Chapter 9

Sensation and Perception: The Chemical Senses

Chapter 9 outline

9.1 Olfactory system

- Smell; activated by **odorants**

9.2 Gustatory system

- Taste; activated by **flavorants**

9.3 Internal chemosensory system

- Activated by **chemicals in the body**
- E.g., amount of carbon dioxide in the blood
- Induces unconscious or involuntary physiological changes to restore homeostasis

Olfaction

- Ability to sense and perceive volatile chemicals that are suspended in the air
- Closely intertwined with gustatory system (taste)
- Typical human can distinguish up to 10,000 distinct odours
- Affect our conscious behaviour
  - Bread: energy-rich carbohydrates
  - Decaying carcass: disease exposure

Odorant examples

- Esters
  - Apples and oranges
- Sulfurous compounds
  - Skunks and rotten eggs
- Romantic partner’s scent during sleep
  - More efficient sleep
- Subliminal citrus smells
  - More thorough cleaning post-crumbly biscuit

Mercaptans

A threatened skunk produces mercaptans, volatile chemicals that serve as a warning signal against to deter predators.

% of brain that mediates smell

Mouse: 2%

Humans: 0.01%

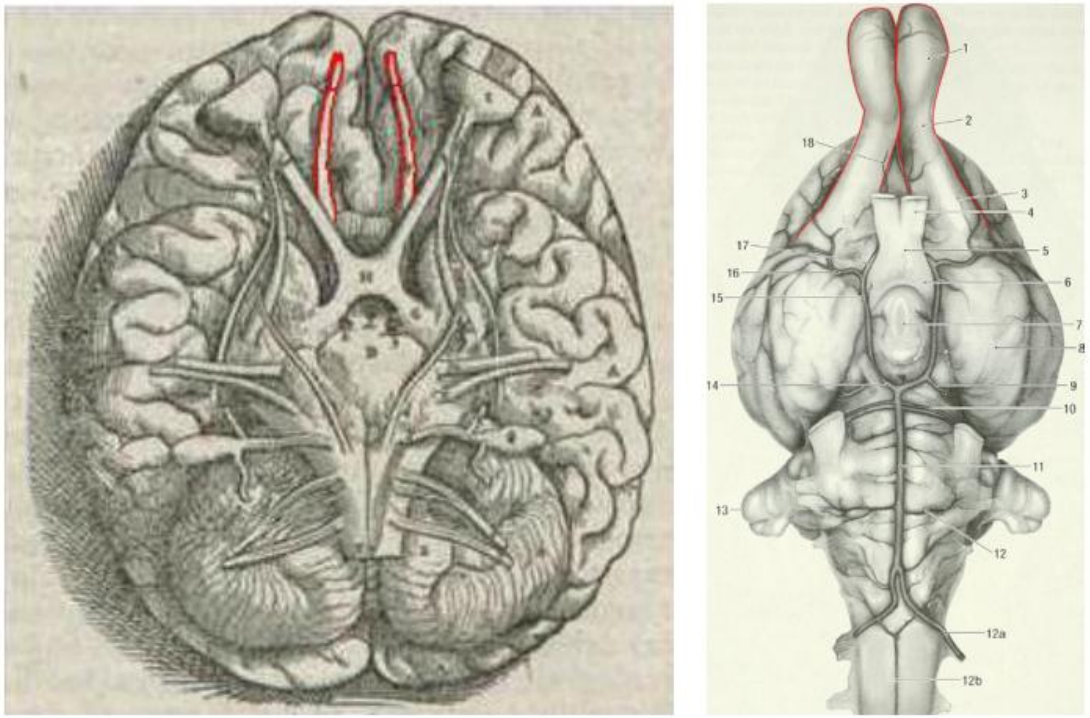


Figure 9.2 Ventral view of a human brain (left) and a woodchuck (right), showing that proportionally less brain tissue is dedicated to olfactory systems (red) in humans compared to other mammals.

Anatomy of the olfactory system

Odorant traverses nostrils and enters nasal cavity

- Empty, air-filled space just behind the front of the skull

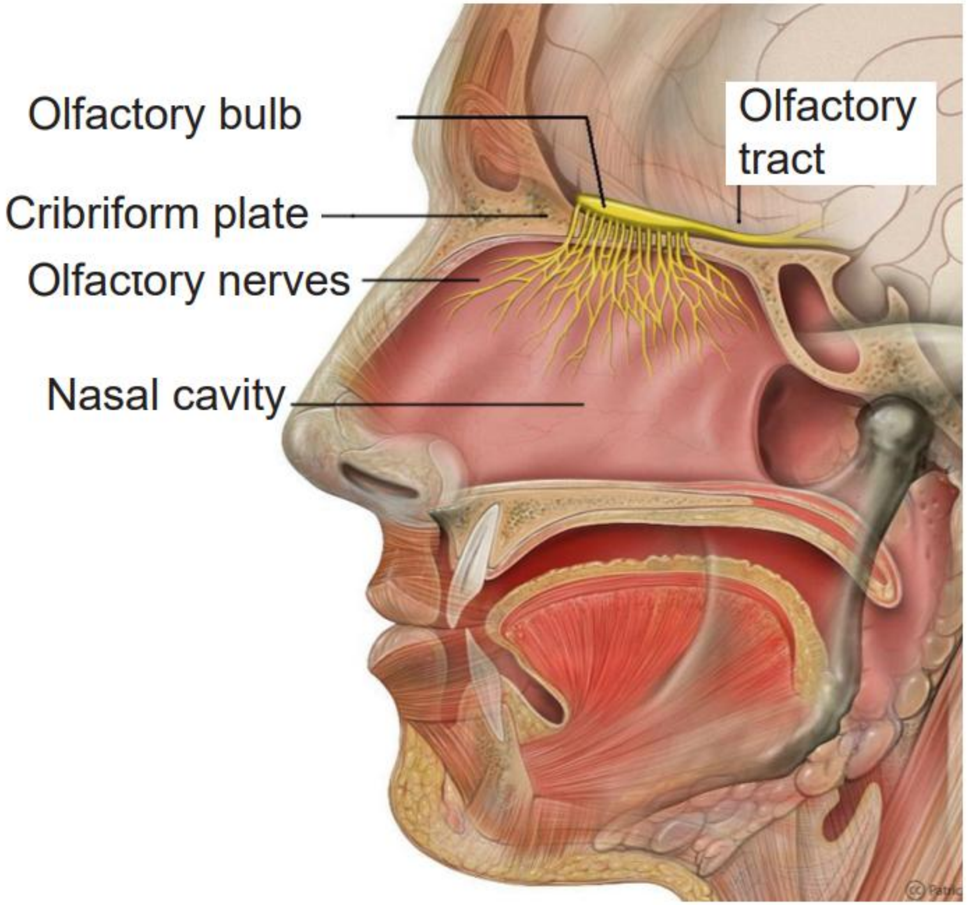


Figure 9.3 Cross section showing the major anatomical structures of the olfactory system.

Cribriform plate

- CG: crista galli (projects upwards)
- CF: cribriform plate

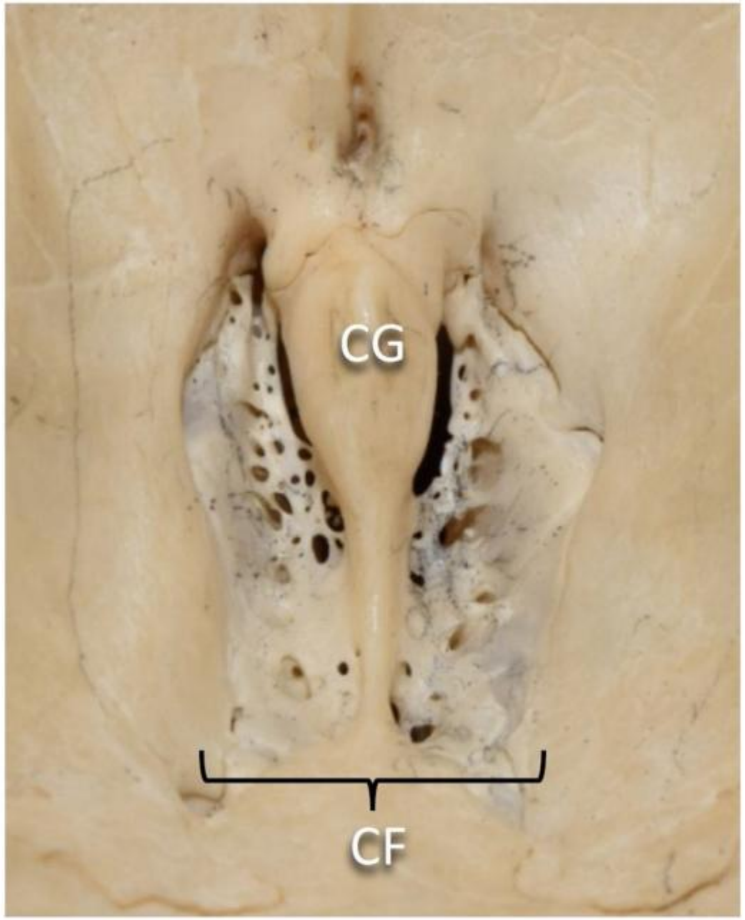


Figure 9.5 The cribriform plate at the base of the skull allows for the axons of the ORNs to pass into the brain.

Olfactory epithelium

- Dorsal-most portion of the nasal cavity
- Mucus-covered patch of tissue
- Houses olfactory receptor neurons (ORNs)
- 6-20 million ORNs in the human olfactory system
- ORNs are
  - the neurons which begin processing smell
  - bipolar neurons with long dendritic projections protruding into epithelium
  - in direct contact with air

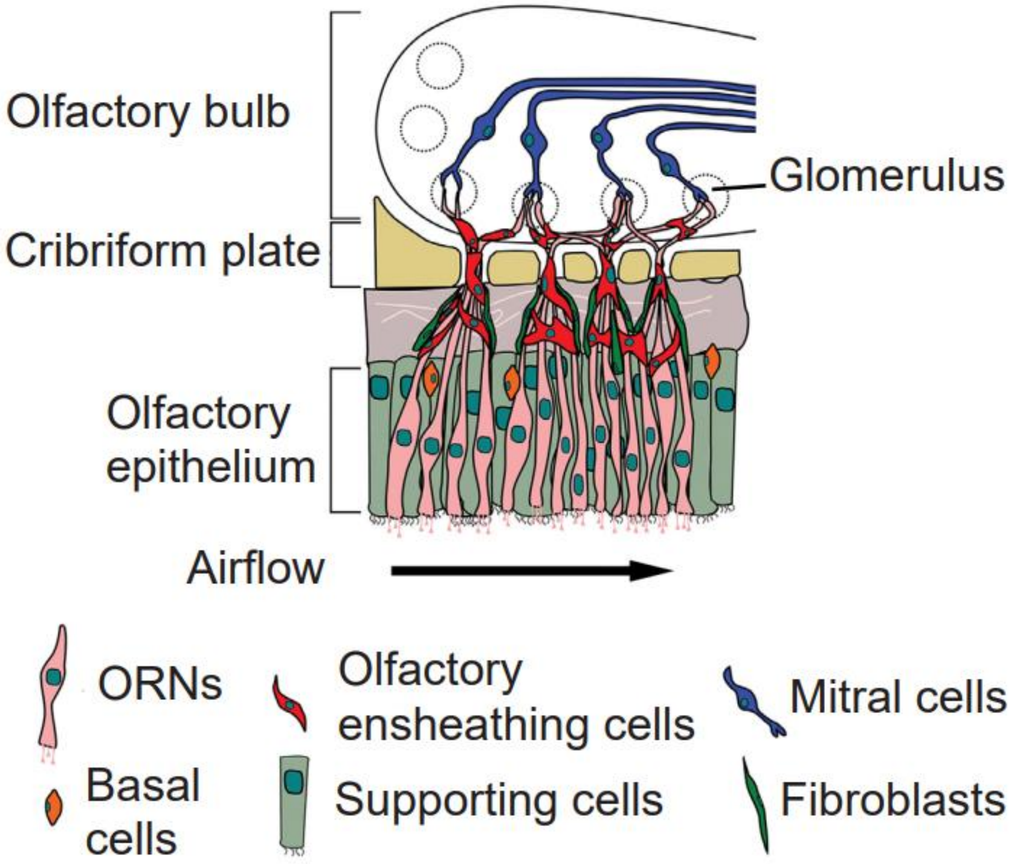


Figure 9.4 The cellular anatomy of the olfactory epithelium and olfactory bulb.

Olfactory epithelium

- Also houses supporting cells
- Much like glia
- Help dispose of dead and dying cells
- Help metabolize pollutants
- Help physically maintain the olfactory epithelium

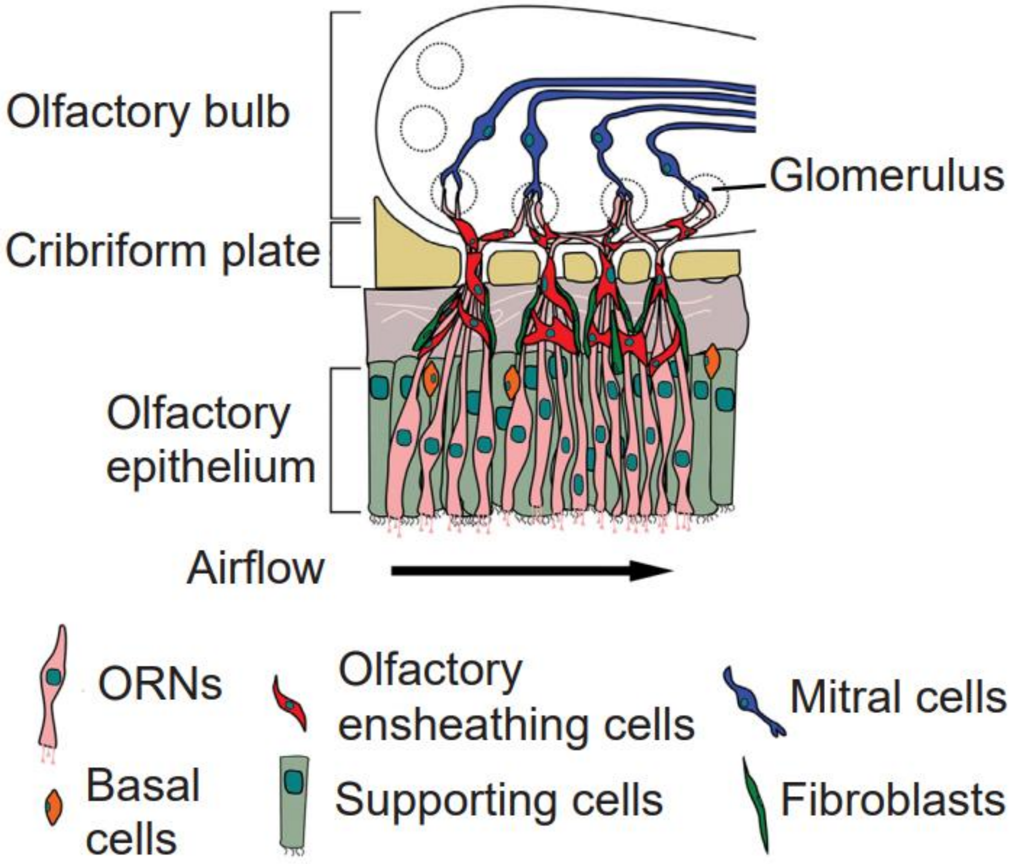


Figure 9.4 The cellular anatomy of the olfactory epithelium and olfactory bulb.

ORNs are the only neurons directly exposed to the outside world

- Exposed to toxins, particulates, and microbes
- One of the few populations of neurons for which **adult neurogenesis** occurs
- Each ORN has a lifespan of 30 days to a year

Olfactory receptors

- On the dendrites of ORNs
- Estimated 1000 different genes (about 3% of the total human genome)
- Roughly 400 different olfactory receptors
- Each ORN expresses only one type of olfactory receptor
- Each olfactory receptor is activated by a different chemical
- E.g., ORN293 responds to cadaverine
- Most have still not been matched to a corresponding odorant

Nobel prize

- Dr. Linda Buck’s work

Olfactory receptors

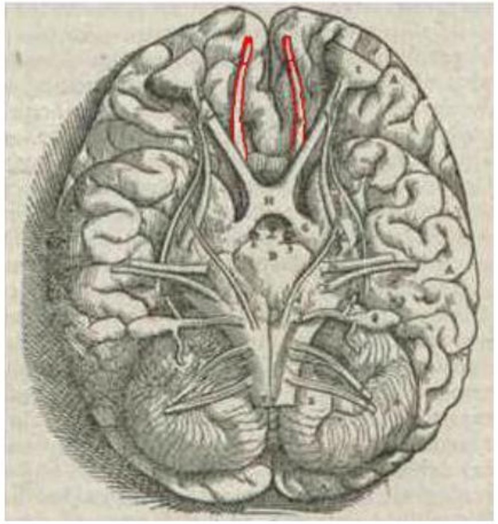
- G protein coupled receptors
- $G_{\alpha \text{olf}}$
- 90% similar to $G_{\alpha \text{s}}$
- Triggers activation of AC (adenylate cyclase)
- Elevates intracellular concentration of cyclic AMP
- Causes depolarization -> ORN more likely to fire an action potential

Smell intensity encoding

- Action potential firing frequency increases with increasing concentration of odorant molecules

Following activation of the receptors …

- Axons of ORNs pass through the skull through tiny series of holes at the cribriform plate
- Form synaptic connections onto neurons in the olfactory bulb (i.e., the beginning of CN I or the olfactory nerve)



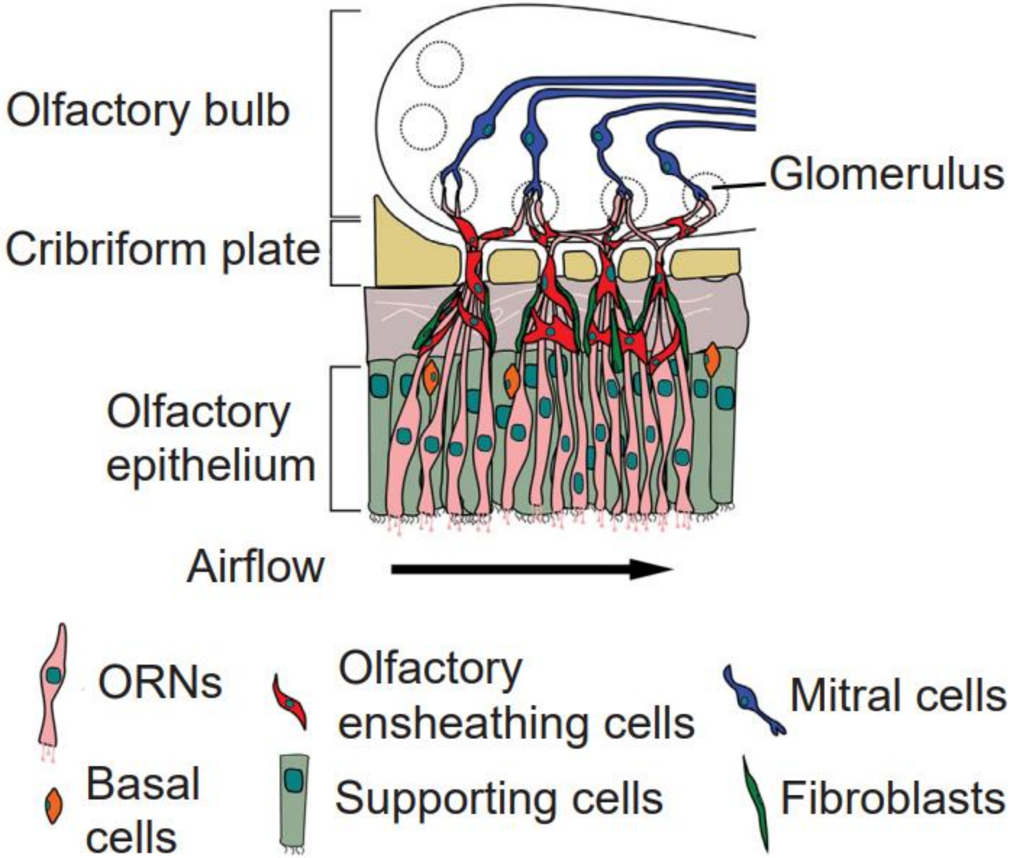


Figure 9.4 The cellular anatomy of the olfactory epithelium and olfactory bulb.

Glomeruli

- Within olfactory bulb
- Highly specialized clumps of tissue
- Typical humans have a little under 2000 glomeruli
- Each glomerulus only receives inputs from ORNs that express the same type of olfactory receptor
- Glomeruli contain dendrites of the secondary neurons

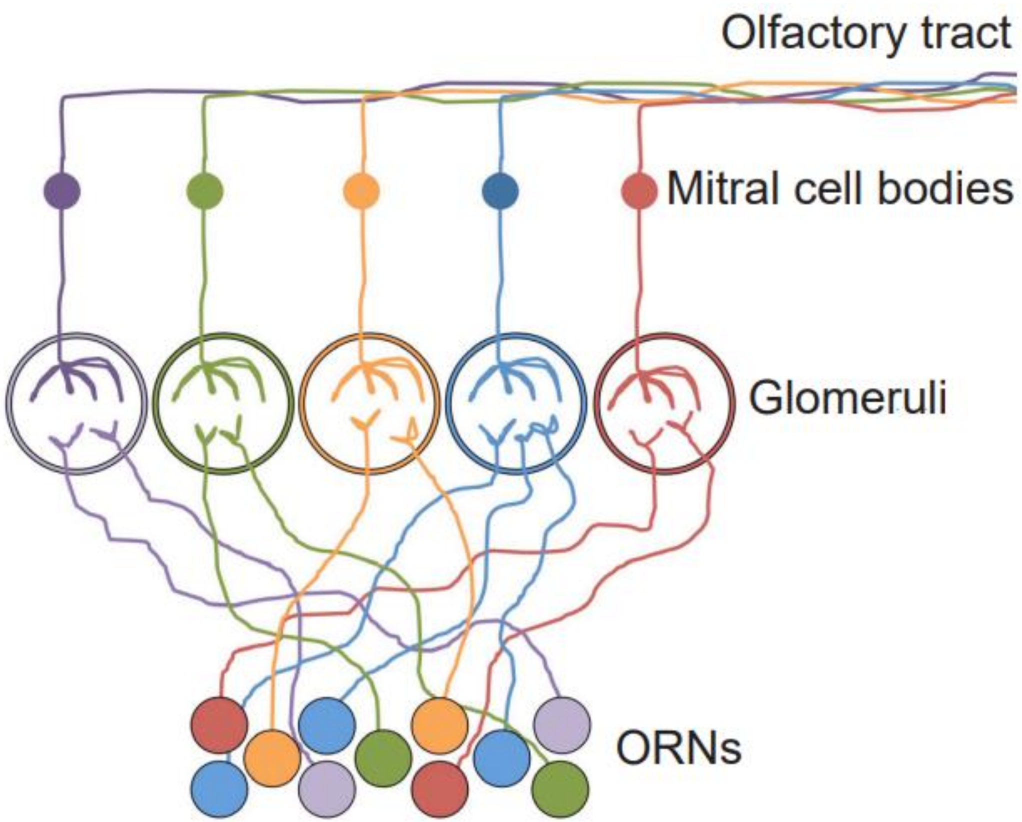


Figure 9.6 Communication between the ORNs and downstream neurons occur at glomeruli. Different colors indicate distinct populations of ORNs, which express only one type of olfactory receptor.

Mitral cells and tufted cells

- Two cell populations
- Their dendrites are in the glomeruli
- Both mitral and tufted cells project axons directly into the olfactory cortex
- Only sensory system that does not pass signals through the thalamus before cortical processing

Lateral inhibition

- Inhibitory cells regulate olfactory pathway, similar to lateral inhibition in retina (Chap 7)
- Refine processing of scent information
- Granule cells
  - Found within glomeruli
- Periglomerular cells
  - Send axonal projections into the glomeruli

Small group activity

- Consider the neurons and receptors of the olfactory system compared to other sensory systems you learned about in PSYC 231. Draw analogies, compare and contrast, etc.
- **Example:** The olfactory receptor neurons (ORNs) are similar to rods and cones in the visual system in that they are the neurons that transduce the physical stimulus into a nervous system signal.

- Assign one person to report back to the class

Glomeruli

- Within olfactory bulb
- Highly specialized clumps of tissue
- Typical humans have a little under 2000 glomeruli
- Each glomerulus only receives inputs from ORNs that express the same type of olfactory receptor
- Glomeruli contain dendrites of the secondary neurons

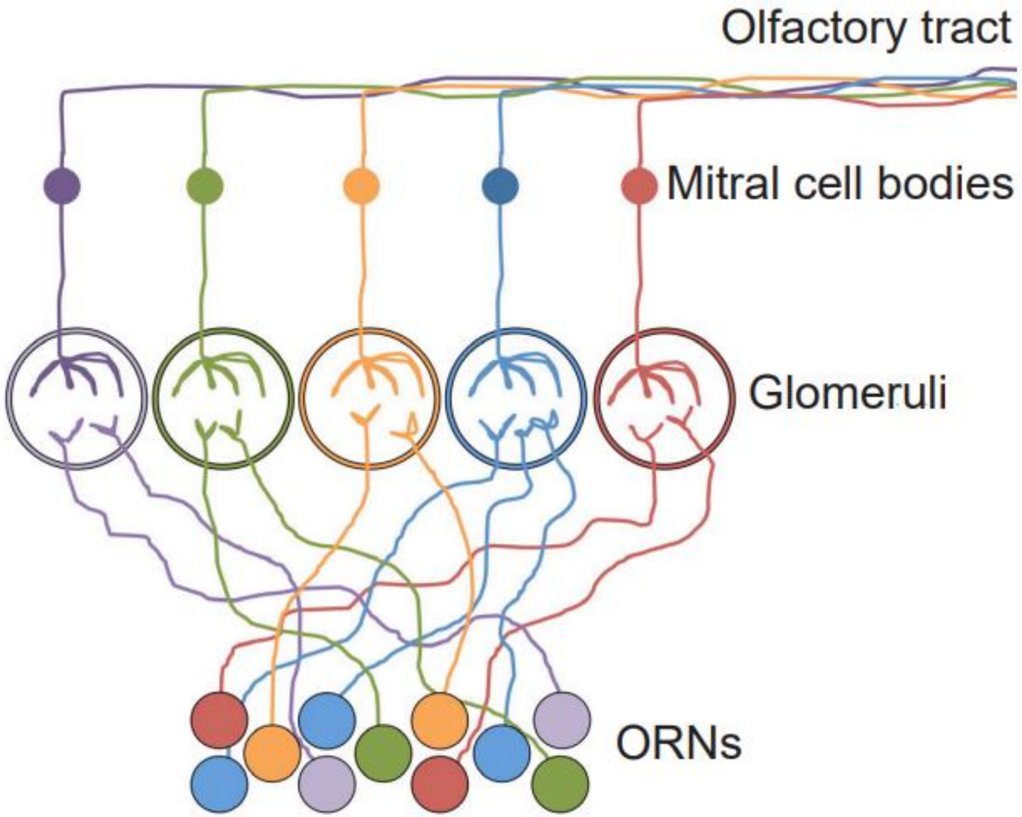


Figure 9.6 Communication between the ORNs and downstream neurons occur at glomeruli. Different colors indicate distinct populations of ORNs, which express only one type of olfactory receptor.

Olfactory cortex

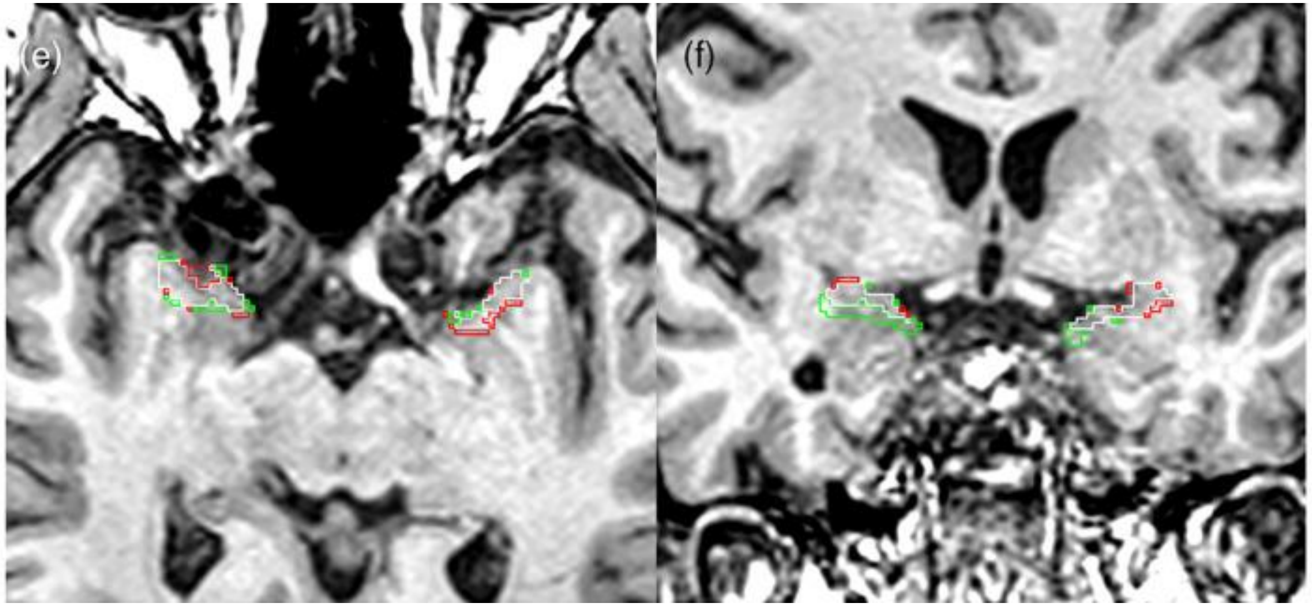
- Receives input from mitral and tufted cells

All these regions are considered olfactory cortex:

1. Piriform cortex
2. Cortical amygdala
3. Entorhinal cortex
4. Orbitofrontal cortex

Piriform cortex

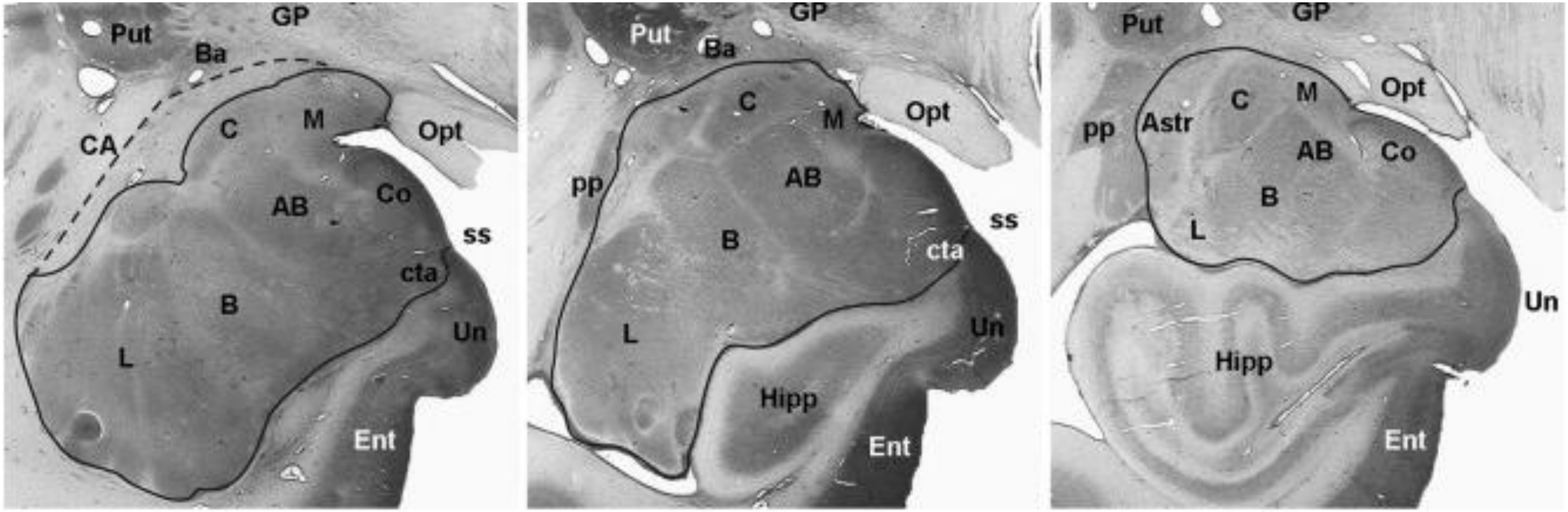
- Main cortical input site for axonal projects from olfactory bulb
- Up to 10% of cortical volume in species that rely heavily on sense of smell
- Output to other structures in olfactory cortex a well as mediodorsal thalamus (learning and decision making)



Steinbart et al., 2023.

Cortical amygdala

- Part of the amygdala, which helps mediate complex emotional states (Chap 15)
- Sends projections to the hippocampus (formation of new memories)
- Explains link between smell and memory



Brabec et al., 2010

Entorhinal cortex

- Small section of the medial temporal lobe
- Sends strong connections to the hippocampus (links olfaction to memory)
- Also involved in spatial navigation tasks

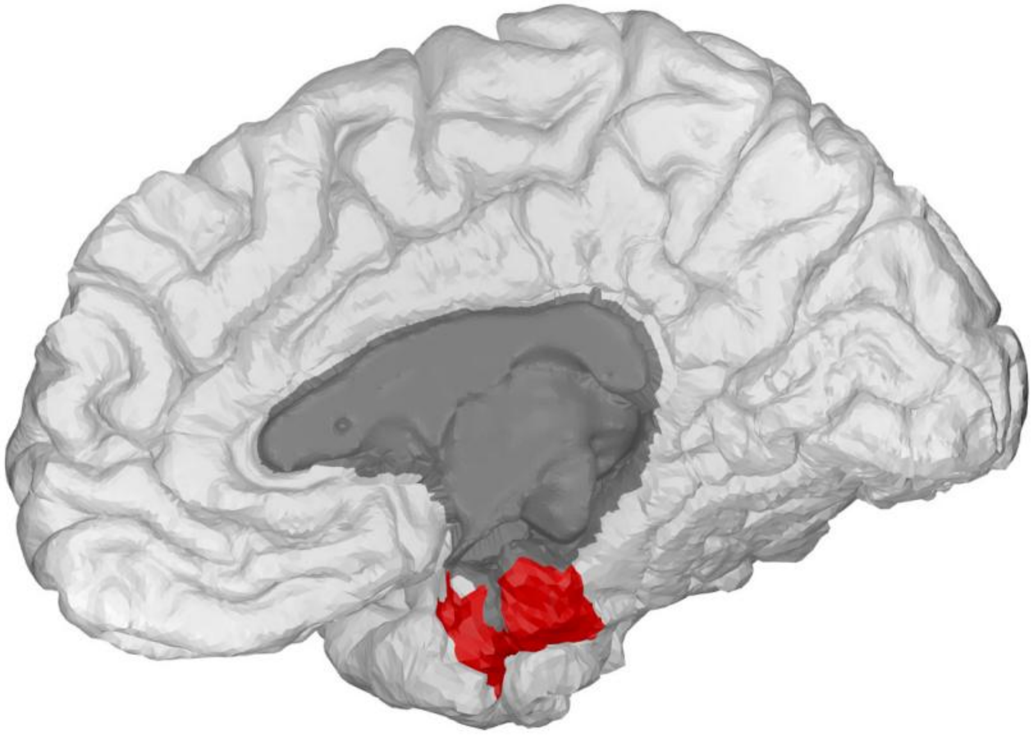


Figure 9.8 The entorhinal cortex (red) is found along the ventral surface of the medial temporal lobe.

Orbitofrontal cortex

- Found just behind the orbit (bony socket of the skull where the eyes sit)
- Ventral surface of frontal lobe
- Functions still under investigation
- Integration site for sensory inputs (also receives projections from visual, taste, and somatosensory cortices)
- Implicated in decision making and social behaviours

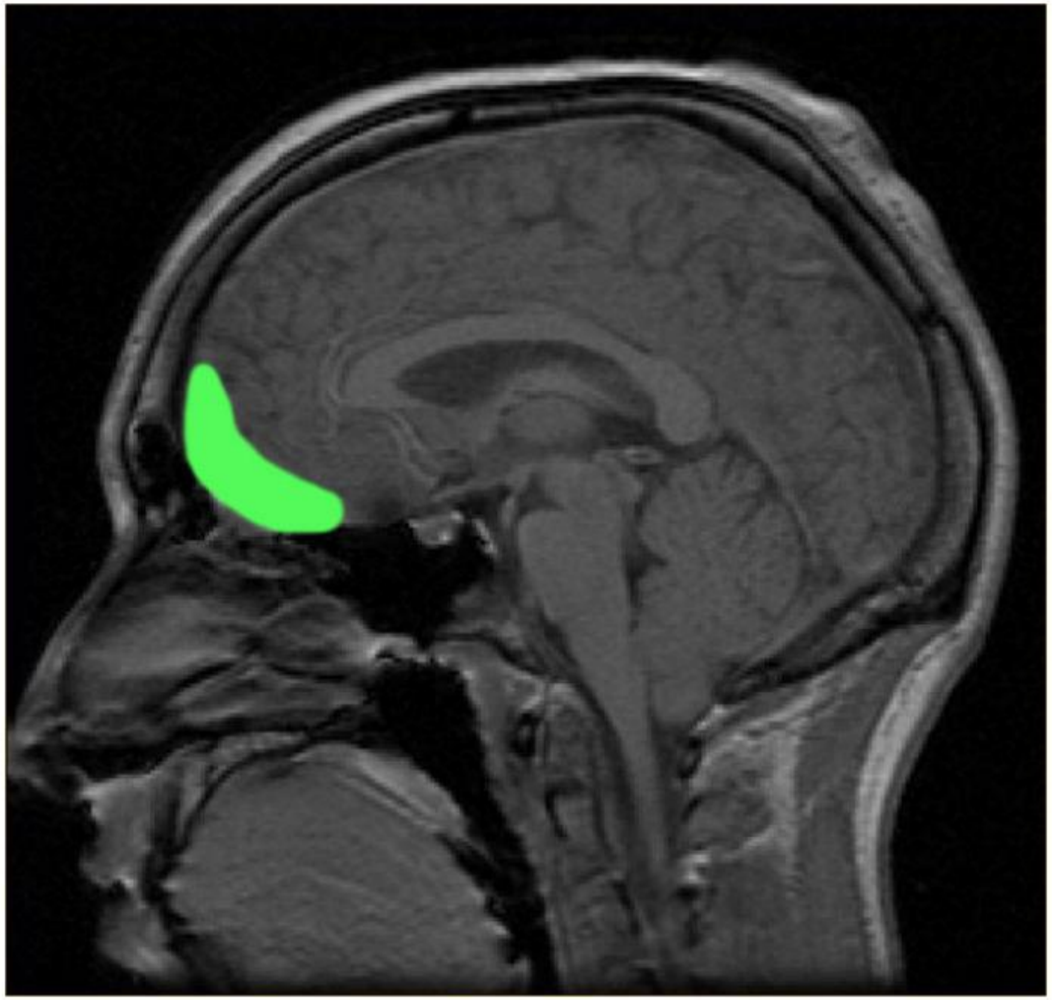
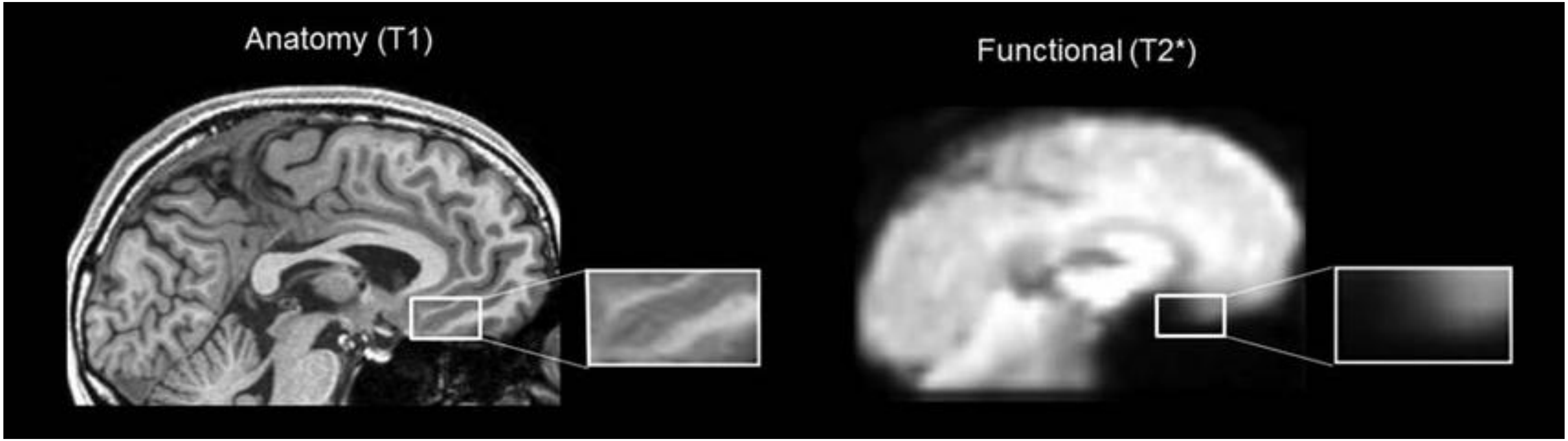


Figure 9.9 MRI image of a parasagittal section of the brain showing the orbitofrontal cortex (green).

It's hard to study the orbitofrontal cortex in human: fMRI artifacts



Peer et al., 2016

Small group activity

- Consider the cranial nerves and brain regions involved in olfaction. Draw analogies, compare and contrast, etc.
- **Example:** The olfactory system is different from other sensory systems because the signals do not pass through the thalamus

- Assign one person to report back to the class

Olfaction and the autonomic nervous system

- https://pubmed.ncbi.nlm.nih.gov/21224443/

Pheromones

- Debated in humans (read more here)
- Many nonhumans have a **vomeronasal organ**
- Detects organic compounds produced by predators and reproduction-related hormones produced by the opposite sex
- Signals are sent to the brain via cranial nerve 0
- Behaviour changes triggered

Disorders of the olfactory system

- Hyposmia – reduced ability to smell
- Anosmia – complete loss of smell
- Phantosmia – olfactory hallucination

- Nasal congestion often causes temporary hyposmia due to physical blockage of nasal cavities (fewer particles reach olfactory epithelium)
- COVID-19 related hyposmia thought to have neurological origin
- Hyposmia common in aging
- Hyposmia precedes many symptoms in neurodegenerative disorders such as Parkinson’s disease (biomarker?)

Gustatory system

- Guides us to energy-rich foods
- Helps us avoid foods that could make us sick
- Tastant – substance that has a taste
- 5 taste modalities
  - Sweet, salty, sour, bitter, umami
- Humans have evolved …
  - to like sweet foods to ensure energy consumption
  - to avoid bitter foods because toxins are often bitter

Appeal of a tastant depends on its concentration

- Mild bitterness of coffee OK/delicious
- Excessive sweetness or saltiness not appealing

Anatomy of the gustatory system

- Lingual papillae
  - Give tough rough appearance
  - Can be seen with the naked eye
- Taste buds
  - Up to 100 on each papilla
  - Onion-shaped structure
  - Also found on palate and in throat
  - Total of about 10000 depending on age

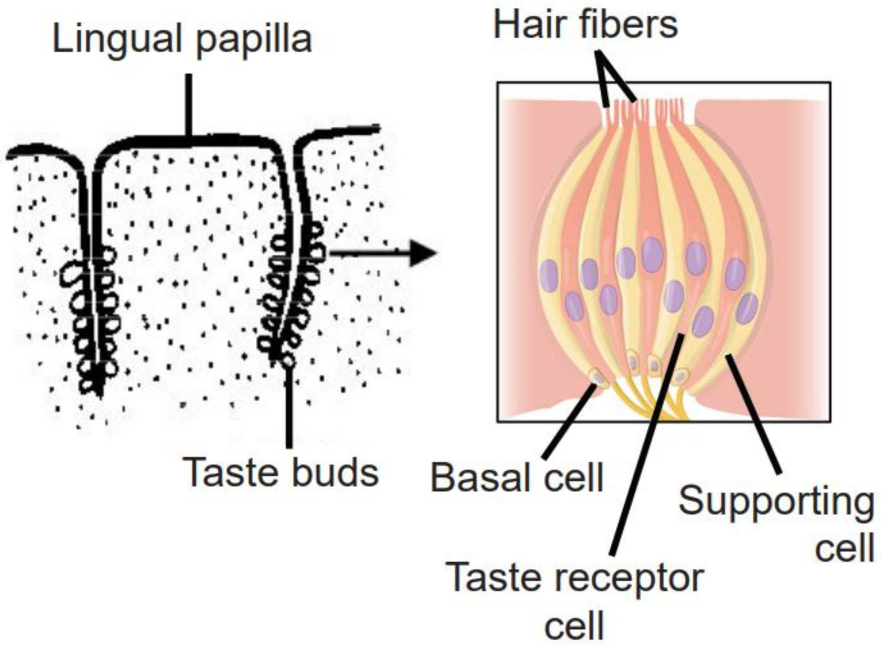


Figure 9.10 On each lingual papilla are taste buds (left). A magnified view of a taste bud (right).

Anatomy of the gustatory system

- Taste receptor cell
  - About 100 per taste bud
  - Technically not neurons; derived from specialized epithelial cells
  - Sprout taste hairs at the apical tip of the taste bud
  - Taste hairs extend into taste pores
  - Taste hairs meet saliva in taste pores

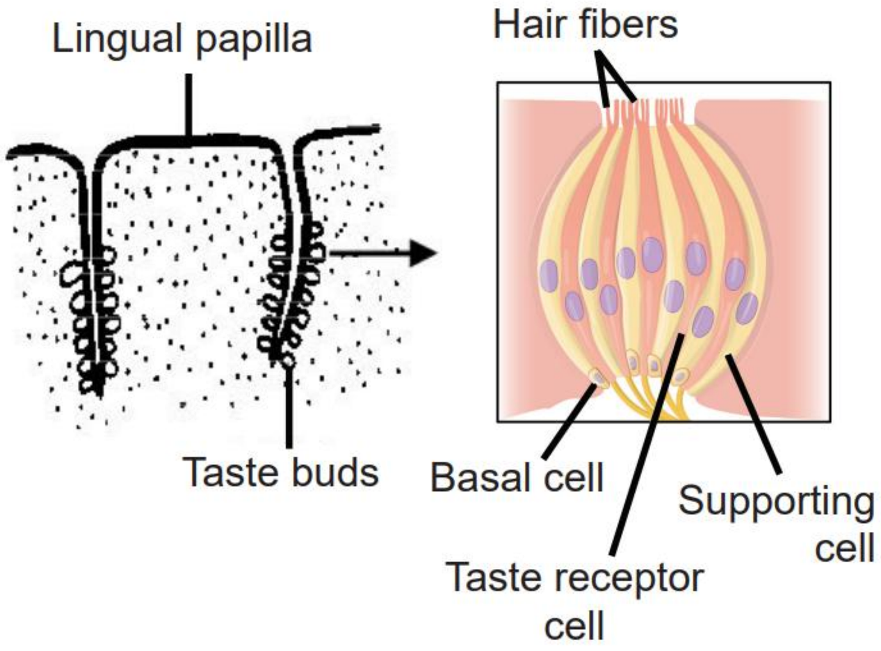


Figure 9.10 On each lingual papilla are taste buds (left). A magnified view of a taste bud (right).

Activity
Label:
1. Apical tip of taste bud
2. Taste pore

Anatomy of the gustatory system

- Basal and supporting cells
  - Contained in taste buds
  - Basal cells reproduce to form supporting cells
  - Over time, support cells mature into taste receptor cells (taste receptor cells turnover every 8-22 days)

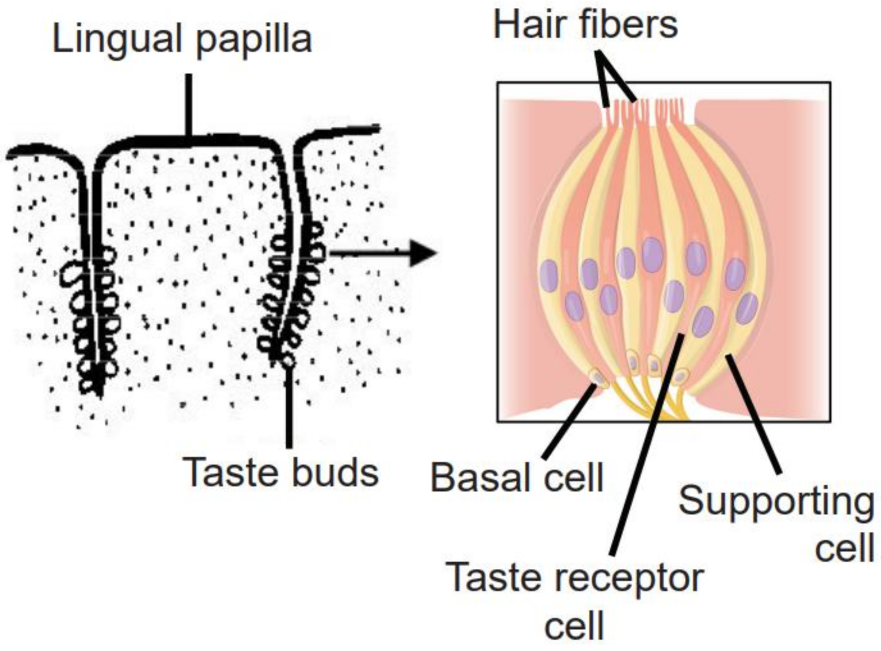


Figure 9.10 On each lingual papilla are taste buds (left). A magnified view of a taste bud (right).

Taste receptor cells

- Responsible for sensing and conveying information about taste in accordance with the main taste modalities (salty, sweet, etc.)
- Taste receptor cells express receptors for only one taste modality
  - This is similar to which sensory system?

Taste receptor cell communication

- Communicate with afferent gustatory neurons which originate from three of the 12 cranial nerves
- These neurons communicate with second order neurons in the rostral **medulla** in an area called the solitary nucleus (or gustatory nucleus)

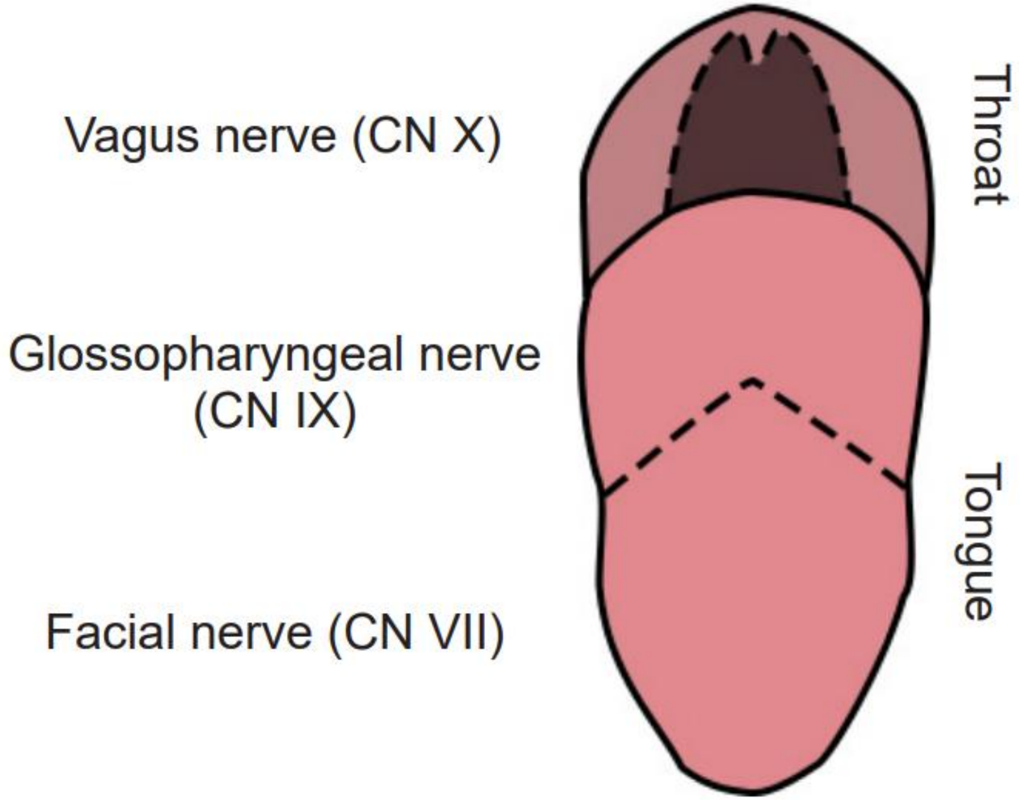
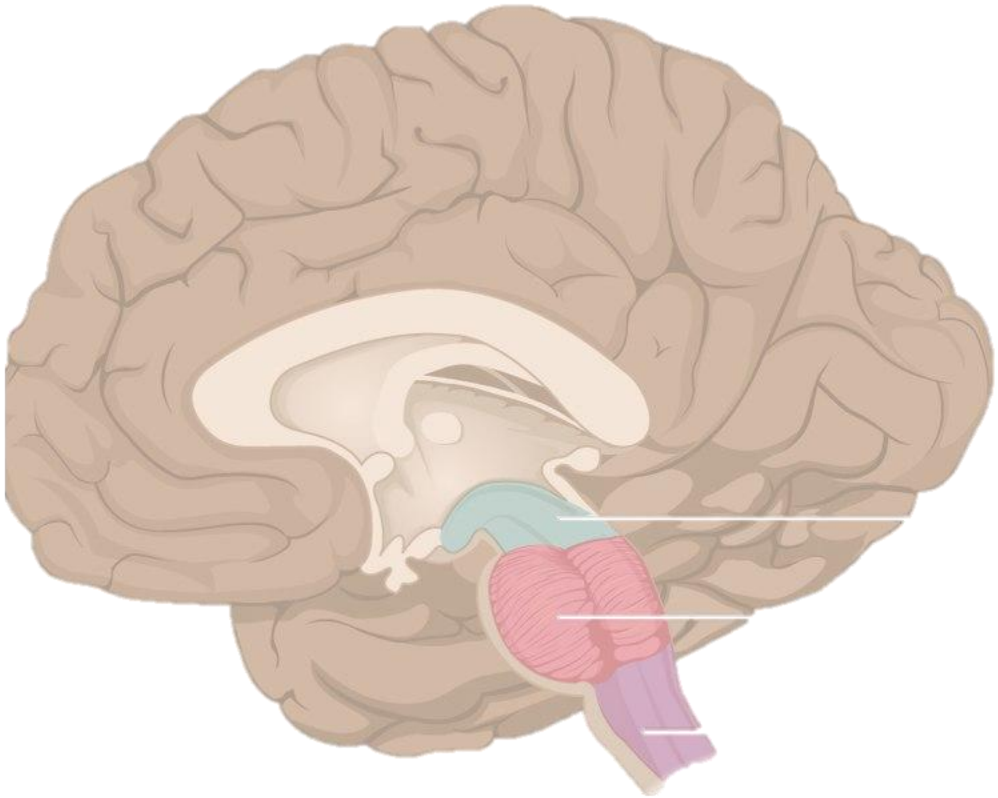


Figure 9.11 Different cranial nerves communicate information from different areas of the gustatory system.

Review: Which region is the medulla?



Solitary nucleus sends ipsilateral projections to the rest of the CNS

- Is this similar or different from other sensorimotor systems?

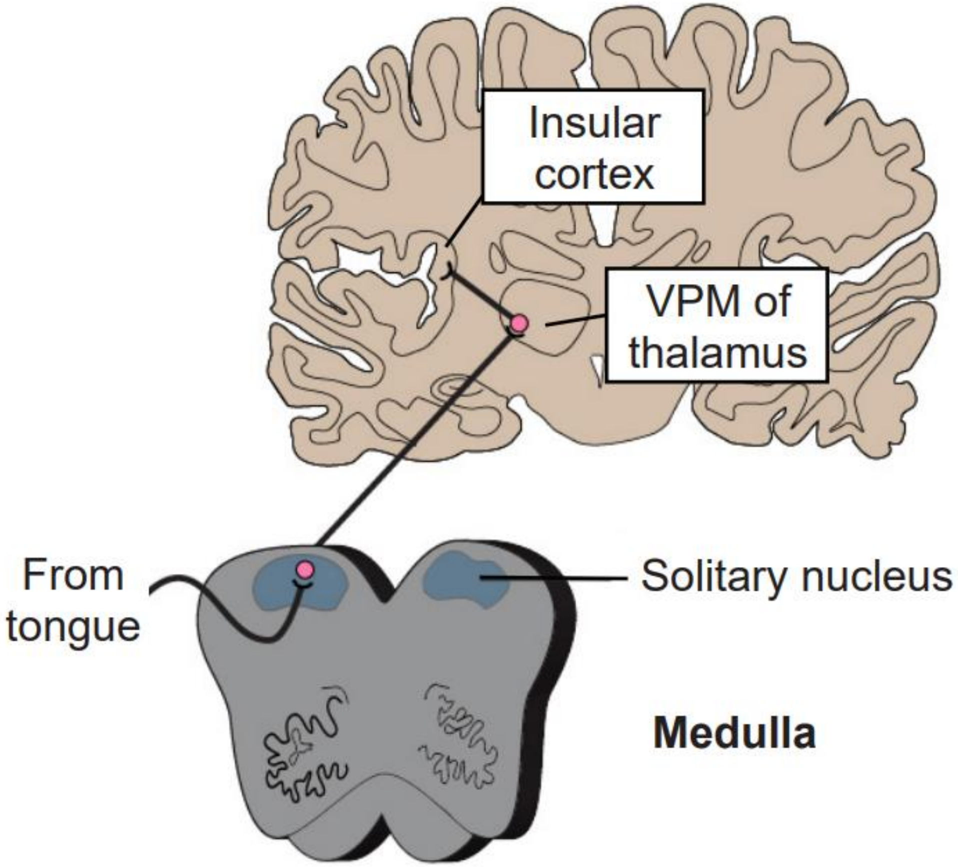


Figure 9.12 Afferent signaling from the tongue passes through medulla, then thalamus, then cortex.

Gustatory cortex

- Beginning of taste perception processing
- Includes anterior end of insular cortex and the frontal operculum of the frontal lobe
- These neurons convey information such as taste modality and intensity

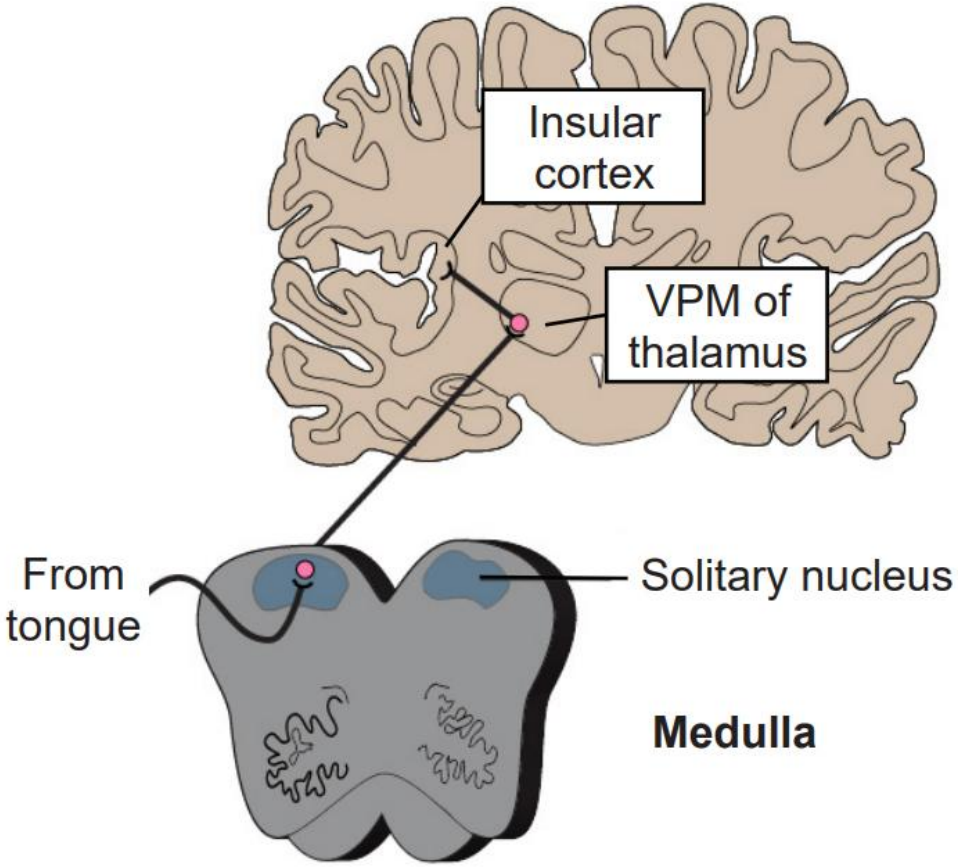
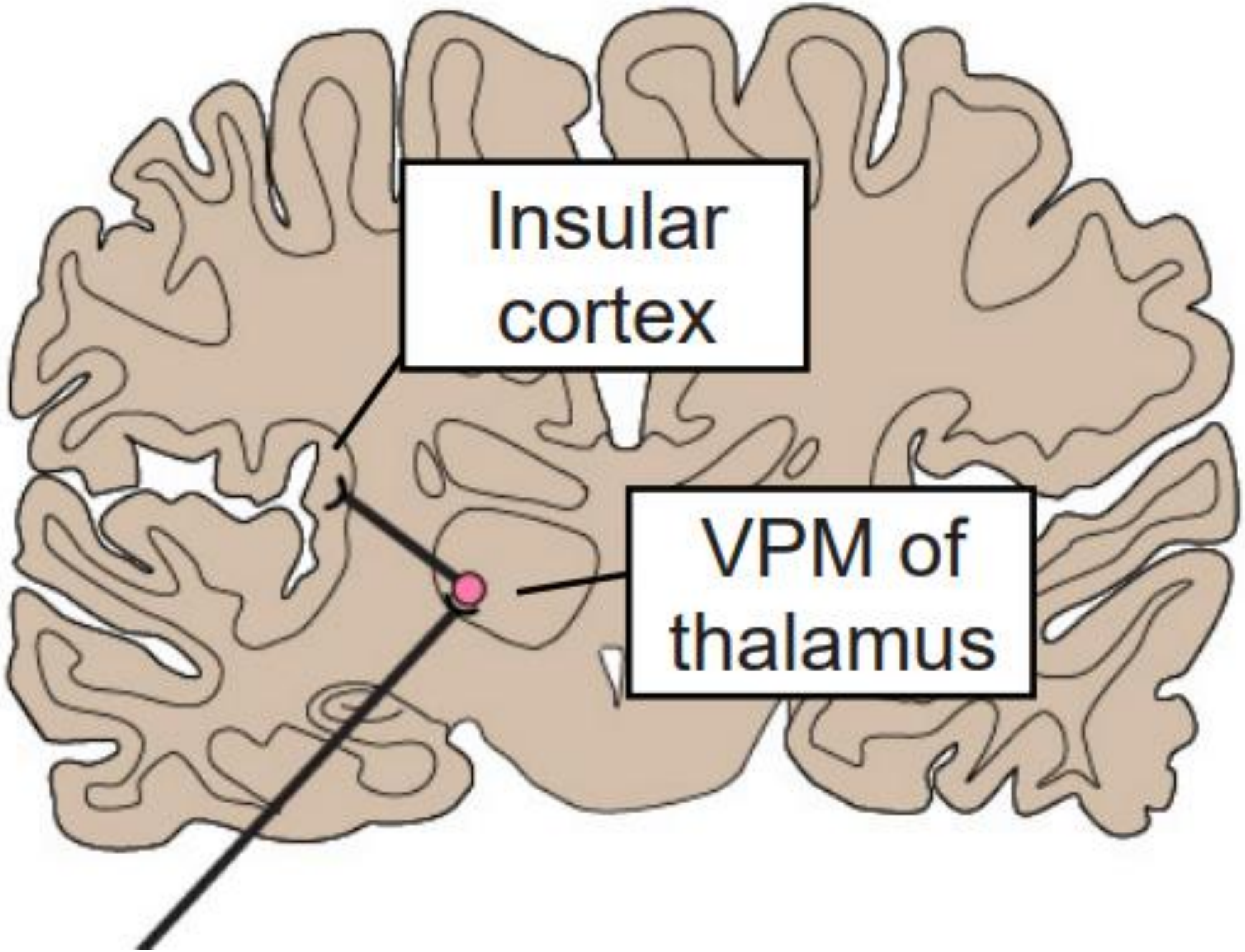
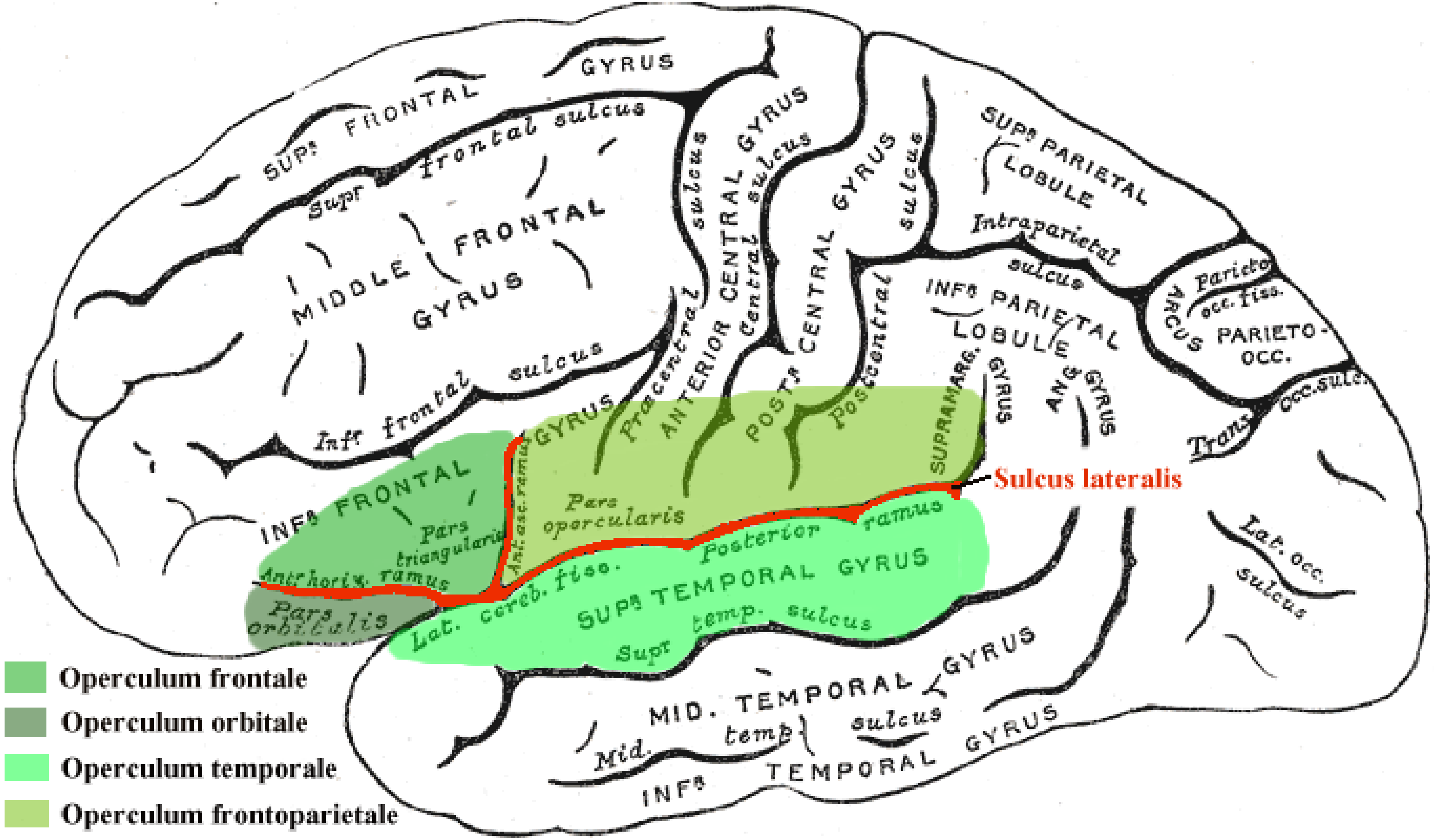


Figure 9.12 Afferent signaling from the tongue passes through medulla, then thalamus, then cortex.


Insular cortex
VPM of thalamus



Sulcus lateralis
Operculum frontale
Operculum orbitale
Operculum temporale
Operculum frontoparietale
SUPR FRONTAL GYRUS
Supr frontal sulcus
MIDDLE FRONTAL GYRUS
Infr frontal sulcus
INFR FRONTAL GYRUS
Pars triangularis
Pars opercularis
Pars orbitalis
Ant. horiz. ramus
Ant. asc. ramus
Precentral sulcus
ANTERIOR CENTRAL GYRUS
Central sulcus
POSTR CENTRAL GYRUS
Postcentral sulcus
SUPR PARIETAL LOBULE
Intraparietal sulcus
INFR PARIETAL LOBULE
SUPRAMARG. GYRUS
ANG. GYRUS
Parieto occ. fiss.
ARCUS PARIETO-OCC.
Trans. occ. sulc.
Lat. occ. sulcus
Lat. cereb. fiss.
Posterior ramus
SUPR TEMPORAL GYRUS
Supr temp. sulcus
MID. TEMPORAL GYRUS
Mid. temp. sulcus
INFR TEMPORAL GYRUS

Taste modalities

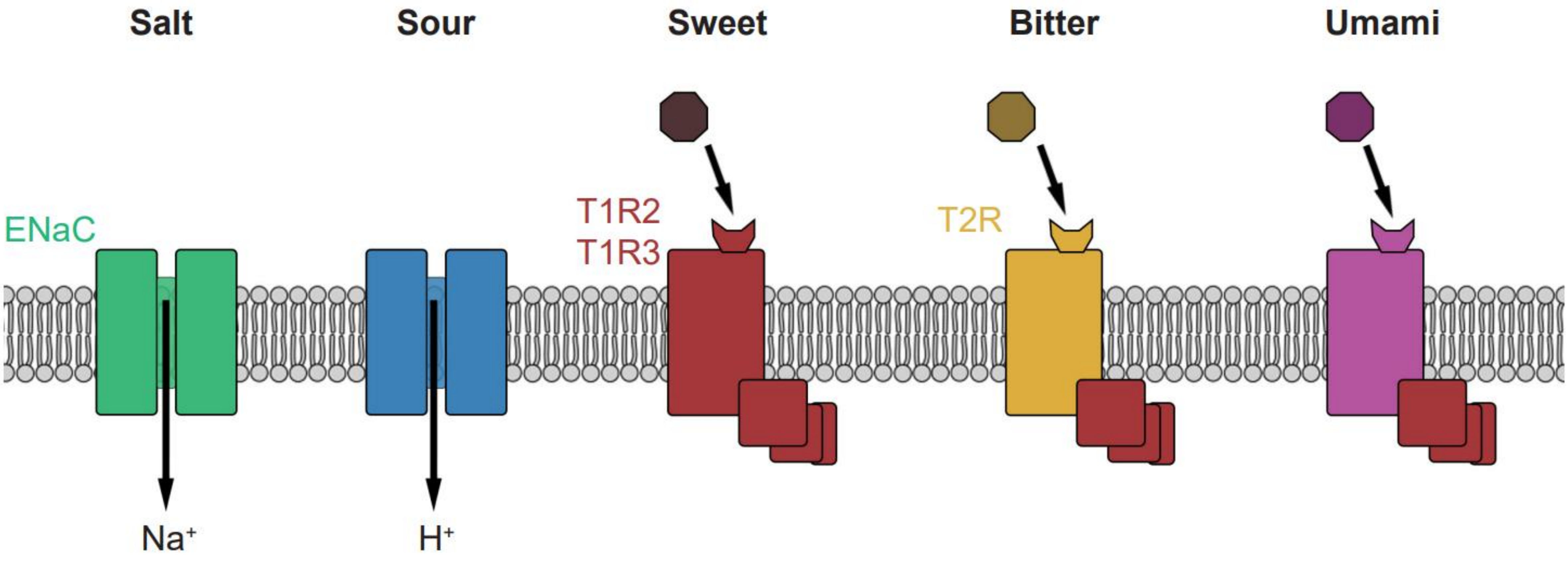
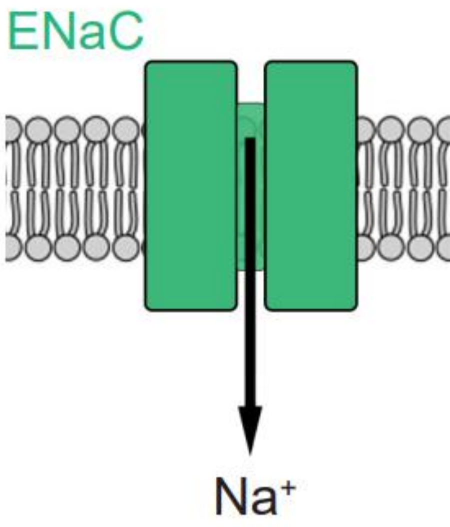


Figure 9.13 Taste modalities signal using different populations of receptors. Salt and sour are detected with ionotropic receptors, while sweet, bitter, and umami are sensed with metabotropic receptors. Many of the metabotropic receptors signal inside the cell using the α-gustducin molecule.

Salt



- Primarily driven by Na^+ ions
- NaCl (table salt) dissolves in saliva
- Free sodium ions can passively influx into salt taste receptor cells through epithelial sodium channels (ENaCs)
- Causes depolarization of taste receptor cells
- Depolarization activates voltage-gated calcium channels, prompting neurotransmitter release that activates that gustatory nerve afferent fibres
- Salty foods elicit a biphasic response
  - Too little salt – not appealing
  - Too much salt – aversive

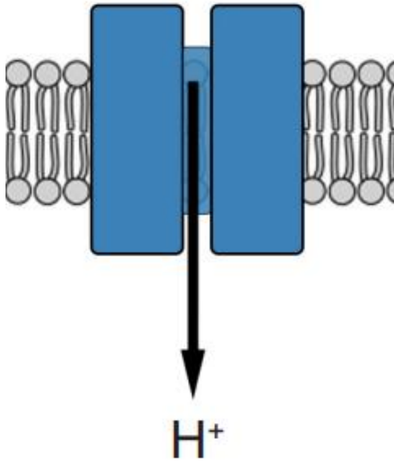
Appeal of salt depends on body’s needs at any given time

- Mediated by hormones such as ghrelin (appetite stimulating hormone)
- Regulates salt concentration in the body by mediating Na^+ absorption
- Current salt levels can impact appetite for salt
  - E.g., animals chronically deprived of salt find high salt solutions rewarding

Why are we so sensitive to taste of salt?

- Both Na^+ and Cl^- are essential nutrients
- Critical for maintaining blood volume and pressure, regulating body water, maintaining muscle contractions, and mediating action potentials
- Cl^- helps us maintain a healthy pH balance
- These functions depend on our salt concentrations falling within a specific range

Sour

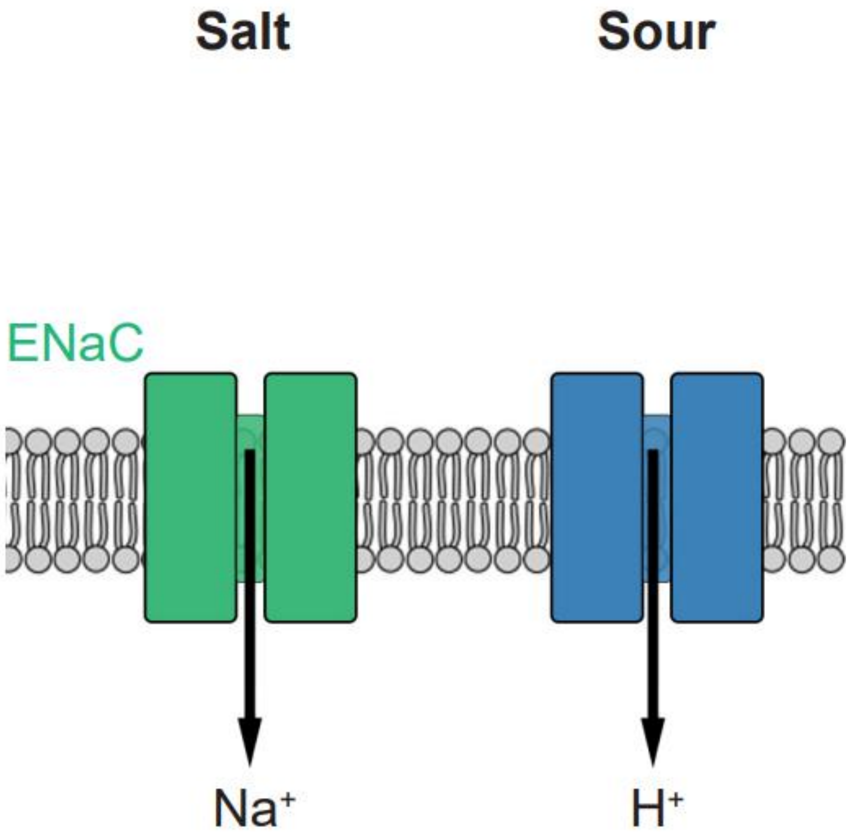


- Mediated by proton-selective channels, which is why acids are sour
- Entry of H^+ into cell will depolarize it

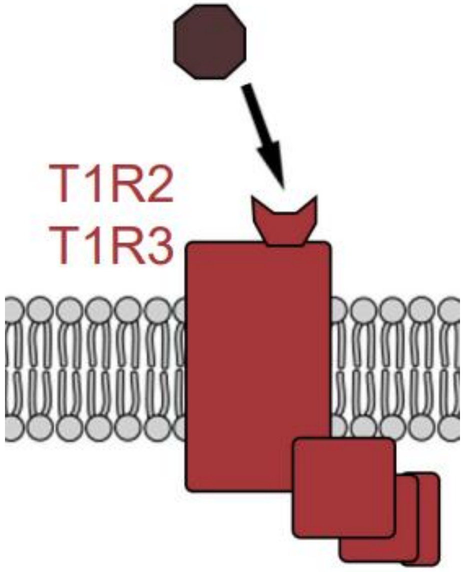
Why are we sensitive to sour tastes?

- Under debate
- No nutritional value (except Vitamin C)
- Sour can be adverse, helping us avoid spoiled or unripe foods

Salt and sour sensation versus ionotropic receptors



Sweet

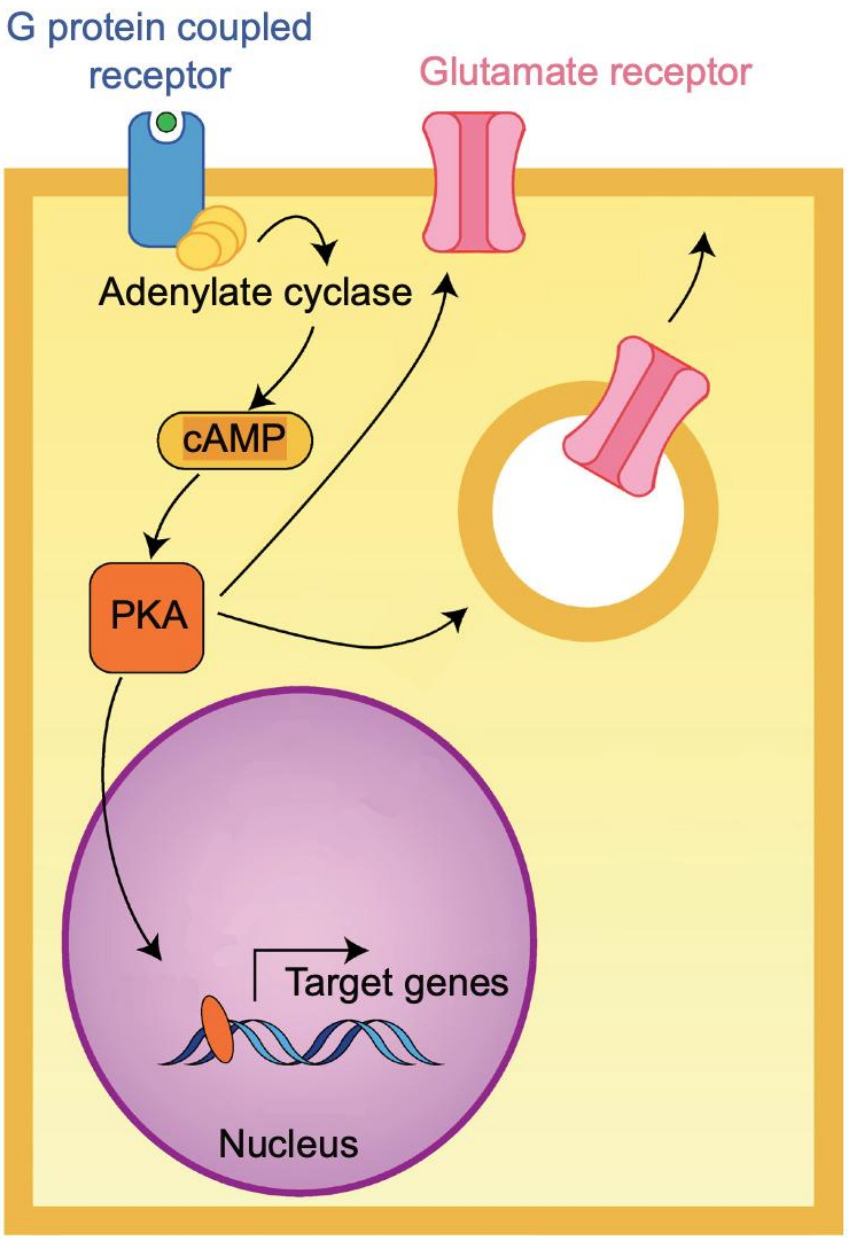


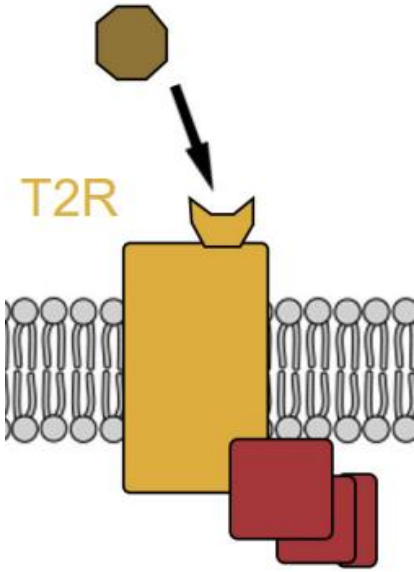
- Activation of G-protein coupled receptors
- Heterodimeric receptor with the subunits **taste receptor type 1 member 2** and **taste receptor type 1 member 3**
- All sweet substances (including artificial sweeteners) activate the taste pathway through these receptors
- T1R2 and T1R3 are also found in the brain, pancreas, GI tract, and fat tissue (possibly for homeostasis)
- Sweet is the strongest driver of food selection

Bitter

- Sensed by the T2R receptor, which activates two distinct signaling pathways
    1. Similar to sweet/umami pathway (described in a moment)
    2. Taste-specific phosphodiesterase, which lowers the intracellular concentration of cAMP (recall from Chap 5: cAMP increases PKA)

Fig 5.13 GPCRs that are coupled with $G_{\alpha s}$ are excitatory through adenylate cyclase signaling.

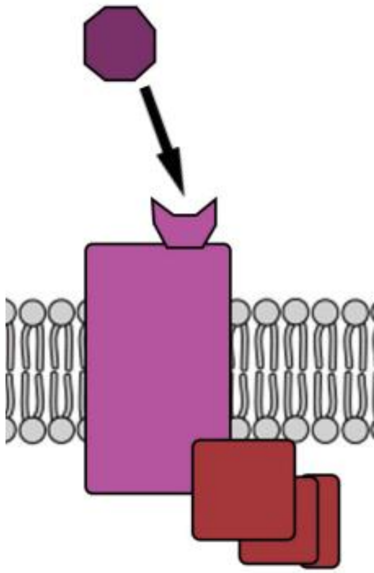




Why are we sensitive to bitter tastes?

- Bitter taste prompts avoidance because bitterness often indicates toxicity
- Some plants may have evolved to taste bitter as an anti-herbivory defense mechanism (e.g., cucurbitacins in gourds)

Umami

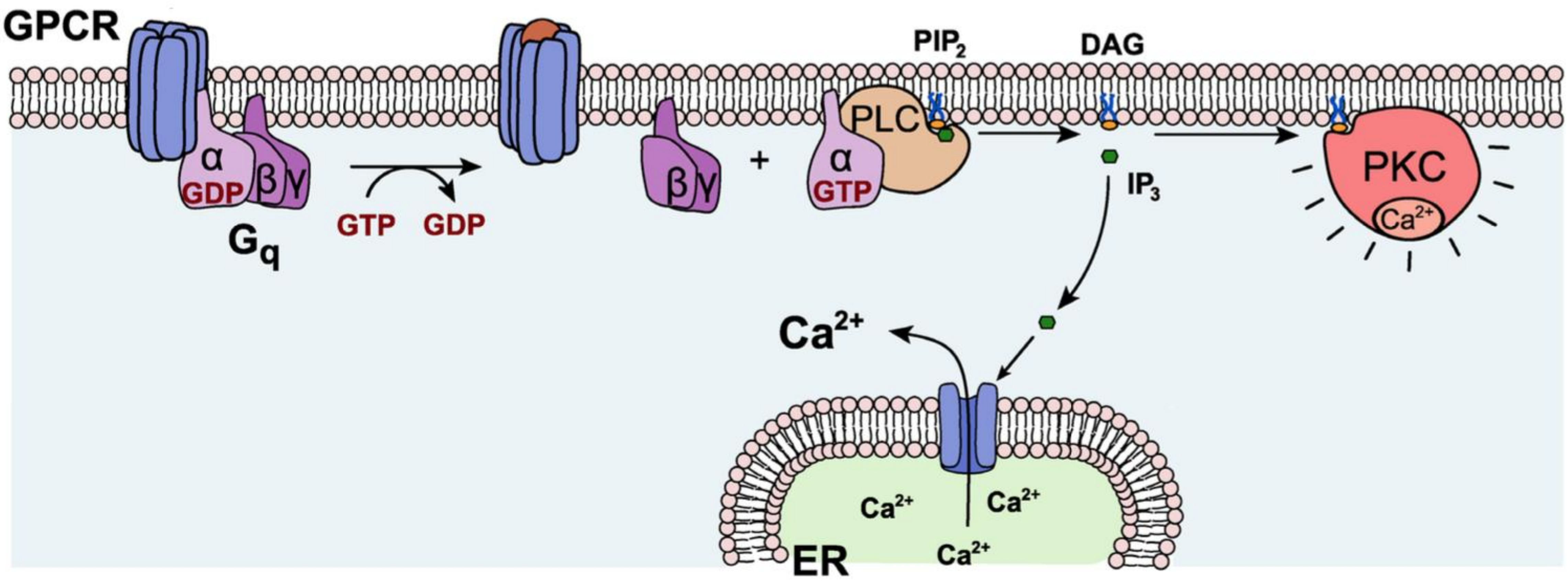


- Savory deliciousness
- Derived from Japanese word *umai*, which means delicious
- Sensed when molecules of glutamate bind to T1R1/T1R3 receptors
- Similar intracellular signaling mechanism as sweet and bitter
- Why are we sensitive to umami tastes?
    - Glutamate is a byproduct of cooking food, which improves their digestion, reduces toxicity, and increases absorption of nutrients

Signaling mechanism of sweet, bitter, and umami

- Activation of G-protein α-gustducin
- Increase activity of phospholipase C-β2, which in turn activates IP3, causing release of calcium into the cytoplasm

Fig 5.14 $G_{\alpha q}$ signals using PLC, which then produces two signaling molecules, IP3 and DAG.



Signaling mechanism of sweet, bitter, and umami

- This calcium opens TRPMP5 (transient receptor potential cation channel subfamily member 5), which cases the taste cell membrane to depolarize and generate an action potential
- Causes the release of ATP into the synapse, which activates afferent nerve fibres to signal the presence of tastants

Spicy

- Hot (e.g., capsaicin)
- Signals brain via C fibres (same neural pathway that carries afferent pain info – Chap 8)
- TPRV1 receptor (nonselective cation channel)
- Activation causes depolarization of taste cell

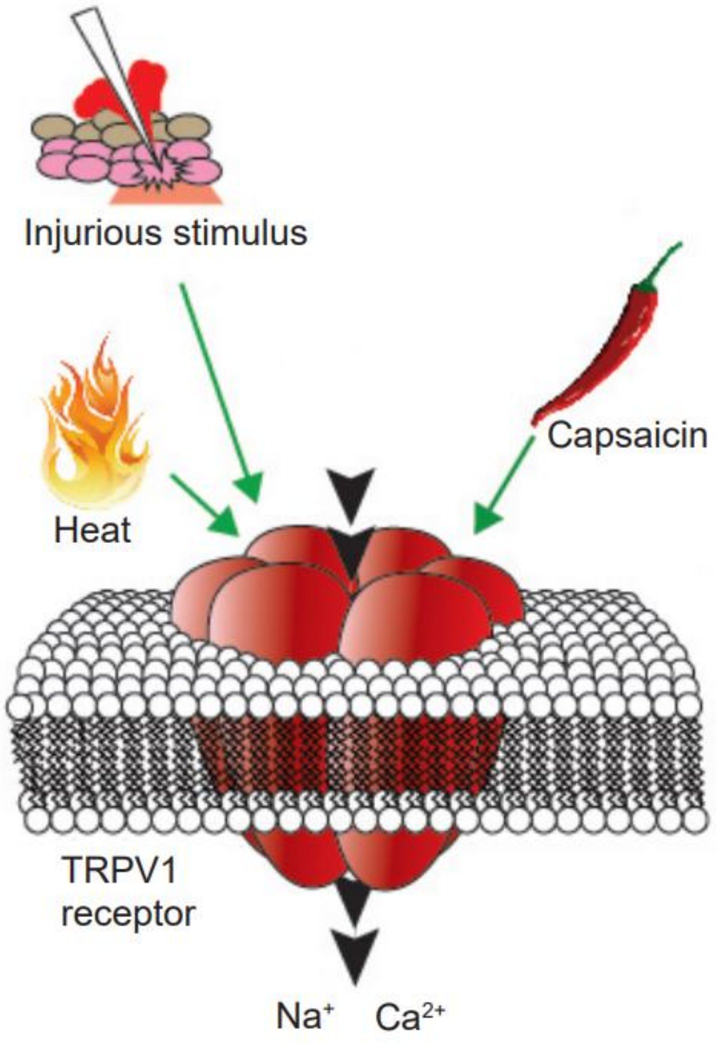


Figure 9.14 TRPV1 recptors are activated by different stimuli, ranging from physical heat to the chemical capsaicin.

Fat

- Oleogustus – different from mouthfeel of foods rich in fat
- Still under investigation

Internal chemosensory systems

Contribute to maintenance of homeostasis

Respiration

- Controlled by several circuits in the hindbrain, especially the medulla
- Communicate with descending motor signals that drive two main nerves
- Phrenic nerve: innervates the diaphragm
  - Spinal injuries at C5 or higher can damage phrenic nerve and thus sometimes require a ventilator
- Intercostal nerves: innervate the intercostal muscles
- These circuits express opioid receptors -> fatal respiratory depression in opioid overdose
- Regular respiration is an autonomic function

What happens when CO_2 levels rise?

- Called hypercapnia
- Hindbrain neurons drive increased respiratory rate, which helps the body expel excess CO_2

Mechanism

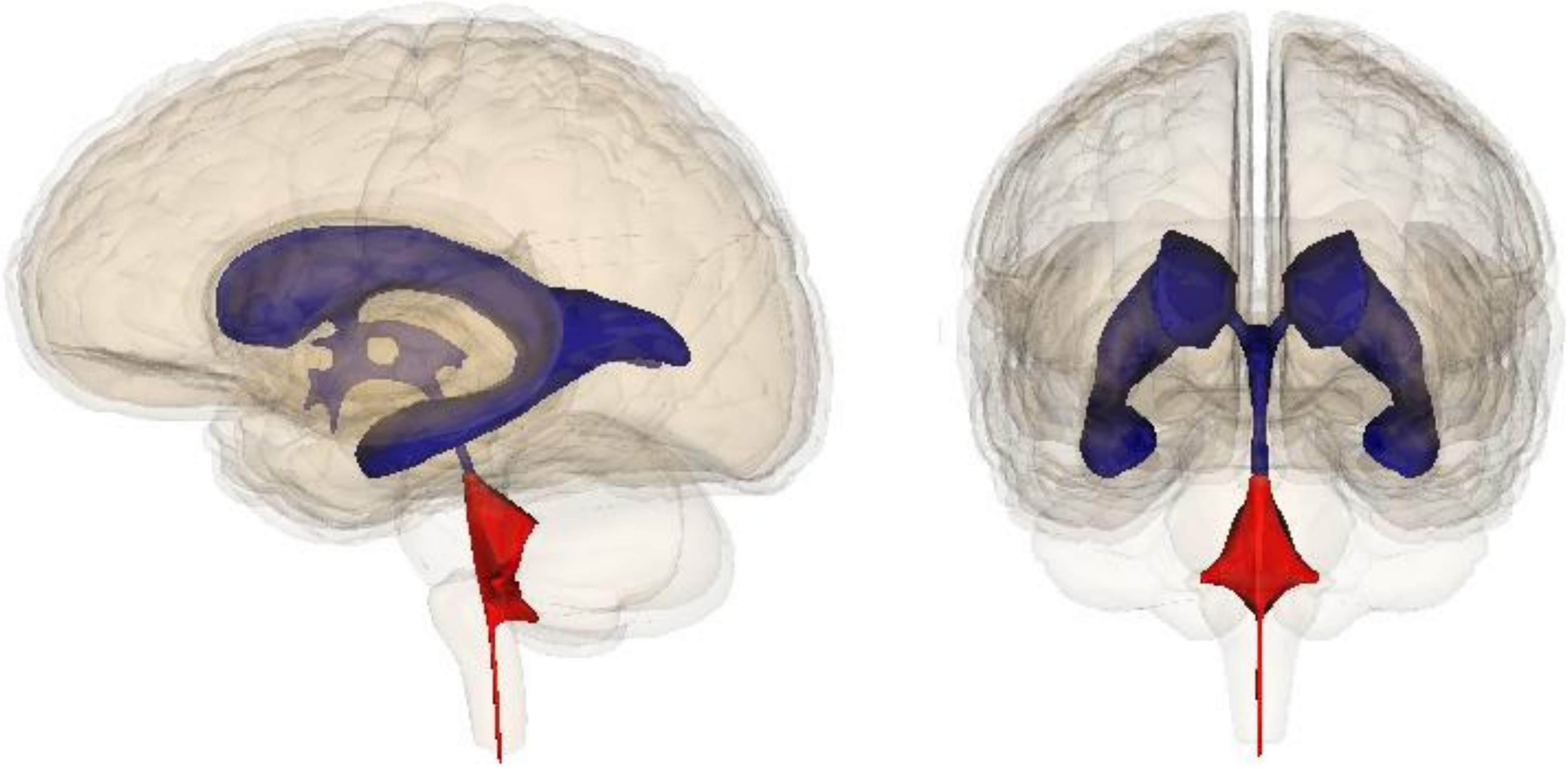
- pH of CSF is a proxy measure for CO_2 in the blood
- CO_2 diffuses easily across the blood brain barrier into the CSF
- CO_2 reacts with H_2O to form carbonic acid, which dissociates into a bicarbonate ion and an H^+ ion
- Central chemoreceptors detect changes in the pH level of CSF by sensing H^+, which enters the cell through acid-sensing ion channels (ASICs)
- When these neurons detect low pH, they send signals to the phrenic and intercostal nerves to increase respiration
- More CO_2 is exchanged out of the lungs, raising pH levels

Vomiting (emesis)

- Rapid contraction of respiratory and abdominal muscles, compressing the stomach, thereby expelling stomach contents through the esophagus
- Often preceded by nausea
- Can be a natural and healthy protective response (e.g., food poisoning)

Neural signals that lead to vomiting

- Original at the afferents of the vagus nerve (Cranial Nerve X)
- Ascending inputs form connections with the dorsal vagal complex, a series of nuclei found in the medulla of the brain stem
- Includes area postrema, which is found on the floor of the fourth ventricle



https://commons.wikimedia.org/wiki/File:Fourth_ventricle.png; CC BY-SA 2.1 JP

Area postrema

- Contains the chemosensory trigger zone
- Dense with neurons that sense the presence of various chemicals
- Considered a circumventricular organ
  - Not isolated from the blood by a blood brain barrier
  - Toxins in blood can influence area postrema directly
  - Also bathed in CSF and thus is directly influenced by toxins in CSF

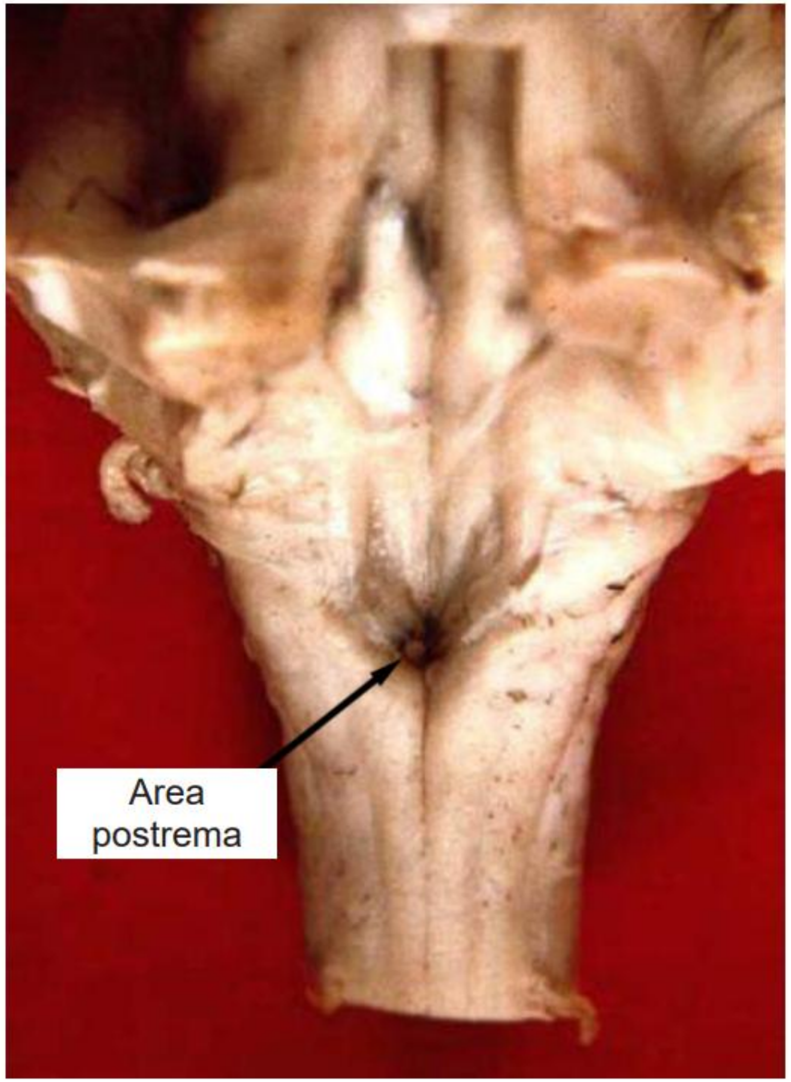


Figure 9.17 Posterior view of the brain stem showing area postrema, the emetic center of the brain.

Compare and contrast olfactory receptor neurons and taste receptor cells.

Compare and contrast the pathways for perceiving for salty flavorants versus sweet flavorants, starting from the flavorant entering the mouth and ending at the gustatory cortex.

Rubric (points awarded between categories as appropriate)

- Advanced knowledge demonstrated – 100%
- Good knowledge demonstrated – 70 %
- Acceptable knowledge demonstrated – 50%
- No knowledge demonstrated – 0 %

Compare and contrast the pathways for perceiving for salty flavorants versus sweet flavorants, starting from the flavorant entering the mouth and ending at the gustatory cortex.
Example of a 100% answer

BOTH

- Flavorant dissolves in saliva, interacts with receptors on taste hairs of taste receptor cells

SALTY FLAVORANT PERCEPTION	SWEET FLAVORANT PERCEPTION
• Primarily driven by Na^+ ions • Passively passing through epithelial sodium channels (ENaCs) • Causes depolarization of taste receptor cells • Depolarization activates voltage-gated calcium channels	• Activates heterodimeric G-protein coupled receptor with the subunits taste receptor type 1 member 2 and taste receptor type 1 member 3 • Activates of G-protein α-gustducin • Increases activity of phospholipase C-β2, which in turn activates IP3, causing release of calcium into the cytoplasm

BOTH

- Increase in intracellular calcium prompts neurotransmitter release that activates that gustatory nerve afferent fibres, which projects to gustatory cortex

Compare and contrast the pathways for perceiving for salty flavorants versus sweet flavorants, starting from the flavorant entering the mouth and ending at the gustatory cortex.
Example of a 70% answer

BOTH

- Flavorant dissolves in saliva, interacts with receptors on taste hairs of taste receptor cells

SALTY FLAVORANT PERCEPTION	SWEET FLAVORANT PERCEPTION
• Na^+ ions pass through ion channels	• Activates G-protein coupled receptor

BOTH

- Activate gustatory nerve which projects to gustatory cortex

Brain Bee opportunity

- Executive committee positions are posted on lab Moodle site. Please apply if interested.