Sensory and Motor Mechanisms

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Sensing, Acting, and Brain

The brain's processing of sensory input and motor output is cyclical rather than linear

- It is customary to think of sensations causing brain changes which then cause action as a linear process. This is not the case: All animals are in constant motion, probing the environment with that motion, sensing the changes that result, and then using the information to generate the next action.
- Our memories of similar sounds and objects can strongly influence our final perceptions.
- The process of perception starts with a fairly simple input – information about physical sensations carried by action potentials to the brain – and ends with a very complex result that can be biased by our history of sensing.

Introduction to Sensory Reception

- **Sensation**: An action potential reaches the brain via sensory neurons.
  - An action potential triggered by light striking the eye is no different from an action potential triggered by air vibrating in the ear: The different depends on the part of the brain that receives the signal.
- **Perception** such as pain in a phantom limb: an interpretation by the brain.

Sensory receptors transduce stimulus energy and transmit signals to the nervous system

- Sensory receptors are specialized neurons or epithelial cells that exist singly or in-groups with other cell types within the sensory organs.

1. Sensory Transduction: The conversion of stimulus energy into electrochemical activity of nerve impulses.
   - **Receptor potential**: The initial response of the receptor to the stimulus is a graded potential.
2. Amplification: The stimulus energy is often too weak to be carried into the nervous system and must be amplified.
3. Transmission:
   - Receptor/sensory cell: the intensity of the receptor potential will affect the frequency of action potentials that travel as sensations to the CNS.
   - Receptor → sensory cell: Many sensory spontaneously generate signals at a low rate. A stimulus does not really switch the production of action potentials no or off; it modulates their frequency – CNS is sensitive not only to the presence or absence of a stimulus but also to change in stimulus intensity.
4. Integration: summation
   - **Sensory adaptation**: a decrease in sensitivity during continued stimulation-receptors are selective in the information they send to the CNS.
   - The threshold for transduction by receptor cells varies with conditions: sugar level

Sensory receptors are categorized by the type of energy they transduce

- **Mechanoreceptor**s: mechanical energy such as pressure, touch, sound etc.,
  - Bending or stretching of the plasma membrane of a mechanoreceptor, such as muscle spindle, increases its permeability resulting in a depolarization.
  - Hair cells: in vertebrate ears, fish lateral line, arthropods' setae, etc.,

- **Pain receptor**s:
  - Pain is detected by a class of naked dendrites, **nociceptor**s.
  - Prostaglandins increase pain by sensitizing the receptors - lowering their threshold. Aspirin reduces pain by inhibiting prostaglandin synthesis.
- **Thermoreceptor**s:
  - Heat receptors and cold receptors in the skin, as well as interothermoreceptors in the anterior hypothalamus of the brain; send information to the body's thermostat, located in the posterior hypothalamus.
- **Chemoreceptor**s: **Gustatory** (taste) receptors and **Olfactory** (smell) receptors
- **Electromagnetic receptor**s: radiation of different wavelengths.
  - **Photoreceptor**: for visible light.
  - **Infrared receptor**: rattlesnakes sense body heat.
  - **Electroreceptor**: Platypus detects electrical fields generated by prey muscles
  - **Magnetoreceptor**: Beluga whales contain the ferrous mineral magnetite in their skulls - The mechanism of the magnetic sense is unknown.

Photoreceptors and Vision

- All photoreceptors contain pigment molecules to absorb light. The molecular evidence indicates that most photoreceptors in the animal kingdom may be homologous: **ancient gene**s associated with photoreceptors

A diversity of photoreceptors has evolved among invertebrates

- **Eyecups** of planarians provide information about light intensity and direction without actually forming an image.

- Image-forming eyes:
  - **Compound eye**s, found in insects and crustaceans, consist of up to several thousand light detectors, **ommatidia**, each with its own cornea and lens.
    - The advantage of the compound eye is due to the rapid recovery of the photoreceptors, and more acute at detecting movement by **mosaic image**: 330 flashes per second.
    - The human eye can distinguish light flashes up to about 50 flashes per second
  - **Single-lens eye**: It works on a principle similar to that of a camera.

Vertebrates have single-lens eyes

- A vertebrate eye consists of **sclera**, **choroid**, **retina**, **conjunctiva**, **cornea**, **iris**, **pupil**, and **lens**:
  - **Optic disc**: the place optic nerve attaches to the eye.
  - **Blind spot**: no photoreceptors in the optic disc.
  - **Ciliary body**: constantly produces the clear watery **aqueous humor**.
    - Blockage of the ducts that drain the aqueous humor can produce **glaucoma**: increased pressure leads to blindness by compressing the retina.
  - **Vitreous humor**: help focus light onto the retina.

- Focusing of the eyes:
  - Many fishes and cephalopods focus by moving the lens forward or backward: **camera-style**.
  - Human and other mammals focus by changing the shape of the lens: spherical lens to focus on a close object - **accommodation** (ciliary muscle contraction, and the suspensory ligament relax), and flat lens for viewing a distant object.

- The retina contains two types of photoreceptors: **rod cell**s and **cone cell**s
  - Rod cells more sensitive to light but do not distinguish colors: Most mammals are nocturnal - keen night vision.
  - Cone cells can distinguish colors in daylight: Fishes, amphibians, reptiles, and birds have well-developed color vision. Only few mammals can see color.
  - **Fovea**, the center of visual field, is consisted by **cones cell**s, not rod cells in human eyes.

The light-absorbing pigment rhodopsin triggers a signal-transduction pathway

- **Retinal**, the actual light-absorbing pigment molecule, derives from vitamin A.
- **Opsin**: a membrane protein along with retinal
  - **Rhodopsin**s: the opsin of rod cell.
  - **Photopsin**s: Color vision results from the presence of three subclasses of cones in the retina - red cones, green cones, and blue cones.
    - **Color blindness**: a sex-linked trait is due to a deficiency or absence of one or more types of cones.

- Photo-signal transduction by rhodopsin:
  1. In the dark, when rhodopsin is inactive, cGMP is bound to Na^+ channels in the rod cell plasma membrane and keep those channels open: the rod cell membrane is actually depolarized and releases the inhibitory neurotransmitter glutamate at its synapses with **bipolar cell**s.
  2. When **retinal** absorbs light, it changes shape to cause the conformation change of rhodopsin, which activates **transducin** (Gt) to trigger phosphodiesterase to convert cGMP to GMP. The GMP disengages from the Na^+ channels.

3. The disengagement causes the Na^+ channels to close: the membrane becomes hyperpolarized and inhibits releasing of the inhibitory neurotransmitter.

- Bright light bleaches the rhodopsin (become unresponsive) and cones take over. In the dark, enzymes convert the rhodopsin back to its original form.

The retina assists the cerebral cortex in processing visual information

- **Vertical pathway**: Information passes from the **receptor cell** through the **bipolar cell**s to the **ganglion cell**s.
- **Lateral pathway**: **Amacrine cell**s (spreading the information from one bipolar cell to several ganglion cells) and **horizontal cell**s.
  - **Lateral inhibition**: The activated **horizontal cell**s stimulate nearby receptors but inhibit more distant receptors and bipolar cells that are not illuminated - sharpens edges and enhances contrast in the image.
- Axons of ganglion cells form the optic nerves that transmit sensations from the eyes to the brain:
  - **Optic chiasm** near the center of the base of the cerebral cortex: visual sensations from both eyes in the **left** visual field are transmitted to the **right** side of the brain, *vice versa*.
  - **Lateral geniculate nuclei** of the thalamus and **primary visual cortex** in the occipital lobe of the cerebrum:

- How does the brain convert a complex set of action potentials representing 2-D images projected onto our retinas into 3-D perceptions of our surroundings?

Hearing and Equilibrium

- Both senses involve mechanoreceptors containing hair cells.

The mammalian hearing organ is within the inner ear

- The ear itself can be divided into three regions:
  - **Outer ear** (**pinna** and the **auditory canal**) collects sound waves and channels them to the **tympanic membrane** (eardrum) of the middle ear.
  - **Middle ear** conducts vibrations through three **ossicle**s-the **malleus (**hammer**)**, **incus** (anvil), and **stapes** (stirrup)-to the inner ear, passing through the **oval window**.
    - The middle ear also opens into the **auditory (Eustachian) tube**.
  - **Inner ear**: **cochlea** has two large chambers, an upper **vestibular canal** and a lower **tympanic canal**, separated by a smaller cochlear duct.
    - The cochlear canal is filled with **endolymph**.
    - The floor of the cochlear canal, the **basilar membrane**, bears the **organ of Corti**: consisting the actual receptor cells of the ear, hair cells.
      1. The stapes vibrating against the oval window creates a traveling pressure wave in the fluid of the cochlea that passes into the vestibular canal.
      2. As the basilar membrane vibrates in response to the pressure waves, it presses the hair cells into and draws them away from the **tectorial membrane**.
      3. This wave continues around the tip of the cochlea and through the tympanic canal, dissipating as it strikes the round window.

- Two important aspects of sound are **volume** and **pitch**.
  - Volume (loudness): the amplitude of the sound wave.
  - Pitch is a function of the frequency of sound waves: expressed in **hertz** (**Hz**).
    - Human normally can hear sounds in the range of 40 to 20,000 Hz.
    - Pitch can be distinguished due to the basilar membrane is not uniform along its length.

The inner ear also contains the organs of equilibrium

- **Utricle** opens into three **semicircular canal**s.
  - Hair cells are arranged in clusters, and project into a gelatinous material: Each cell contains a small calcium carbonate particle, **otolith** (ear stone). Gravity pulls downward the hair cells to send action potential. Similarly, the semicircular canals, arranged in the three planes of space, detect rotation of the head.

A lateral line system and inner ear detect pressure waves in most fishes and aquatic amphibians

- Water enters animal's lateral line system through numerous pores and flows along a tube past the mechanoreceptors.
  - **Neuromast**, resemble **ampulla** in the semicircular canals, has a cluster of hair cells, with the sensory hairs embedded in a gelatinous cap, **cupula**.

- Fish have inner ears (no eardrum) that don't open to the outside of the body - homologous to the equilibrium sensors of human ears, but no cochlea.
- Frog and toad: Air vibration (sound) is conducted through tympanic membrane and stapes to the inner ear.

Many invertebrates have gravity sensors and are sound-sensitive

- Male mosquito having fine hairs on its antennae and some insect having ears on their legs:
- Most invertebrates have mechanoreceptors, **statocyst**s, to sense equilibrium.
  - **Statolith**: like ear stone

Chemoreception - Taste and Smell

- Many animals use their chemical senses to find mates, to recognize territory, and to help navigate during migration. Taste (gustation) and smell (olfaction) are important in animal feeding behavior:

Perceptions of taste and smell are usually interrelated

- The receptors and brain pathways for taste and olfactory are independent, however, these chemical senses are usually closely related.
  - Hydra: glutathione.
  - Insects smell airborne chemicals using olfactory setae (sensory hairs), which usually located on the antennae, and the taste receptor of insects is located on the feet and mouthpart.
  - Mammals' receptor cells for taste: Most of the **taste bud**s are associated with raised papillae on the tongue.
- We cannot distinguish different types of taste receptors from their structures, but we recognize four primary taste perceptions: **sweet**, **sour**, **salty**, and **bitter**.
  - These primary tastes are associated with specific molecular shapes or charges, e.g., the ring structure of glucose for sweet, and the positive ion for salty, that bind to separate receptors.

Movement and Locomotion

- Movement is a hallmark of animals.

Locomotion requires energy to overcome friction and gravity

- Water is much denser medium than air: resistance (friction) is more important than gravity for aquatic animals.
- On land, animal must be able to support itself and move against gravity, therefore strong skeletal support is more important than a streamlined shape.
- To be airborne, the wings must develop enough lift to enable the animal to completely overcome the downward force of gravity.

<u>Cellular and Skeletal Underpinnings of Locomotion</u>

- At the cellular level, all animal movement is based on one of two basic contractile system, **microtubule** and **microfilament**. Both of which consume energy to move protein strands against one another.

Skeletons Support and Protect the Animal Body and are Essential to Movement

- Three functions of a skeleton are support, protection, and movement.

<u>Hydrostatic skeleton</u>s consist of fluid held under pressure in a closed body compartment and provide no protection: well suited for aquatic life

  - Hydrostatic skeletons could not support a large animal living on land.
  - These animals control their form and movement by using muscles to change the shape of fluid-filled compartments: **Peristalsis** in earthworm.

Exoskeletons: a hard encasement deposited on the surface of an animal.

- Calcareous shell secretes by the mantle in mollusks.
- **Chitin**, the main component of **cuticle**, is a polysaccharide similar to cellulose.
  - Fibrils of chitin are embedded in a matrix made of protein, analogous to fiberglass, that combines strength and flexibility.
  - **Quinone** cross-links the proteins of the exoskeleton to harden the cuticle.

Endoskeletons

- Sponges: hard spicules and soft spongins.
- Echinoderms have hard plates (ossicles) beneath the skin.
- The mammalian skeleton: Some fused together, and others connected at **joint**s by **ligament**s that allow freedom of movement.
  - Types of joints: 1) Plane joint, 2) hinge joint, 3) pivot joint, 4) condyloid joint, 5) saddle joint, 6) ball-and-socket joint.

Physical support on land depends on adaptations of body proportions and posture

- Physical laws dictate that the strength of a building support depends on its cross-sectional area, which increases as the square of its diameter. And the strain on the supports depends on the building's weight, which increases as the cube of its height or other linear dimension.
  - Imagine a mouse scaled up to elephant size: size of leg **bone**

- **Muscle**s and **tendon**s, which hold the legs of large mammals relatively straight and under the body, bear most of the load.

Muscles move skeletal parts by contracting

- **Antagonistic muscles**: The action of a muscle is always to contract.
- To raise the appendage, the skeleton acts as a **level**, with the joint as a **fulcrum** and the limb as the load.

<u>Structure and Function of Vertebrate Skeletal Muscle</u>

- A skeletal muscle is a bundle of long muscle fibers: each muscle fiber is a single cell with many nuclei.
  - Each cell consists of a bundle of small **myofibril**s, which are composed of two kinds of **myofilament**s: thin filaments (**actin**) and thick filaments (**myosin**).
- Striated muscle: repeating pattern of light and dark bands.
  - **Sarcomere**: the repeating and fundamental unit of the muscle.
  - **Z line**, **I band**, **A band**, and **H zone**:

Interactions between myosin and actin generate force during muscle contraction

- **Sliding-filament model**:
  - This cycle, detach, straighten out, attach, and bend, occurs repeatedly.
  - myosin head+ATP → myosin head+P (high energy configuration) → myosin head+P/actin → myosin head-P (low energy configuration)/actin (muscle contraction)
    - Muscle cell stores only enough ATP for a few contractions. The cells also store glycogen between the myofibrils, but most of the energy is in **phosphagen**s.
      - Creatine phosphate: the phosphagen of vertebrate can supply a phosphate to ADP to make ATP.

Calcium ions and regulatory proteins control muscle contraction

- **Tropomyosin**: compete with myosin
- **Troponin** complex: Ca^{++} binding protein regulates tropomyosin
- **Sarcoplasmic reticulum**: a specialized endoplasmic reticulum.
- **Transverse** (T) **tubule**s: infoldings of the plasma membrane carry the action potential deep into the muscle cell.
  - As soon as the action potential passes, the sarcoplasmic reticulum pumps the calcium back out of the cytoplasm.

Diverse body movements require variation in muscle activity

- Each muscle fiber is innervated by only one motor neuron, but one branched motor neuron may innervate many fibers.
  - When the neuron fires, all of the muscle fibers of the motor unit contract.
  - Motor unit consists of a single motor neuron and all the muscle fiber it controls:

- We can voluntarily alter the extent and strength of muscle contraction: whole-muscle contractions are graded
  - "all-or-none" contraction in a single muscle fiber.
  - **Muscle tension** can be increased:
    - Wave summation: high frequency of stimulation causes smooth and sustained contraction, **tetanus**.
    - **Multiple motor recruitment**:
- **Muscle fatigue**: depletion of ATP, dissipation of the ion gradients required for depolarization of the muscle cell membrane, and accumulation of lactic acid.

<u>Fast and Slow Muscle Fibers</u>

- Slow fibers are found in muscles used to maintain posture, because they can sustain long contraction. Fast muscles are used for rapid, powerful contractions.
  - Slow fibers have less sarcoplasmic reticulum, so calcium remains in the cytoplasm longer.
  - Slow fibers are specialized to make use of a steady supply of energy: many mitochondria, a rich blood supply, and an oxygen-storing protein, **myoglobin**.
- "**Dark meat**" in poultry and fish

Other Type of Muscles

- Cardiac muscle: only in heart; striated, branched.
  - **Intercalated disc**s are gap junctions that electrically couple all the muscle cells in the heart.
  - Cardiac muscle cells can generate action potential on their own, without any input from the nervous system.
- Smooth muscle
  - Lacking the striations: actin and myosin filaments are not all aligned along the length of the cell - spiral arrangement.
  - Smooth muscles do not have either a T-tubule system or a well-developed sarcoplasmic reticulum.