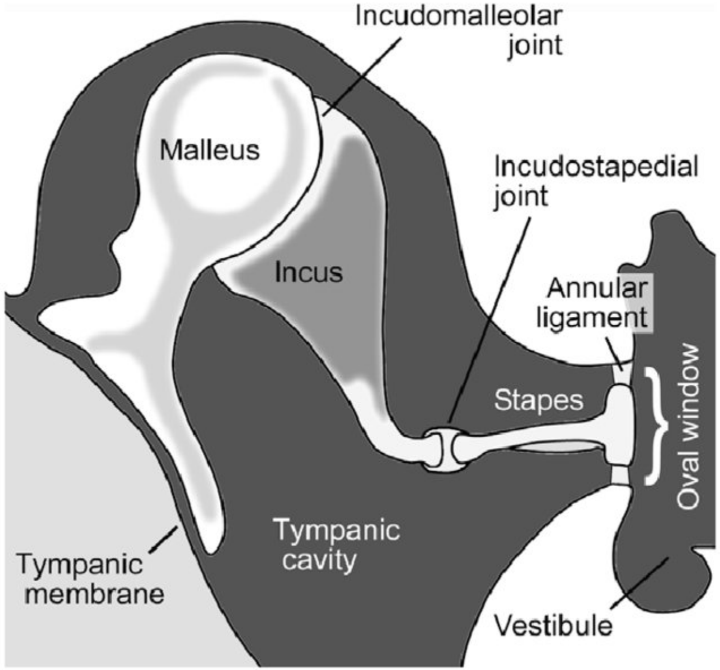


Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014



Kandel, Principles of neural science

The Auditory System – The middle ear

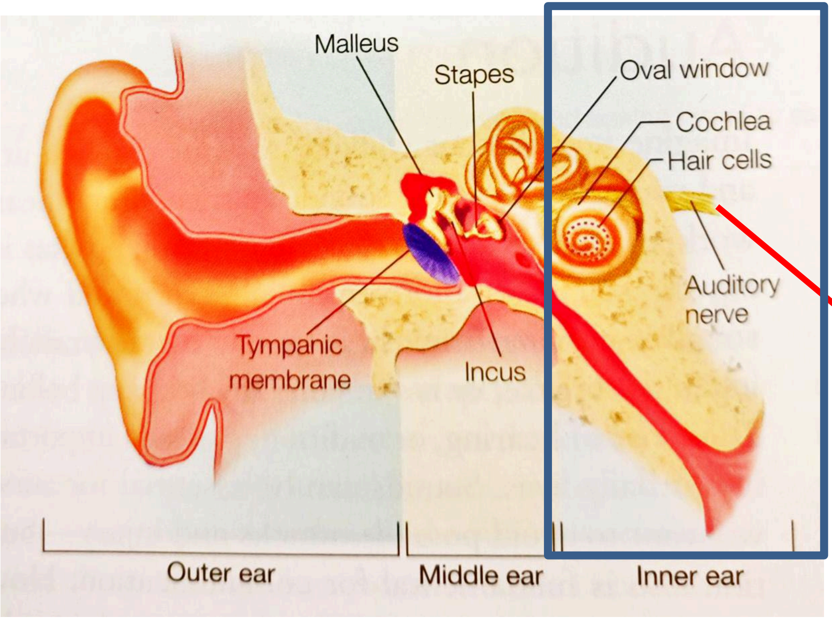


- Pressure fluctuations have to be transmitted to fluid
- 98% of the sound would be reflected at the border from air to fluid
- 3 ossicles of middle ear -> impedance adjustment
- Instead of 98% only 40% of the sound is reflected
- Better hearing of 27 dB

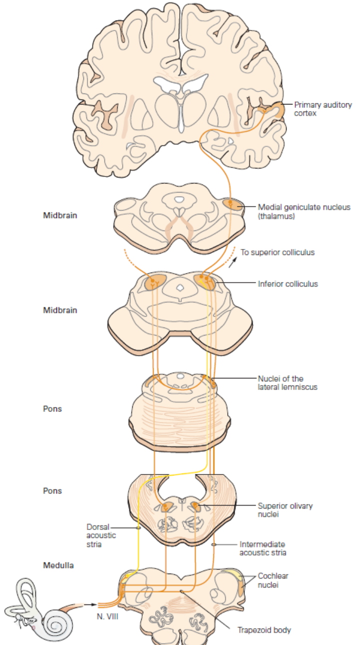
Tucker, R. P., Peterson, C. A., Hendaoui, I., Bichet, S., & Chiquet-Ehrismann, R. (2016). The expression of tenascin-C and tenascin-W in human ossicles. *Journal of anatomy*, *229*(3), 416-421.

The auditory System: Inner Ear

The Auditory System – The inner ear- The cochlea



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

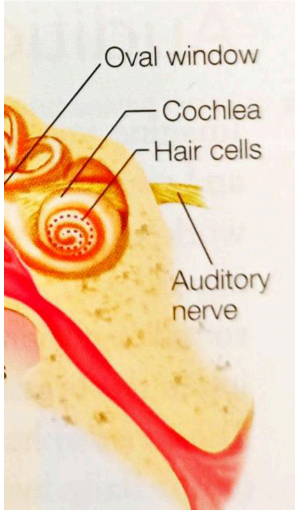


Kandel, Principles of neural science

The Auditory System – The inner ear- The cochlea

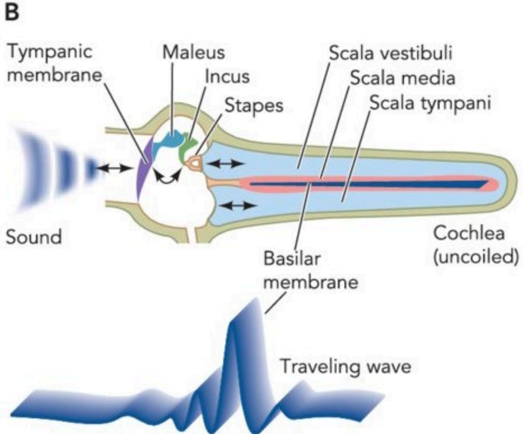
- Mechanotransduction: Mechanical signal is transduced to electrical signal

Cochlea looks like snail



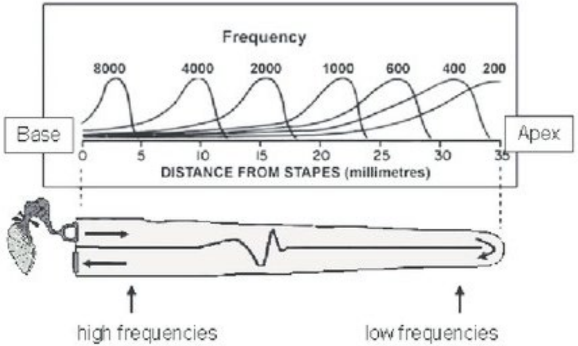
From: Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Uncoiled cochlea



Zdebik, A. A., Wangemann, P., & Jentsch, T. J. (2009). Potassium ion movement in the inner ear: insights from genetic disease and mouse models. *Physiology*, *24*(5), 307-316.

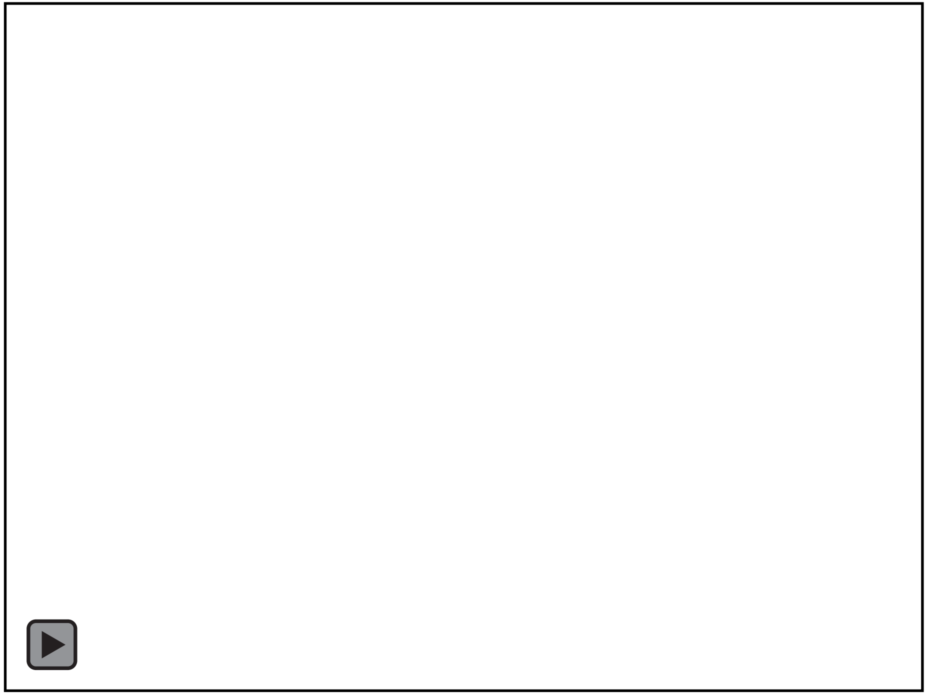
Travelling wave



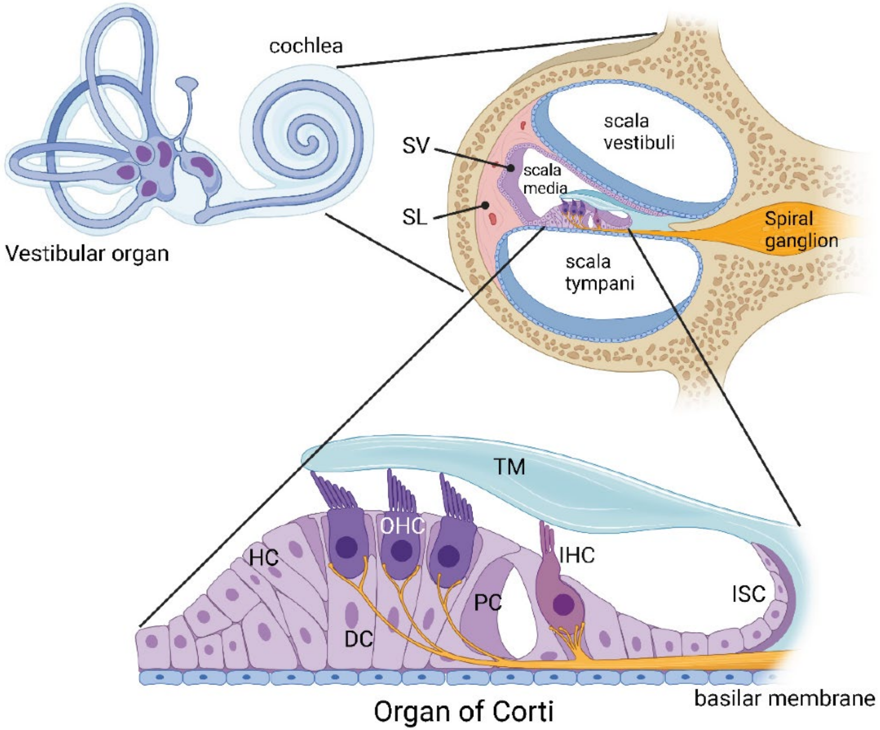
Tonotopy

Emanuel, D. C., Maroonroge, S., & Letowski, T. R. (2009). Auditory function. *Helmet-Mounted Displays: Sensation, Perception and Cognitive Issues*.

The Auditory System – The inner ear- The cochlea



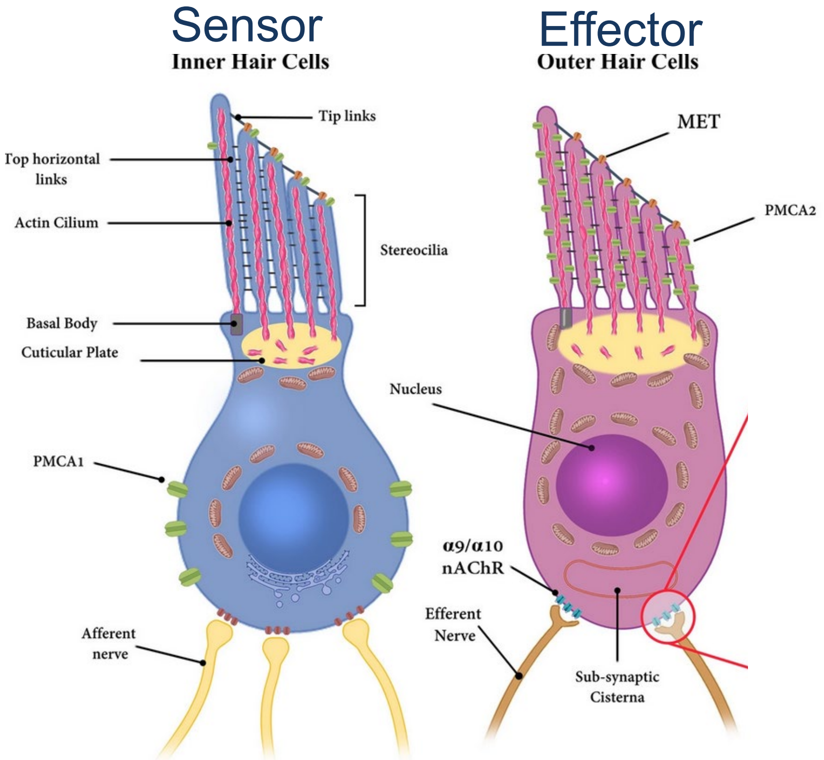
The Auditory System –The cochlea



- **Organ of corti** transduces mechanical signal into chemical signal (neurotransmitter release)
- **Inner hair cells** are moved by the flow endo lymphe (not connected to tectorial membrane)
- **Outer hair cells** move to further enhance the amplitude of the stimulus

Vlajkovic, S.M.; Thorne, P.R. Purinergic Signalling in the Cochlea. *Int. J. Mol. Sci.* **2022**, *23*, 14874. https://doi.org/10.3390/ijms232314874

The Auditory System –The cochlea

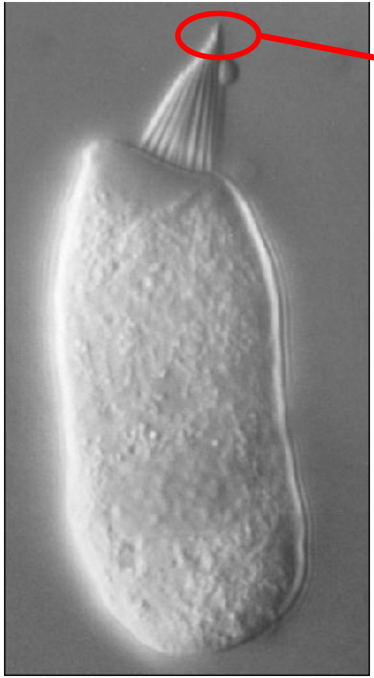


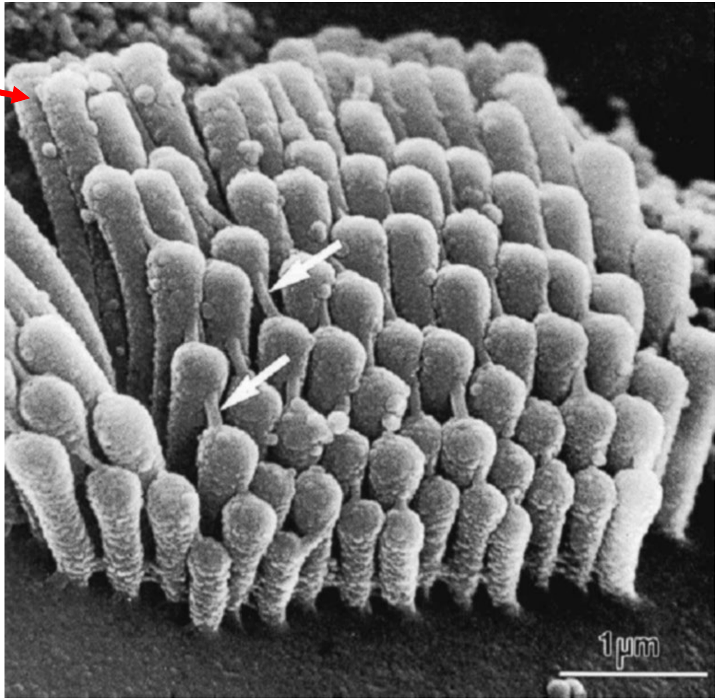
- Inner hair cells: Transduce mechanical deflection to electrical/chemical signal
- Tip links at top of stereocilia pull on ion channels
- Inner hair cell is depolarized
- Releases Glutamate

- Outer hair cells are no sensory cells
- Amplification of travelling wave
- Outer hair cells can contract: Protein Prestin
- Get signals from superior olive

Farhadi, M., Razmara, E., Balali, M., Hajabbas Farshchi, Y., & Falah, M. (2021). How Transmembrane Inner Ear (TMIE) plays role in the auditory system: A mystery to us. *Journal of Cellular and Molecular Medicine*, *25*(13), 5869-5883.

The Auditory System –The cochlea

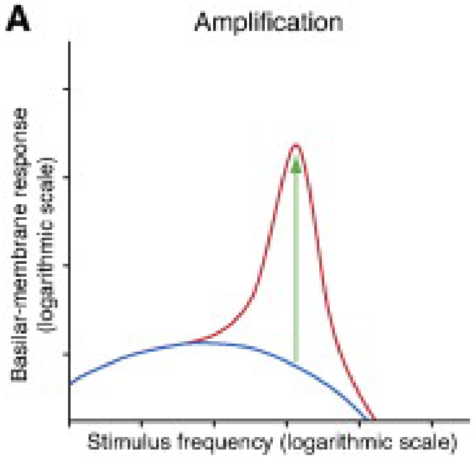




Pickles and Corey (1992)

The Auditory System –The cochlea

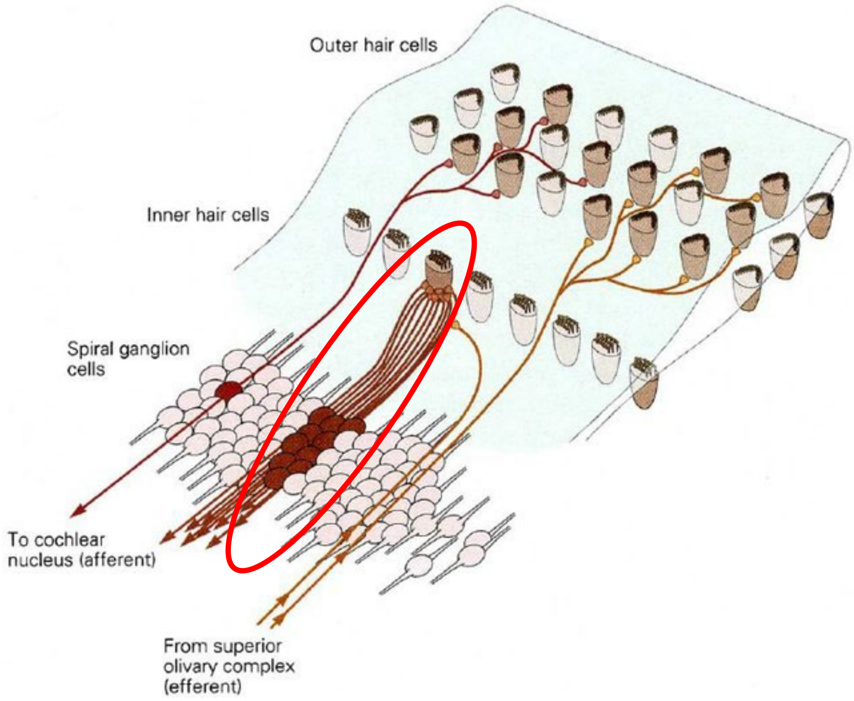
Outer Hair Cells



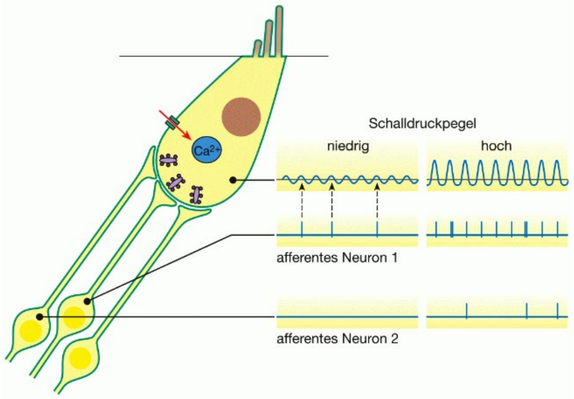
Hudspeth, A. J. (2008). Making an effort to listen: mechanical amplification in the ear. *Neuron*, *59*(4), 530-545.

The Auditory Pathway

The Auditory System –The auditory nerve



- Transformation: Neurotransmitter (glutamate) depolarizes cells of spiral ganglion
- Spiking of spiral ganglion neurons



Up to approx. 4 kHz phase locking

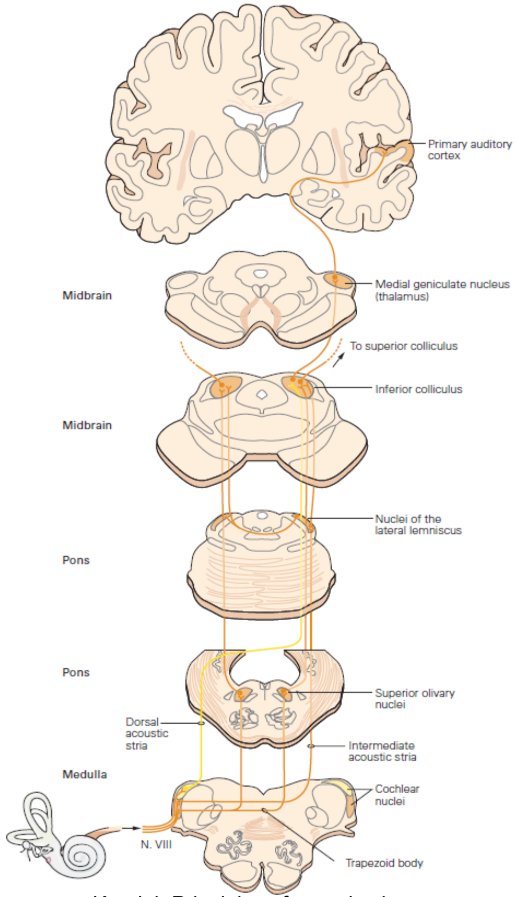
Graven, S. N., & Browne, J. V. (2008). Auditory development in the fetus and infant. *Newborn and infant nursing reviews*, *8*(4), 187-193.

The Auditory System –The brainstem - Cochlear Nucleus

- Spiking signal is transmitted to the second synapse (**dorsal cochlear nucleus, ventral cochlear nucleus**) ir medulla

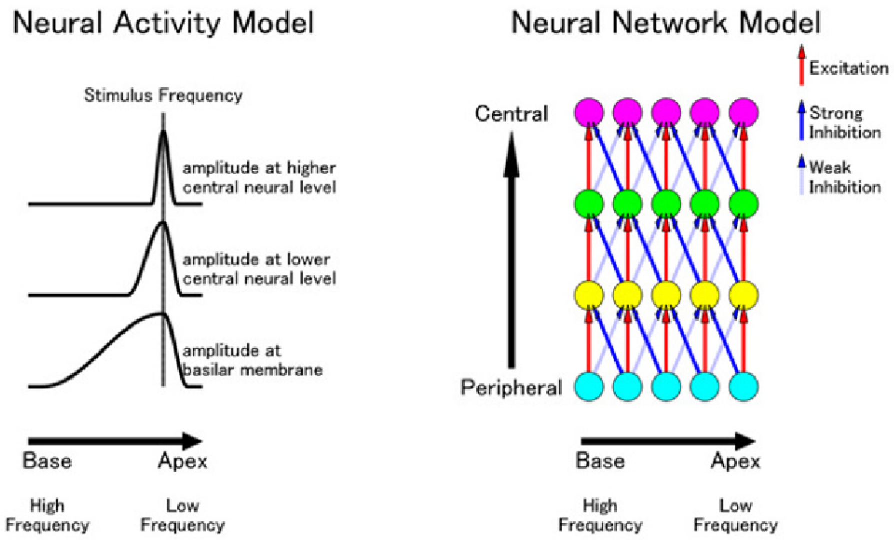
- **Ventral cochlear** nucleus extracts temporal an spectral structure of the signal

- **Dorsal cochlear** nucleus integrates auditory signal with somatosensory signal -> perhaps to detect sound sources



Kandel, Principles of neural science

The Auditory System –The brainstem: Lateral Inhibition



Okamoto, H., Kakigi, R., Gunji, A., & Pantev, C. (2007). Asymmetric lateral inhibitory neural activity in the auditory system: a magnetoencephalographic study. *BMC neuroscience*, *8*(1), 1-6.

- Along the whole auditory pathway including auditory cortex -> **lateral inhibition**
- Cells inhibit **neighboring** cells

-> sharpening of the frequency selectivity of the auditory system -> **contrast enhancement**

The Auditory System –The brainstem: Lateral Inhibition

2082 IEEE TRANSACTIONS ON CYBERNETICS, VOL. 43, NO. 6, DECEMBER 2013

Lateral Inhibition Pyramidal Neural Network for Image Classification

Bruno José Torres Fernandes, *Member, IEEE*, George D. C. Cavalcanti, *Member, IEEE*, and Tsang Ing Ren, *Member, IEEE*

Applied Intelligence
https://doi.org/10.1007/s10489-023-04517-4

Check for updates

Olfactory perception prediction model inspired by olfactory lateral inhibition and deep feature combination

Yu Wang[1] · Qilong Zhao[2] · Mingyuan Ma[1] · Jin Xu[1]

Accepted: 7 February 2023

Dilated Convolutions with Lateral Inhibitions for Semantic Image Segmentation

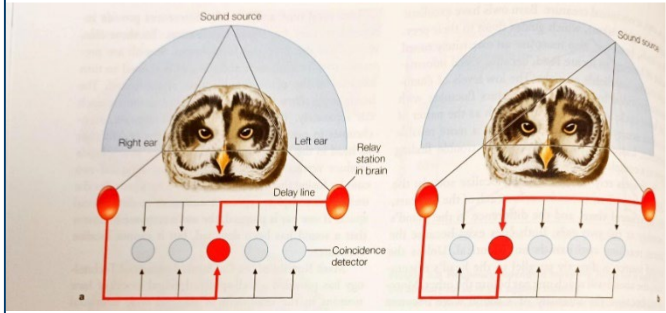
Yujiang Wang, Mingzhi Dong, Jie Shen, *Member, IEEE,* Yiming Lin, *Graduate Student Member, IEEE,* and Maja Pantic, *Fellow, IEEE*

Lateral Inhibition is used in AI research!

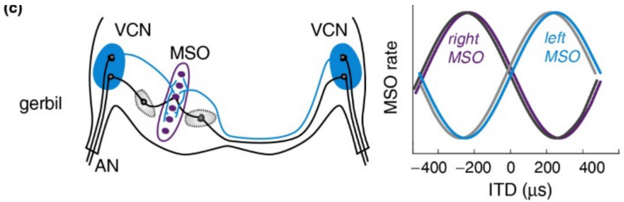
The Auditory System –The brainstem

- Axons from ventral cochlear nucleus innervate ipsi-lateral and contra-lateral (pons) superior olivary nucleus -> shared information from both ears

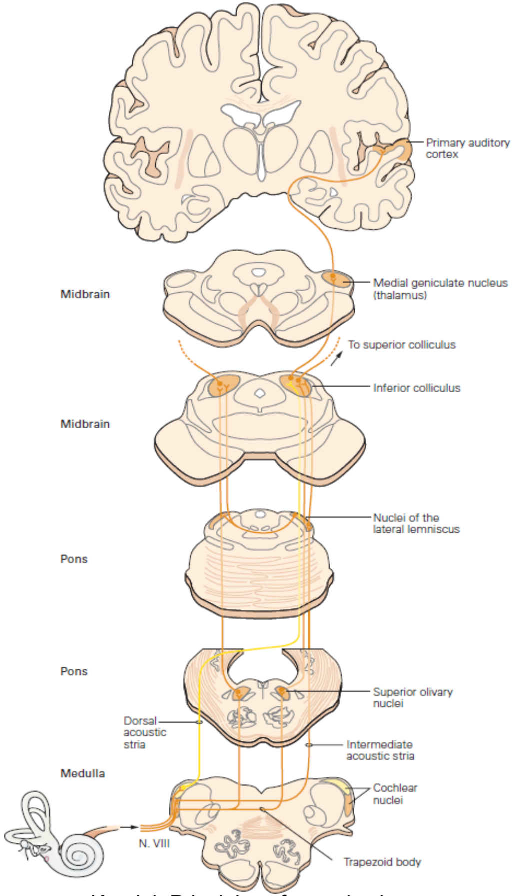
- Superior olivary nucleus supposed to create a map of inter-aural time differences -> it was proposed that therefore delay lines are used -> **no! not in mammals!**



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014



Carr & Christensen-Dalsgaard, 2016



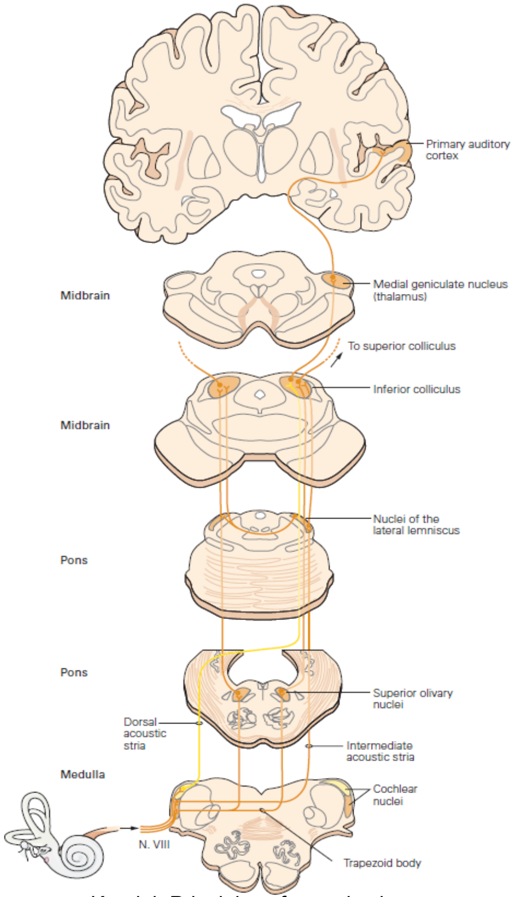
Kandel, Principles of neural science

The Auditory System –The brainstem

- Lateral Lemniscus (Pons):
  - Inhibitory neurons
  - Plays a role in source localization

- Inferior colliculus (Midbrain):
  - Is used to suppress reflections of sounds from surfaces
  - This is necessary to perform a source localization

- Medial Geniculate Body (Thalamus in diencephalon, not brainstem!):
  - Gate to consciousness
  - Filters out signal that should not ascend to cortex and thus consciousness

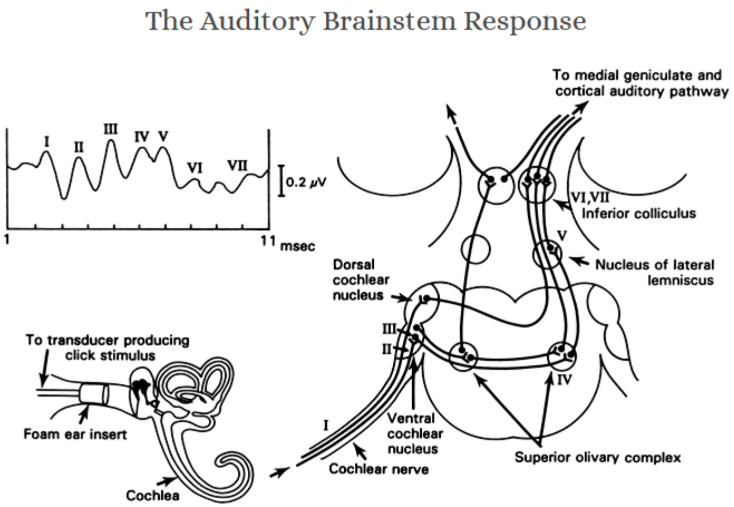


Kandel, Principles of neural science

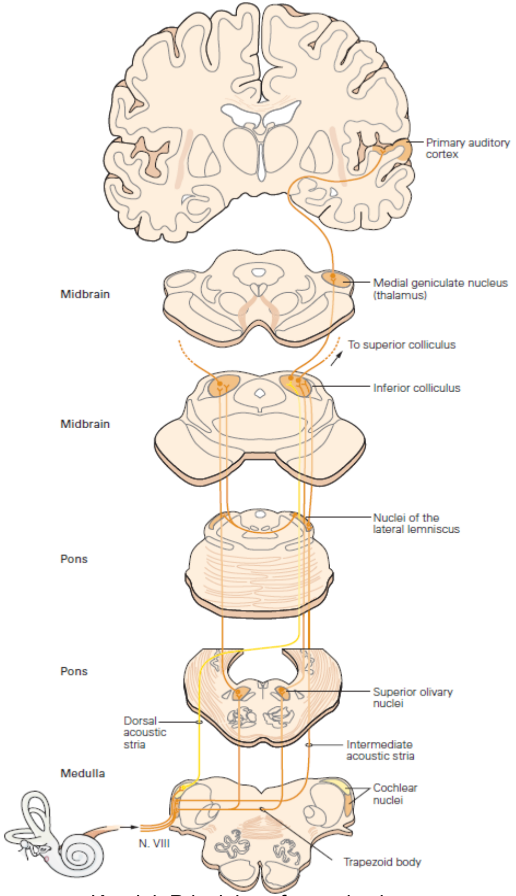
Masterton, R. B., Granger, E. M., & Glendenning, K. K. (1992). Psychoacoustical contribution of each lateral lemniscus. *Hearing research*, *63*(1-2), 57-70.

The Auditory System –The brainstem

Measurement of brainstem function (BERA)



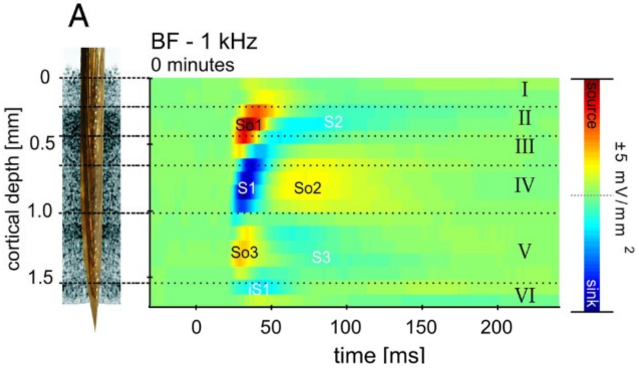
https://www.evokedpotential.com/the-auditory-brainstem-response.html



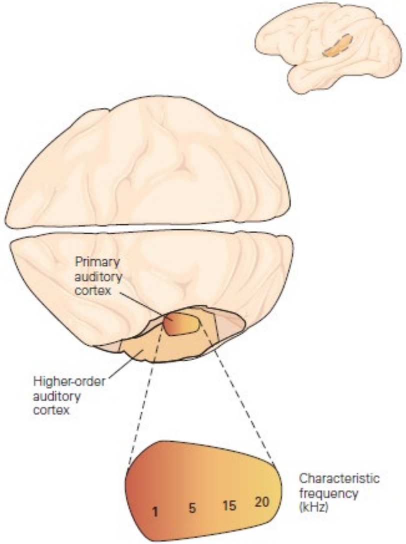
Kandel, Principles of neural science

The Auditory System – The auditory cortex

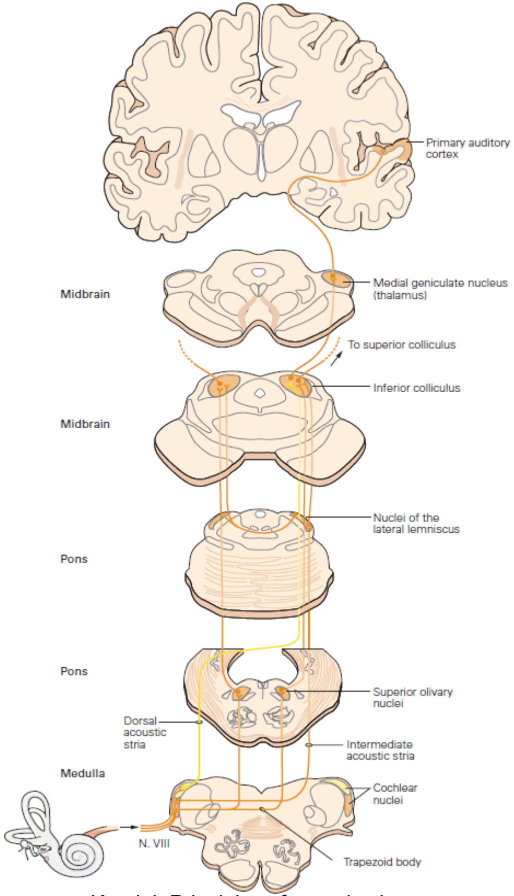
- **Primary Auditory Cortex:**
  - gets input from thalamus
  - Tonotopically organized
  - Processes input from both ears -> dominant contra-lateral ear
  - Structure with six layers



Happel, M. F., Jeschke, M., & Ohl, F. W. (2010). Spectral integration in primary auditory cortex attributable to temporally precise convergence of thalamocortical and intracortical input. *Journal of Neuroscience*, *30*(33), 11114-11127.



Kandel, Principles of neural science



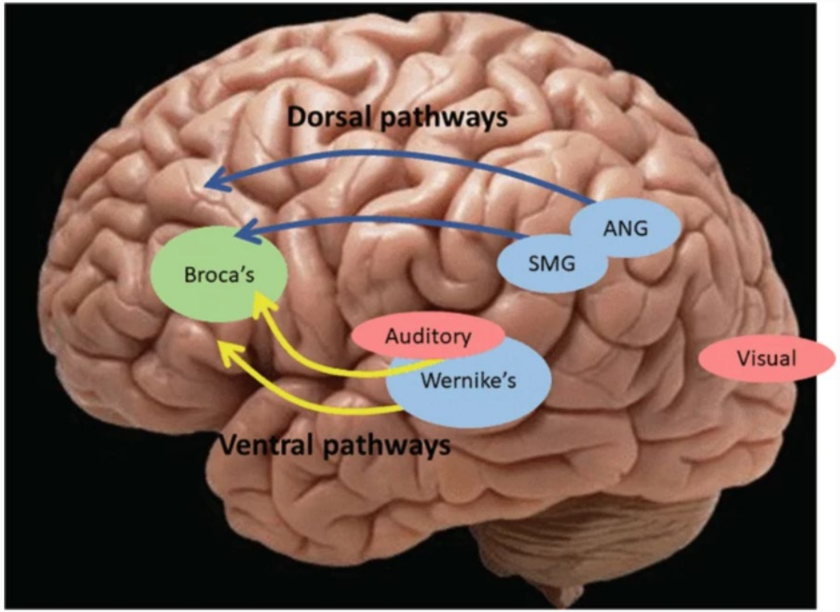
Kandel, Principles of neural science

The Auditory Systems-Higher Processing

The auditory ventral and dorsal streams

Dorsal stream:
Sensori-motor integration
Speech production
„Where stream“

Ventral stream:
Phonological processing
Auditory objects
Speech comprehension
„What stream“



Analogy to visual system!

Bowyer, S. M., Biondo, A., Funk, B., Greenwald, M., Lajiness-O'Neill, R., & Zillgitt, A. (2019). Presurgical Localization of Language Regions and Their Networks. *Magnetoencephalography: From Signals to Dynamic Cortical Networks*, 1079-1098.

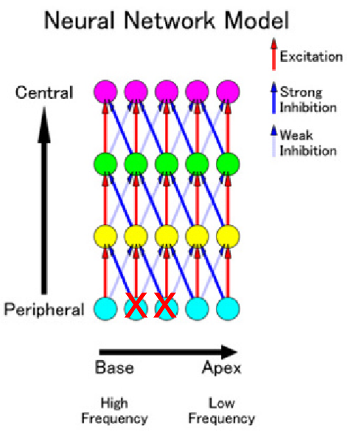
Tinnitus

The Auditory System: Hearing something without an external tone -> Tinnitus

- Tinnitus demonstrates that we hear not with the ears but with the **brain**
- Tinnitus is related to hearing loss -> synapses in the cochlea are damaged -> less input in the cochlear nucleus

Mechanistic Theories 1

1) Decreased lateral inhibition -> does not fit to observations



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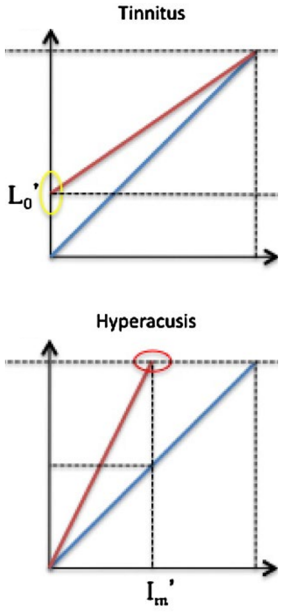
The Auditory System: Hearing something without an external tone -> Tinnitus

Mechanistic Theories 2

1) **Central gain increase** -> amplification of low signal along auditory pathway -> however if this would be true real tones would be overamplified -> hyperacusis -> however not everyone with tinnitus has hyperacusis
2) **Central noise** -> internally generated neural noise is added to the auditory system to lift subthreshold signal over threshold

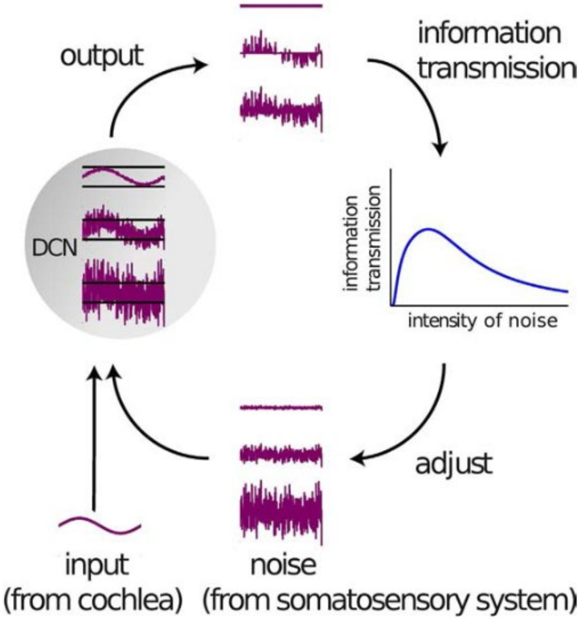


Zeng, F. G. (2013). An active loudness model suggesting tinnitus as increased central noise and hyperacusis as increased nonlinear gain. *Hearing research*, *295*, 172-179.

The Auditory System: Hearing something without an external tone -> Tinnitus

Central Noise and Stochastic Resonance

- Neuronal noise is added to lift sub-threshold above detection threshold
- Feedback-loop implemented in dorsal cochlear nucleus
- Information transmission is maximized
- Auto-correlation as measure for information

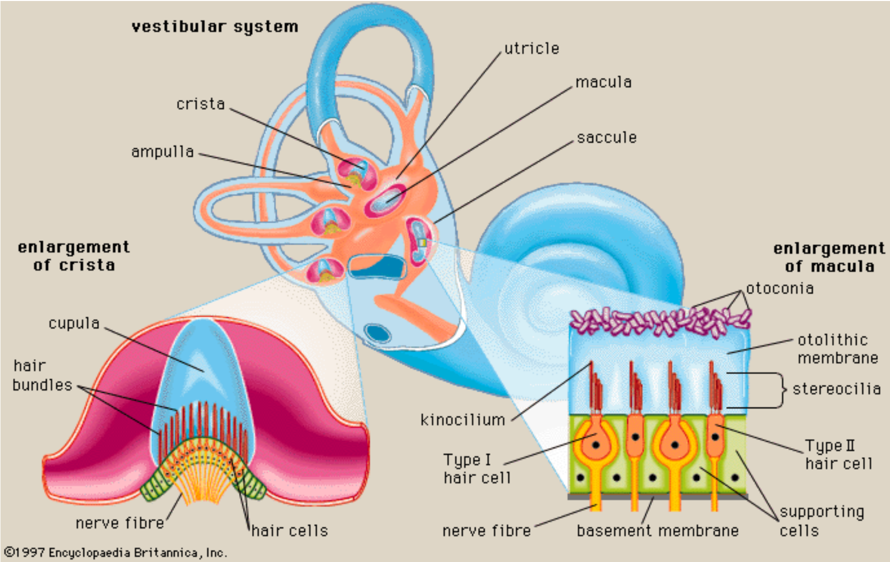


Schilling, A., Tziridis, K., Schulze, H., & Krauss, P. (2021). The Stochastic Resonance model of auditory perception: A unified explanation of tinnitus development, Zwicker tone illusion, and residual inhibition. *Progress in brain research*, *262*, 139-157.

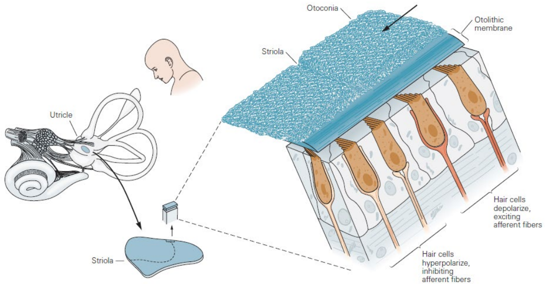
Vestibular System (Balance)

The Vestibular Systems

(just for the sake of completeness)



https://www.britannica.com/science/human-nervous-system/The-vestibular-system

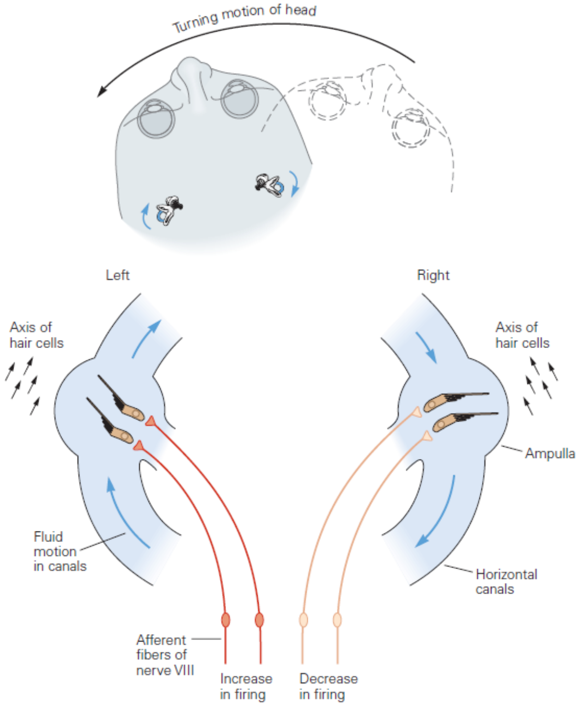


Kandel, Principles of neural science

- **Vestibular system**:
  - **5 Vestibular organs**
    - **1 Utricle**: Linear motion
      - Otoconia: inert mass
      - Macula: sensory epithelia
      - (Horizontal movements)
    - **1 Saccule**: Linear motion
    - **3 semicircular canals** (anterior vertical, posterior vertical, horizontal): Rotation
      - When head rotates cupula is sheared
      - Stereocilia are bend

The Vestibular Systems

(just for the sake of completeness)



Kandel, Principles of neural science

- **3 semicircular canals**: Rotation of the head leads to flow of endolymphe
- **Stereocilia are bend** (by the endolymphe flow) -> increase/decrease of firing of connected neurons

- **Signals of both ears** is needed to detect head rotation and the direction of the rotation

Cognitive Neuroscience for AI Developers

Week 8b– Sensation and Perception: The Olfactory System

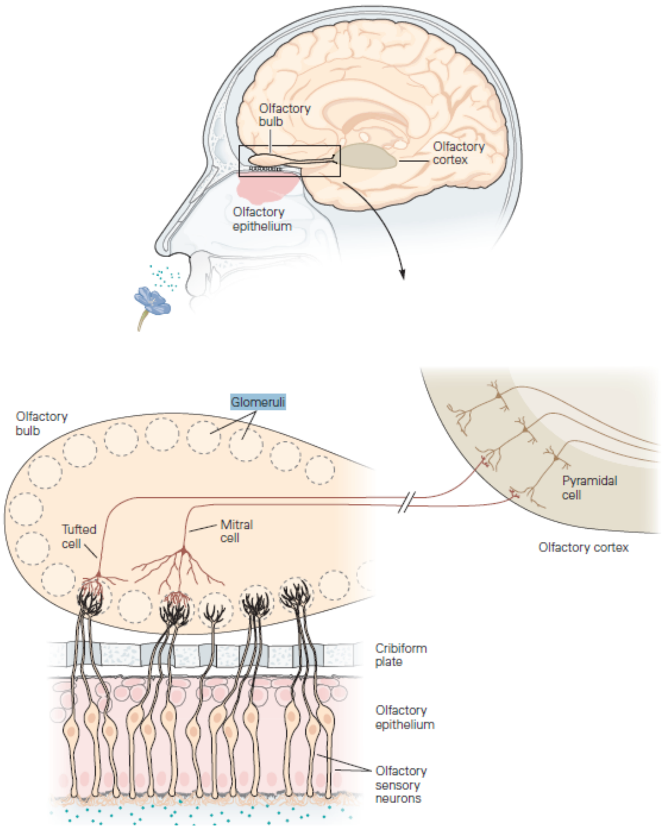
The **sense of smell**, or **olfaction**, is the special sense through which smells (or odors) are perceived.

- Chemical sense like gustatory sense

Source: wikipedia.org

Olfactory System

- Smell is triggered by odor molecules -> **odorants**
- **Odorants bind to odor receptors**/ or small vibrations of odors lead to the sensation
- Bipolar cells (receptors) are embedded in olfactory epithelium (1000 different receptors, Receptor cells are **bipolar neurons**)
- Bipolar neurons send signal to olfactory bulb (glomeruli)

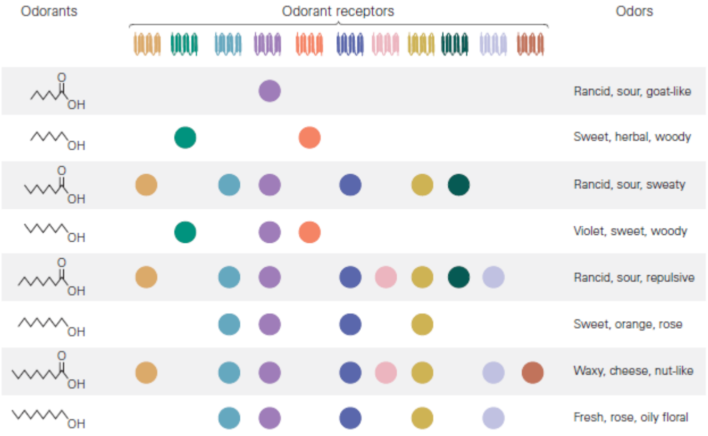


Kandel, Principles of neural science

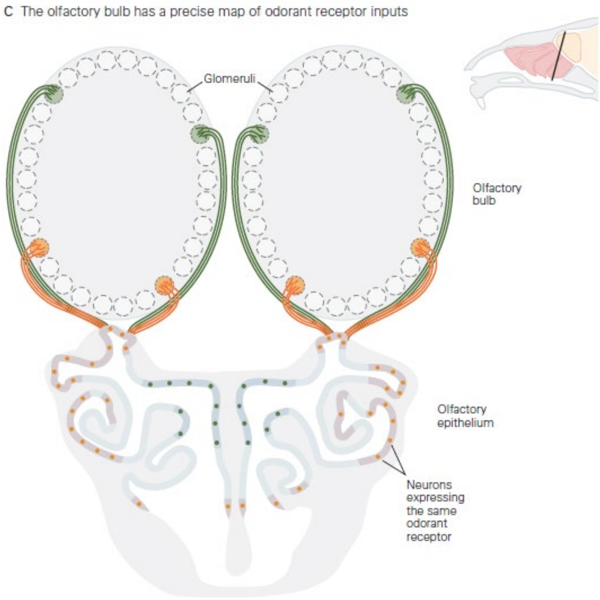
Olfactory System

- Different combinations of receptor encode different odors, each receptor responds to different odors
  -> unique constellation of receptors

- Signal is transmitted to glomeruli of olfactory bulb

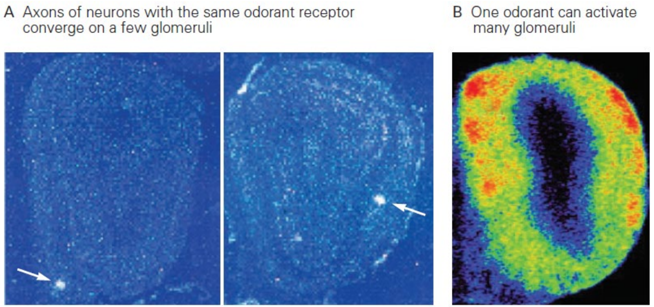


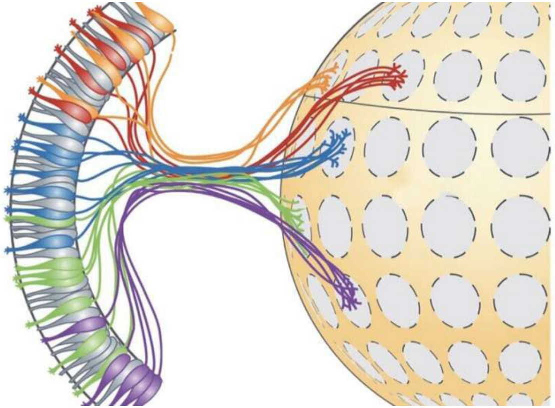
Kandel, Principles of neural science



Olfactory System (Receptor to olfactory bulb)

- Each glomerulus receives only input from one receptor type
- Each odor is recognized by many receptor types -> many glomeruli are activated by one odor
- Closely related odors activate neighboring glomeruli
- Axons of the glomeruli project to the primary olfactory cortex

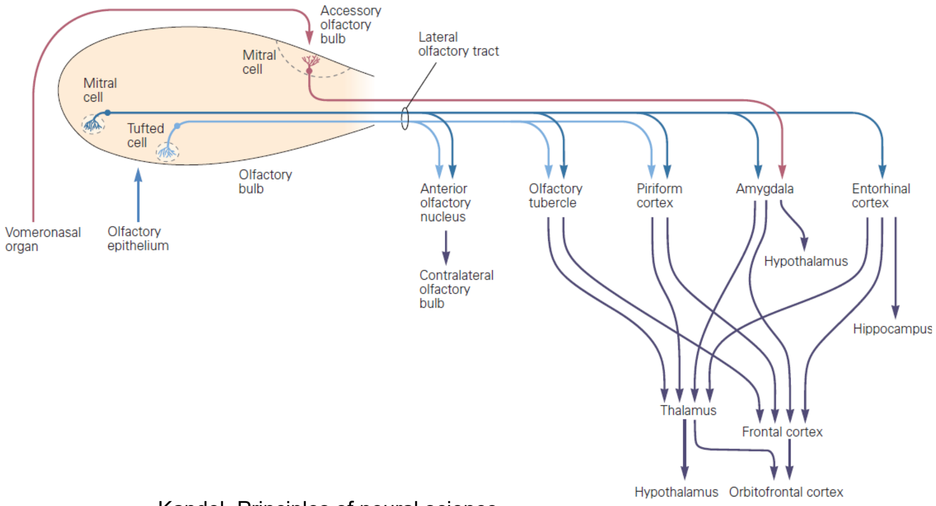




https://medicalxpress.com/news/2022-04-mouse-olfactory-glomeruli-state-of-the-art-techniques.html

Olfactory System (olfactory bulb to cortex)

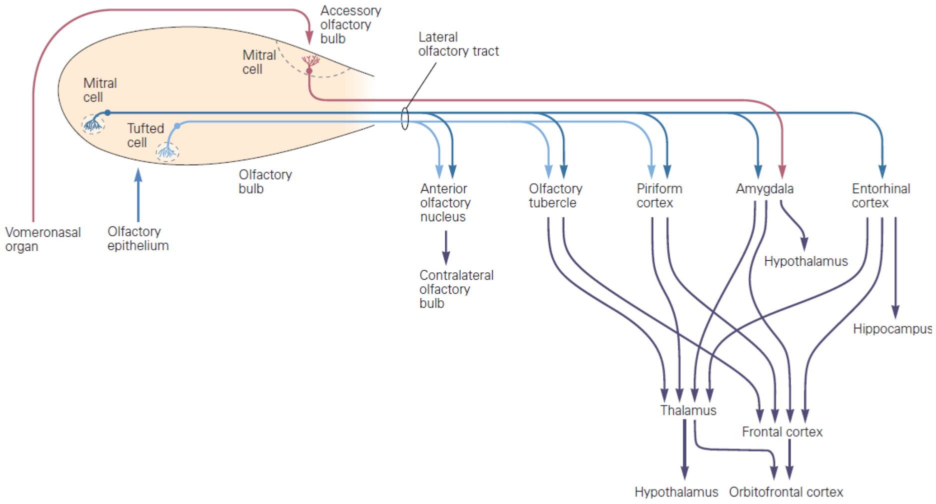
- Signal from glomeruli project to ipsilateral primary olfactory pathway



Kandel, Principles of neural science

Olfactory System (olfactory bulb to cortex)

- Signal from glomeruli project to ipsilateral primary olfactory pathway



- Ipsilateral -> no crossing
- Does not pass the thalamus
- Projects to amygdala -> emotions

-> autonomous functions and so on

Kandel, Principles of neural science

Olfactory System Based Machine Learning Algorithm

The olfactory system of fruit flies as inspiration for AI research!

COMPUTER SCIENCE

A neural algorithm for a fundamental computing problem

Sanjoy Dasgupta,[1] Charles F. Stevens,[2,3] Saket Navlakha[4]*

Dasgupta, Stevens, & Navlakha. 2017

Fruit Fly Algorithm

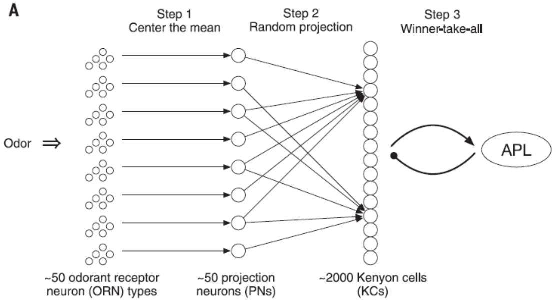
- **Problem:** Similarity search (e.g. find images in the internet that are similar, find odors that are similar important for fruit fly) -> nearest neighbor search

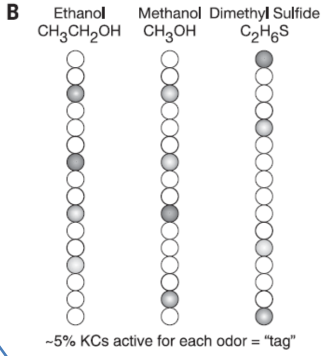
Fruit fly generates a tag for every odor (sparse representation, little overlap in active neurons between different odors) in 3 steps:

1) **Feed-Forward** connection from odor receptor to projections neurons in glomeruli (50 dimensional vector to 50 dimensions), make coding concentration independent (“centers the mean”)

2) **Random projection** of 50 dim vector to 2000 Kenyon cells (40 fold expansion) via a **sparse, binary random connection matrix**

3) **Winner takes all algorithm** via strong inhibitory neuron (5% of 2000 neurons remain active) -> tag of an odor is firing rates of 5% active neurons (tag = hash)



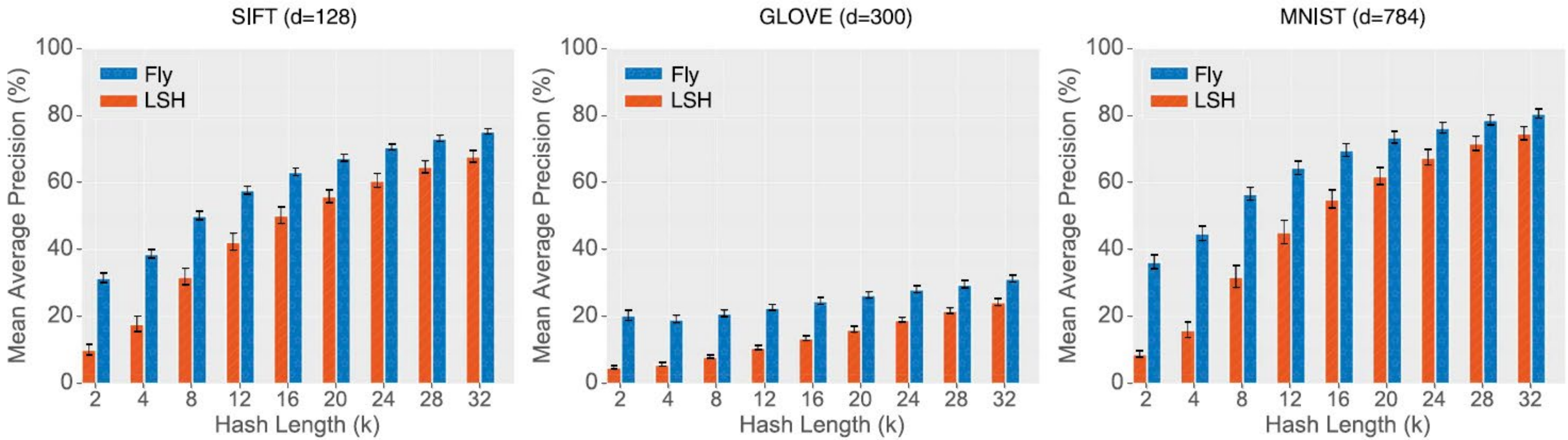


Tag is locality sensitive (similar odors have similar tags)

computationally efficient!

Fruit Fly Algorithm

Fruit Fly Algorithm outperforms standard locality sensitive hashing for all hash lengths!



Dasgupta, Stevens, & Navlakha. 2017

Fruit Fly Algorithm

Table 1. The generality of locality-sensitive hashing in the brain. Shown are the steps used in the fly olfactory circuit and their potential analogs in vertebrate brain regions.

	Step 1	Random projection	Step 2 (expansion)	Step 3 (WTA)
Fly olfaction	Antennae lobe; 50 glomeruli	Sparse, binary; samples six glomeruli	Mushroom body; 2000 Kenyon cells	APL neuron; top 5%
Mouse olfaction	Olfactory bulb; 1000 glomeruli	Dense, weak; samples all glomeruli	Piriform cortex; 100,000 semi-lunar cells	Layer 2A; top 10%
Rat cerebellum	Precerebellar nuclei	Sparse, binary; samples four precerebellar nuceli	Granule cell layer; 250 million granule cells	Golgi cells; top 10 to 20%
Rat hippocampus	Entorhinal cortex; 30,000 grid cells	Unknown	Dentate gyrus; 1.2 million granule cells	Hilar cells; top 2%

Dasgupta, Stevens, & Navlakha. 2017

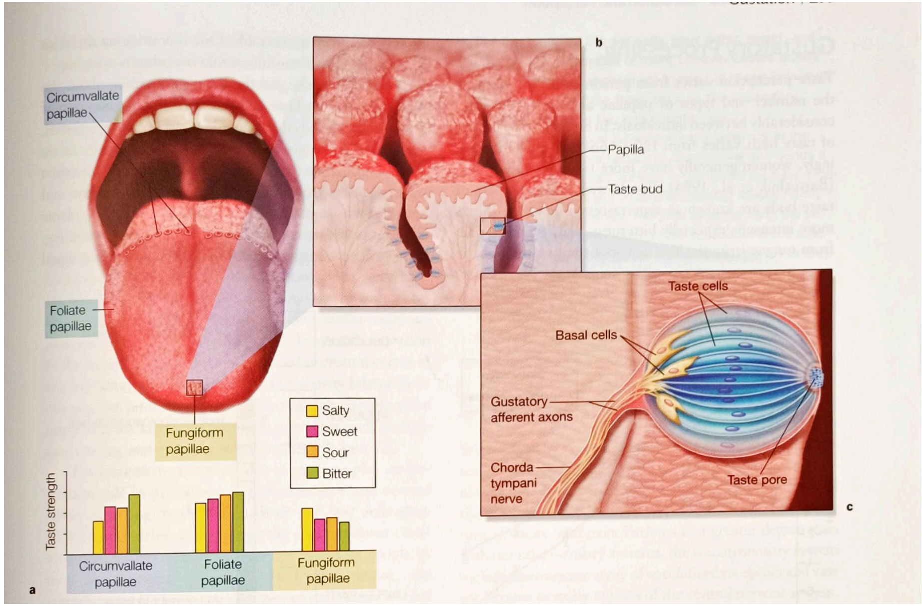
Perhaps locality sensitive hashing through random projections and dimensionality expansions is a standard algorithm in the brain!

Gustatory System

The gustatory system

The **sense of taste**, or **gustation** is the sense through which tastes are perceived.

- Chemical sense like olfactory sense

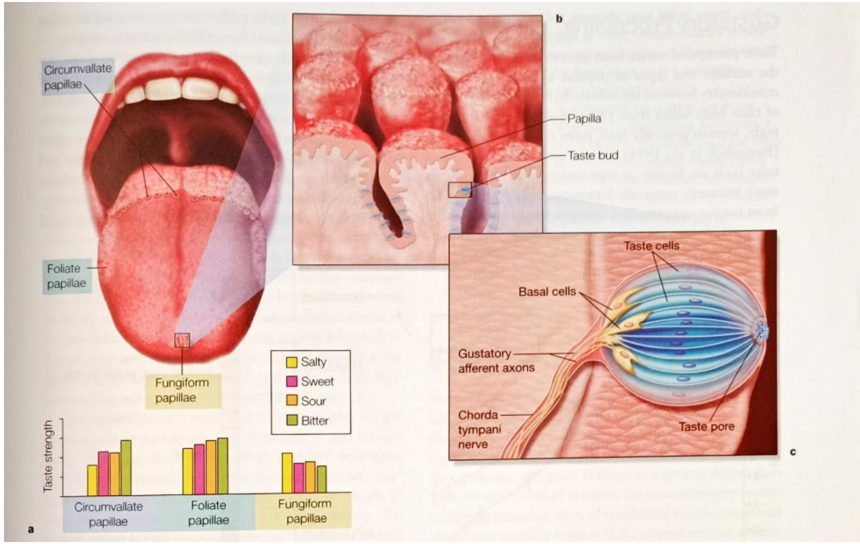


Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

The gustatory system

- Chemical sense like olfactory sense

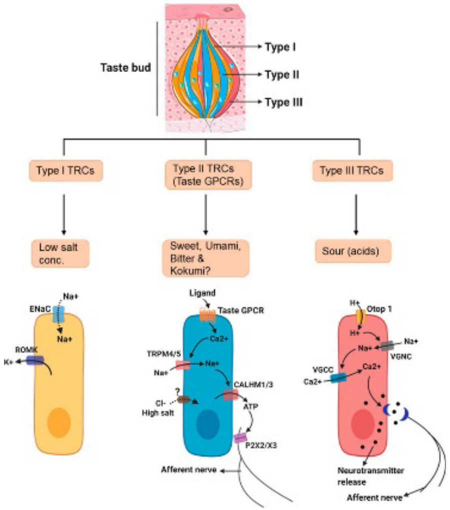
- **Papillae** on the tongue contain several taste buds
- Taste buds contain several **taste cells**
- **Five basic tastes:** salty, sour, bitter, sweet and umami
- Taste begins when a tastant stimulates a receptor

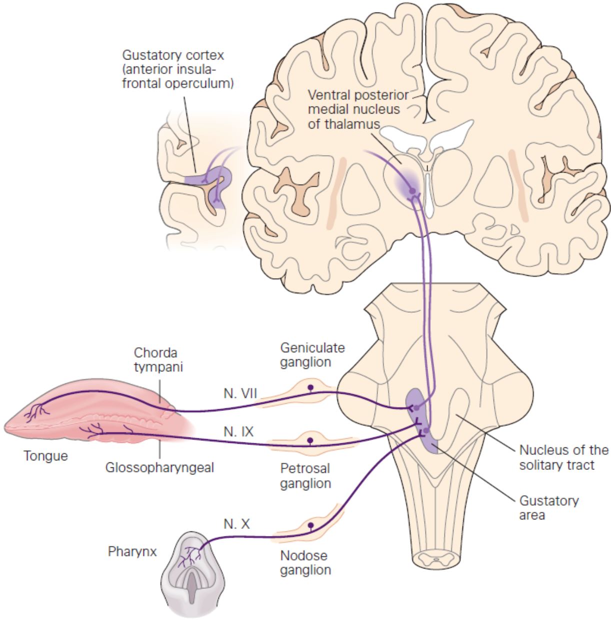


Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

The gustatory system

- **Taste receptor**:
  - For bitter, sweet, umami -> complicated protein cascade
  - for salty and sour -> change of ion concentration (bitter has low detection threshold)
- Signal transmitted to **gustatory cortex** (in insular cortex) via brainstem, thalamus
- **Orbitofrontal cortex** is important for processing the pleasantness of stimulus (chocolate)





Ahmad, R., & Dalziel, J. E. (2020). G protein-coupled receptors in taste physiology and pharmacology. *Frontiers in pharmacology*, *11*, 587664.