Sensory Systems
Zelick’s principles of sensory biology:

1. Not all animal biosensors are equal! What you detect depends on your biology/ecology.

For example, many insects can detect U.V. light, but humans cannot. Is human vision inferior? Not necessarily, rather there is just no survival advantage for humans.
2. When important, sensory organs are so sensitive as to be at the limit of the physical phenomenon.

For example, best photoreceptor systems can detect a single photon. There is nothing less than a single photon that *could* be detected!
3. Sensory systems do not evolve to provide exact/correct information, rather to accentuate important information and minimize un-important information.

For example, retinal edge detectors and contrast enhancement.

Note: the enhancement and minimization of information often involves a process of filtering.
4. What is “signal” to one organism is “noise” to another.

For example, barn owls adapted to hear rustling “noises” – this is music to the barn owl!

A major force in evolution of sensory systems is to improve the signal/noise ratio.
5. Sensory systems are often more sensitive than any one receptor.

Sensory systems use signal averaging (like the evoked potential lab)

Note: receptors are cheap!
6. Sensory processing is dynamic – there is not a single, stable sensitivity or filtering process. Rather there is real-time adjustment of parameters.

   For example, gustation controlled by olfaction, gain compensation in the auditory system.
Electrical signals originate in sensory cells. **Graded potentials**

Membrane of moth ear

Inside of sensory cell is negative relative to outside

Positively charged ion

Negatively charged ion

Almost always an accessory organ
Sound-receptor cells depolarize in response to sound.

Figure 46-3b Biological Science, 2/e
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Sound-receptor cells respond more strongly to louder sounds.

Frequency tuning characteristic of auditory system
Hair cells have many stereocilia and one kinocilium.

- **Stereocilia** (extend into fluid-filled chamber)
- **Kinocilium**
- **Hair cell**
- **Afferent sensory neurons**
- **Efferent sensory neurons**

Hair cells in vertebrates only

Pressure waves

Hair cell hyperpolarized

Hair cell depolarized

Figure 46-4a part 1 Biological Science, 2/e © 2005 Pearson Prentice Hall, Inc.
HC’s are epithelial-derived; not true neurons
Outer & middle ear overcome energy loss trying to drive fluid-filled inner ear with airborne sound waves.
Axons of Auditory neurons (to brain)

Outer ear

Middle ear

Inner ear

Ear canal

Cochlea
The middle chamber of the fluid-filled cochlea contains hair cells.

Three fluid-filled chambers

Cochlea

Auditory nerve

Neurons (to auditory nerve)
Hair cells are sandwiched between membranes.
Basilar membrane

Outer wall of cochlea (shown uncoiled)

Wide part of membrane is flexible—vibrates in response to low frequencies
- 500 Hz
- 1 kHz
- 2 kHz
- 4 kHz
- 16 kHz

Narrow part of membrane is stiff—vibrates in response to high frequencies
46.3 Vision
Ommatidia are the functional units of insect eyes.
Vertebrate Eyes
(a) The structure of the vertebrate eye

(b) In the retina, cells are arranged in layers.

- Ganglion cells
- Connecting neurons
- Photoreceptor cells

Axons to optic nerve

Figure 46-9  Biological Science, 2/e
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The structure of the vertebrate eye

- Sclera
- Retina
- Iris
- Fovea
- Pupil
- Optic nerve (to brain)
- Cornea
- Lens
In the retina, cells are arranged in layers.

- **Ganglion cells**
- **Connecting neurons**
- **Photoreceptor cells**

Light enters the retina and travels through the photoreceptor cells, then to the ganglion cells, and finally to the axons that connect to the optic nerve.

*Figure 46-9b Biological Science, 2/e © 2005 Pearson Prentice Hall, Inc.*
Rods and cones contain stacks of membranes.
Rhodopsin is a transmembrane protein complex.
When the retinal molecule inside rhodopsin absorbs light, retinal changes shape.

*Figure 46-10c Biological Science, 2/e © 2005 Pearson Prentice Hall, Inc.*
In the dark

The disk of a photoreceptor cell (a rod) before stimulation

Figure 46-11a Biological Science, 2/e © 2005 Pearson Prentice Hall, Inc.
Absorb a photon or two

The same disk after stimulation

Figure 46-11b Biological Science, 2/e © 2005 Pearson Prentice Hall, Inc.
aa substitutions in opsin molecule cause more or less π-bond de-localization of electrons in retinal – shifts spectrum
Pit vipers can detect infrared radiation.
Warm animals give off infrared radiation.

What we see in the light (box contains a light bulb wrapped in dark cloth)

What pit vipers “see” in the dark
chemoreception
Taste bud

Pore

Taste cells (salt, acid, sweet, bitter, meaty, etc.)

Afferent neuron (to brain)
Olfactory receptors are true neurons. Chemicals bind to receptors in dendrite membranes.

Swim in ocean → salt water in nose → wash away mucus → zap sense of smell!
46.5 Movement
(a) Cartilage provides cushioning.

Protein fibers in gelatinous matrix

Cartilage cell

(b) Bone provides structural support.

Bone Blood Matrix of CaPO$_4$

cells vessels CaCO$_3$

proteins
Cartilage provides cushioning.

Protein fibers in gelatinous matrix

Cartilage cell

Figure 46-16a Biological Science, 2/e © 2005 Pearson Prentice Hall, Inc.
Bone provides structural support.

Figure 46-16b Biological Science, 2/e
© 2005 Pearson Prentice Hall, Inc.
Ball-and-socket joints swivel

Hinge joints hinge
Endoskeleton

Flexor (hamstring) contracts

Extensor (quadriceps) contracts
Exoskeleton

Flexor muscle contracts

Extensor muscle contracts

Figure 46-18b  Biological Science, 2/e
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Hydrostatic skeleton

Circumferential muscles contract

Circumferential muscles relax

Longitudinal muscles relax

Longitudinal muscles contract
<table>
<thead>
<tr>
<th>Location:</th>
<th>Attached to bones</th>
<th>Heart</th>
<th>Intestines, arteries, other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function:</td>
<td>Move skeleton</td>
<td>Pump blood</td>
<td>Move food, help regulate blood pressure, etc.</td>
</tr>
<tr>
<td>Characteristics of cells:</td>
<td>• Multinucleate</td>
<td>• 1 or 2 nuclei</td>
<td>• Single nucleus</td>
</tr>
<tr>
<td></td>
<td>• Unbranched</td>
<td>• Branched; intercalated discs form direct cytoplasmic connection end to end</td>
<td>• Unbranched</td>
</tr>
<tr>
<td></td>
<td>• Activity is “voluntary,” meaning that signal from motor neuron is required</td>
<td>• Activity is “non-voluntary,” meaning that signal from motor neuron is not required</td>
<td>• Activity is “non-voluntary,” meaning that signal from motor neuron is not required</td>
</tr>
</tbody>
</table>

Figure 46-19 Biological Science, 2/e  
© 2005 Pearson Prentice Hall, Inc.
Muscles

Muscle tissue

Bundle of muscle fibers (many cells)

Muscle fiber (one cell) contains many myofibrils

Sarcomere

Myofibril

Dark band

Light band

Relaxed

Contracted

Figure 46-20 Biological Science, 2/e © 2005 Pearson Prentice Hall, Inc.
CHANGES IN THE CONFORMATION OF THE MYOSIN HEAD PRODUCE MOVEMENT.

1. ATP binds. Head releases.

2. ATP is hydrolized. Head pivots, binds to new actin subunit.

3. $P_i$ is released. Head pivots, moves filament (power stroke).

4. ADP is released. Cycle is ready to repeat.

Actin in thin filament

Myosin head of thick filament

ADP

$P_i$

ADP + $P_i$

ATP

Figure 46-23 Biological Science, 2/e
© 2005 Pearson Prentice Hall, Inc.
1. SR releases Ca$^{2+}$, troponin subunit C binds Ca$^{2+}$, changes conformation & moves out of the way.
2. Myosin head binds to actin.

3. After binding to site 4, Mg$^{2+}$-ATPase on head hydrolyses ATP, $\Delta G$ allows head to detach from actin

Note: ATP not used to form attachment, only to re-arm the ratchet.
HOW DO ACTION POTENTIALS TRIGGER MUSCLE CONTRACTION?

1. Action potential arrives, and ACh is released.
2. Acetylcholine binds to ACh receptors on the muscle cell, triggering depolarization that leads to action potential.
4. Proteins in T tubules open Ca²⁺ channels in sarcoplasmic reticum.
5. Ca²⁺ is released from sarcoplasmic reticum. Sarcomeres contract when troponin and tropomyosin move in response to Ca²⁺ and expose actin binding sites in the thin filaments.

Figure 46-24 Biological Science, 2/e
© 2005 Pearson Prentice Hall, Inc.
What controls the speed, strength, and endurance of muscle activity?

The answer involves aspects that...

1. Genetics has control over
2. The nervous system has control over
3. You have control over
Motor neuron 2392 and fibers 3 & 5 are always linked to form a motor unit.
A hypothetical muscle with just 3 motor units. So how many steps of contraction strength?

Ans = 5
Muscle with fine motor control \( \rightarrow \) many motor units relative to the number of fibers.

Muscles with coarse motor control \( \rightarrow \) fewer motor units relative to the number of fibers.
What the nervous system has control over…

1. How many motor units are recruited.
2. The total number of APs sent to each motor unit.
3. The rate at which APs are sent to each motor unit.

These parameters completely determine the overall strength of contraction, overall speed of contraction, and the ultimate amount of contraction.
If CNS makes 10 AP’s per second, \(10 \times 3 = 30\) microns of shortening per second.
More total motor units recruited = more strength

More AP’s sent in total = a greater extent of shortening
What you have control over...

Note – still 3 muscle fibers in this muscle.
More genetics – not all muscles are created equal.

<table>
<thead>
<tr>
<th>Type</th>
<th>Contraction</th>
<th>Fatigue Rate</th>
<th>ATP</th>
<th>Myosin Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast twitch</td>
<td>rapid</td>
<td>fast—within minutes</td>
<td>primarily anaerobic</td>
<td>type II (Ilb faster than Ila)</td>
</tr>
<tr>
<td>Slow twitch</td>
<td>relatively slow</td>
<td>slow—active for hours</td>
<td>primarily aerobic</td>
<td>type I</td>
</tr>
</tbody>
</table>

Table 46.1 Muscle-Fiber Types in Vertebrates

Table 46-1 Biological Science, 2/e
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What genetics has control over –

• In addition to the motor unit ratio, the total number of muscle fibers in a particular muscle.

• The proportion of fast and slow fibers (and including the proportion of myoglobin and endurance).

• The ratio of myofibrils:sarcoplasmic reticulum:mitochondria.

• Biochemical variation and some structural tricks.
Muscle speed of contraction varies a lot. The time to reach full strength of contraction (in milliseconds):

Gut smooth muscle: 30,000

Giant sloth skeletal muscle: 300

Vertebrate middle ear: 2

... and, the fastest muscles are not the strongest, and the strongest are not the best for endurance.

*Why you can’t have it all....*
Toadfish – sound production muscles

200 contractions/second (vertebrate record for high rate).

Tricks:

1. rapid mobilization of Ca$^{2+}$ from S.R. (50x faster than regular skeletal muscle)
2. Troponin has lower affinity for Ca$^{2+}$ compared with normal muscle – Ca$^{2+}$ falls away faster
3. Myosin heads have different geometry & detach faster
Let’s say muscle volume is 100% (+/-) SR, contractile protein, mitochondria.

Fast mobilization of Ca\textsuperscript{2+} requires extra large S.R., so either protein or mitochondria must be reduced.

Toadfish has 4% mitochondria and reduced actin & myosin.

Trade-off: can only make sound intermittently, and muscles are weak
Another fast contraction system = rattlesnake tail muscle.

90 contractions per second – so slower than toadfish… but rattlesnake can go for hours. Snake has 26% mitochondria (toadfish 4%).

What about trade-off of endurance for strength and speed?

Fast-twitch locomotion muscles are at 10% mitochondria + S.R., 90% protein.

So - rapid *single* (non-repetitive) contraction, high strength, but rapid fatigue.
Slow-twitch locomotion muscles:

70% myofibrils (actin & myosin protein)
25% mitochondria
5% S.R.

So reasonably good strength & endurance, but small percent S.R. compromises speed.

And then there are hummingbirds!!!

Wing muscles are very fast, high endurance sustained activity, and very strong. Hmm...
Flight muscles are 25% of bird’s body mass, and 35% mitochondria per muscle cell.

Can calculate that HB should need 30% S.R. and 70% mito to sustain muscle activity.

This leaves 0.0% for myofibrils (= no lift)!

Hummingbirds use two tricks, one is unique:

HB muscles have have (1) a novel anatomical trick to pack double mitochondria/cell and (2) run muscles at 40 ºC, giving a 2X increase in mito ATP production rate.
Fatigue – not well understood

Some factors:

Lactate build-up
Lowering pH
Repetetive contraction blocks blood flow
Heat build-up
Friction associated with movement & pulling apart antagonist muscle → heat!

Mechanical Efficiency:
≈ 10 - 35%

bicycling!
Think question:

If you don’t move muscle at all during isometric contraction, why is there any heat produced?