Active sensing

- Passive vs active sensing (touch)
- Comparison across senses
- Basic coding principles

--------

- Perceptual loops
- Sensation-targeted motor control
- Proprioception
- Controlled variables
- Active vibrissal touch: encoding and recoding
Eye movements during fixation
Sensory organs consist of receptor arrays:

- **somatosensation**
  - Finger pad: ~200 µm

- ** audition**
  - Cochlea: 10 µm

- **vision**
  - Retina: 10 µm

**Sensory encoding:**

- **What receptors tell the brain**

**Spatial organization** => **Spatial coding**

- "which receptors are activated"

**Movements** => **Temporal coding**

- "when are receptors activated"
Temporal coding in action
Coding space by time

1. Spatial frequency
2. Spatial phase
Darian-Smith & Oke,
J Physiol, 1980

anesth. monkey,
MR fibers

**Fig. 1.** Details of the stimulator used for presenting gratings to finger pad skin. The grating was mounted on a rotating drum 100 mm in diameter (upper right). The profile of each of the six gratings used is shown (upper left), along with its spatial period. The lower diagram illustrates the mechanisms for controlling the period of contact of the grating moving across the finger pad skin. The drum was mounted at one end of a counter-poised lever and rotated at a preset velocity. This drum was positioned 1 mm above the skin surface; an actuated solenoid held the drum off the skin except for the required contact period. The perpendicular force at which the moving grating was applied to the skin during this contact period was determined by the counter-weight: this could be set in the range 20–100 g wt.
Vel - constant

\[ f = SF \times V \]

\[ dt = \frac{dx}{V} \]

---

**Fig. 3.** Responses of a rapidly adapting fibre to different gratings moving across its receptive field on the ridged glabrous skin of terminal phalanx of thumb. The tangential velocity was 72 mm/sec in a direction at right angles to the long axis of the finger and the applied force was 60 g wt. for all records; successive stimuli were presented every 3 sec. Each row of dots indicates the occurrence of action potentials in response to a single passage of the grating across the skin; twelve successive responses are illustrated for each grating; spatial periods of these gratings are indicated on the right. The 80 msec response segment illustrated had its onset at approximately 500 msec after the beginning of stimulation, as is shown in Fig. 2. With these records there was both precise alignment of the time of occurrence of action potentials after the onset of stimulation, and also alignment relative to the instantaneous position of the grating on the skin. The stimulus spatial and temporal periods are indicated for each data block on right side of Figure. The mean interspike interval is to the left of each data block.
Fig. 6. Responses of a slowly adapting fibre to gratings moving across its receptive field on the finger pad of the middle finger. The format of display of responses to three gratings moving at three different velocities across the skin is similar to that of Figs. 4 and 5; there was, however, a small difference in the velocities used (24, 70 and 160 mm/sec) and hence a change in the stimulus temporal frequencies generated by the moving surfaces. A phase-locked discharge reflecting the stimulus temporal frequency is readily detected in the display in the range 23–68 Hz, but not at higher stimulus temporal frequencies.
Fig. 4. Responses of a rapidly adapting fibre to three different gratings (spatial period of 1025, 790 and 540 \( \mu \text{m} \)) moving across the receptive field at three different velocities (22, 66 and 142 mm/sec). The fibre's receptive field was on the finger pad of the index finger. The radial force was 60 g wt. and contact area was approximately 5 x 5 mm.

Each response block is a segment of the response beginning approximately 500 msec after the onset of stimulation; other response and stimulus measures were as indicated in Fig. 3. The stimulus temporal frequency is indicated by the vertical bars above each response block, and its numerical value is stated below the block. The response frequency accurately reflected the stimulus frequency in the range 64-140 Hz. At frequencies below 64 Hz the stimulus temporal frequency was represented in the modulation of discharge but not in the mean discharge frequency; at stimulus temporal frequencies above 140 Hz, although the response was phase-locked to the stimulus, the fibre did not respond to each successive cycle of the stimulus and hence mean discharge frequency did not equal the stimulus temporal frequency.
Fig. 5. Responses of a Pacinian fibre to gratings moving across part of its receptive field on the terminal pad of the index finger. The same combination of surfaces and velocities were used as in Fig. 4, and the display format is the same as in that Figure. Except with the lowest stimulus temporal frequencies (upper left corner) the fibre’s response was modulated with a cycle period matching the temporal period of the stimulus. However only with stimulus temporal frequencies of 180 Hz or higher did the interspike interval match the stimulus temporal period (right column of the response blocks). In the stimulus temporal frequency range 64–140 Hz the fibre usually fired in phase twice per stimulus cycle, and at lower frequencies up to 5–7 spikes occurred within each stimulus temporal cycle.
Fig. 7. Relationship of response modulation pattern to the stimulus temporal frequency.

Coding ranges
Temporal filtering (by intrinsic factors)

- **Eye**: K, P, M
  - W, X, Y
  - Frequency (Hz) range: 0.5, 2, 8, 32

- **Whisker**
  - Frequency (Hz) range: 1, 10, 100, 1000

- **Finger**: SA, RA, PC
  - Frequency (Hz) range: 1, 10, 100, 1000
Coding space by time

1. Spatial frequency
2. Spatial phase
Vision: Temporal encoding due to eye movement

\[ V_{\text{eye}} \rightarrow \text{RF(1)} \]

\[ \text{RF(2)} \]

retinal outputs

\[ 1 \]

\[ 2 \]

time

space

space
Vision: Temporal encoding due to eye movement
Vision: Temporal encoding due to eye movement
Vision: Temporal encoding due to eye movement

$\Delta x$  

$V_{eye}$  

RF(1)  

RF(2)  

retinal outputs

1  

2  

$\Delta t$  

space  

time
Vision: Temporal encoding due to eye movement

\[ \Delta x \]

\[ \Delta t \]

\[ V_{\text{eye}} \]

RF(1)

RF(2)

retinal outputs

1

2

space

time
### Spatial vs temporal coding

<table>
<thead>
<tr>
<th>Spatial</th>
<th>Temporal</th>
</tr>
</thead>
<tbody>
<tr>
<td>faster</td>
<td>better resolution</td>
</tr>
</tbody>
</table>

- scanning allows sensing in between receptors
Passive vs Active sensing

of stationary objects

<table>
<thead>
<tr>
<th></th>
<th>Passive</th>
<th>Active</th>
</tr>
</thead>
<tbody>
<tr>
<td>threshold</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>accuracy</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Systems involved</td>
<td>sensory</td>
<td>Sensory + motor</td>
</tr>
<tr>
<td>coding</td>
<td>spatial</td>
<td>Spatial + temporal</td>
</tr>
<tr>
<td>Processing speed</td>
<td>fast</td>
<td>slow</td>
</tr>
<tr>
<td>Used in</td>
<td>detection</td>
<td>Exploration Localization Identification ...</td>
</tr>
</tbody>
</table>
Central processing of touch

where touch begins?

Text book: at the receptors
Localization (‘where’)  Identification (‘what’)  Whisking
Sensory-motor loops of the vibrissal system
Sensory-motor loops of the vibrissal system
Central processing of touch

**where touch begins?**

*Text book: at the receptors*

**Active touch does not begin at the receptors**

Sensor motion determines the interaction between the receptors and external objects
• Break ?
Motor control

- Closed loops
- Proprioceptive feedback
- Reflexes – tool for probing loop function
- Controlled variables – motor vs sensory
Motor control

- Closed loops
- Proprioceptive feedback
- Reflexes – tool for probing loop function
- Controlled variables – motor vs sensory
Excitation Contraction Coupling

Phase 1:
Firing of Motor Neuron

Phase 2:
Release of Neurotransmitter
Excitation Contraction Coupling

Phase 1:
Firing of Motor Neuron

Phase 2:
Release of Neurotransmitter

Phase 3:
Muscle contraction
Open-loop system

Information flows in one direction (from neurons to muscles)
Open-loop system

Information flows in one direction (from neurons to muscles)

Closed-loop system

Information flows in a closed loop: from neurons to muscles and from muscles to neurons

What kind of information?
Closed-loop system

The direct feedback from muscles and joints is mediated by **proprioceptive signals**

**Proprioceptive receptor types**

- Name:
  - Muscle spindle receptors
  - Golgi tendon organs
  - Joint receptors

- Sensitive to:
  - muscle length
  - muscle tension
  - Flexion, extension
Proprioceptive receptor types

Name:
- Muscle spindle receptors
- Golgi tendon organs
- Joint receptors

Sensitive to:
- Muscle length
- Muscle tension
- Flexion, extension

Location:
- Fleshy part of the muscle
- Between muscle and tendon
- Joint capsule

Parallel to muscle fibers
Serial to muscle fibers
Between bones
Motor control

- Closed loops
- Proprioceptive feedback
- Reflexes – tool for probing loop function
- Controlled variables – motor vs sensory
What proprioceptors encode?
Proprioceptive receptor types

Name:
- Muscle spindle receptors
- Golgi tendon organs
- Joint receptors

Sensitive to:
- muscle length
- muscle tension
- Flexion, extension

From
Arthur Prochazka,
University of Alberta
Proprioceptive receptor types

Name:
- Muscle spindle receptors
- Golgi tendon organs
- Joint receptors

Sensitive to:
- Muscle length
- Muscle tension
- Flexion, extension

Encode:
- Force
  \[ f = k_1F \]
Proprioceptive receptor types

Name:
- Muscle spindle receptors
- Golgi tendon organs
- Joint receptors

Sensitive to:
- Muscle length
- Muscle tension
- Flexion, extension

Encode:
- Length + velocity: \( f = k_1L + k_2V^{0.6} \)
- Force: \( f = k_1F \)
- Angle: \( f = k_1\theta \)
Proprioceptive receptor types

**Name:**
- Muscle spindle receptors
- Golgi tendon organs
- Joint receptors

**Sensitive to:**
- Muscle length
- Muscle tension
- Flexion, extension

**Encode:**
- Length + velocity: \( f = k_1L + k_2V^{0.6} \)
- Force: \( f = k_1F \)
- Angle: \( f = k_1\theta \)

Diagram showing the interaction between cutaneous receptors, interneurons, and joint receptors.
PID control

- **Proportional** (to the controlled variable)
- **Integral** (of the controlled variable)
- **Derivative** (of the controlled variable)

Present \( \dot{\theta} \)
Past \( \dot{\theta} \)
Future \( \ddot{\theta} \)

```plaintext
Spindle Tendon Joint
```

![PID Control Diagram](image)
Negative feedback loop

- **Characteristic**: The effect of a perturbation is in the opposite direction
- **Requirement**: The cumulative sign along the loop is negative
- **Function**: Can keep stable fixed points
Positive feedback loop

- **Characteristic**: The effect of a perturbation is in the same direction
- **Requirement**: The cumulative sign along the loop is positive
- **Function**: amplifies perturbations
Motor control

- Closed loops
- Proprioceptive feedback
- Reflexes – tool for probing loop function
- Controlled variables – motor vs sensory
The stretch reflex probes the control function of muscle spindles
Is the loop positive or negative?

- The stroke **stretches** the muscle
- As a result the muscle **contracts**
- The result opposes the perturbation

=> negative FB loop
the anatomical loop

- Muscle spindle **excites** the motor neuron
- Motor neuron **excites** muscle fibers
- Muscle contraction **suppresses** spindle response
Proprioceptive receptor types

**Name:**
- Muscle spindle receptors
- Golgi tendon organs
- Joint receptors

**Sensitive to:**
- Muscle length
- Muscle tension
- Flexion, extension

**Encode:**
- Force
  \[ f = k_1 F \]

Why proprioceptors fire at rest?

And why aren’t we aware of it?
What about the flexor muscles?

Positive or negative loop?

What is the underlying circuit?

Take it as homework – may appear in the exam...
Pain reflex

Positive or negative?
What is the underlying circuit?

Same...
Motor control

- Closed loops
- Proprioceptive feedback
- Reflexes – tool for probing loop function
- Controlled variables – motor vs sensory
• Break?
Sensory-motor loops of the vibrissal system
Basic principles of closed-loop control
Set point

\[ V_m = f(-V_s) \]

\[ V_s = g(V_m) \]
Set point

\[ V_d \rightarrow f \rightarrow V_m \]

\[ V_m = f(V_d - V_s) \]

\[ V_s = g(V_m) \]

\[ V_s \rightarrow V_m \]

\[ V_s_0 \]

\[ V_{sd} \]

\[ V_{md} \]

\[ V_{m0} \]
Direct control without direct connection

\[ V_m = f(V_d - V_s) \]

\[ V_s = g(V_m) \]
Nested loops

\[ V_m = f(V_d - V_s) \]
\[ V_s = g(V_m) \]
Parallel loops

\[ V_m0 = f(V_d - V_s) \]
\[ V_s = g(V_m1) \]

\[ V_m1 = f(V_d - V_s) \]
\[ V_s = g(V_m1) \]
Parallel loops

\[ f_2 \]

\[ V_m = g(V_s) \]

\[ V_m = f_2(V_d - V_s) \]

\[ X_s = g(X_m) \]

\[ X_s = f_2(V_d - V_s) \]

\[ X_s = g(X_m) \]

\[ V_m = f(V_d - V_s) \]

\[ V_s = g(V_m) \]
Closed loops in active sensing

The controlled variables can be

- **Motor** (Xm)
  (velocity, amplitude, duration, direction, …)
- **Sensory** (Xs)
  (Intensity, phase, moment, …)
- **Object** (via Xm – Xs relationships)
  (location, SF, identity, …)
Sensory-motor loops of the vibrissal system
Sensory-motor loops of the vibrissal system
Sensory-motor loops of the vibrissal system

Motor

Sensory

Brainstem

Loop

Facial Nucleus

Zona Incerta

Cerebellar/Olivary

Thalamic Nuclei

VL

POm

VPM-vl

VPM-dm

Trigeminal Nuclei

Trigeminal Ganglion

Primary Sensory Cortex

Secondary

Cortex

Thalamus

Superior Colliculus

Red Nucleus

Pontine Reticular Nucleus

Brainstem Reticular Formation

Facial Nucleus

Brainstem Loop

Primary Motor Cortex

Reticular Formation

Brainstem

67
Sensory-motor loops of the vibrissal system
Active sensing in the vibrissal system
Sensory signal conduction

The vibrissal system
Sensory signal conduction

The vibrissal system

whisker

Meisner
Merkel
Ruffini
Lanceolate
free endings
Sensory-motor loops of the vibrissal system
Motor control of whiskers

Intrinsic muscles
Follicle as a motor-sensory junction

- Motor signals move the follicle and whisker
- Follicle receptors report back details of self motion = proprioception
- Plus perturbations of this motion caused by the external world
Motor control of whiskers

Intrinsic muscles
Vibrissal proprioception

- Each follicle contains ~2000 receptors
- About 20% of them convey pure proprioceptive information
Vibrissal system

Proprioceptive loop

Skeletal system

Proprioceptive loop
Whiskers come with different muscle sizes

Intrinsic muscles

Motor-Sensory-Motor (MSM) loops

External perception

Body perception
Perception of external objects

Object localization

• What signals must the brain process in order to infer a location of an external object in space?
• Reafferent + exafferent signals
What the whiskers tell the rat brain

Reafference:

Their own movement

(“Whisking”)

Exafference:

Touch
What the whiskers tell the rat brain

Whisking

Whisker position vs. time
What the whiskers tell the rat brain

**Whisking**

Whisker position vs. time

space

time
What the whiskers tell the rat brain

Whisking

Whisker position vs. time

What the whiskers tell the rat brain

Whisking

space

Whisker position vs. time

time
What the whiskers tell the rat brain

**Whisking**

Whisker position vs. time
What the whiskers tell the rat brain

Whisking

Whisker position vs. time

space

time
What the whiskers tell the rat brain

Whisking

Whisker position vs. time

space

time
What the whiskers tell the rat brain

Whisking

Whisker position vs. time
What the whiskers tell the rat brain

**Whisking**

Whisker position vs. time

Space

Time
What the whiskers tell the rat brain

**Whisking**

Whisker position vs. time
What the whiskers tell the rat brain

Whisking

Whisker position vs. time
What the whiskers tell the rat brain

Whisking

Whisker position vs. time
What the whiskers tell the rat brain

Reafference:

Their own movement

(“Whisking”)

Exafference:

Touch
What the whiskers tell the rat brain

Touch

Whisker position vs. time

space

time
What the whiskers tell the rat brain

Touch

Whisker position vs. time
What the whiskers tell the rat brain

**Touch**

Whisker position vs. time

---

space

---

time
What the whiskers tell the rat brain

Touch

Whisker position vs. time

space

time

[Diagram of a rat's head with whiskers and a graph showing whisker position vs. time]
What the whiskers tell the rat brain

Touch

Whisker position vs. time
What the whiskers tell the rat brain

Touch

Whisker position vs. time

space

time
What the whiskers tell the rat brain

**Touch**

space

Whisker *position* vs. *time*

---

106
What the whiskers tell the rat brain

Touch

Whisker position vs. time

space

time
What the whiskers tell the rat brain

Touch

Whisker position vs. time

space
What the whiskers tell the rat brain

Touch

Whisker position vs. time

space

time
What the whiskers tell the rat brain

Touch

Whisker position vs. time

space

time
What the whiskers tell the rat brain

How can the brain use this information?

- **Whisking:**

- **Touch:**

  contact with object
What the whiskers tell the rat brain

How can the brain use this information?

- Whisking:

- Touch:

Where is the object?
How can the brain extract the location of the object

- **Whisking:**
  - Whisker position vs. time
  - Contact with object

- **Touch:**
  - Contact with object
How can the brain extract the location of the object

• Whisking:

• Touch:

contact with object
Sensory organs consist of receptor arrays:

- **somatosensation**: Finger pad (~200 µm)
- **audition**: Cochlea (10 µm)
- **vision**: Retina (10 µm)

**Spatial organization** => **Spatial coding**  
("which receptors are activated")

**Movements** => **Temporal coding**  
("when receptors are activated")
Orthogonal coding of object location

- **Vertical** object position is encoded by space
- **Horizontal** object position is encoded by time
- **Radial** object position is encoded by rate
coding of object location

• **Elevation** is encoded by **space**

• **Azimuth** is encoded by **time**

• **Radial distance** is encoded by **rate**
What is the 3V coding good for?
What is the 3V coding good for?

1. Increasing channel efficiency

In principle, a single cell can encode all 3 coordinates

- The fact that it fires encodes the elevation
- Its latency encodes the azimuth
- Its firing rate encodes the radial distance
coding of object location

In principle, Single cells can encode all 3 coordinates

Another form of efficient coding
Active sensing

The End