9.14 - Brain Structure and its Origins
Spring 2005
Massachusetts Institute of Technology
Instructor: Professor Gerald Schneider

# A sketch of the central nervous system and its origins

G. E. Schneider 2005

**Part 6: A brief look at motor systems**

## MIT 9.14 Class 15

Motor systems 2:

Descending pathways and evolution;

Temporal patterns

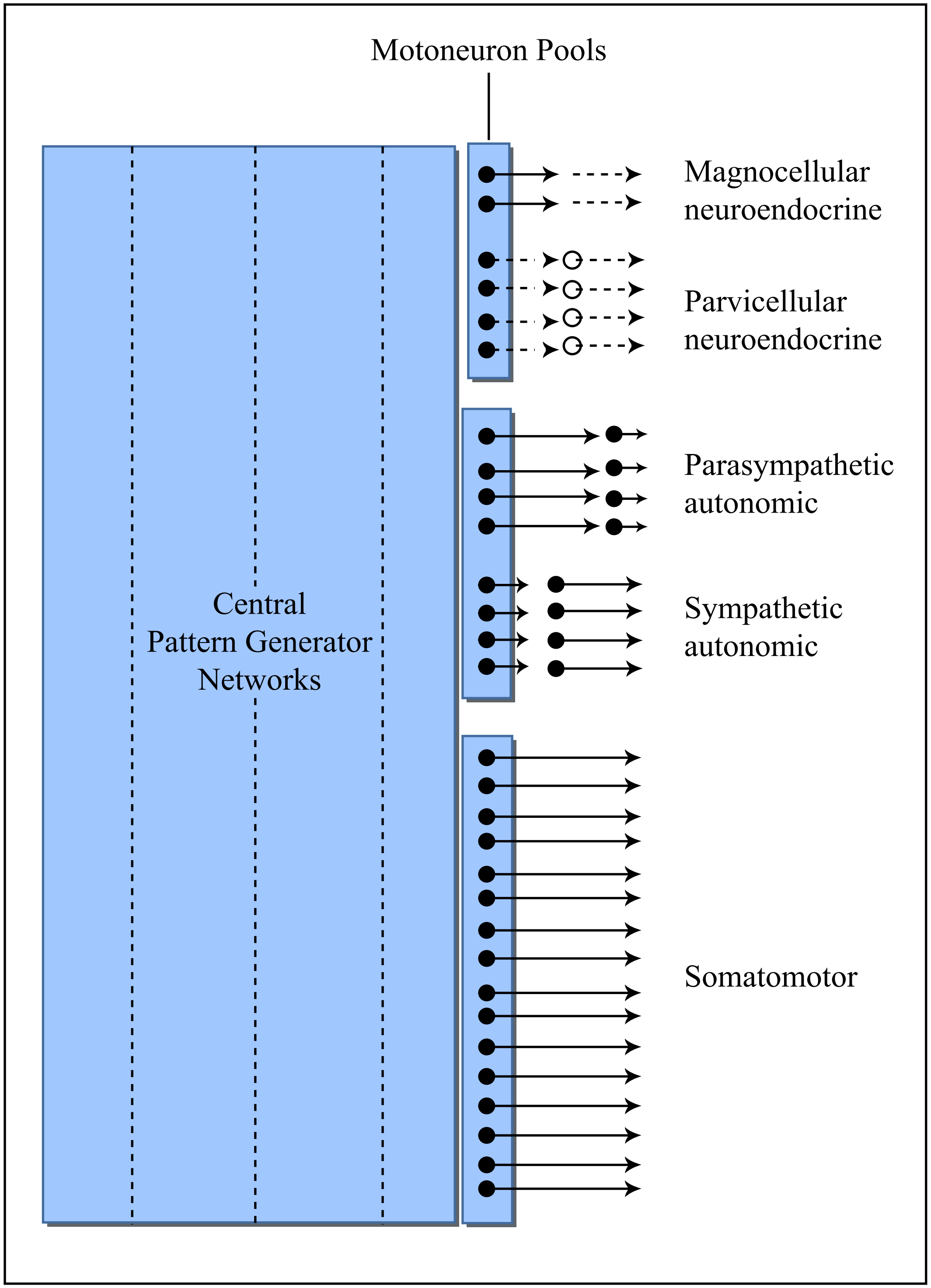


Figure by MIT OCW.

# The three motor systems

*(Where are the central pattern generator networks that coordinate the three systems?)**

# Distribution of somatic motor neurons

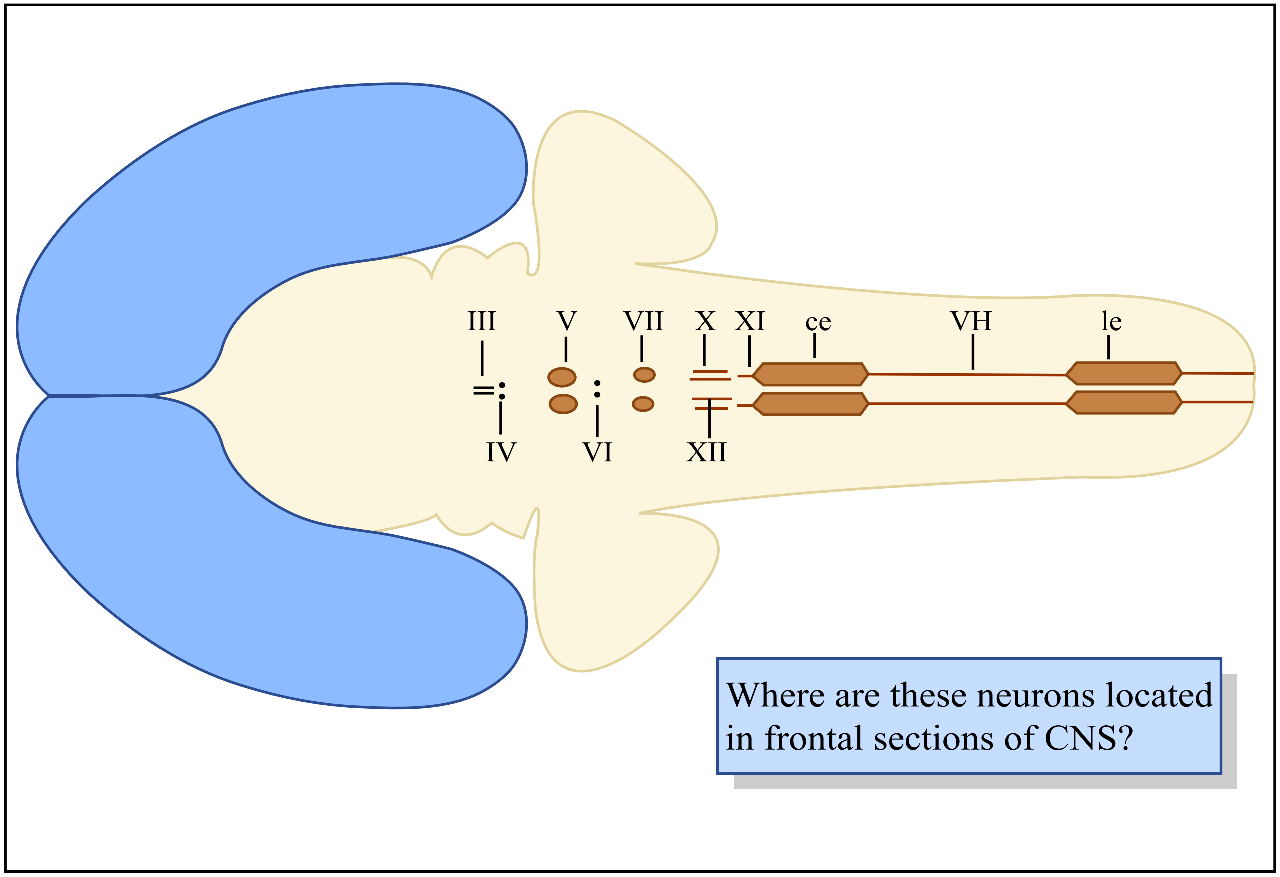


Figure by MIT OCW.

# The spatial arrangements of motor neurons in the spinal cord

- Spinal cord at one of the enlargements
  - Illustrated for human and for monkey
- Radial projections of interneurons
- Descending connections in the cord

- (see figures)

# Topographic distribution of somatic motor neurons, human spinal cord

Figure removed due to copyright reasons.

Please see Figure 6.3 in

Swanson, Larry W. *Brain Architecture, Understanding the Basic Plan.*

Oxford, New York, NY: Oxford University Press, 2003, p. 105. ISBN: 0195105052.

# Topographic distribution of somatic motor neurons, human spinal cord

Figure removed due to copyright reasons.

*From Lawrence & Kuypers, 1968*

# Terminal distribution pattern of descending cortical and subcortical pathways, spinal cord, rhesus monkey

*(Lawrence & Kuypers, 1968)*

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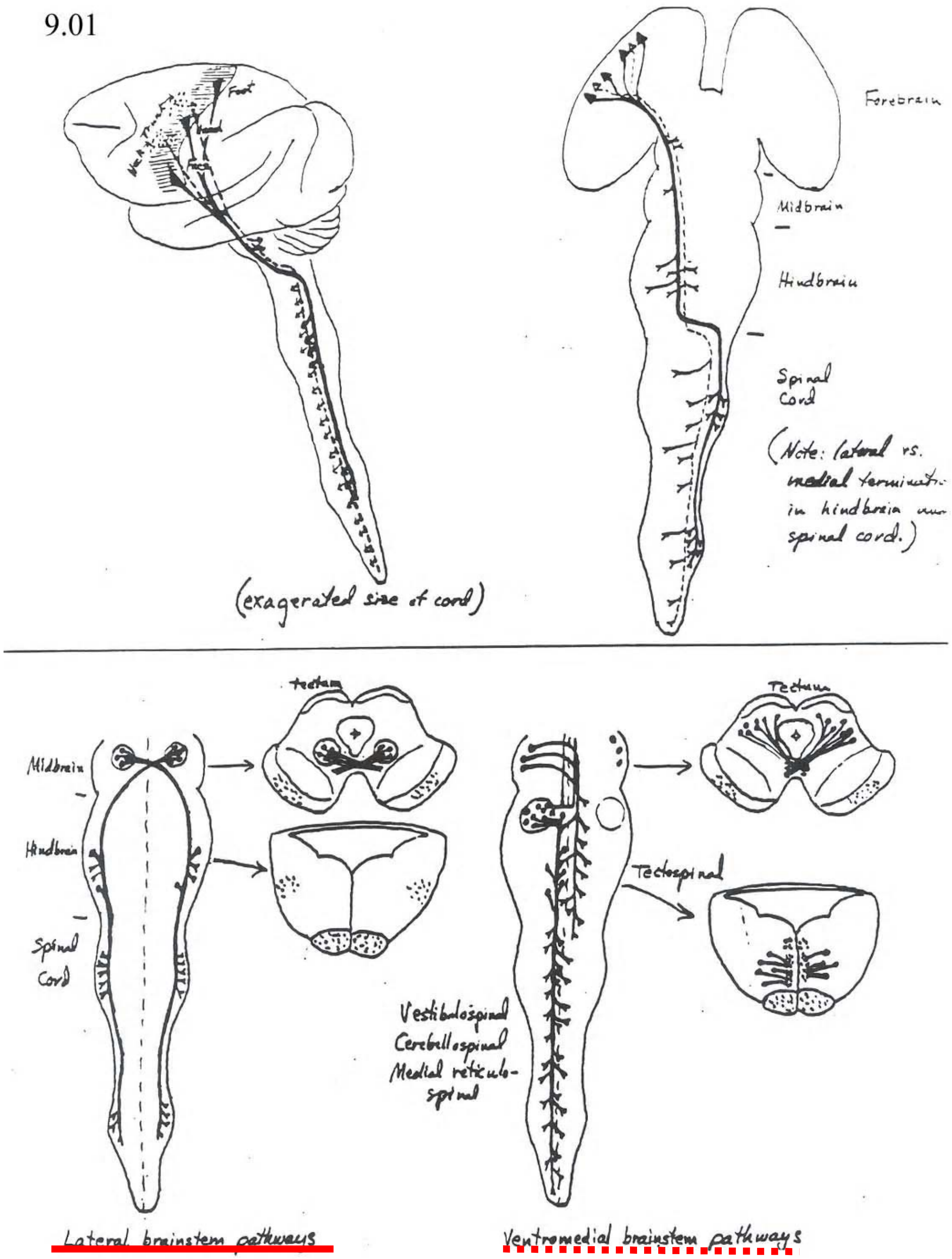
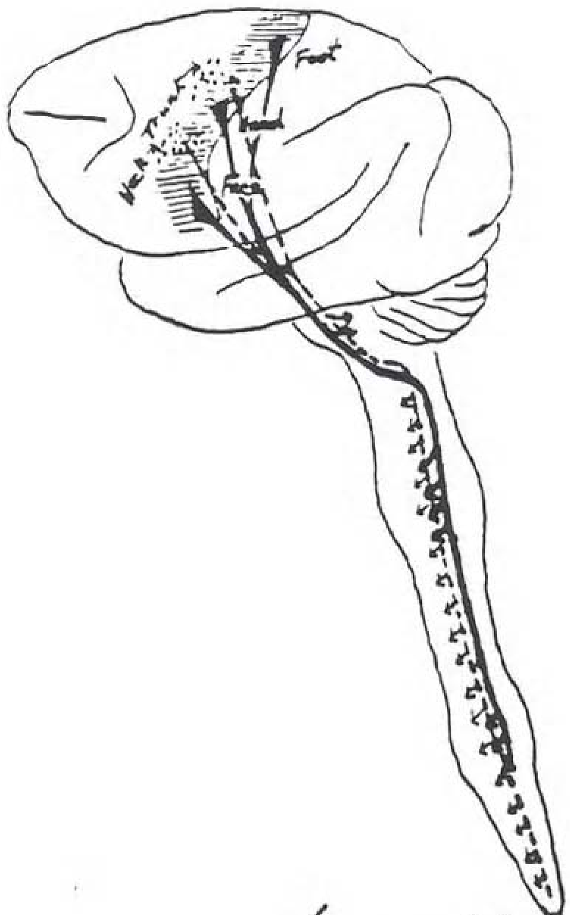
# **Three** Descending Motor Pathways:

**Distinguishing the course of axons influencing axial and distal muscle control**

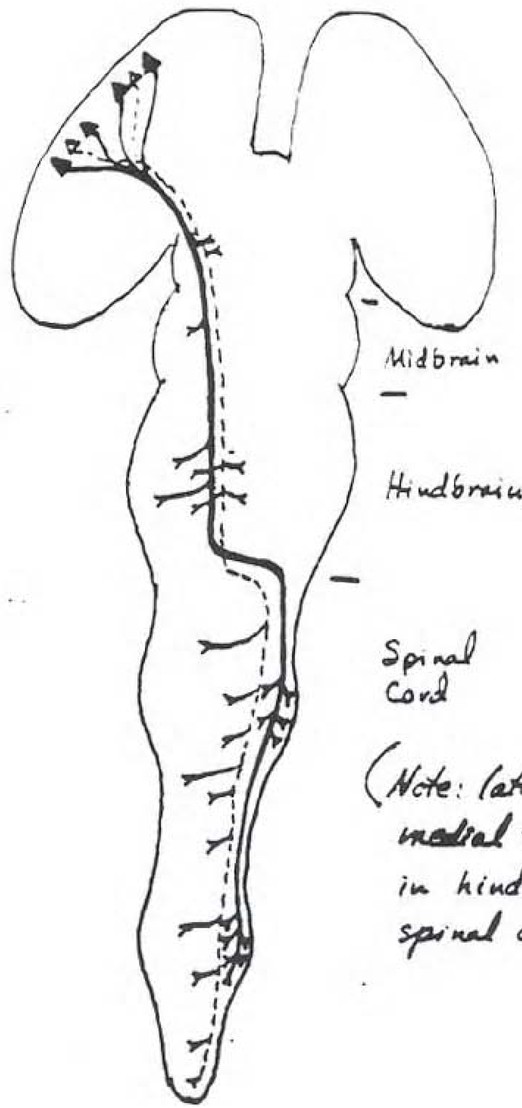
**[Enlarged on next slides]**



# Distinguishing the axons influencing axial *vs* distal muscles:
# Corticospinal pathway

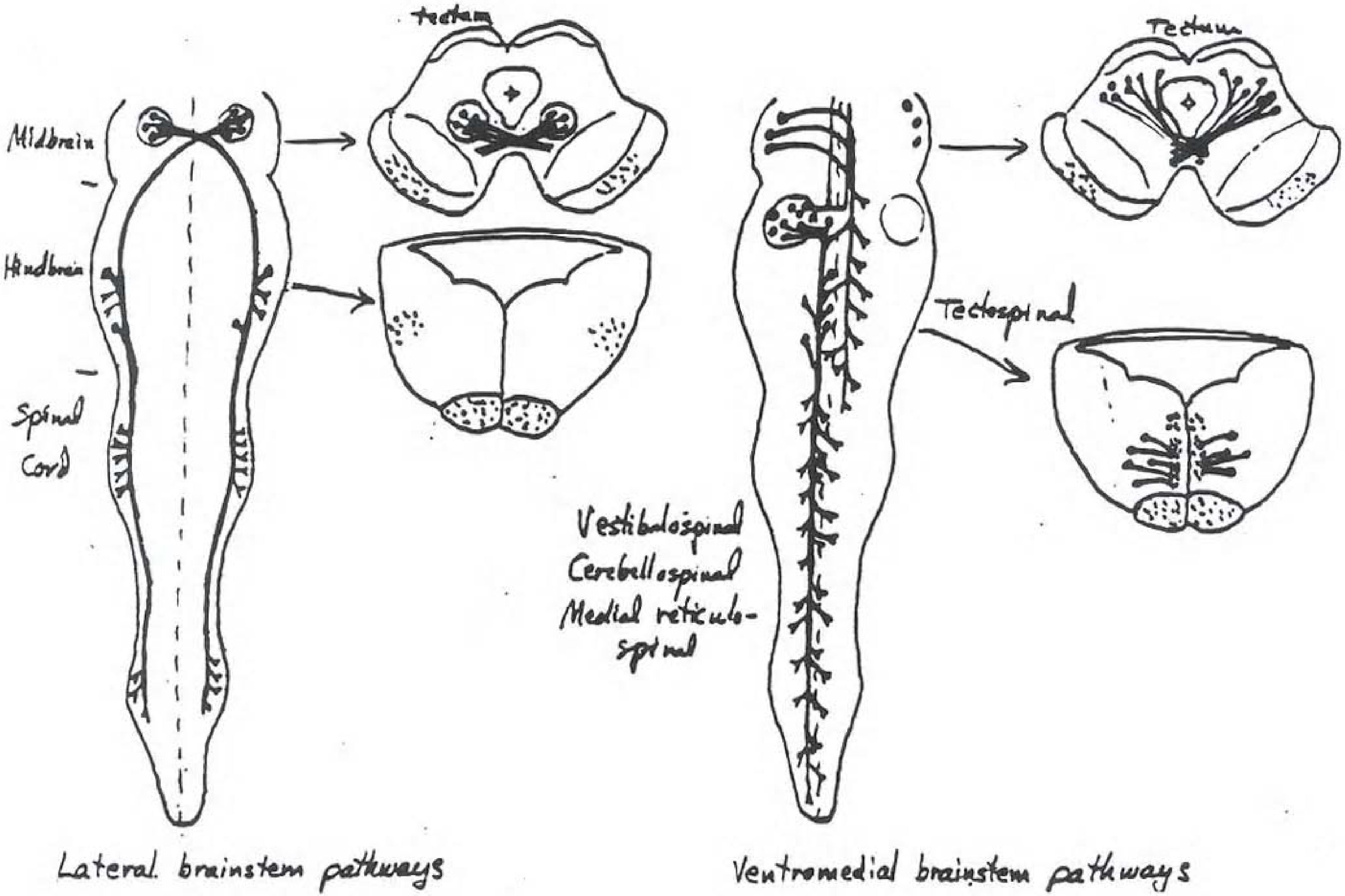



(exagerated size of cord)



## Distinguishing the axons influencing axial *vs* distal muscles:

# Lateral and ventromedial brainstem pathways

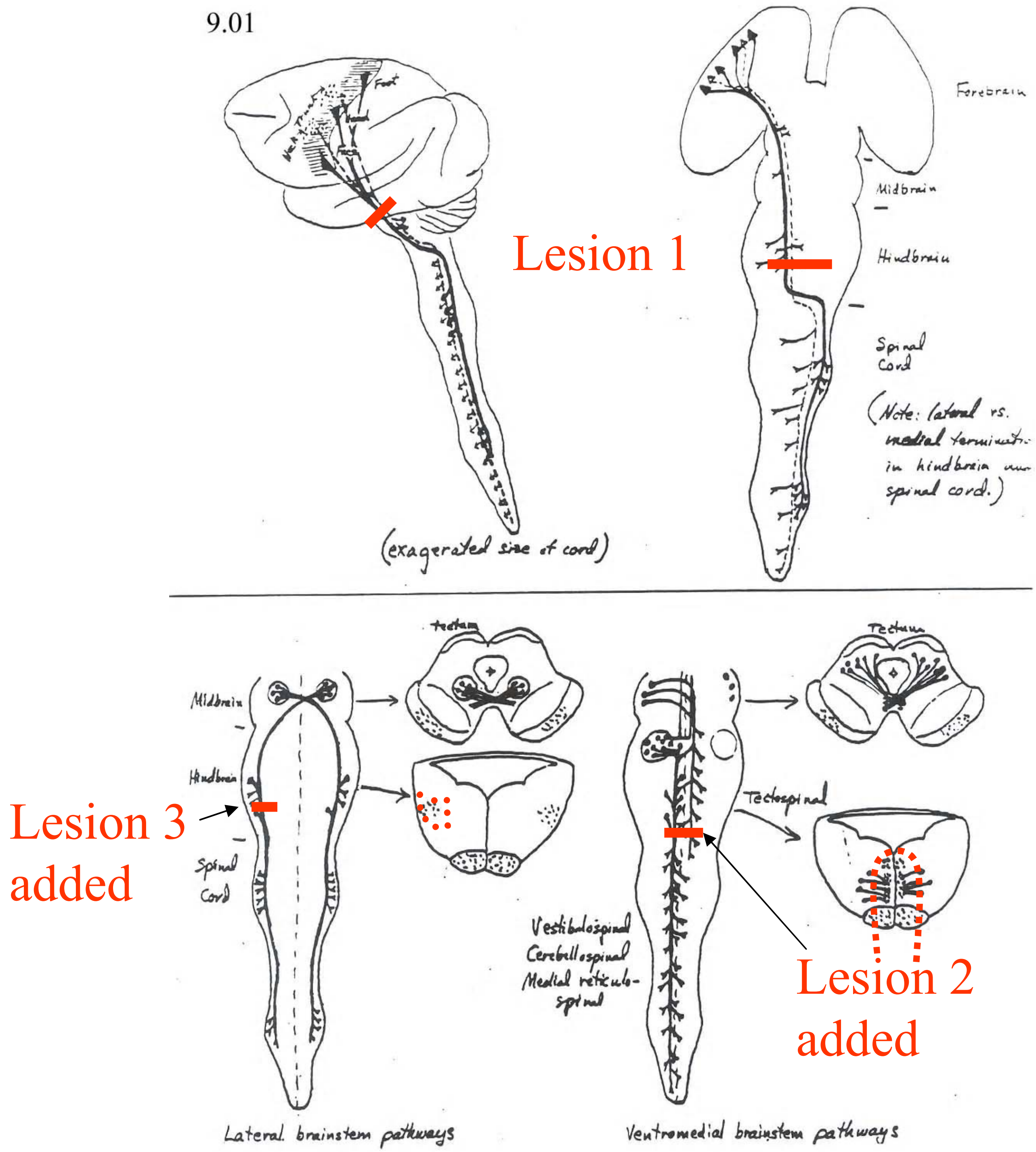


# Effects of lesions:

– The logic of Lawrence & Kuypers, 1968 paper in the journal *Brain*

- Begin with elimination of the corticospinal projections; wait for recovery from diaschisis effects
- Then, ablate either the medial or the lateral pathways descending from the hindbrain and midbrain

# Selective lesions of the descending motor pathways



# *Lawrence & Kuypers, 1968:*

- **Lesion #1: pyramidotomy**
  - Loss of speed and strength
  - Loss of control of digits used one at a time

# *Lawrence & Kuypers, 1968:*

- **Lesion #2: destruction of medial brainstem pathways** (<u>added</u> to pyramidotomy)
  - Defective axial control:
    - Righting: only after 10-40 days
    - Falling: failure to elicit the usual corrective movements
    - Walking: only one monkey could take many steps because of disorientation; he veered from course, bumped into obstacles
  - Better distal control:
    - If monkey was strapped into a chair, it could grasp food objects with the whole hand

## *Lawrence & Kuypers, 1968:*

- **Lesion #3: destruction of lateral brainstem pathways** (<u>added</u> to pyramidotomy)
  - Defective limb control: Hand flexion done only with total arm movements
  - Good axial control
    - Hand used dramatically better in running & climbing (total body movements)

Brief digression:

# The brain disconnected from the motor output:

## **Motor cortical activity in human tetraplegics**

- Thought without the ability to act: Activation of specific parts of the motor cortex
- Question: Can the long pathways be reconnected in people or animals with such injuries?

# Motor-cortical activity in tetraplegics

Figures removed due to copyright reasons.
Please see Figure 1 in
Shoham, S., E. Halgren, E. M. Maynard, and R. A. Normann. "Motor-cortical activity in tetraplegics." *Nature* 413, no. 6858 (October 25, 2001): 793.

# Motor cortex and corticospinal projections in phylogeny (from Striedter, 2005)

1) **The sensorimotor amalgam hypothesis**
   - VL and VP projections (projections to motor and somatosensory cortex): Opossum and rat compared
2) **Corticospinal invasion and dexterity**
   - Correlated
3) **Comparative analysis of corticospinal neurons**
   - More of them when total size of neocortex is greater

# The sensorimotor amalgam hypothesis

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# Penetration of corticospinal axons into ventral horn *vs.* neocortical volume

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# Penetration of corticospinal axons down the spinal cord *vs.* neocortical volume

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# Correlations with dexterity

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# Neocortex : Spinal Cord Ratio
# *vs.* Neocortical Volume

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**The greater invasion of spinal cord with increasing neocortical size fits "Deacon's rule" which is summarized as "large equals well-connected".**

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**(Upper)**

## Corticospinal neuron locations and densities

**A) rhesus monkey**
**B) squirrel monkey**
**C) galago (bush baby)**
**D) tree shrew**
**E) squirrel**
**F) rat**
**G) domestic cat**
**H) mole**
**I) hedgehog**
**J) opossum, short-tailed**
**K) opossum, Virginia**

**(Lower)**

## Corticospinal neuron number *vs.* neocortical surface area

# Rhythmic output and timing
## *Topics*

- Temporal patterns in animal movements: Explanations
  - These have led to basic theoretical ideas of how the brain functions at the level of circuits
- Activity rhythms and behavioral state control: Underlying structures and pathways

# Temporal patterns in movements: types of explanations

- <u>**Straight-through processing concepts (S-R models)**</u>
- Feedback circuitry
- Spontaneous CNS activity

# Straight-through processing concepts (S-R models)

- *Topics*

  - Timing of movements in reflexes
    - Conduction time: temporal pattern in startle reflex
    - Chaining of reflexes or fixed action patterns

  - Lashley's 1917 paper: "The problem of serial order in behavior":

# Timing of movements in reflexes : Conduction time

- Temporal pattern in startle reflex:
  1. eye blink,
  2. then contraction of other facial muscles,
  3. then neck flexion,
  4. then arm flexion,
  5. then leg flexion (with very intense sound).
- Timing due to: fiber size, synaptic delays; temporal summation times

# **Chaining** of reflexes or fixed action patterns

- Tinbergen (1951): the stickleback's courtship pattern as an S-R series
- "Reflex deglutition" (swallowing reflex): Same or different type of explanation?

# Tinbergen (1951): The courtship behavior of the three-spined stickleback fish

- Movements by a pair of animals rather than just one animal
- If a step is interrupted:
  - The sequence cannot proceed
  - Each step gives a necessary stimulus for triggering the next step.

- ***This is presented just to illustrate the chaining of S-R events, often called "reflex chaining"***

# Tinbergen (1951): The courtship behavior of the three-spine stickleback fish

| Female | Male |
|---|---|
| • Appears, swollen belly | |
| | • Zig-zag dance |
| • Courts (approaches) | |
| | • Leads to nest |
| • Follows | |
| | • Special posture at entrance |
| • Enters nest | |
| | • Trembles, snout to her tail |
| • Spawns | |
| | • Fertilizes |

# “Reflex deglutition” (swallowing)

- Involves about 20 muscles controlled by neurons from midbrain to cervical spinal cord levels.
- In this case the pattern of contraction is centrally programmed:
  - It is a “fixed action pattern” (FAP), inborn, and is executed rhythmically with a steady or varied stimulus *via* the superior laryngeal nerve.
  - Pattern is not changed by elimination of proprioceptive feedback during any stage of the movement once it is triggered.
  - It is normally triggered by stimulation of the tongue deep in the throat, but there is also an endogenous input that builds up over time and lowers the threshold for eliciting the response.

[*Study by Doty & Bosma, 1956*]

# Karl Lashley's 1917 paper:
# "The problem of serial order in behavior"

- He argued against the adequacy of the reflex chaining hypothesis. Example:
  - "The finger strokes of a musician may reach 16/sec in passages which call for a definite and changing order of successive finger movements."
  - **"The succession of movements is too quick even for visual reaction time."**
- **Therefore, there must be central generation of patterns of movement.**

# Similarly, many fixed action patterns are centrally generated. They are inherited movement abilities.

- Grooming by mice (Fentriss' experiments): Movement patterns continue even without the usual feedback stimulation.
- Egg rolling in gulls (Tinbergen): Movements can occur in absence of stimulus
- Other examples of "*in vacuo*" movement patterns
- Locomotor movements in fish: Central generation
- Locomotor movements in mammals are similarly generated in the spinal cord, but they require activation from the periphery or from descending fiber systems (from the brain)

**How are these action patterns generated, if not by reflex circuitry?**

# Temporal patterns in movements: types of explanations

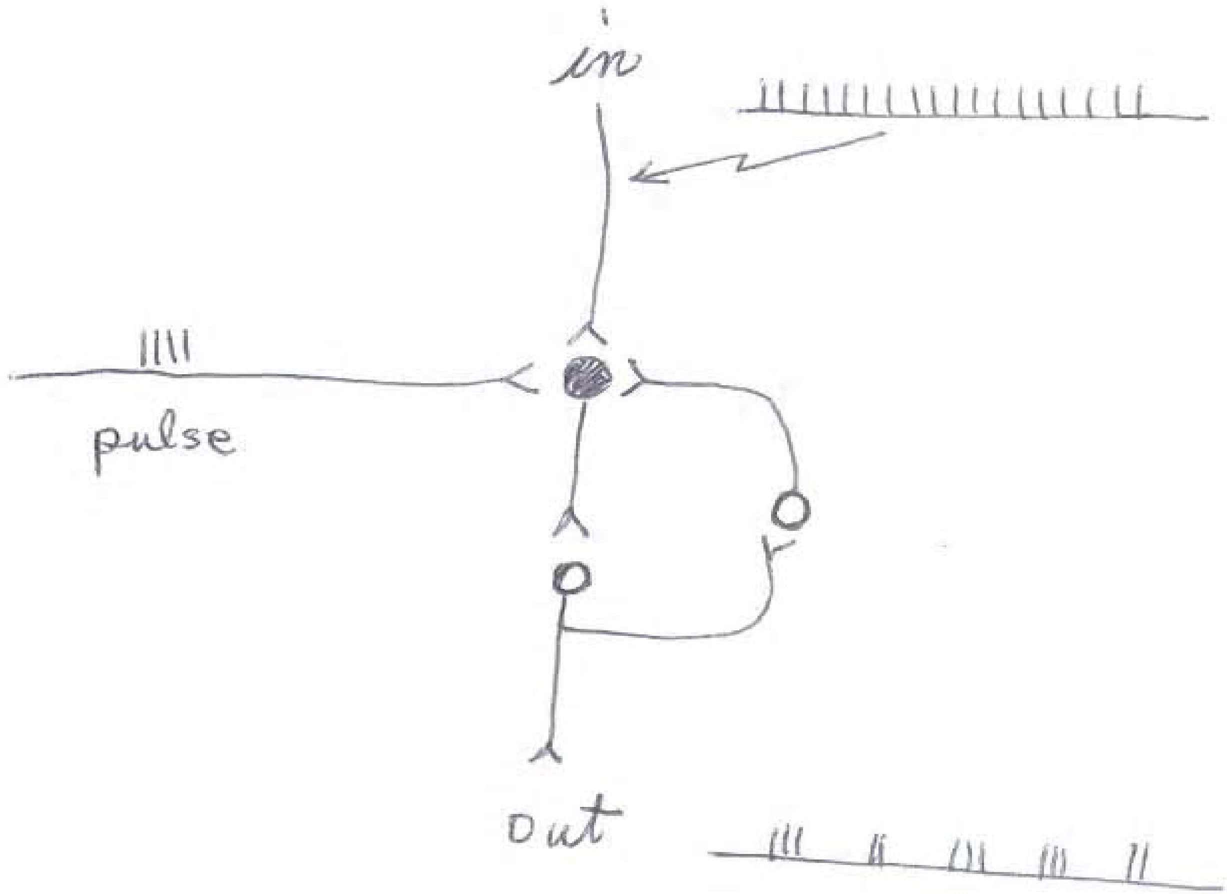
- Straight-through processing concepts (S-R models)
- **Feedback circuitry**
- Spontaneous CNS activity

# Feedback circuitry: the “reverberating circuits” idea

- Self re-exciting loops
  → regular bursts of action potentials (a kind of central oscillator)

- Negative feedback in homeostatic mechanisms:
  - The response oscillates around a certain level of some input (the set point).

# Feedback circuit:
# patterned output from unpatterned input



# Complexity and control

- To get more complex patterns, combine more than one such circuit.
  – How stop the rhythm?
- Example: Breathing rhythms can be at least partially explained by such circuits.

# Temporal patterns in movements: types of explanations

- Straight-through processing concepts (S-R models)
- Feedback circuitry
- **Spontaneous CNS activity**

# Spontaneous CNS activity

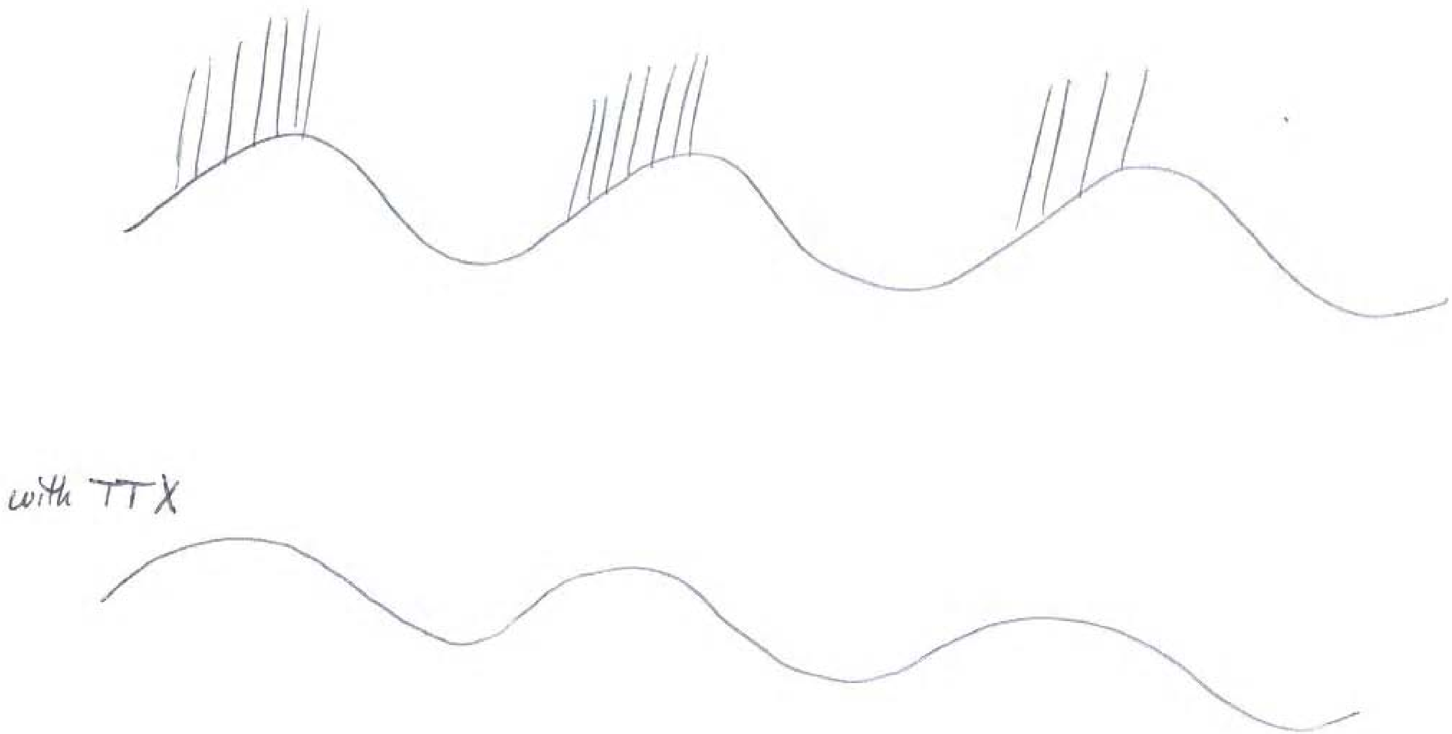
- Endogenously generated rhythmic potentials can also cause bursting patterns of action potentials
  - Felix Strumwasser's Aplysia (sea slug) recordings
- Circadian rhythms in vertebrates

# Felix Strumwasser's Aplysia (sea slug) experiments

- Recordings form an identifiable large secretory neuron of the abdominal ganglion:
  - T=40 sec (rhythm persists if action potentials are blocked with TTX),
  - but not if sodium pump is blocked with Ouabain.

- This cell also showed a circadian rhythm that could be entrained by light.

# Endogenous oscillator




**The potential for complex temporal pattern generation:**
**Multiple oscillators added together could give any pattern!**

**This is known from the mathematics of Fourier Analysis.**

# Circadian rhythms in vertebrates

- Dependence of animals on such "biological clocks" with a period of approximately 24 hr.
  - Temporal schedules are crucial to animal survival
- An intriguing experiment:
  - Give mice heavy water ($D_2O$,) and their free-running circadian activity rhythm slows down to a degree proportional to the % $D_2O$ in their drinking water.
- What is the **anatomy of brain-state changes** that underlie changes in behavioral state, such as going to sleep or becoming aroused?

# Contributions to theory

- Study of how organized sequences of movement are produced, and how they can change, has led to the development of basic ideas about how the brain works.
- These ideas are basic organizing concepts in theories of CNS functions when we think of them at the level of connections and circuits.

## Basic organizing concepts in theories of CNS functions: The circuit level

- Straight-through processing concepts
  - Reflexes, S-R models
  - Input analysis
- Feedback control
  - "Reverberating circuits" (positive feedback)
  - Reciprocal inhibition
  - Homeostats
- Spontaneous CNS activity (of endogenous origin)
  - Rhythmic activity; periodic bursts of activity
  - Maintained excitatory states
- Plasticity (usually meaning a change in connections)
  - Molecular (synaptic change, etc.)
  - Anatomical (sprouting of various kinds)

# Behavioral state control:
## **Brain states influenced by widely projecting axon systems, and by chemical secretions**

- State changes involve pathways fundamentally different from the type considered above.
- Examples:
  - The "reticular activating system"
  - Monoamine systems
  - Widely projecting neurons of lateral hypothalamus
  - Secretions into the cerebrospinal fluid should be added to this list, e.g., during sleep onset.

# Reticular activating system:

## Example of widely distributed axon from hindbrain cell

Figure removed due to copyright reasons.

**Many such cells use acetylcholine as their transmitter.**

**Cholinergic cells with widely distributed axons are also found in the basal forebrain; the axons project to neocortex.**

# Monoamine systems

- Serotonin (5 hydroxy tryptamine, 5-HT)
  - Neurons of the raphe nuclei with widely distributed axons
  - Role in sleep and waking/arousal
  - *Reading: Allman pp 19-27*
- Catecholamines
  - Norepinephrine-containing axon systems, e.g., from the locus coeruleus of the rostral hindbrain
    - Role in sleep and waking/arousal
  - Dopamine-containing axon systems, e.g., from the ventral tegmental area of the limbic portions of the midbrain
    - Role in reward/ reinforcement in learning processes

# Other widely projecting axon systems which influence behavioral state

- Cell groups in the paleothalamus (midline and intralaminar nuclei)
  - Projections to large territories in the neocortex
  - One with projections to layer 1 of nearly the entire neocortex
- Cell groups in the lateral hypothalamus and adjoining subthalamus
  - One containing Melanin Concentrating Hormone
  - One using peptides Hypocretin/Oxerin and Dynorphin as transmitters
    - Mutations in the gene for H/O or its receptor cause narcolepsy
  - One using Corticotropin-releasing hormone (CRH) in anorexia states
- *See Swanson (2003), ch 7*

# This is a bare-bones introduction to brain mechanisms that can change the state of much of the brain, if not all.

- They were not all present in the earliest chordates
  - E.g., Amphioxus has only one monoamine system/receptor – dopamine
  - Hagfish and lampreys have at least two: DA and NE
- However, the "primitive state" of many axons was that of widely branched and extensive distribution. In evolution, specific axon systems have become specialized for this kind of connection

# Selected References

Slide 2: Swanson, Larry W. *Brain Architecture, Understanding the Basic Plan*. Oxford, New York, NY: Oxford University Press, 2003, p. 136. ISBN: 0195105052.

Slide 3: Swanson, Larry W. *Brain Architecture, Understanding the Basic Plan*. Oxford, New York, NY: Oxford University Press, 2003, p. 104. ISBN: 0195105052.