Systems Neuroscience
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Motor Systems

Yulia Sandamirskaya
INI, UZH/ETHZ
yuliasa@ethz.ch

Why is motor system important?

- All behavior is directly or indirectly related to activity in the motor system
- Without the neuronal structures that evolved to actively generate behavior, we could not experience sensation, think, reason, problem solve, read, write, and do mental math, and we would not be able to communicate our thoughts and abilities to anyone.

➡story of the mollusk

➡most of the neural system, in the end, serves movement

➡movement is prerequisite for ANY perception and learning

➡"thinking" and cognition use the same structures as physical movement

What’s the brain good for?

A story of Ascidiella Scabra ….

Overview of motor systems

- Spinal reflexes
- Corticospinal and corticobulbar tracts
- Cortical-subcortical-thalamo-cortical systems
  - Involving basal ganglia
  - Involving pons and cerebellum
- Motor, pre-motor, and all the other cortical regions

Skeletal Muscles (vs. smooth muscles)

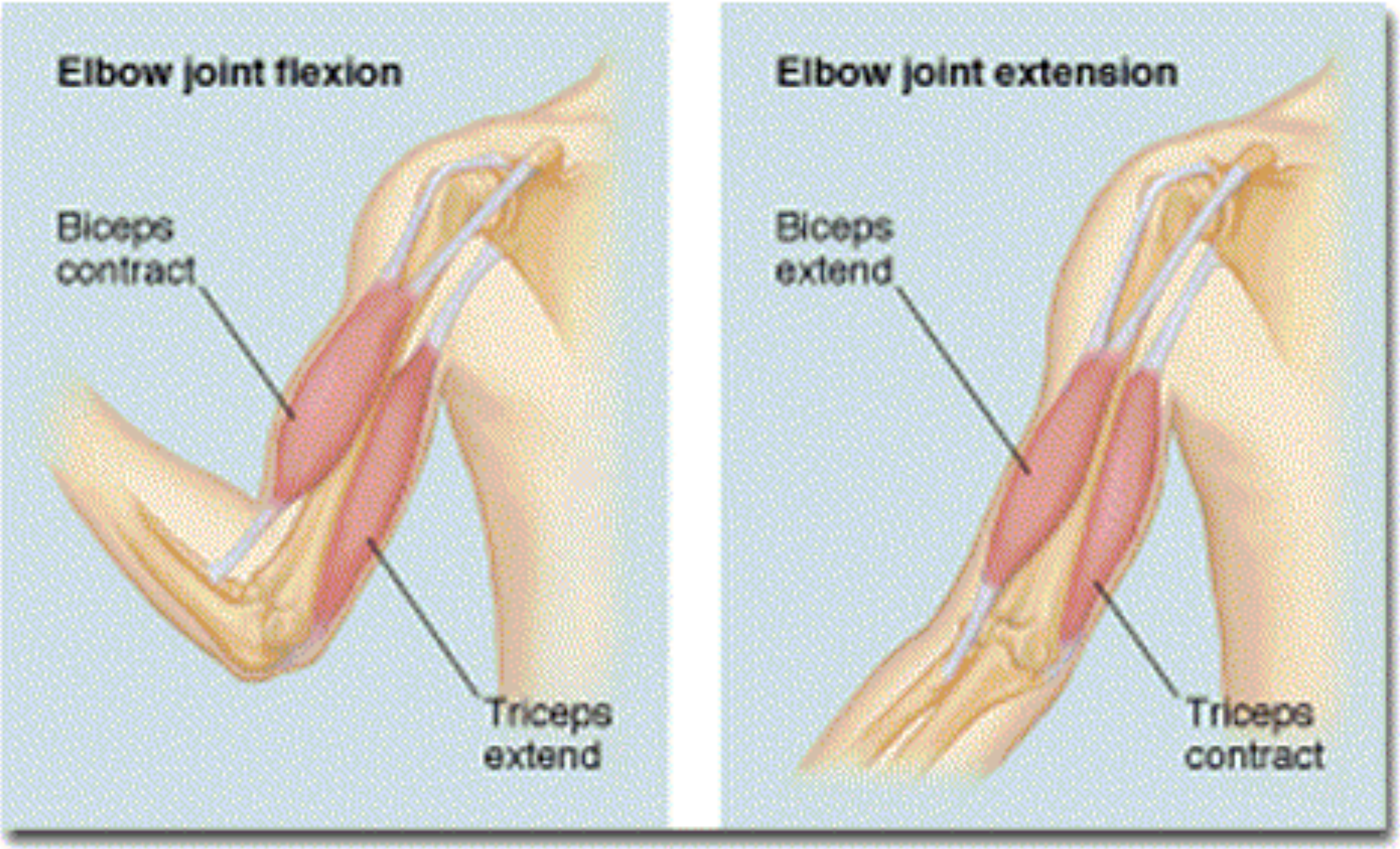
- striated (striped) appearance because they are comprised of muscle fibers

- move through a pull action (contraction)

- work in pairs with a reciprocal muscle (bicep contracts & triceps relaxes)

- stimulated by a Motor Neuron

The Biceps and Triceps



Why?

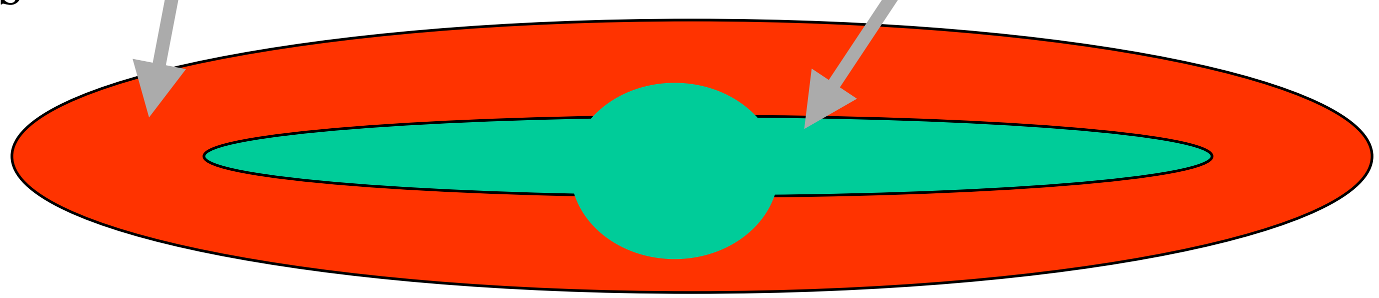
Anatomy of the muscle

- striated muscles are made of muscle fibers that have two parts, outer and inner:

Outer fiber = extrafusal fiber

This represents only one muscle fiber - a muscle has many fibers

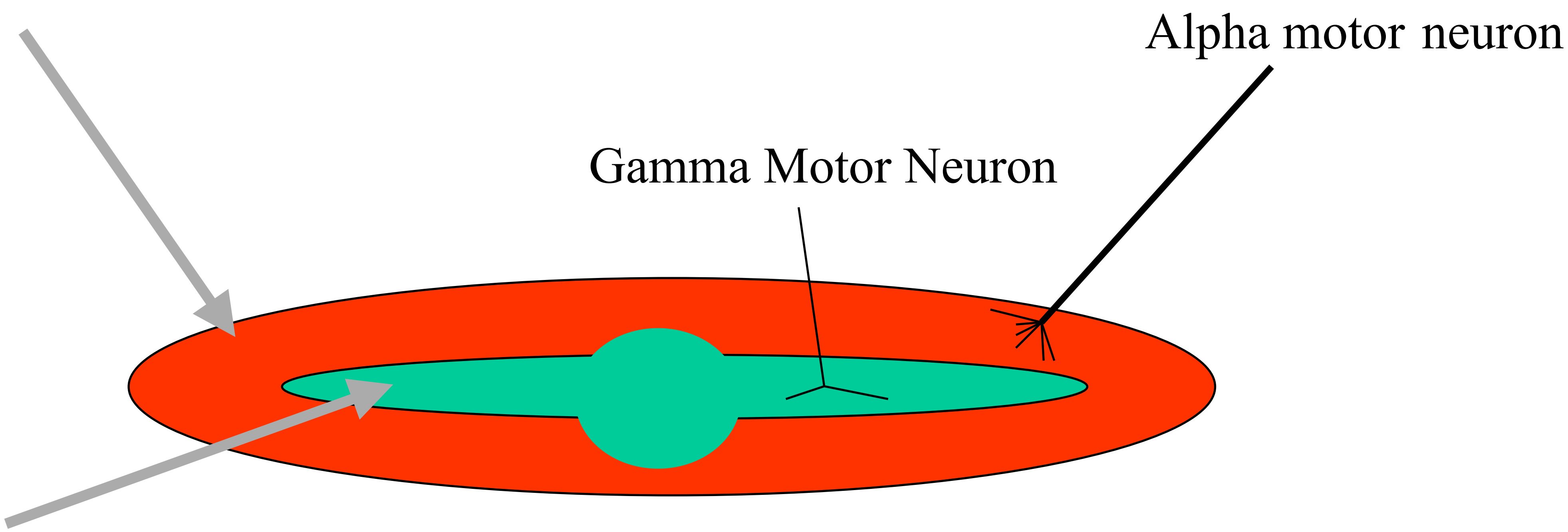
Inner fiber = intrafusal fiber



Wrapped around the intrafusal fiber is a sensory nerve that picks up the sensation of stretch.

Neurophysiology of the muscle

Outer fiber = extrafusal fiber



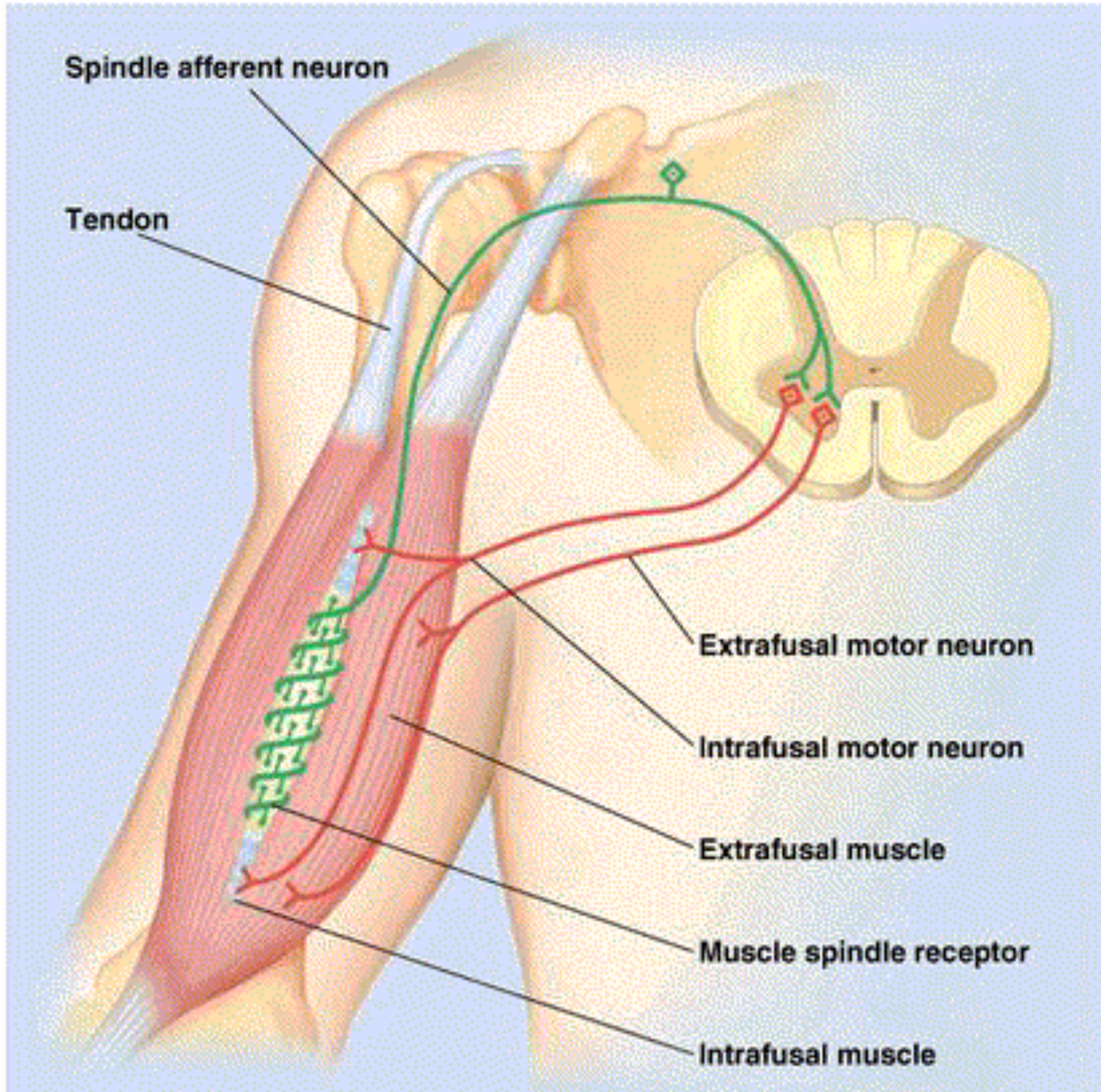
Inner fiber = intrafusal fiber

- **<u>gamma motor neuron</u>** that synapses on the intrafusal fiber
- **<u>alpha motor neuron</u>** synapses on the extrafusal fibers

  - one alpha motor neuron can stimulate numerous fibers (➡ **"Motor unit"**)

  - the neural link between the alpha motor neuron and the muscle fiber is called the **<u>neuromuscular junction</u>**.

Muscle-Spindle Feedback Circuit



Some facts

- The ratio between the alpha motor neuron and the number of muscles fibers it innervates is associated with the degree of dexterity needed in the movement
  - high ratio (1:150) = contraction of large muscles
  - low ratio (1: 10) = contraction of small muscles needed for fine movements

Motor Homunculus is related to the number of alpha motor neurons needed to innervate muscles of various regions of our body.

Comparing the Anatomy of the CNS with the Anatomy of the Neuromuscular Junction

Motor Unit	**CNS Synapse**
•Alpha Motor Neuron	Presynaptic Neuron
•Muscle Fiber	Postsynaptic Neuron
•Endplate	Dendrite
•NT is Acetylcholine	Many different NTs
•Nicotinic Receptors	Many different receptors
•Calcium enters	Sodium enters
•Endplate Potential (EPP)	EPSP
•Muscle Contraction or Muscle Action Potential & movement	Action Potential & release of NT

How is limb position maintained?

- Involuntary movement (i.e. posture):

  ➡ continual contraction and relaxation of the muscles in our feet and calves.

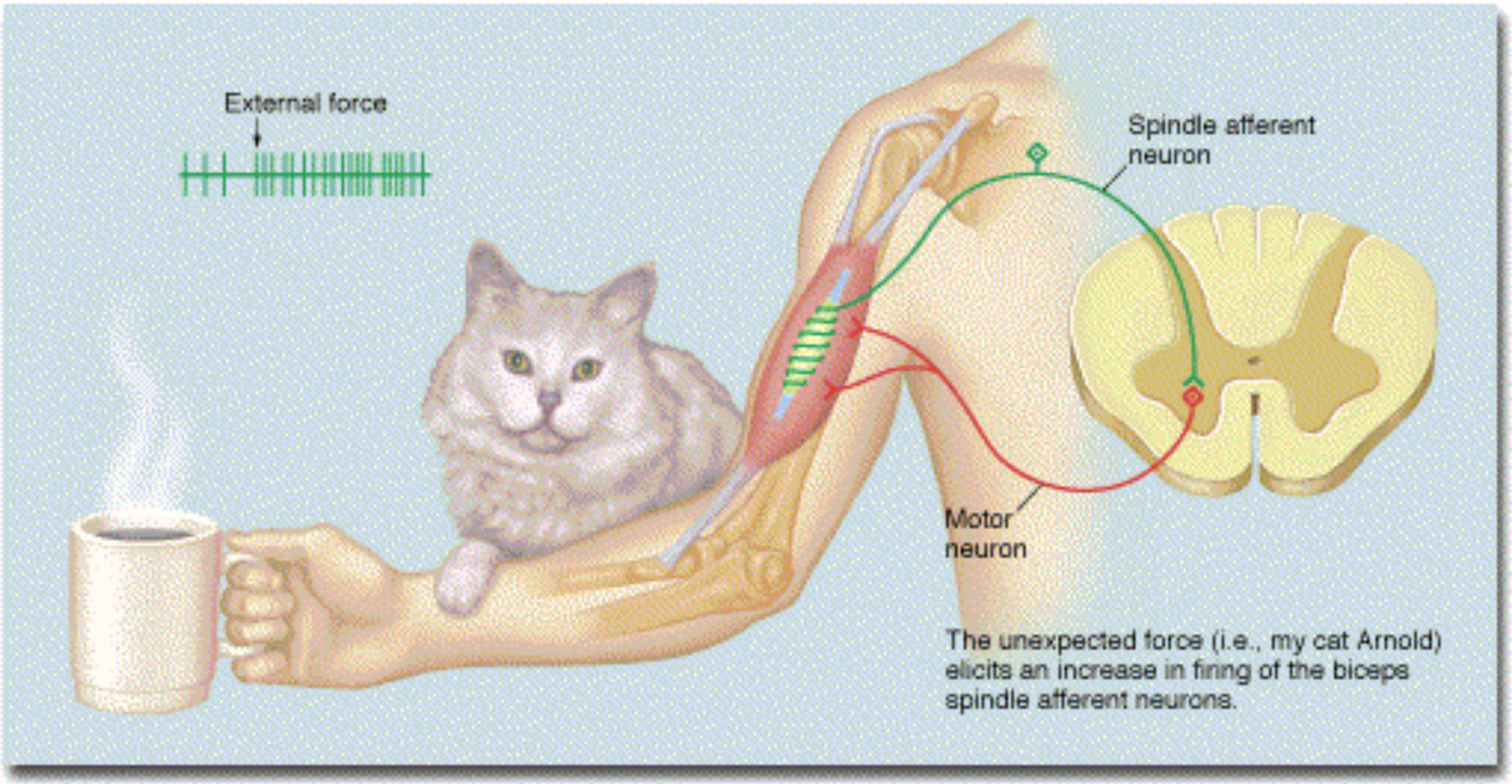
- Voluntary movement:

  ➡ Stretch of the intrafusal fiber causes contraction of the extrafusal fiber via alpha motor neuron.

  ➡ Keeping the movement at this position requires a direct signal from the brain.

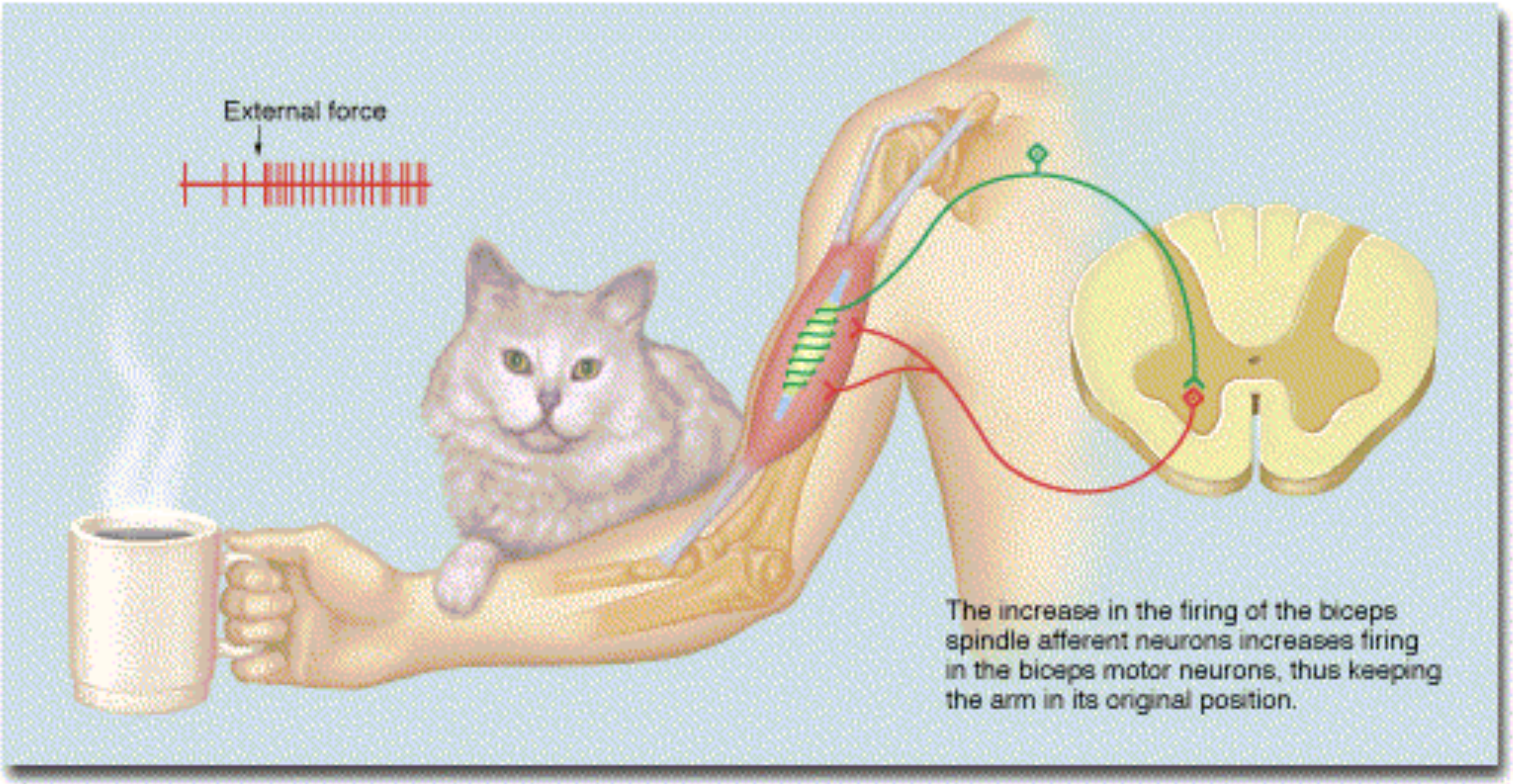
The distinction between voluntary and involuntary might be illusive (posture control and visual feedback, loss of proprioception, “automatic” goal-directed movements…).

Automatic Maintenance of Limb Position (cont.)



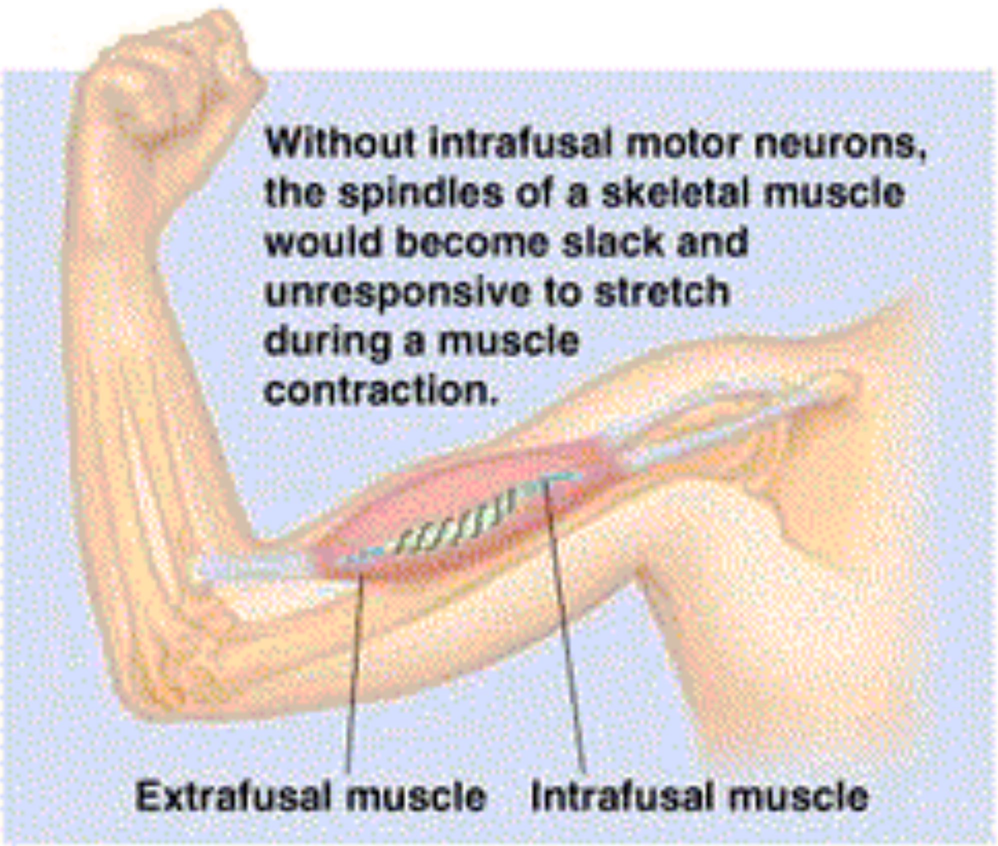
"Force control"

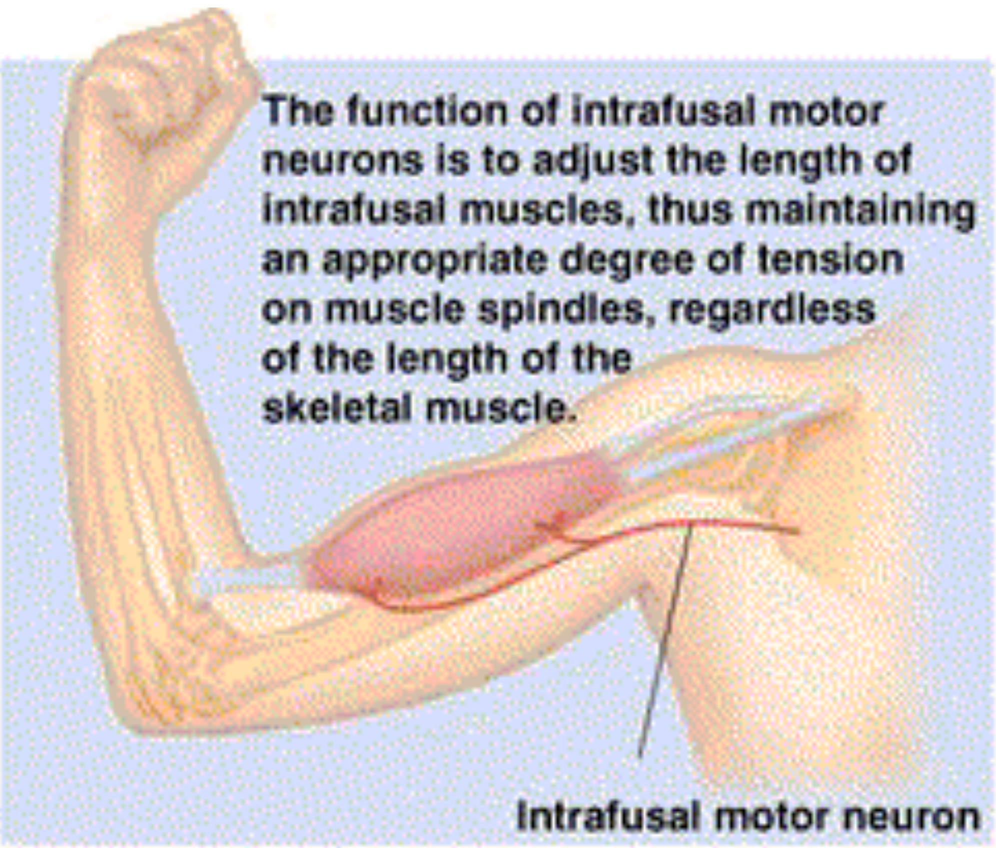
Automatic Maintenance of Limb Position (cont.)



"Force control"

Intrafusal motor neurons



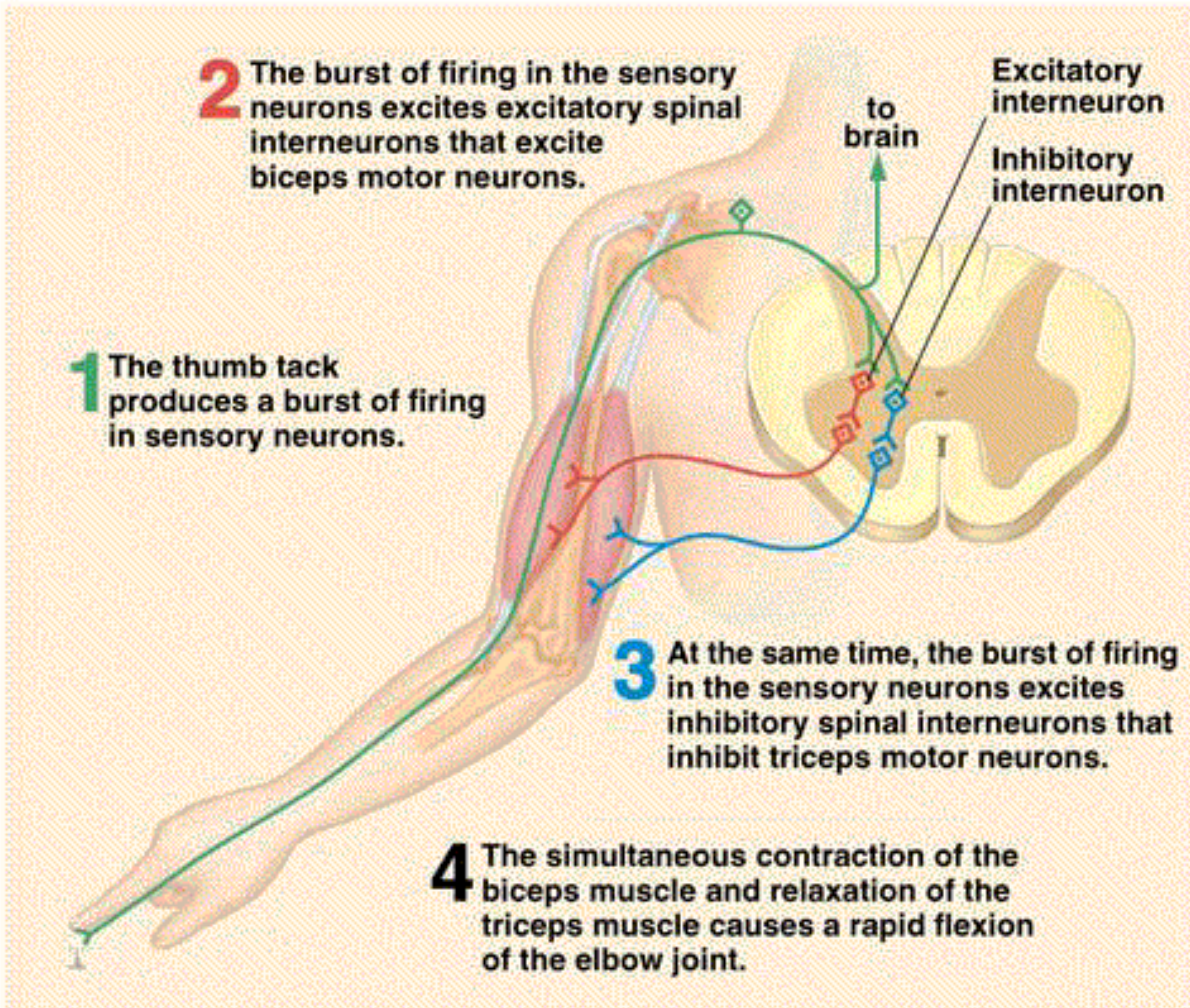


Remember, muscles work in pairs, so if one contracts the other relaxes

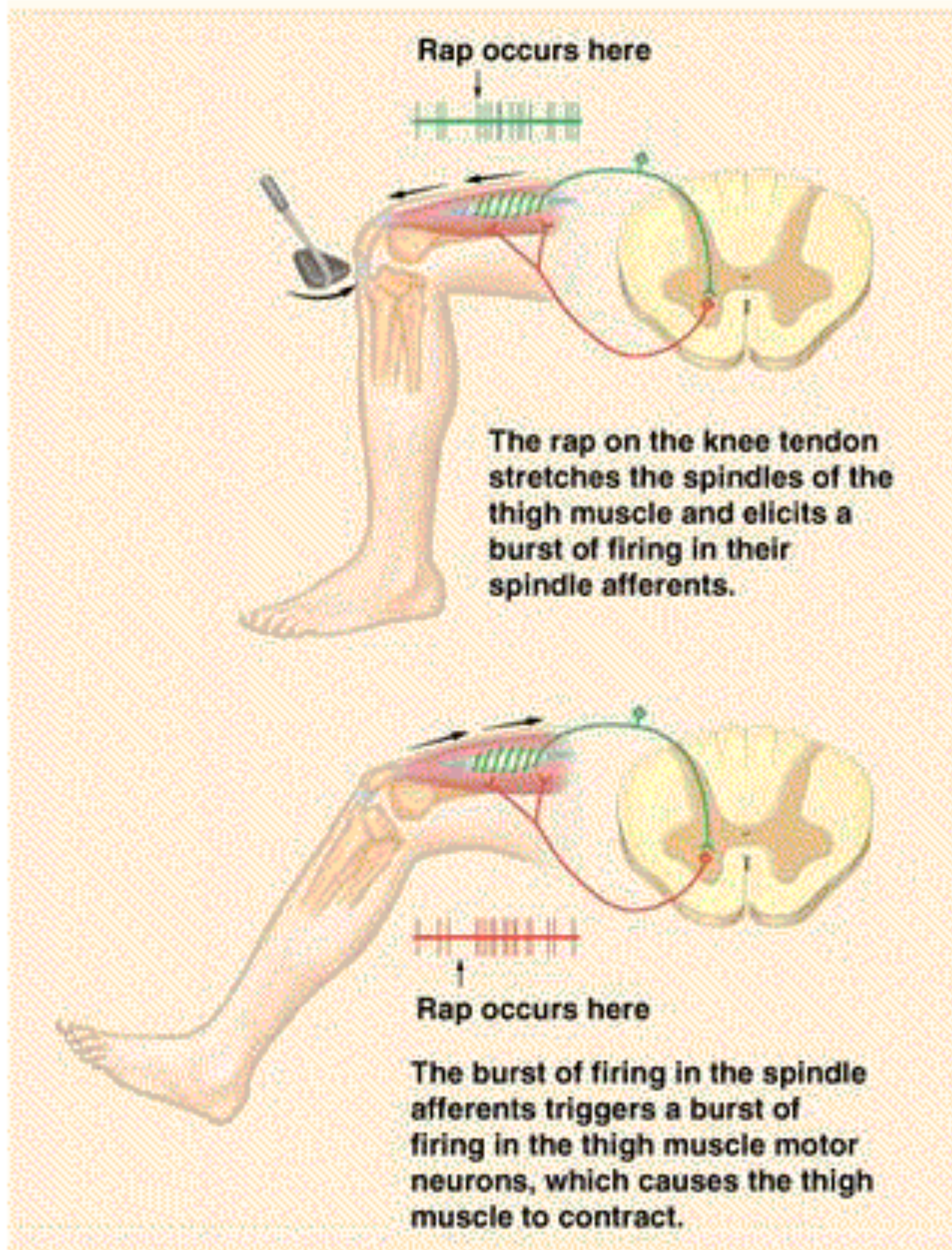
This is referred to as <u>reciprocal innervation</u>.

What if both muscles contracted at the same time?

Reciprocal innervation of Antagonistic Muscles



The elicidation of a Stretch Reflex



Motor Neurons

•Alpha Motor Neuron is the **<u>Final Common Path</u>** for all movement. Movement can be generated from:

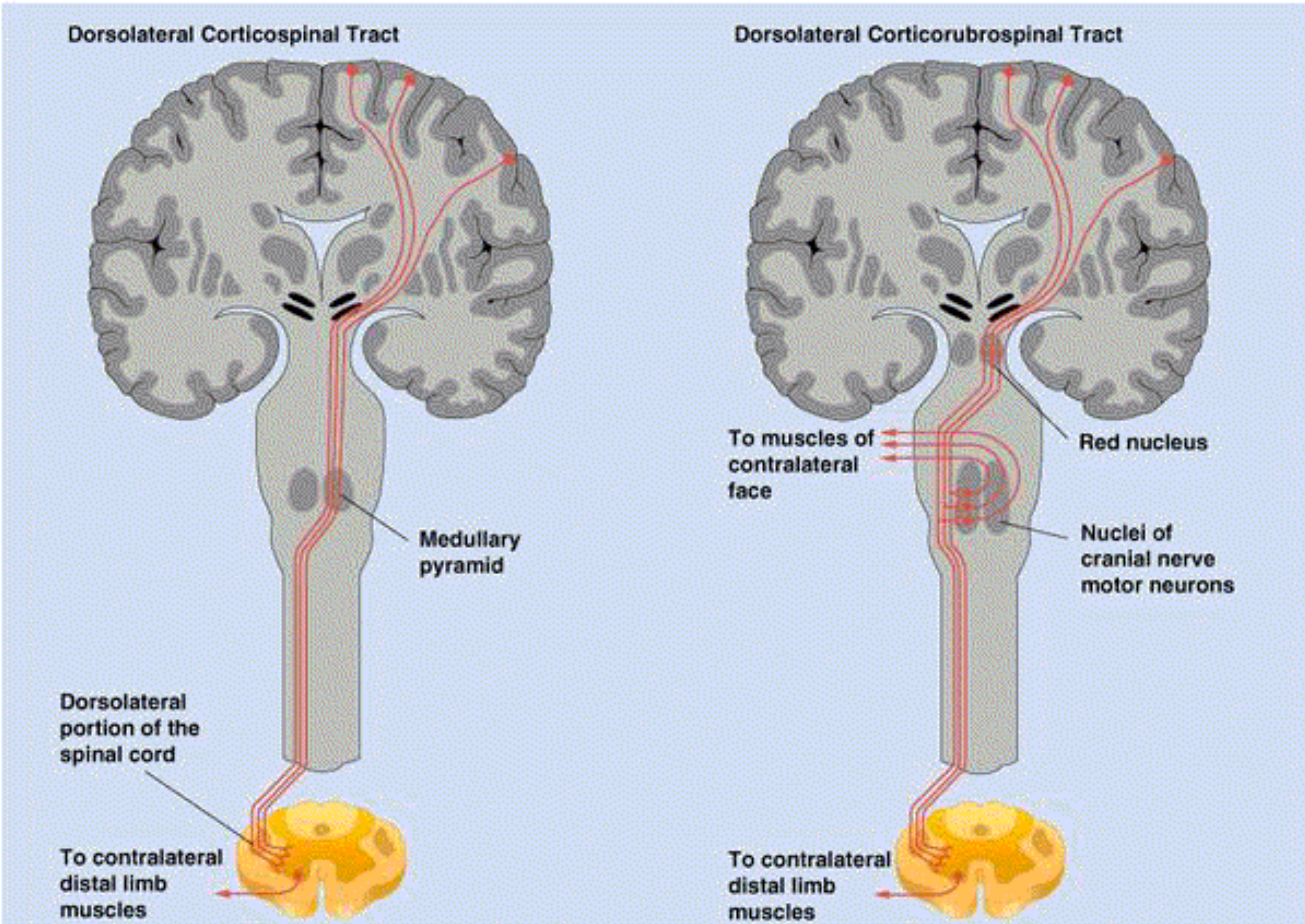
- sensory signals in the muscle spindle like the stretch reflex
- sensory signals from skin as in the pain withdrawal response
- involuntary signals from the brainstem for posture, keeping us upright without conscious attention

goal directed, flexible, adaptive, learned

- signals from the brain for ~~voluntary~~ movement

But, regardless of where the signal originates, all movement is the result of activity in the alpha motor neuron – making this the Final Common Path

The two divisions of the dorsolateral motor pathway



Corticospinal tract

- **Origins:**
  - primary motor cortex (MI)
  - premotor cortex
  - supplemental motor cortex
  - anterior paracentral gyrus
  - parietal lobe (including SI)
  - cingulate gyrus

- **Collaterals: small percentage of corticospinal neurons**
  - midbrain (primarily red nucleus)
  - trigeminal nuclei
  - pontine nucle

Corticospinal tract

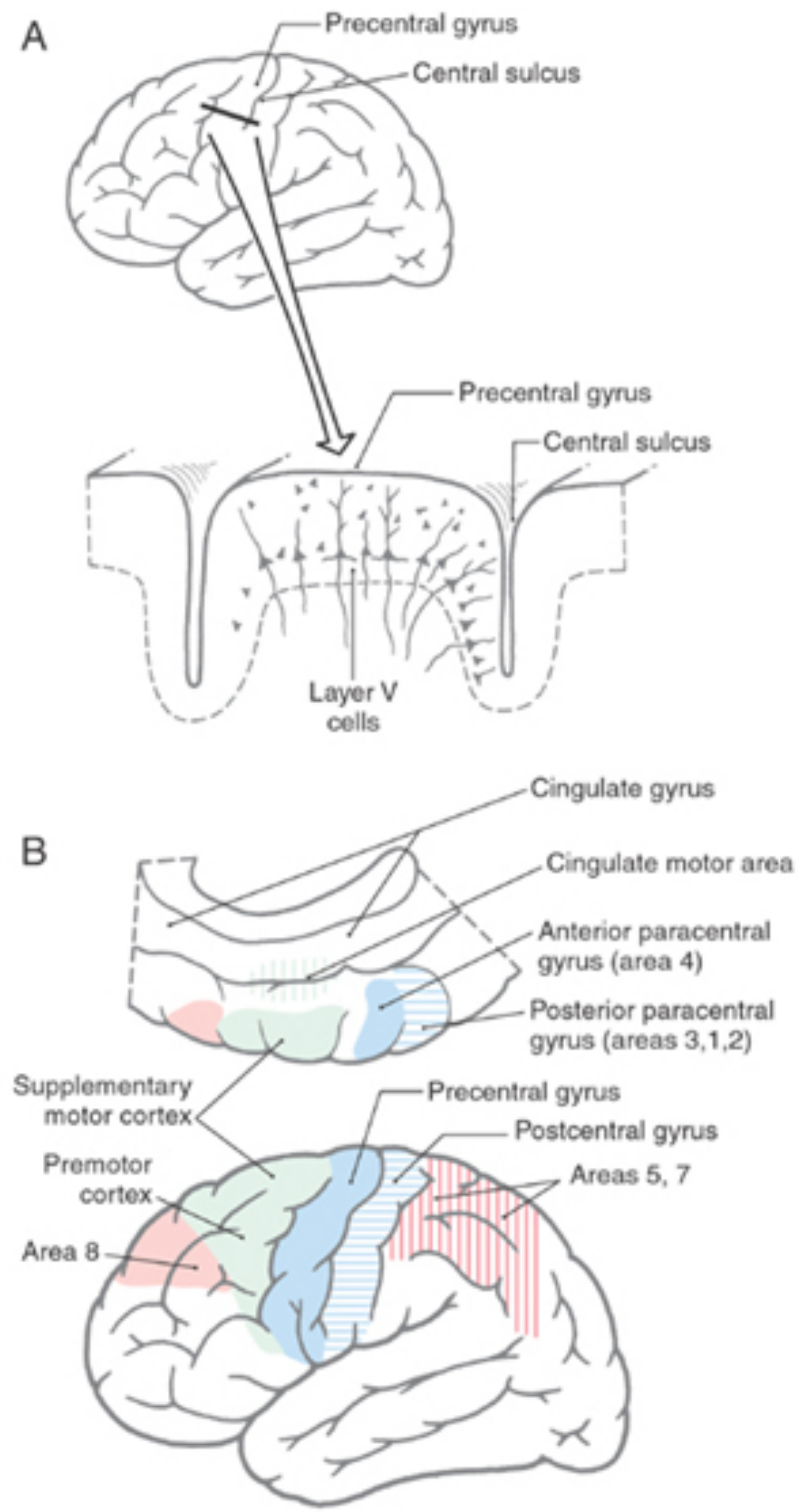
Termination in spinal cord:

- mostly laminae 3-7, few in ventral horn and laminae 1-2;
- mostly innervating interneurons;
- some innervation of alpha motor neurons.

Neurotransmitter:

- glutamate and/or aspartate

Piramidal tract origin



Corticobulbar tracts

A. control over facial muscles; bilateral input to motor neurons controlling muscles in upper face, but contralateral input to motor neurons controlling lower face (in humans, not sure about rodents)

B. control over muscles of mastication: motor trigeminal, and RF

C. control over external eye muscles: input comes from frontal and parietal eye fields, rather than from MI; projection to midbrain and paramedian pontine RF

D. control over tongue: hypoglossal and RF

E. control over swallowing reflexes: nucleus ambiguus and RF

Voluntary movement: Instructions from the cortex

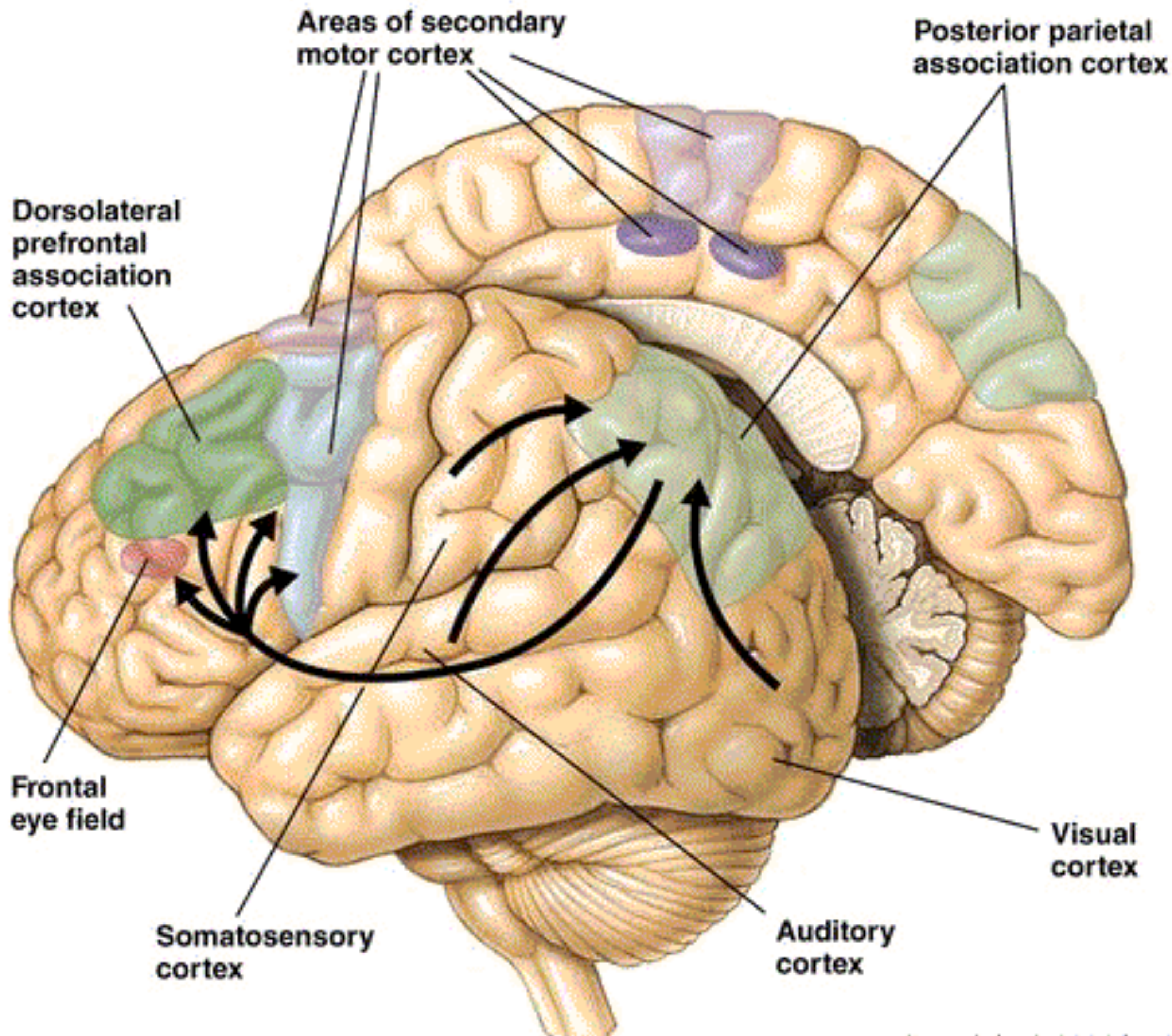
- Dorsolateral Prefrontal Cortex: directs movement of our limbs (as in reaching) and movements of our fingers.

- Actual signal for movement must go through pre-motor cortex, then motor cortex.

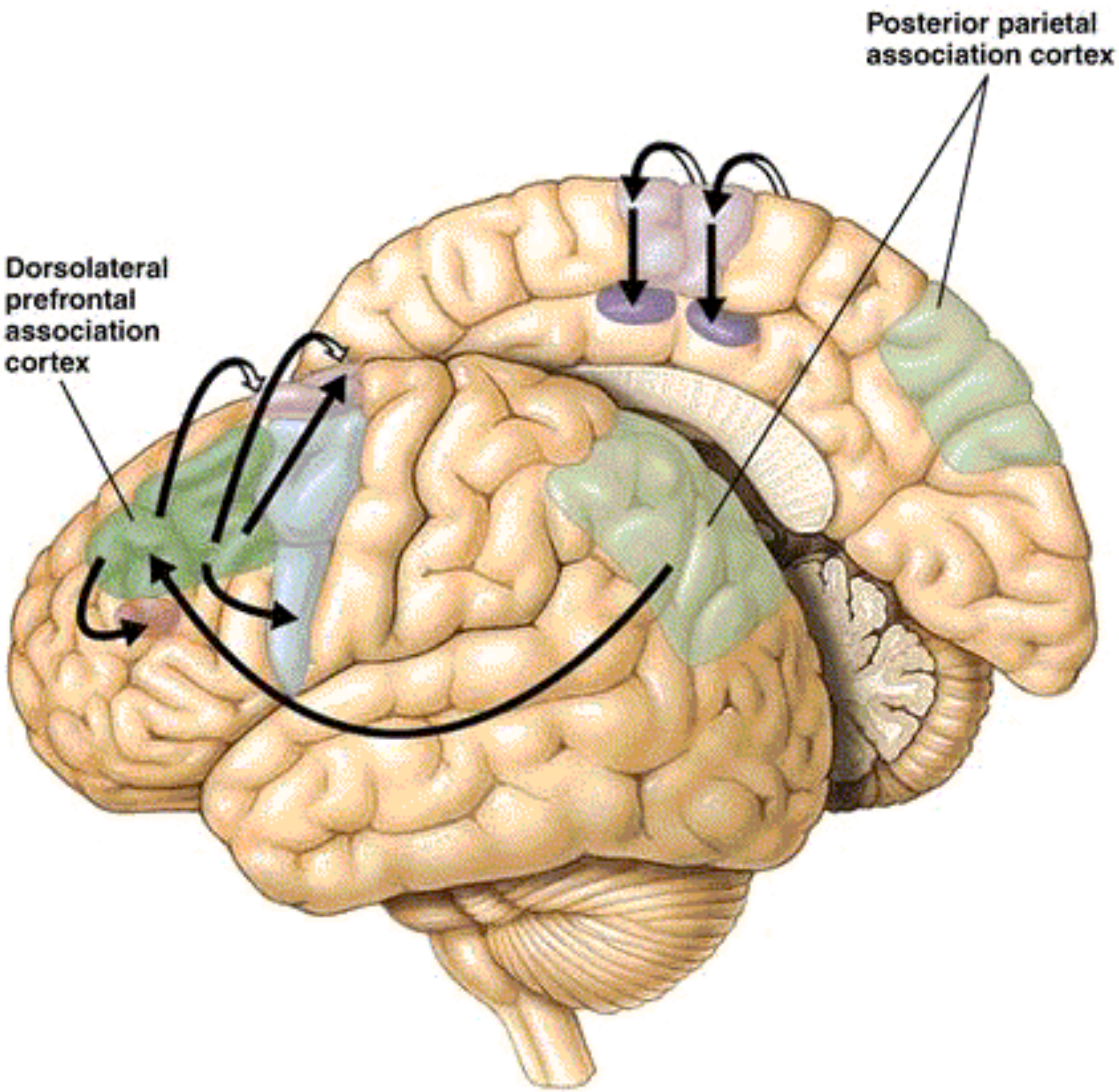
- From motor cortex, signal travels down spinal cord eventually reaching the alpha motor neuron.

- BUT, the instructions for this movement ultimately comes from our Parietal lobe, which receives sensory input.

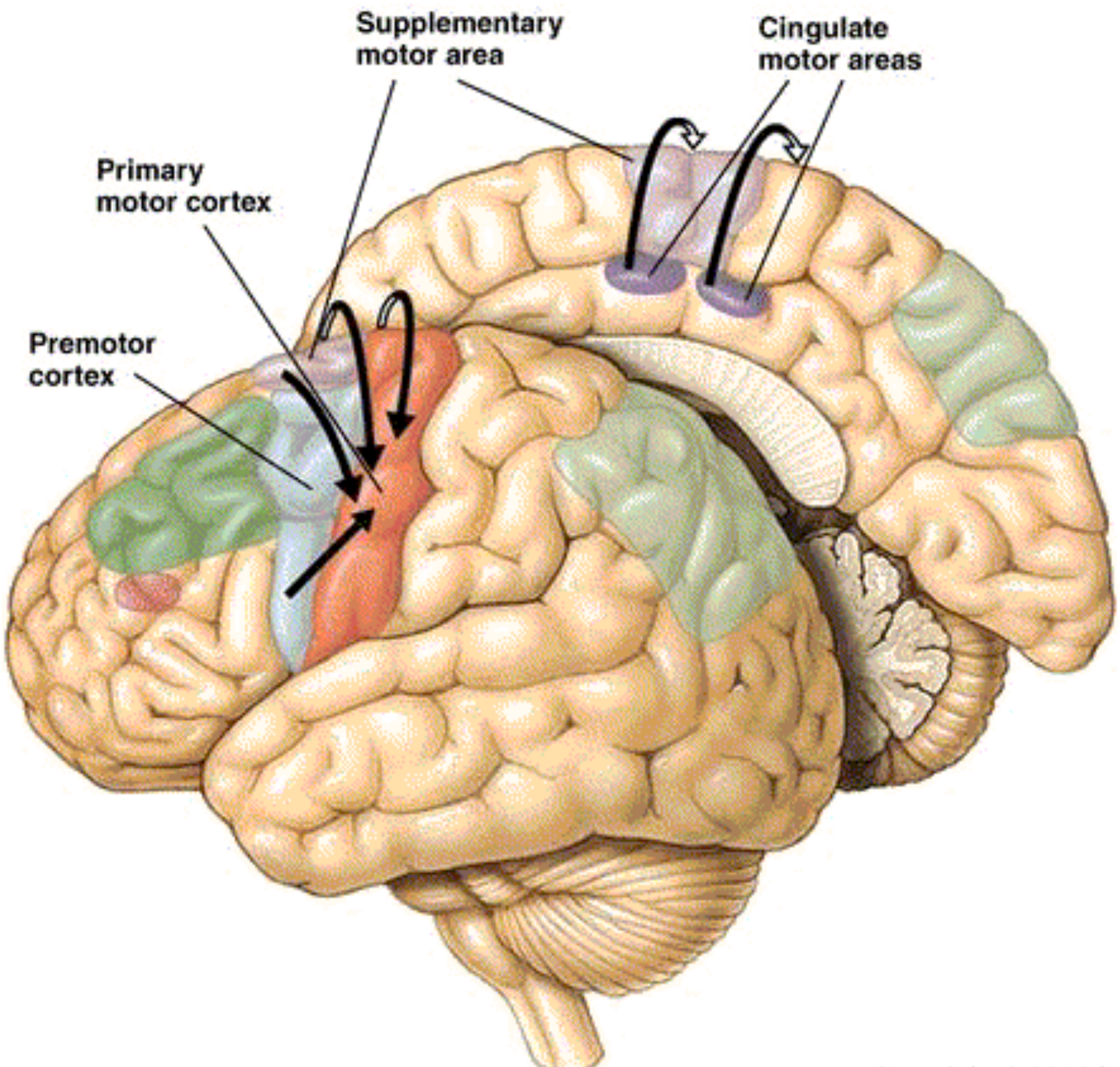
Cortical input and output pathways

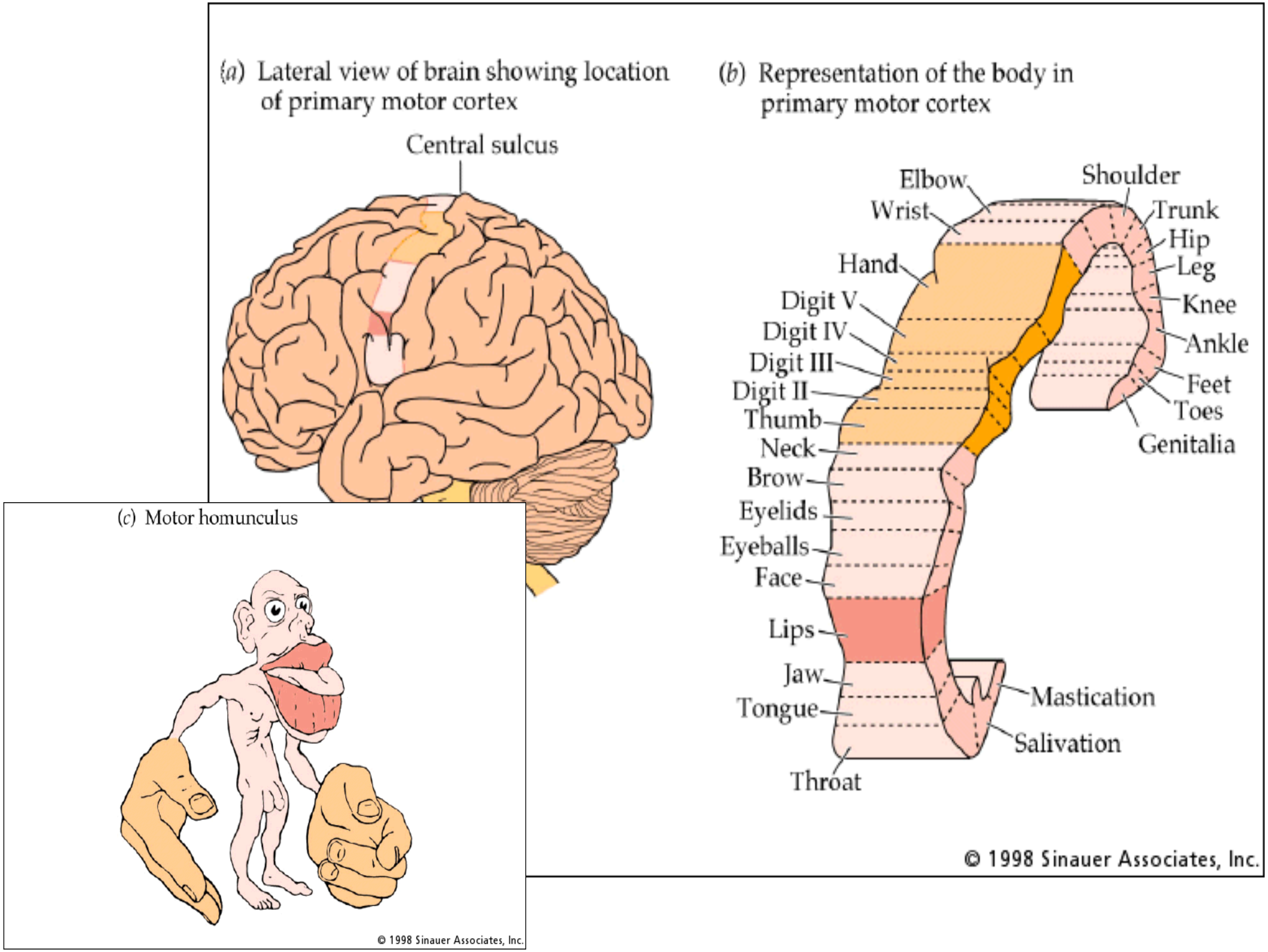


Pathways of the Dorsolateral Prefrontal Association Cortex



Four Areas of the Secondary Motor Cortex




(a) Lateral view of brain showing location of primary motor cortex
Central sulcus
(b) Representation of the body in primary motor cortex
Elbow
Wrist
Hand
Digit V
Digit IV
Digit III
Digit II
Thumb
Neck
Brow
Eyelids
Eyeballs
Face
Lips
Jaw
Tongue
Throat
Shoulder
Trunk
Hip
Leg
Knee
Ankle
Feet
Toes
Genitalia
Mastication
Salivation
© 1998 Sinauer Associates, Inc.
(c) Motor homunculus
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Control of movement by motor cortex

- **A. microstimulation studies:**
  - **in MI movements of particular contralateral joints (e.g. distal finger) can be elicited by microstimulation;**
  - **in MII contractions of groups of muscles sequentially to produce overall movements of limbs, often bilaterally**

Control of movement by motor cortex

- **B. electrical activity during movement:**

  - corticospinal neurons active just before initiation of a movement;

  - activity related to amount of force necessary to produce the movement;

  - directionally-sensitive corticospinal neurons;

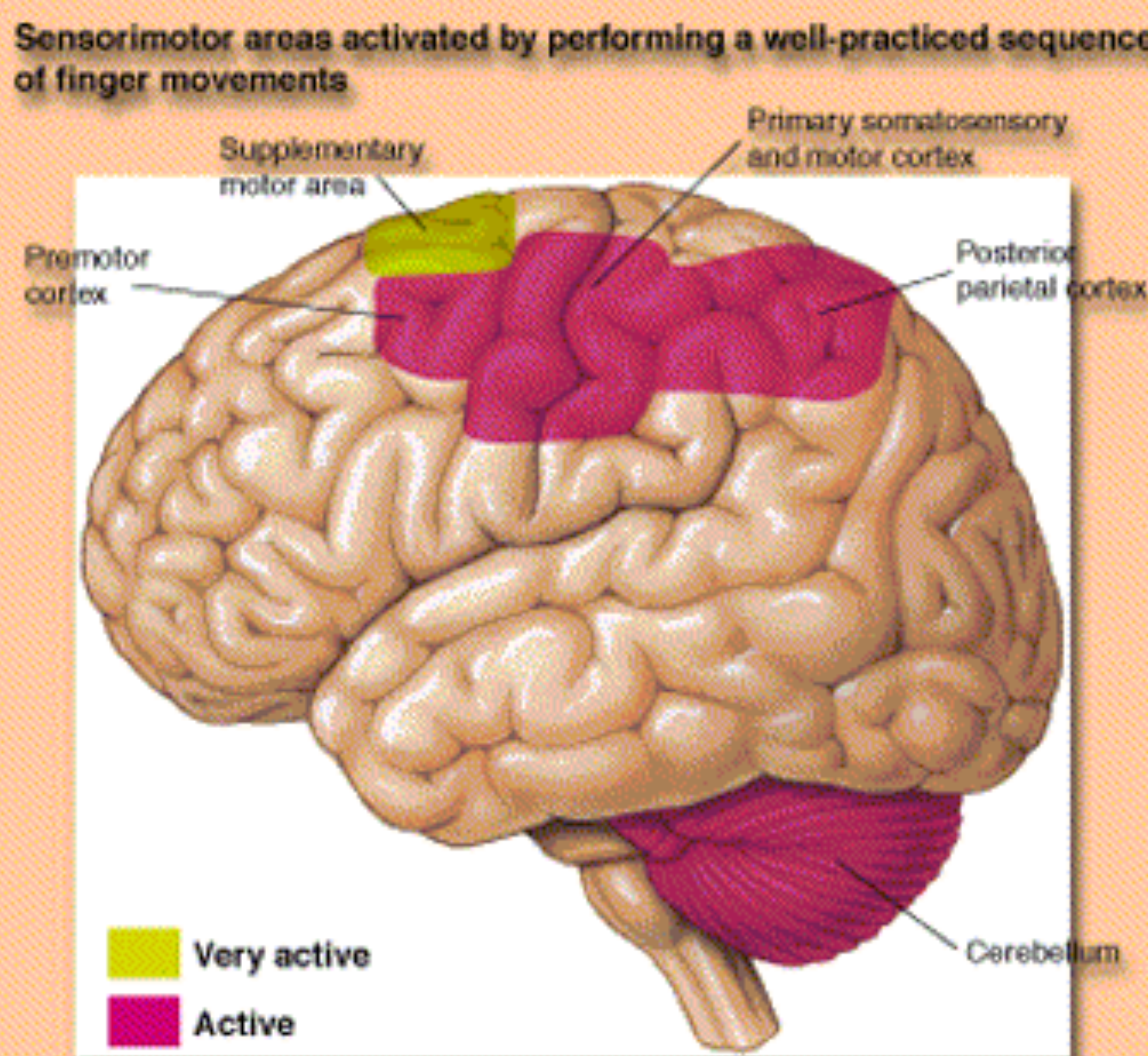
  - higher-order motor cortex involved in calculating trajectories in space (probably in close communication with cerebellum) and in planning larger-scale movements (probably in close communication with the basal ganglia)

Control of movement by motor cortex

C. imaging studies in humans:

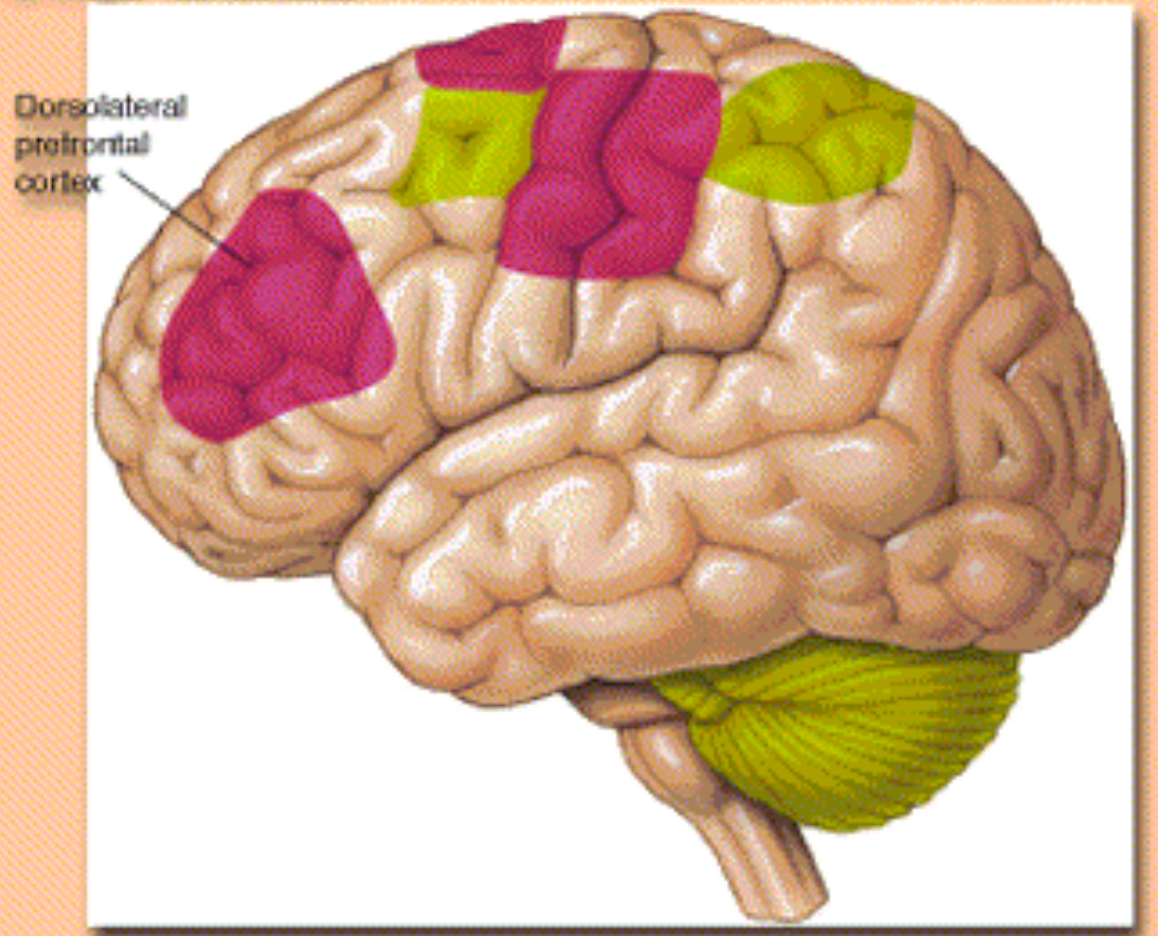
- random movements of digits activates MI (precentral gyrus);
- planned movements activate MI and supplemental motor cortex;
- thinking about planned movements activates supplemental motor cortex, but not MI.

- Sequences of Finger Movements Recorded by a PET



‣ Sequences of Finger Movements Recorded by a PET (continued)

Sensorimotor areas activated by performing a newly learned sequence of finger movements

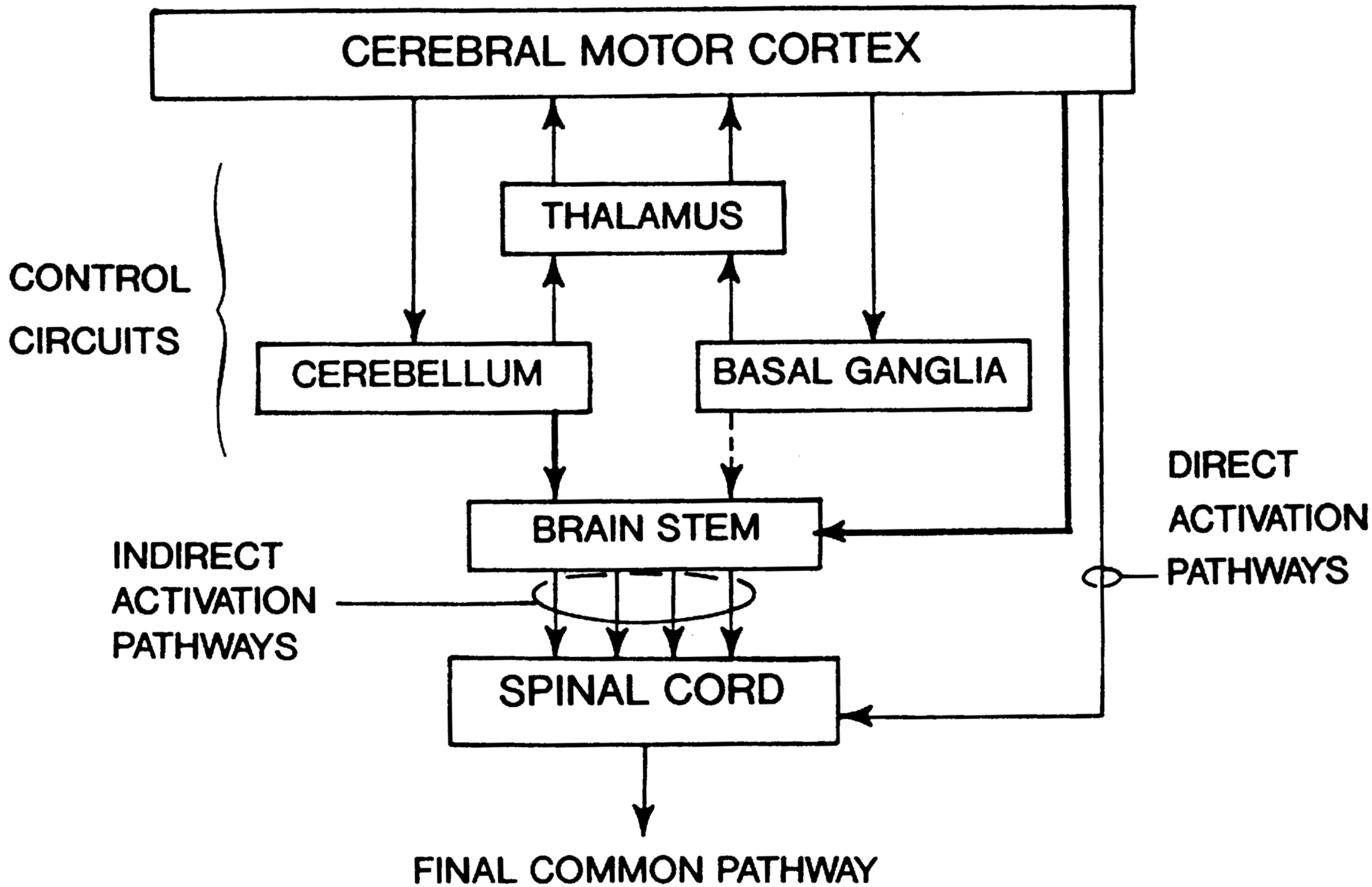


Of course, this is really too simple…

- Other brain areas involved in movement:
  - Ventromedial frontal cortex
    - involved in body control, posture and whole body movements
  - Cerebellum
  - Basal Ganglia
  - Brainstem

- In the end, all movement funnels through the alpha motor neuron (final common path)

Motor Hierarchy and Loops

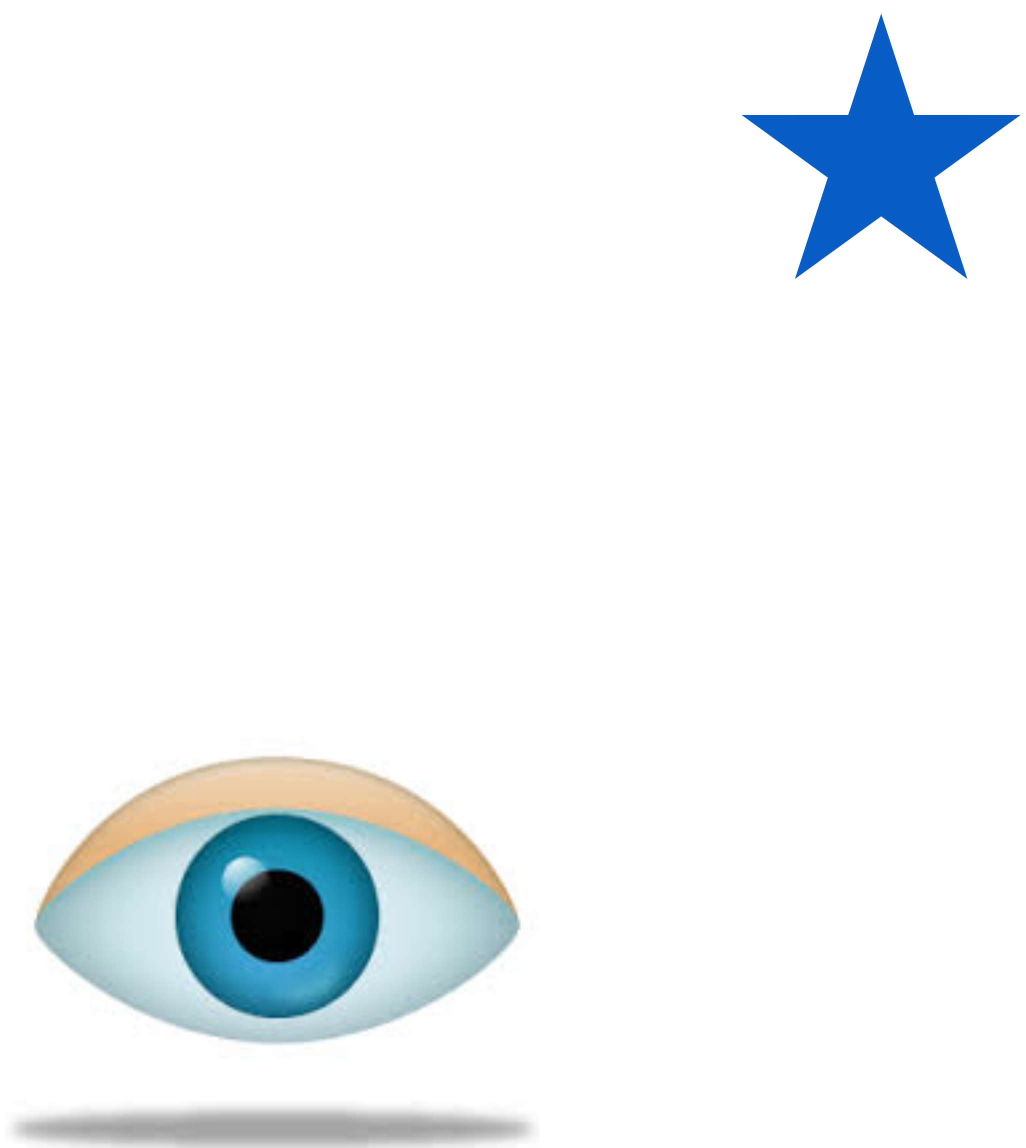


Disorders of the Motor System

- Amyotrophic lateral sclerosis – motor neurons of the brainstem & spinal cord are destroyed.
- Huntington's Disease – progressive destruction of the basal ganglia (GABA).
- Muscular Dystrophy – biochemical abnormality affecting the utilization of Ca++ causing wasting away of muscles.
- Myasthenia gravis – autoimmune disorder that destroys Ach receptors (starts with head as in drooping eyelids then progresses to swallowing & respiration).
- Parkinson's disease – degeneration of neurons in the striatum due to loss of cells in the substantia nigra that synthesis/release dopamine.

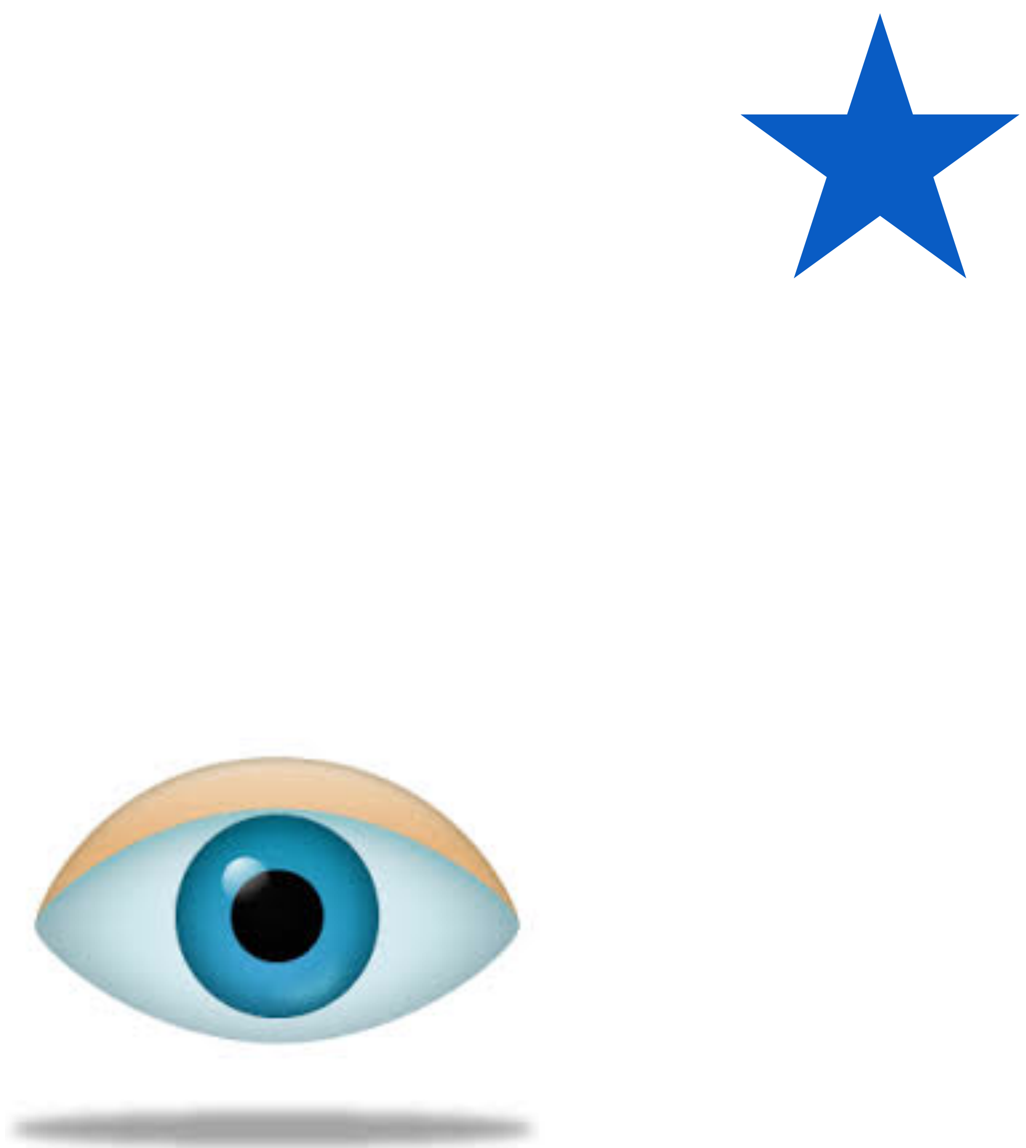
Example: a story of a simple motor system…

Saccadic eye movements

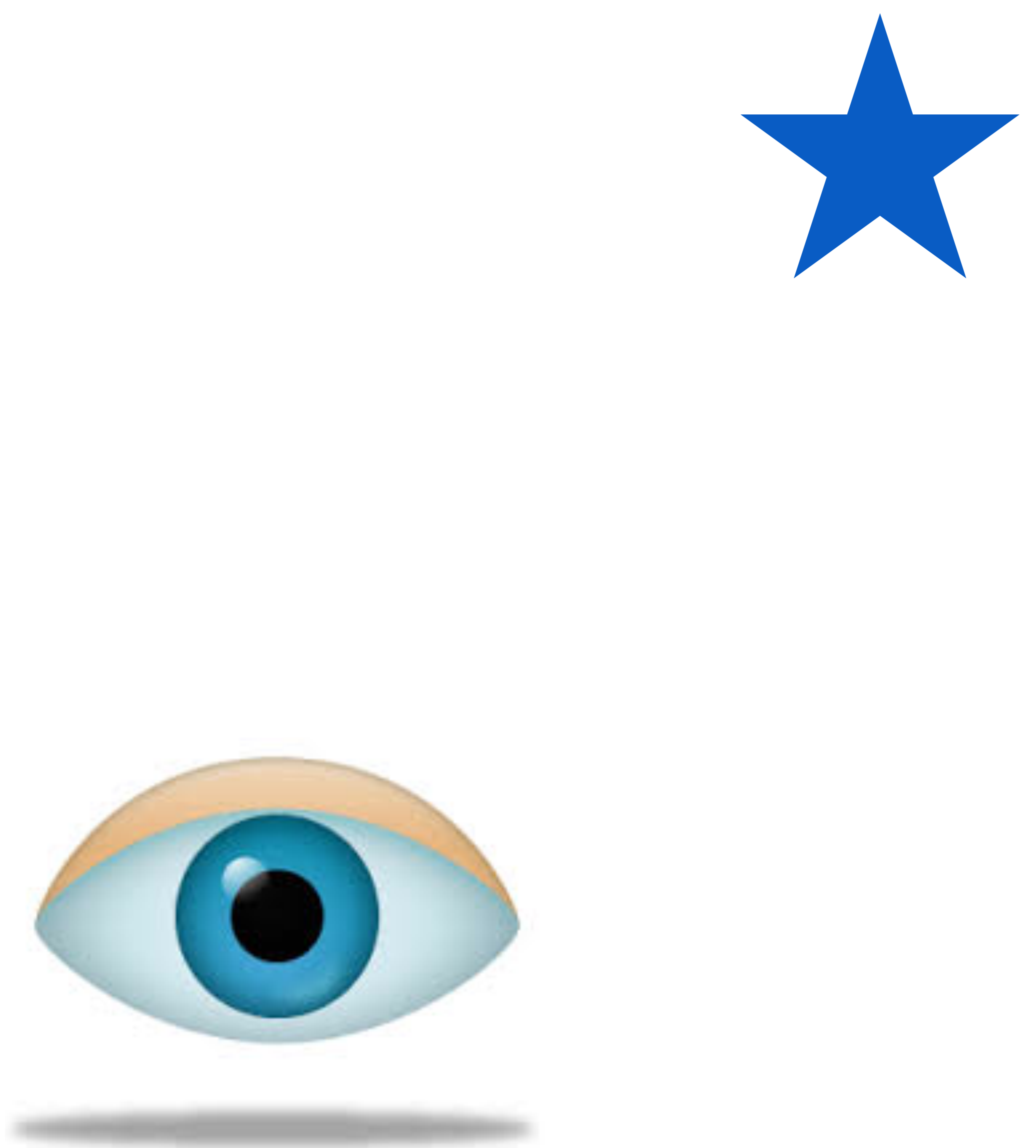


➡ saccades are precise and fast (feedforward)

Saccadic eye movements

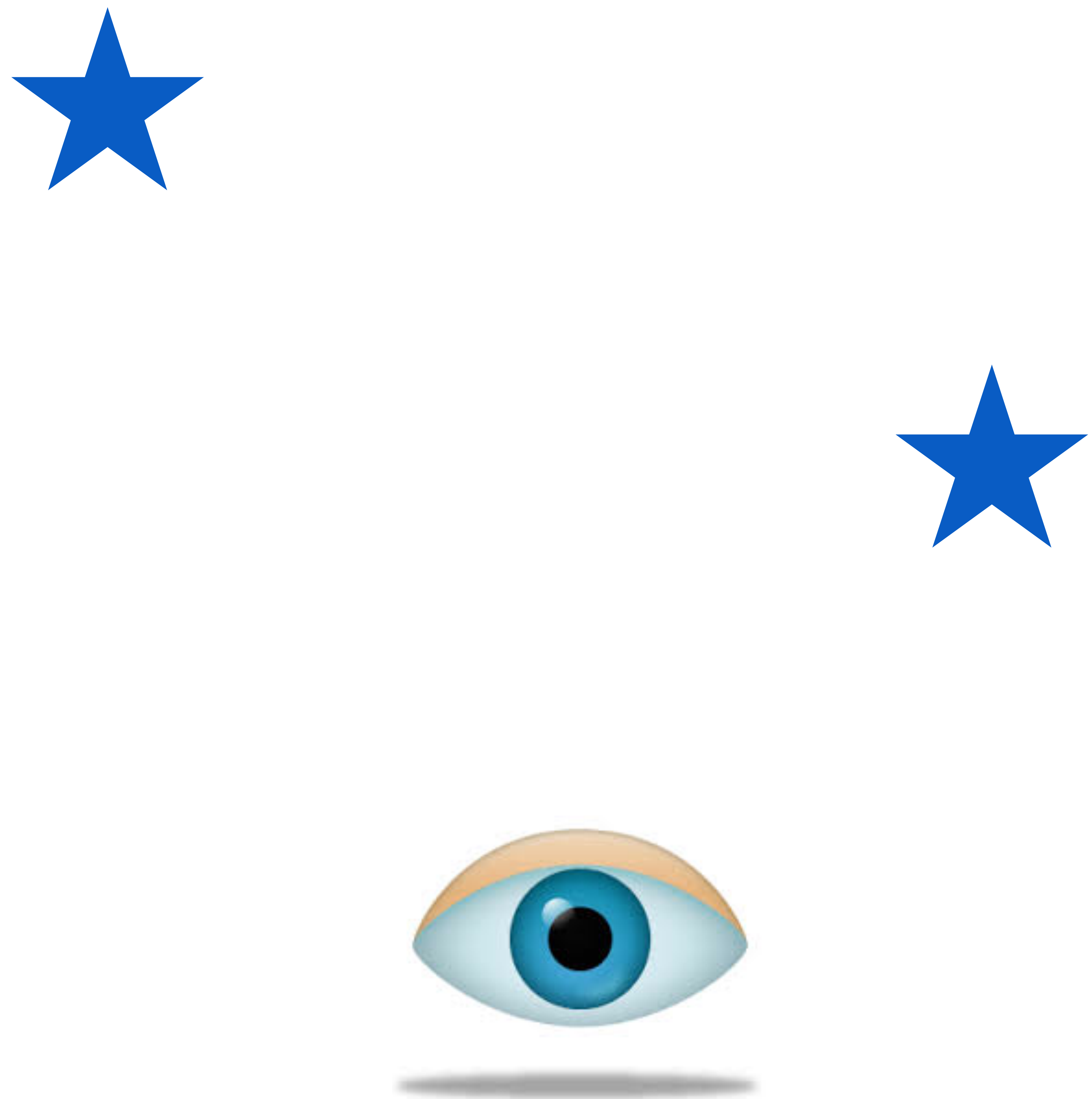


Saccadic eye movements

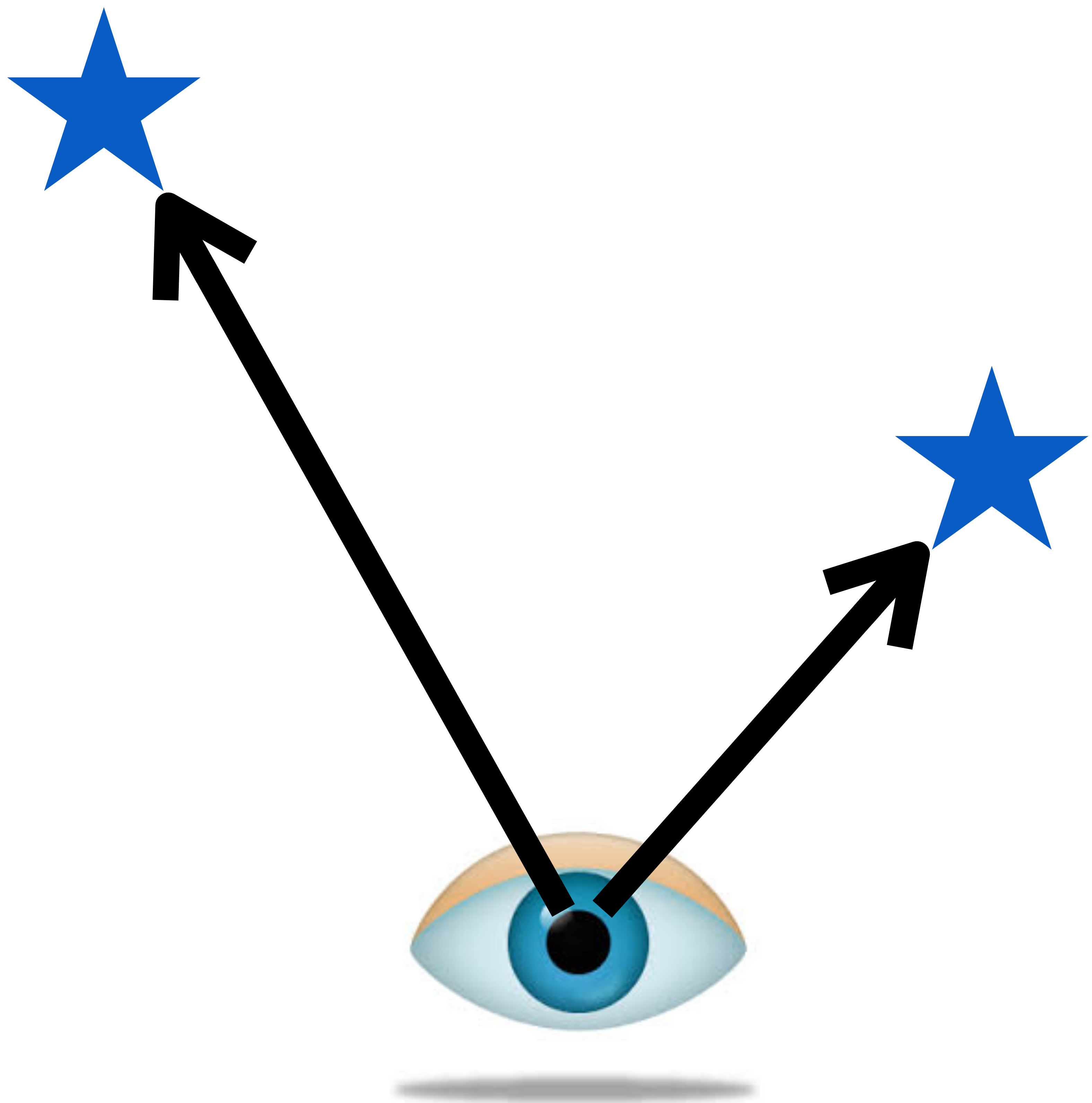


➡ continual, pervasive adaptation

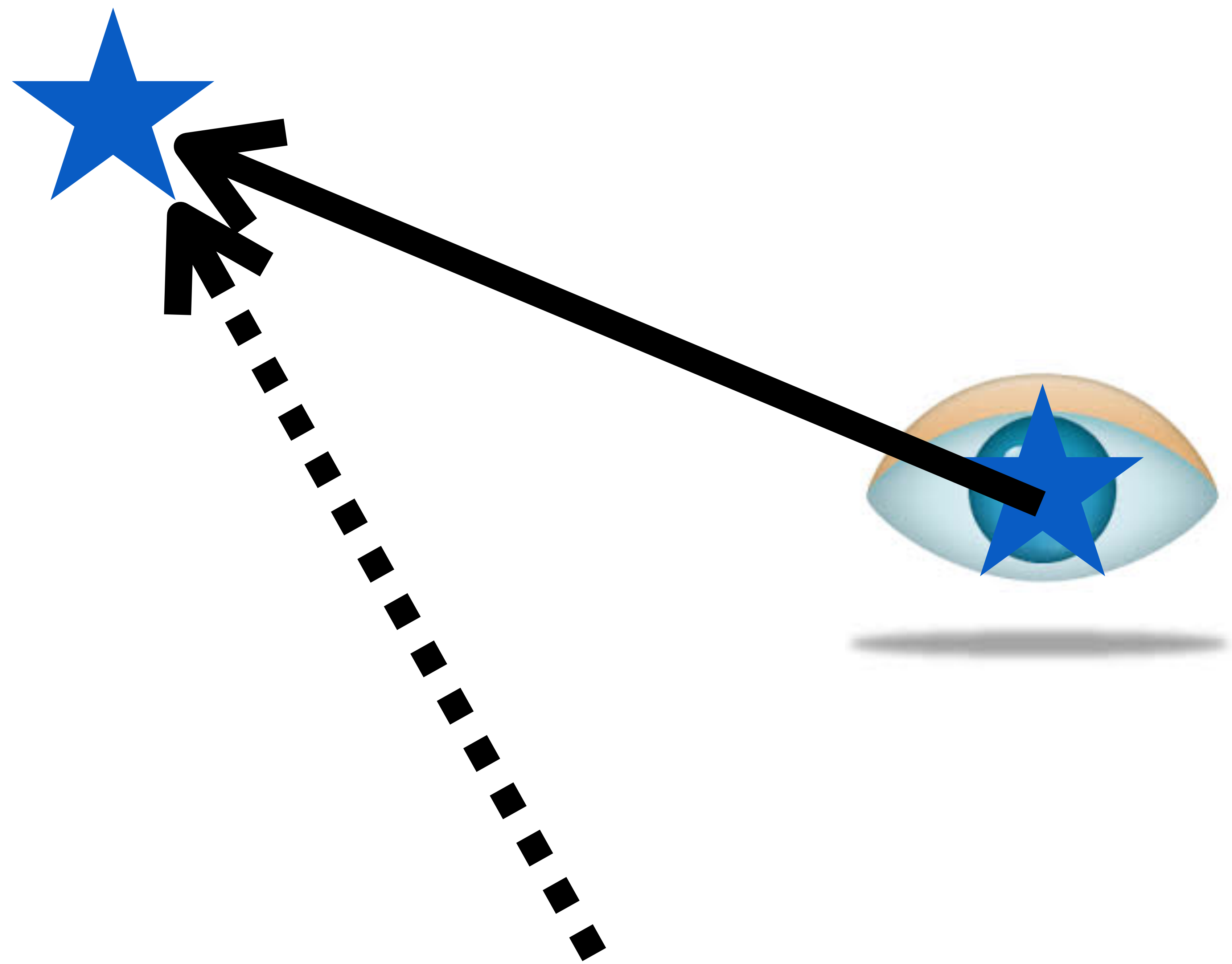
Saccadic eye movements



Saccadic eye movements



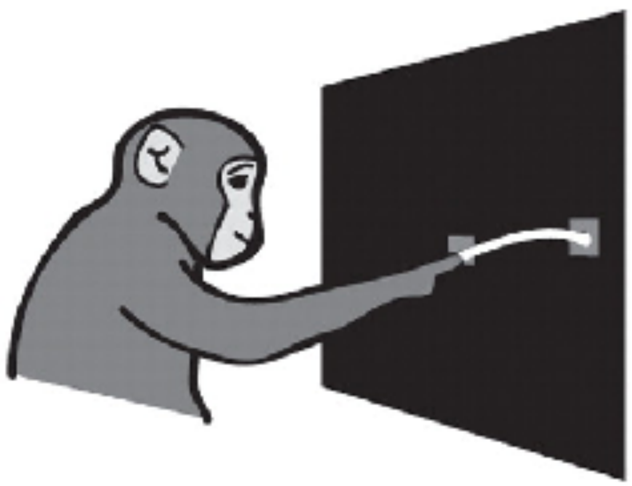
Saccadic eye movements



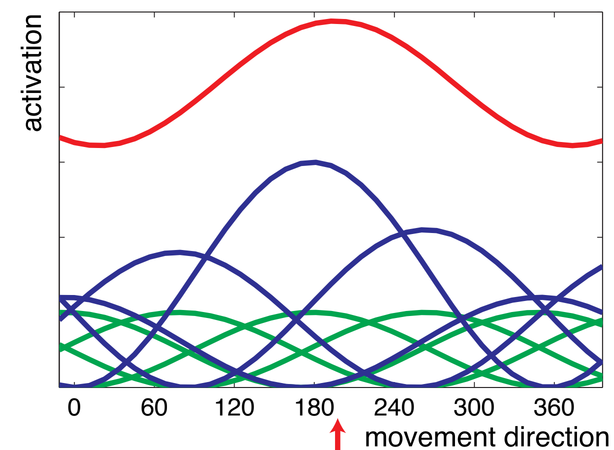
➡ gaze-direction independent representation needed

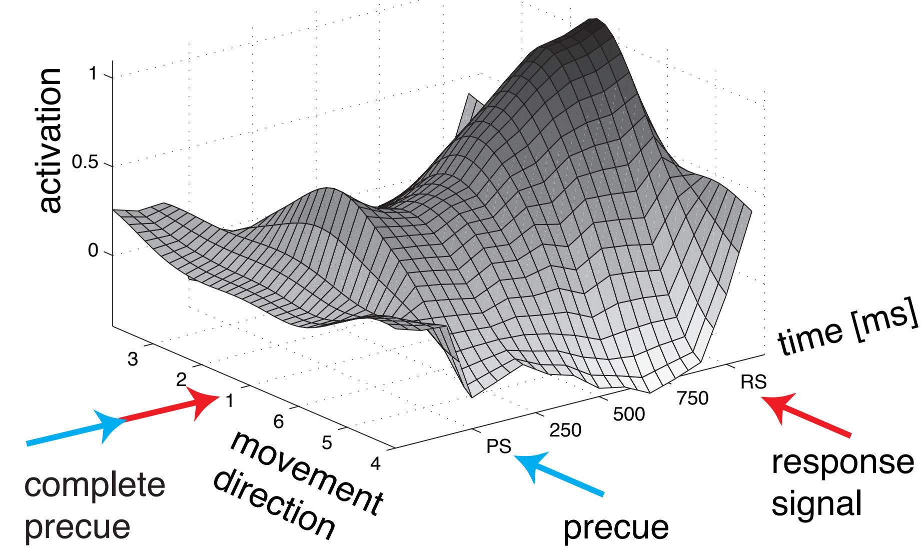
DFT, historically, is an account for neurons' activity

"Reaching" task



Distribution of population activation = $\sum_{\text{neurons}}$ tuning curve * current firing rate





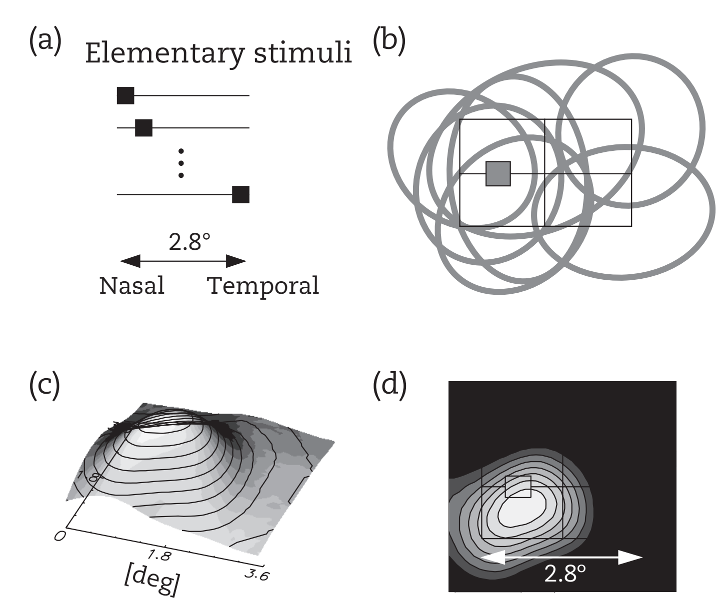
➡"Dynamic neural field" model

$$\tau \dot{u}(x,t) = -u(x,t) + h + \int f\left(u(x',t)\right)\omega(x-x')dx' + I(x,t)$$

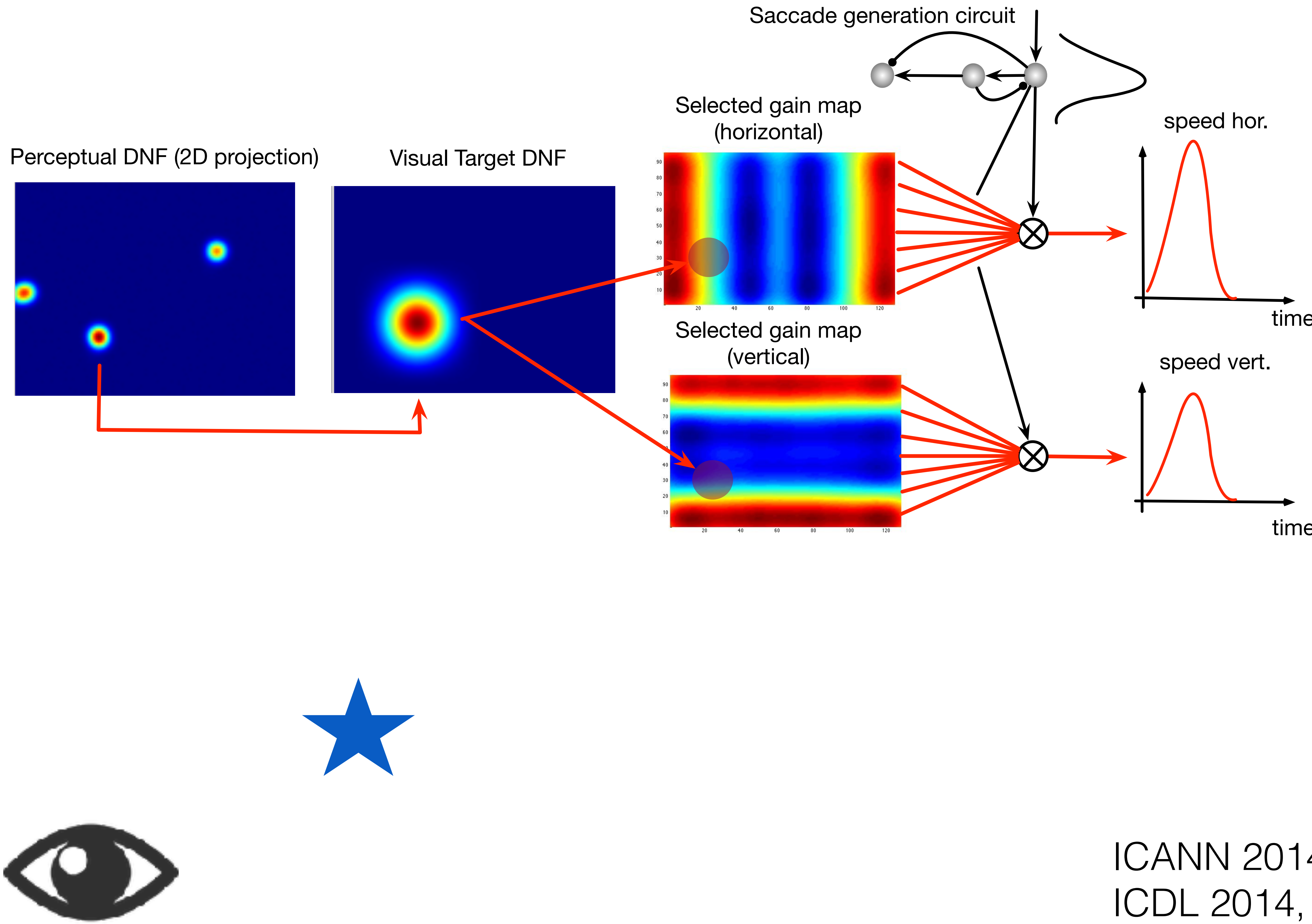
Amari, S. **Dynamics of pattern formation in lateral-inhibition type neural fields**. Biological Cybernetics, **1977**, 27, 77-87

Wilson, H. R. & Cowan, J. D. **A mathematical theory of the functional dynamics of cortical and thalamic nervous tissue**. Kybernetik, **1973**, 13, 55-80

Gerstner, Grossberg, Ermentrout, Coombes, Schöner&Spencer, Erlhagen…

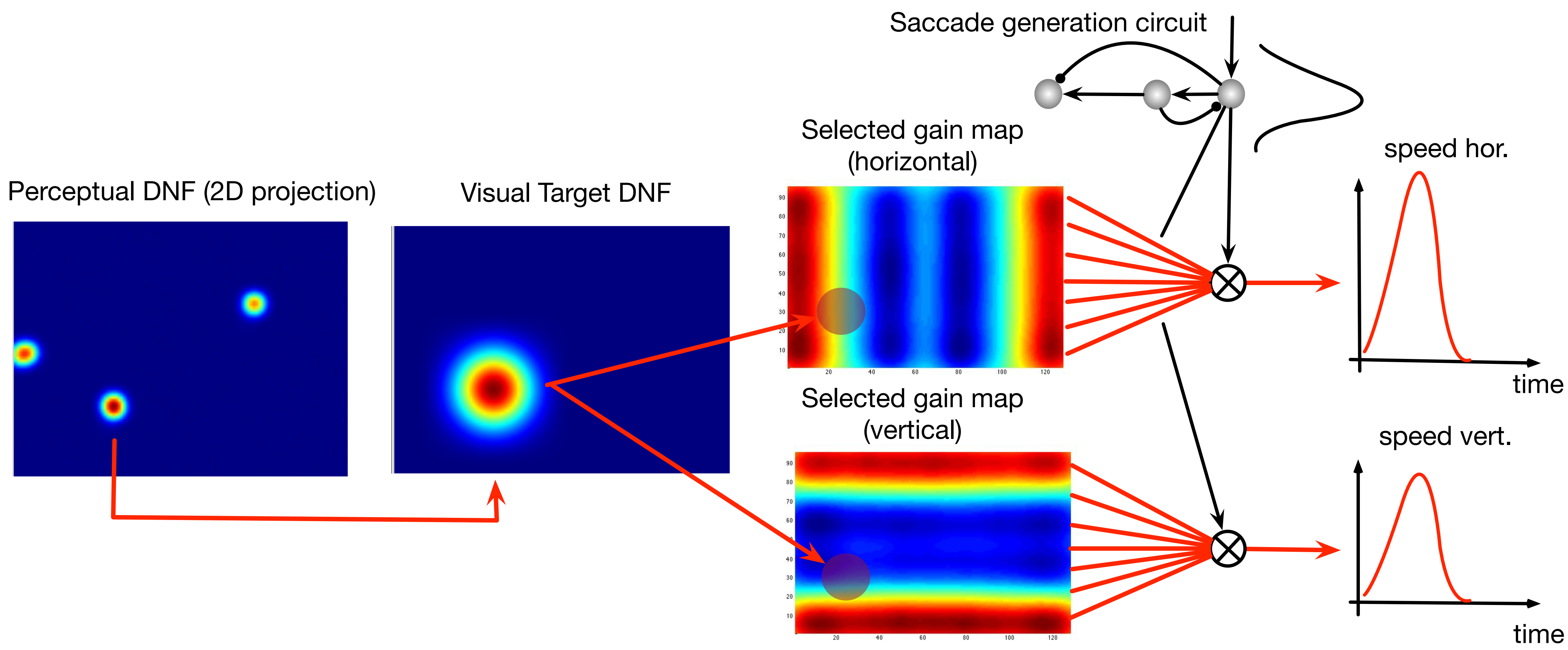


Generating precise saccadic eye movements



ICANN 2014,
ICDL 2014,
Springer 2014

Generating precise saccadic eye movements



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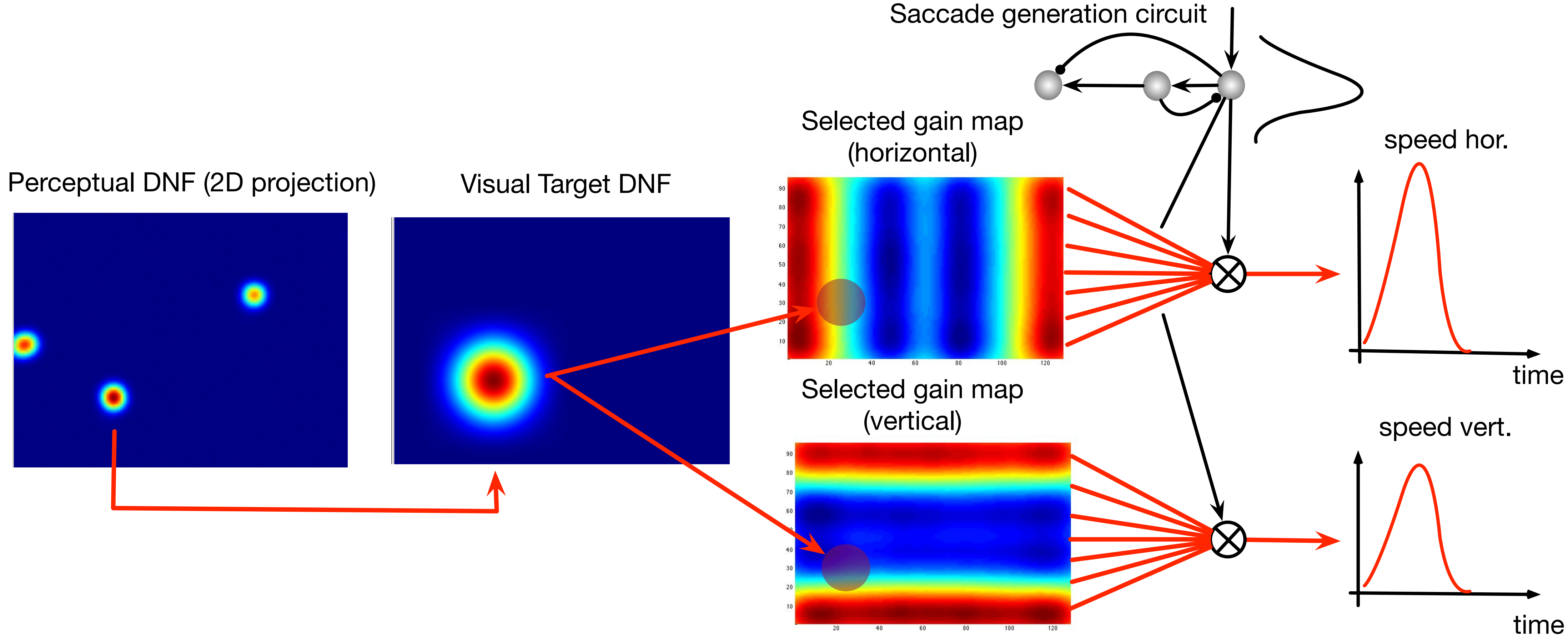
Generating precise saccadic eye movements



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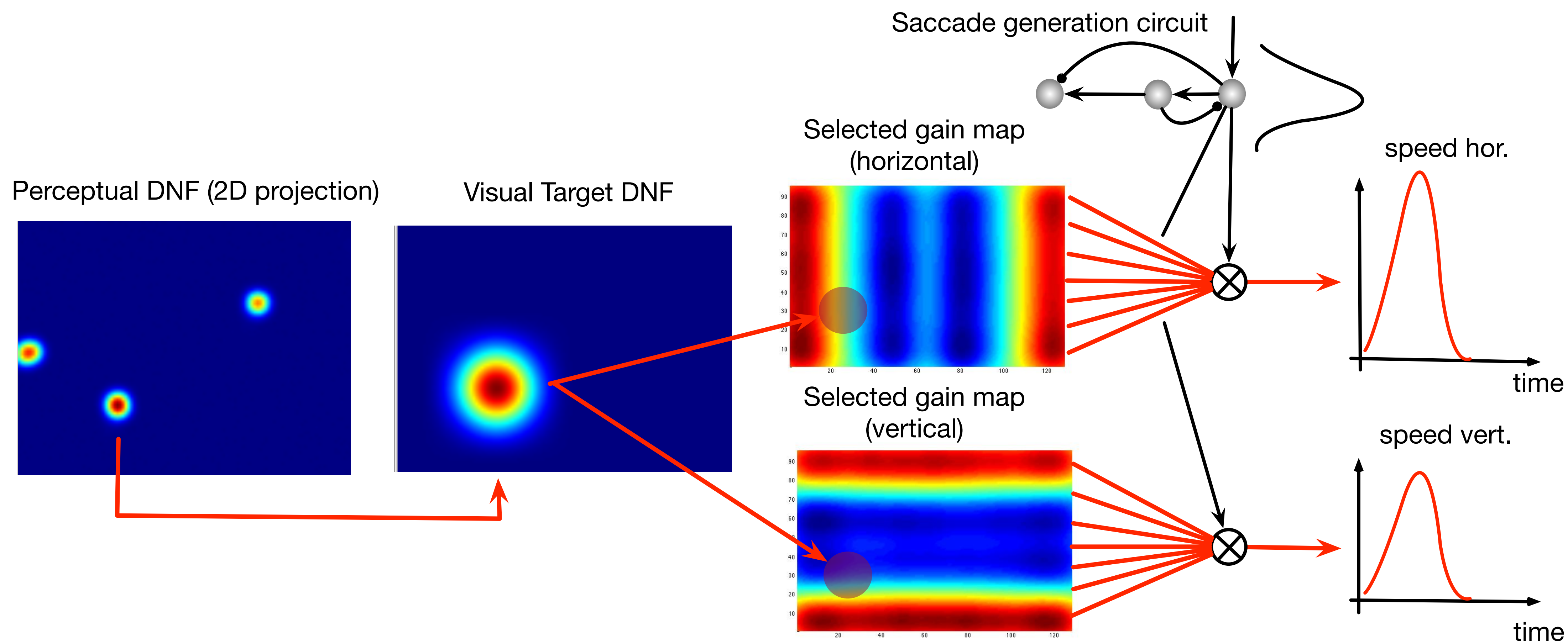
Generating precise saccadic eye movements



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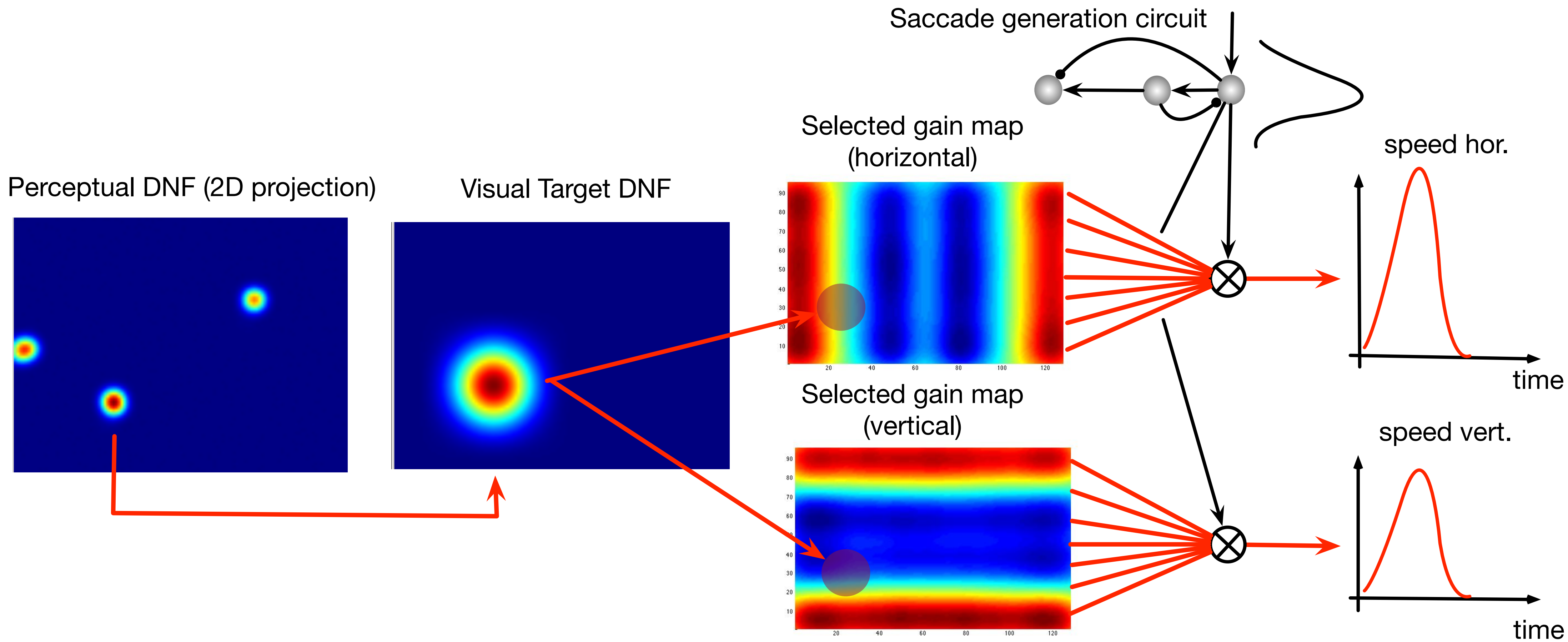
Generating precise saccadic eye movements



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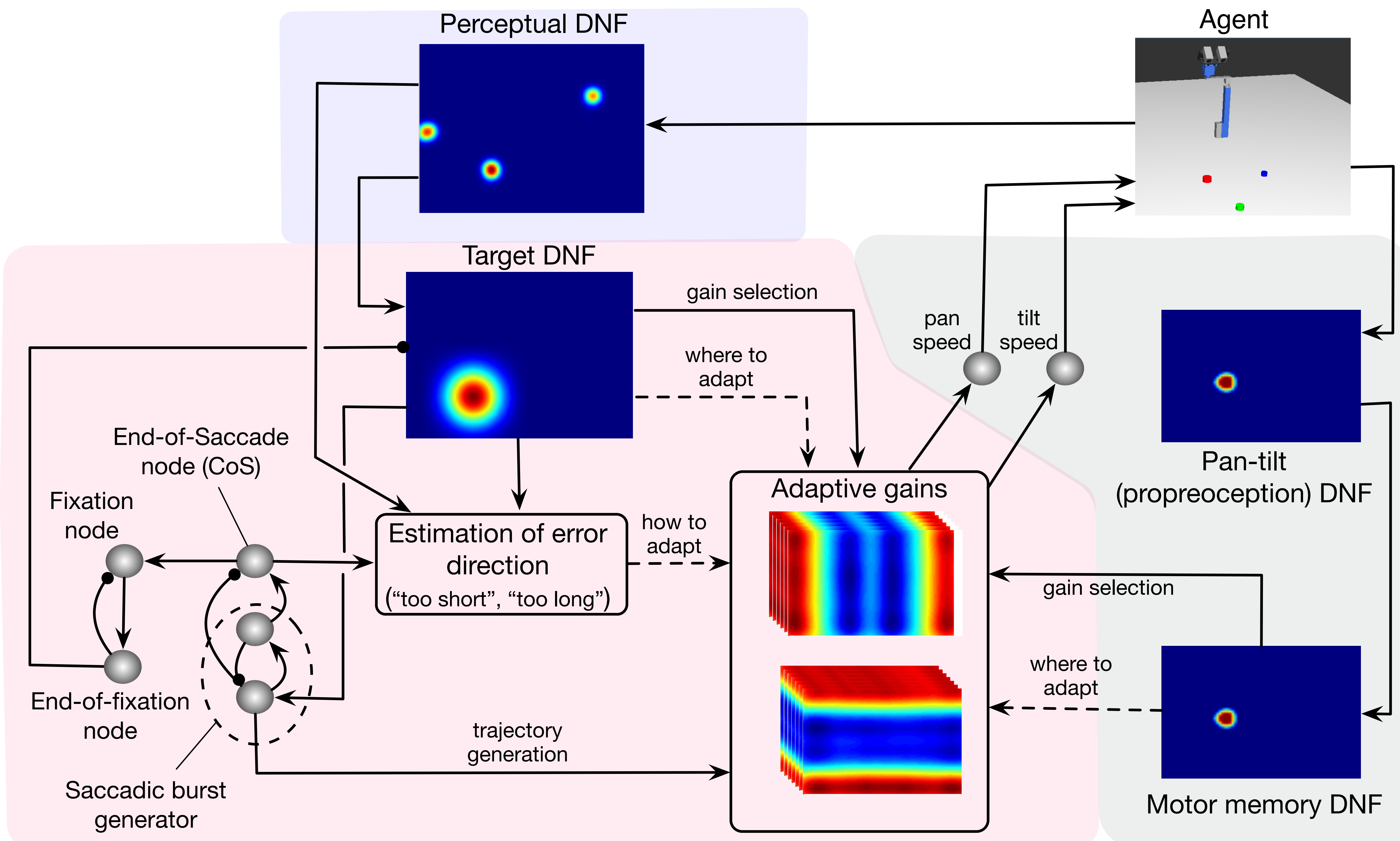
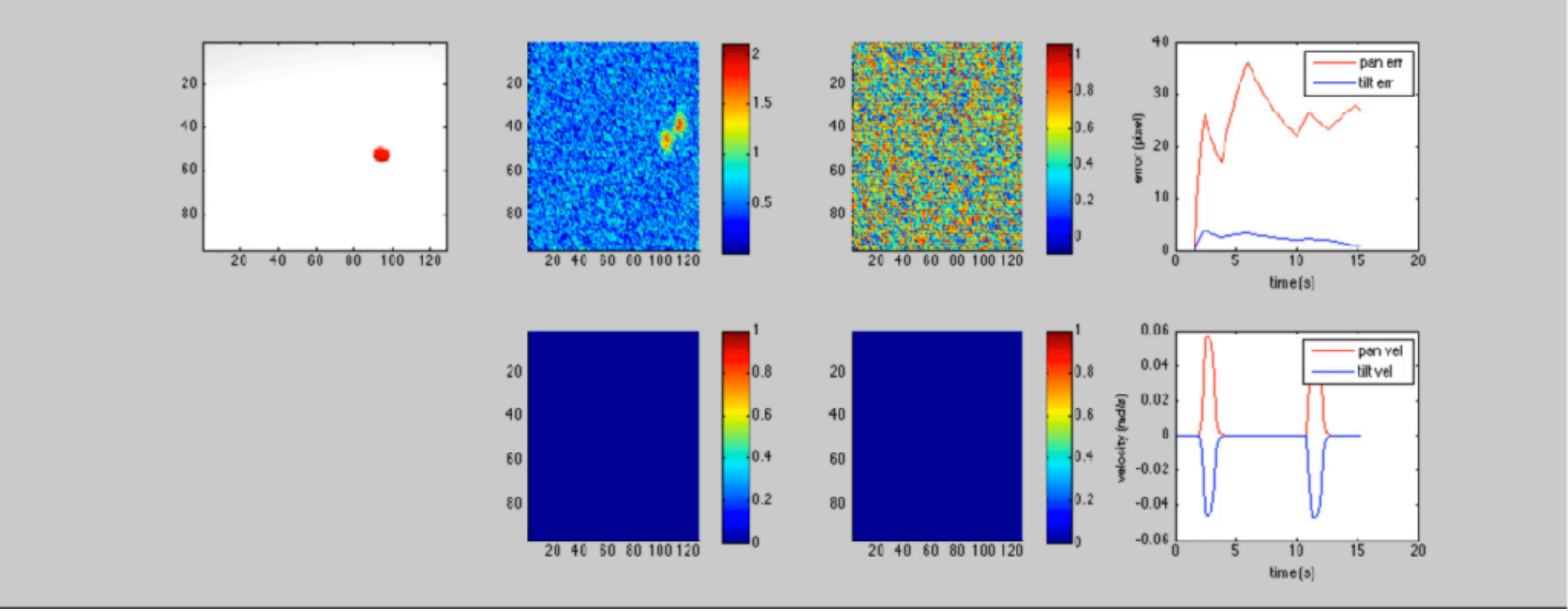
Saccade adaptation

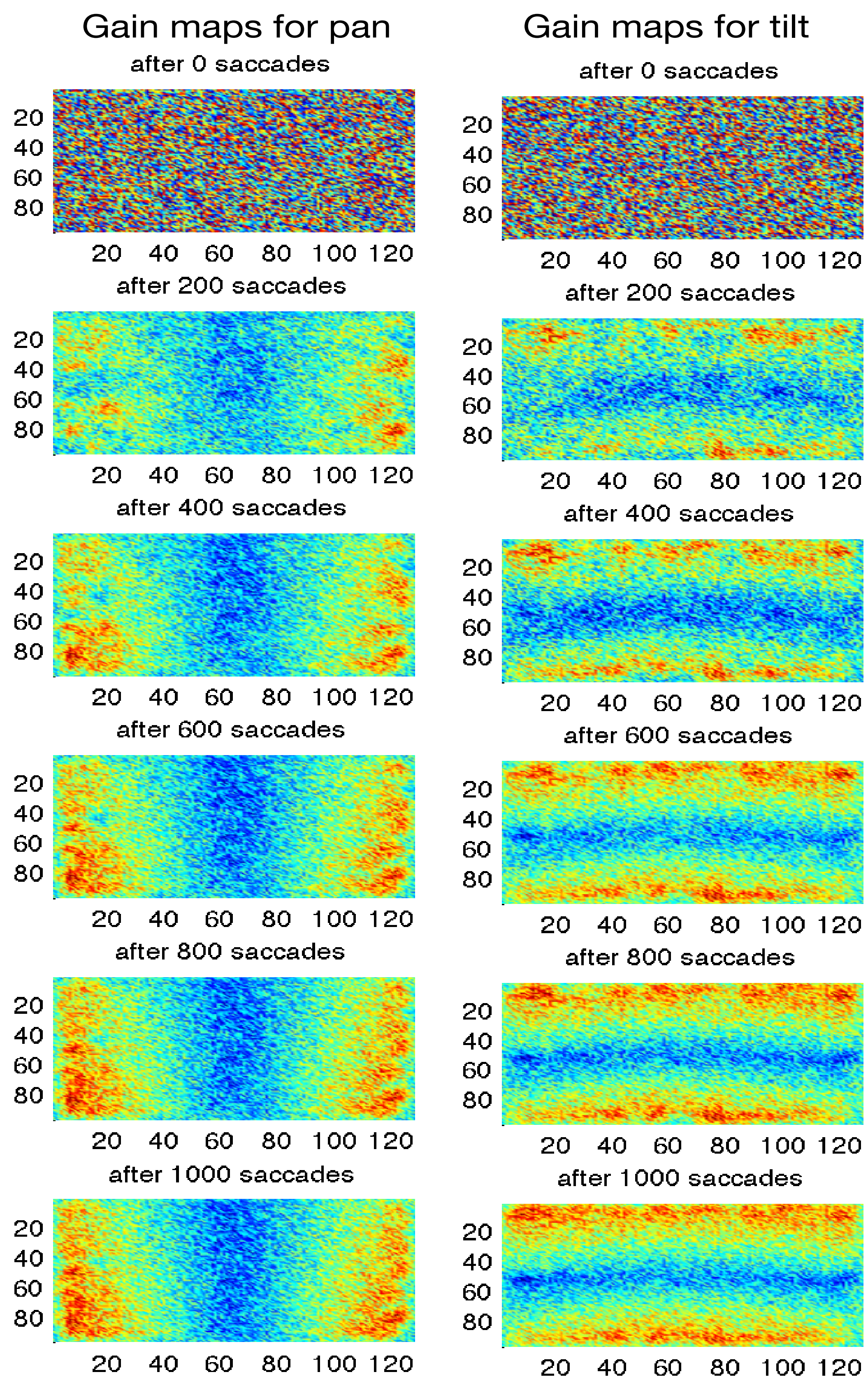


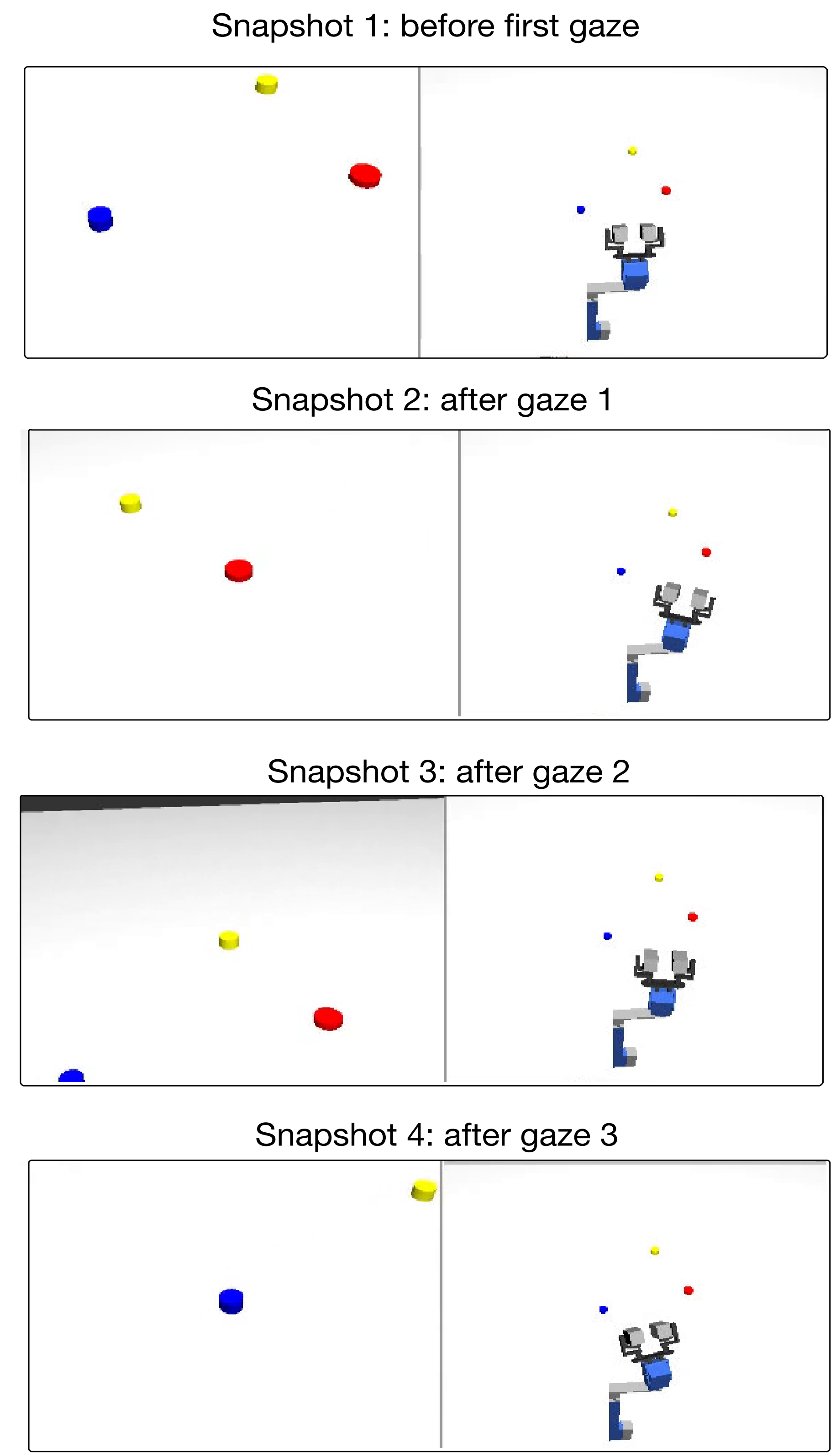
$$\tau \dot{G}(x, y, p, t) = c_{\text{on}} \cdot err_{\text{sign}} \cdot T(x, y) \cdot M(p, t)$$

Results: Learning the Gain Map



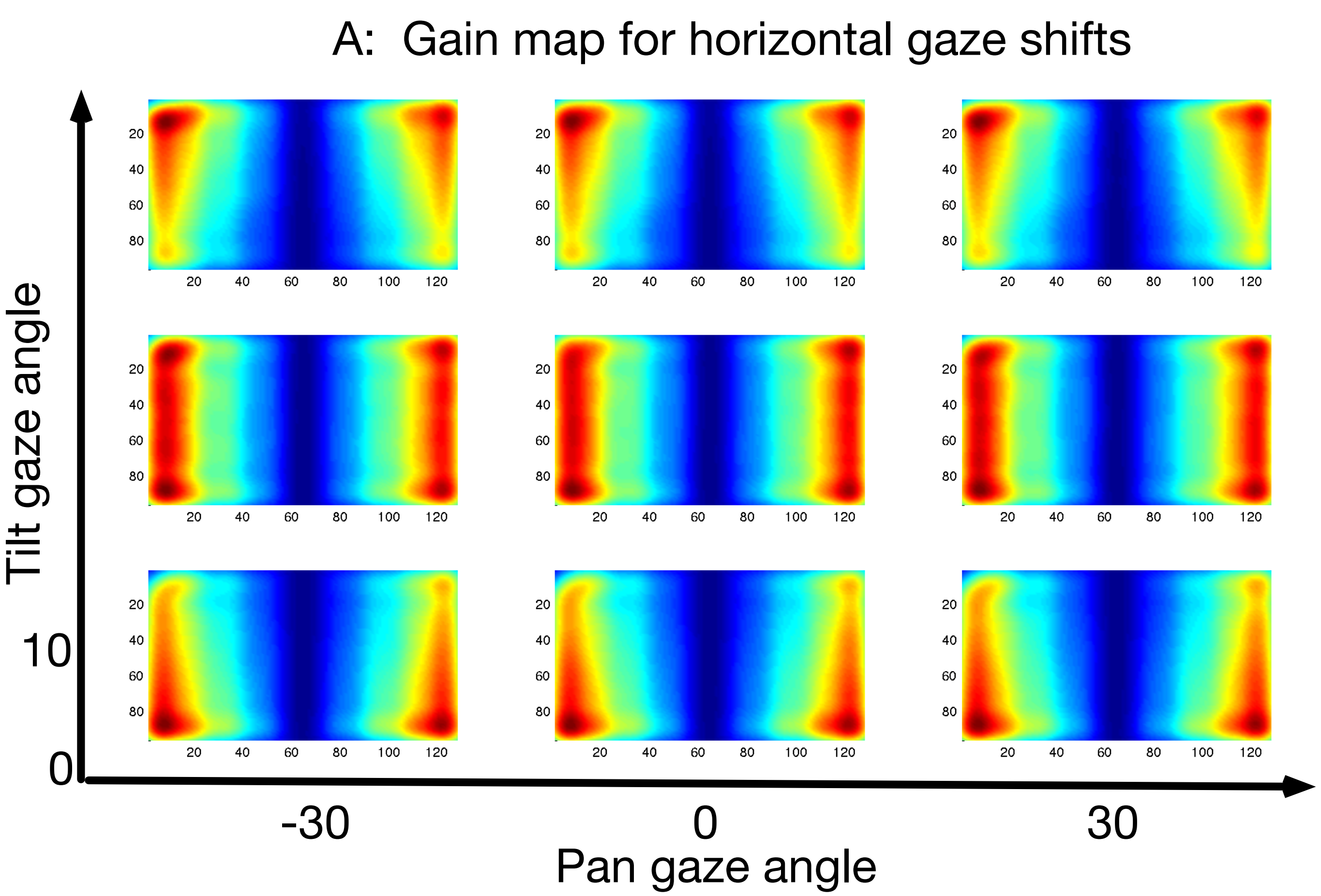
Learning sensorimotor maps in simulations

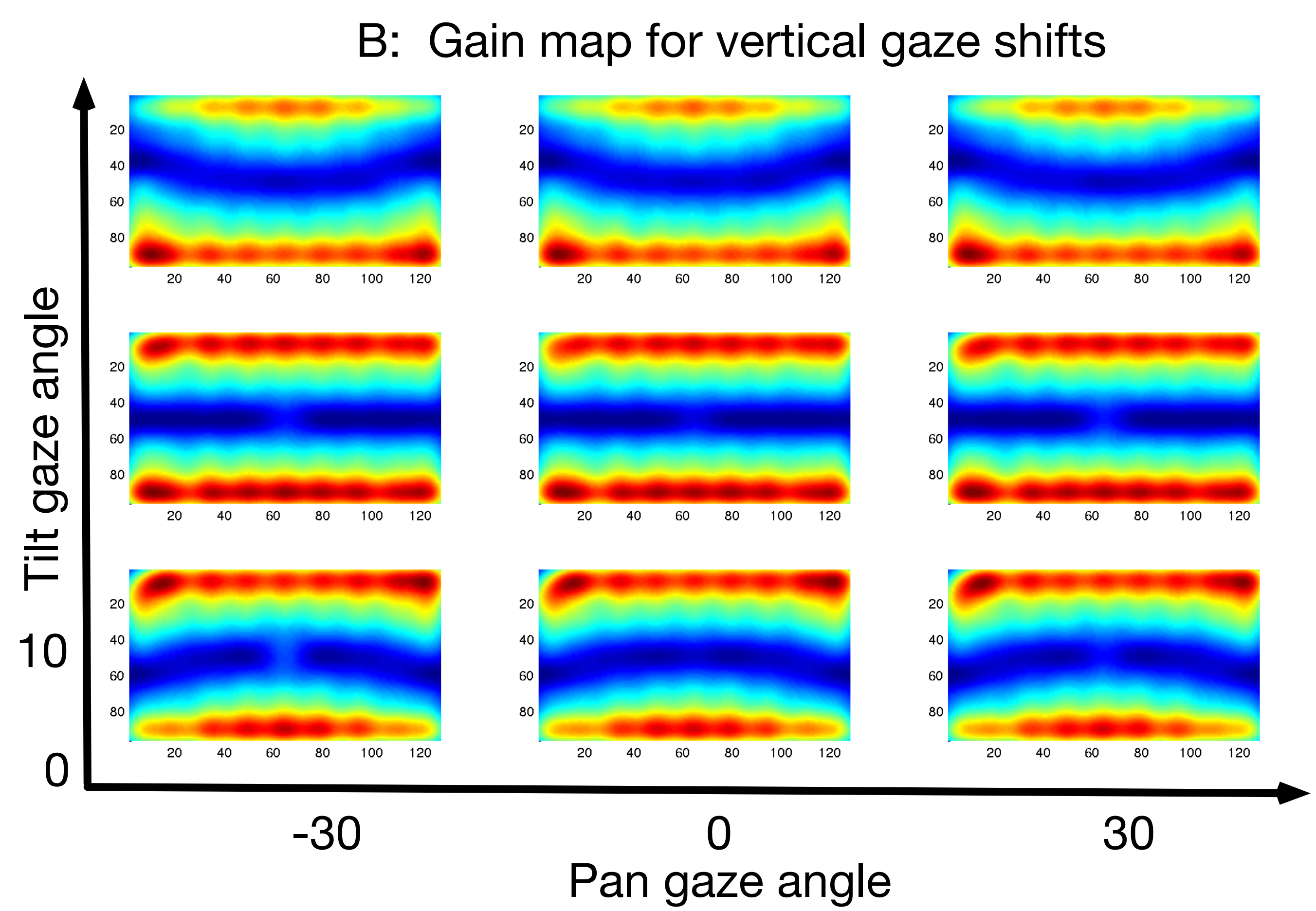




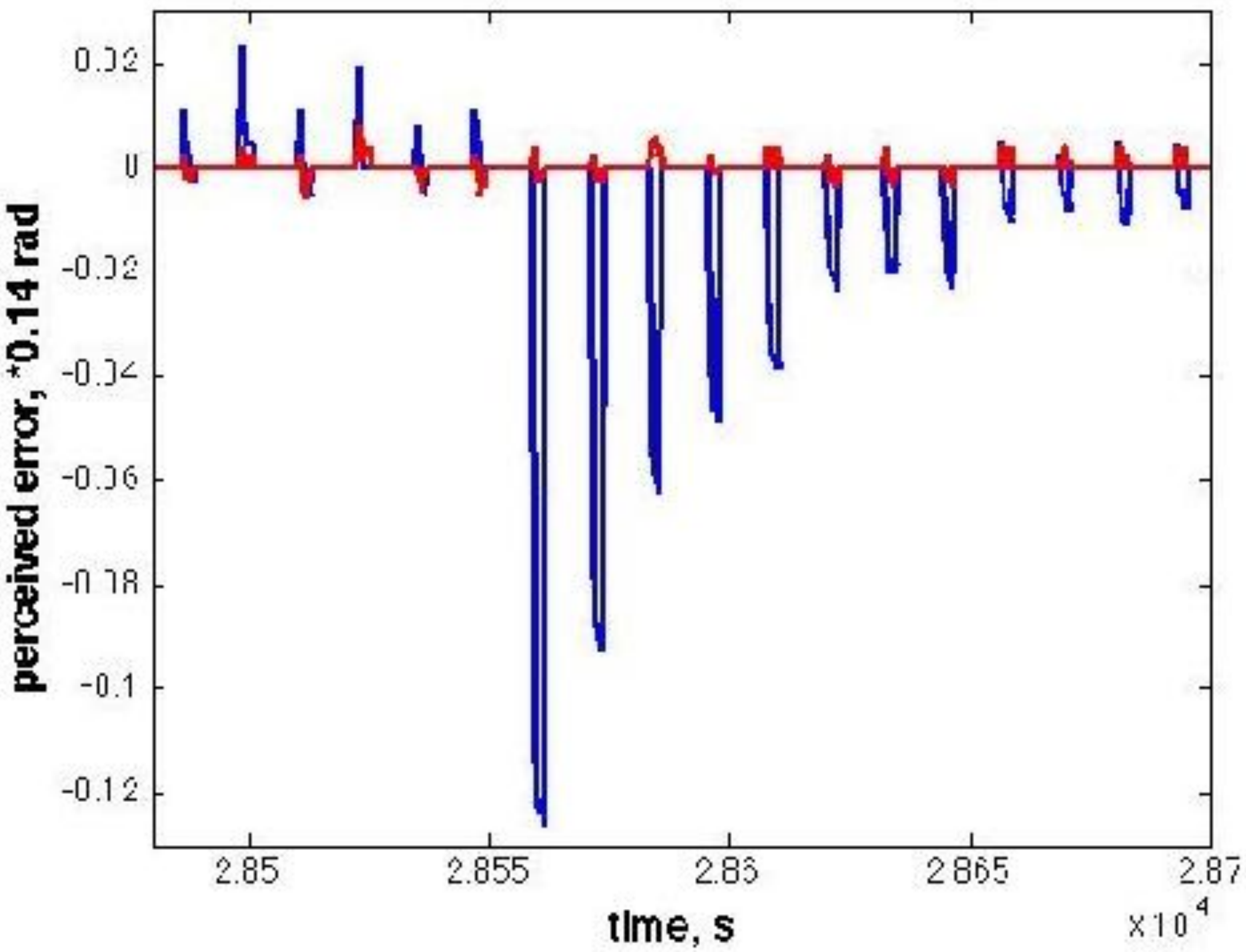
Maps are actually 4D

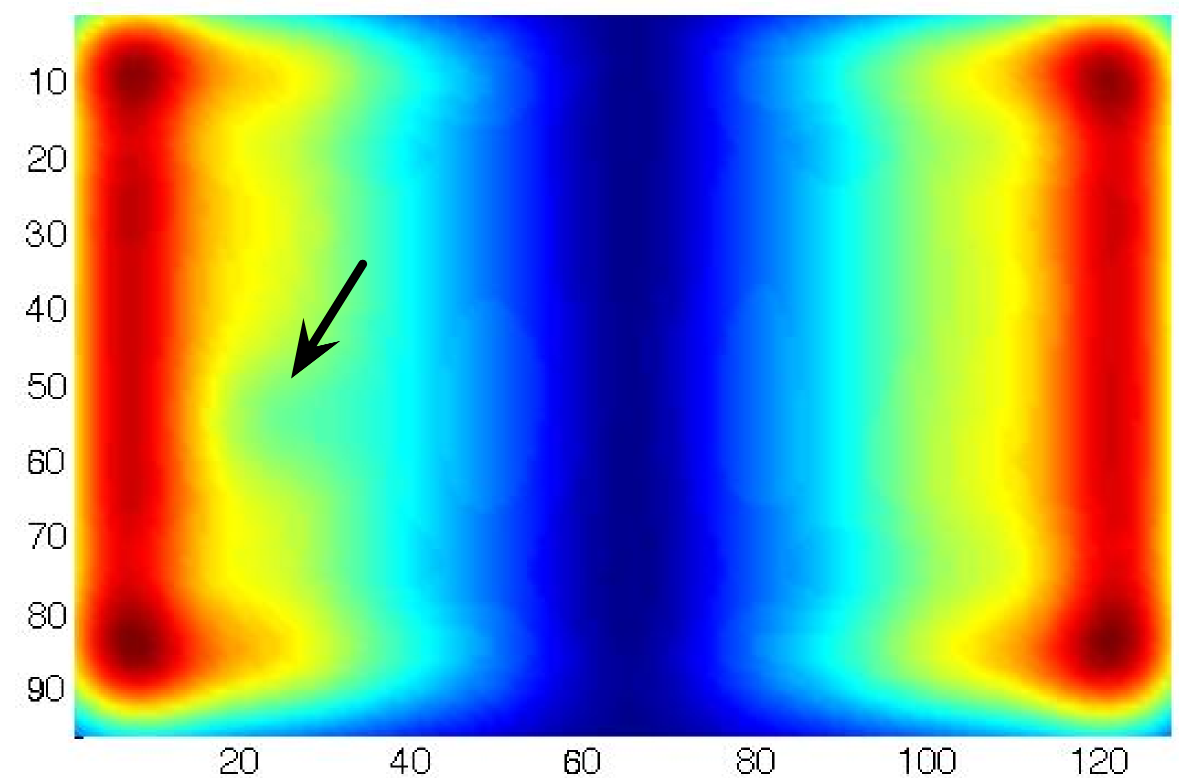
➡Depend on the retinal position of the target and the initial position of the eye



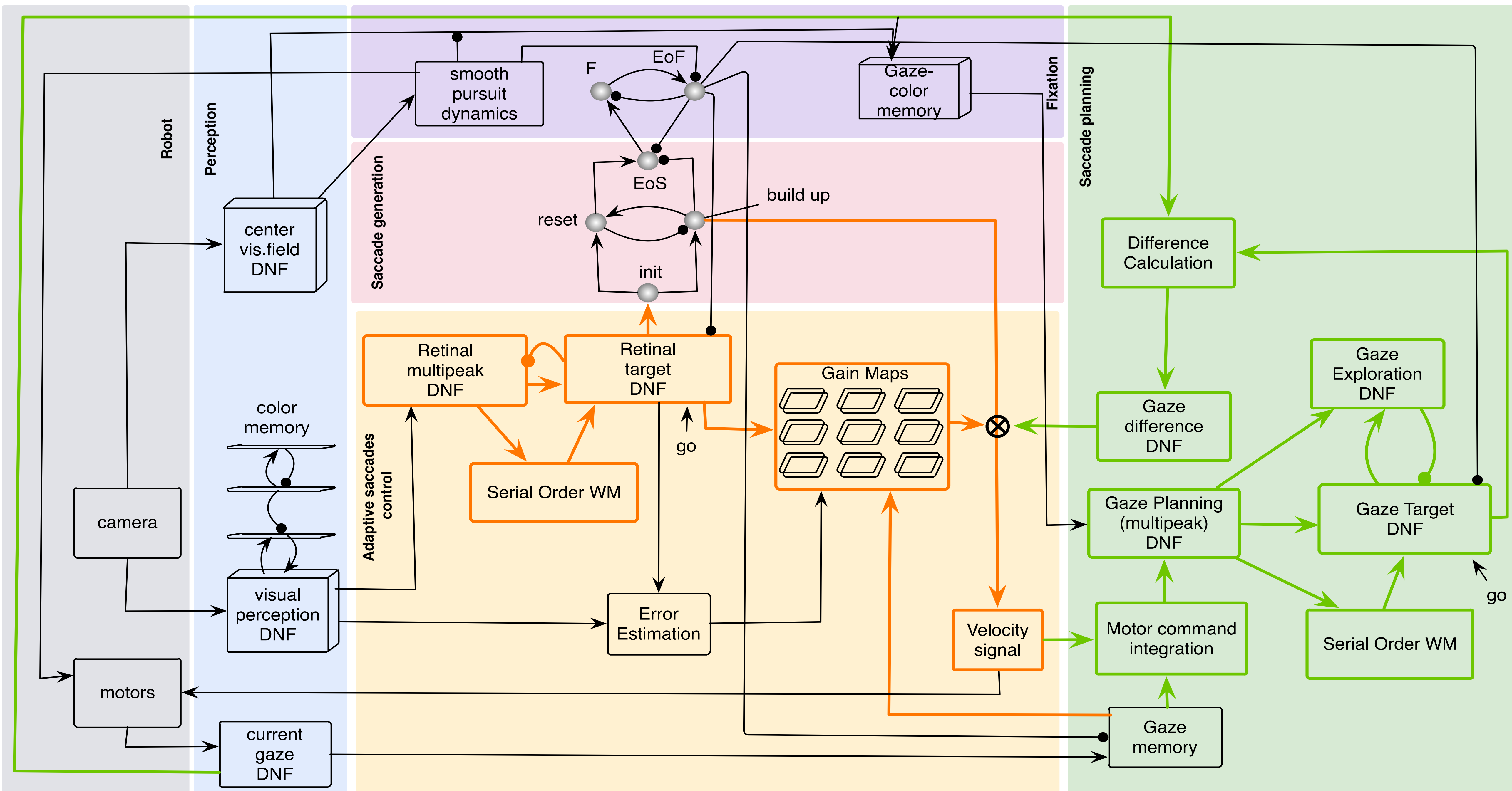


Adaptation of the Gain Maps



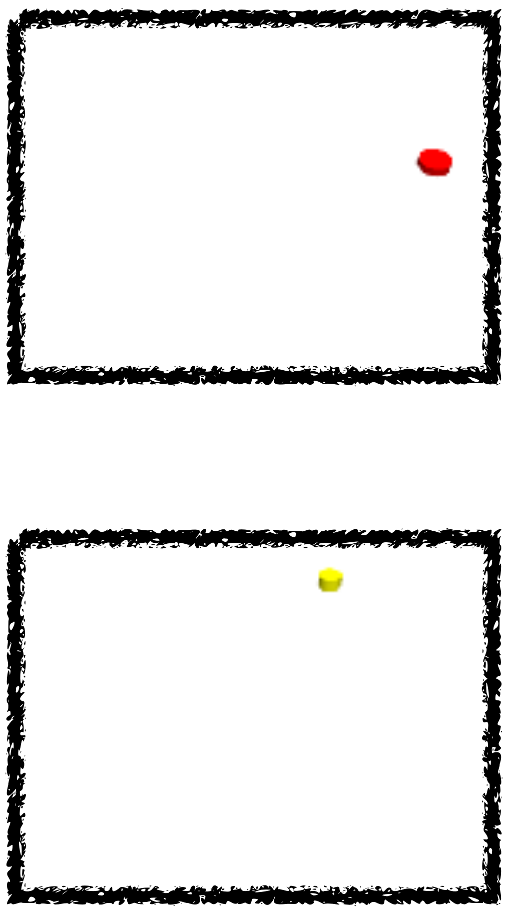


What about memory saccades?

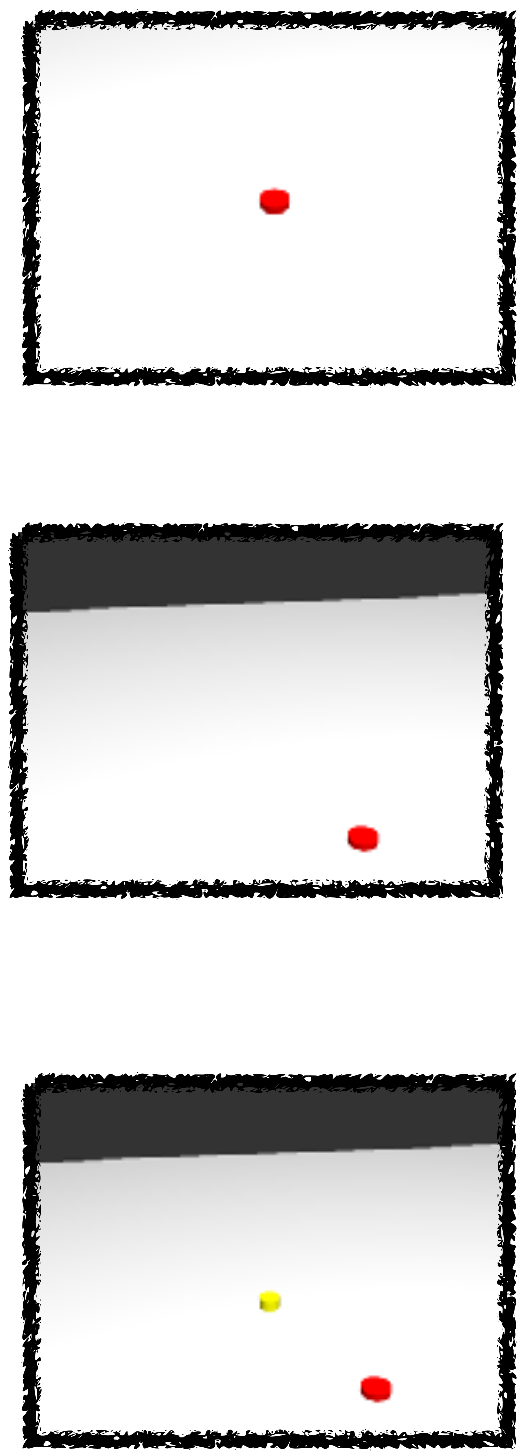


Double-step saccades

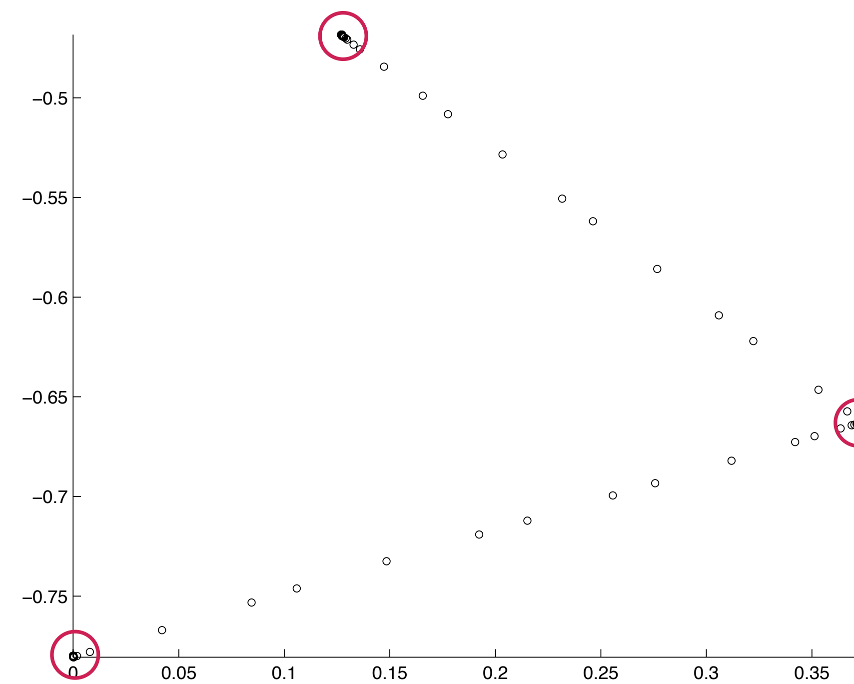
Presentation of targets



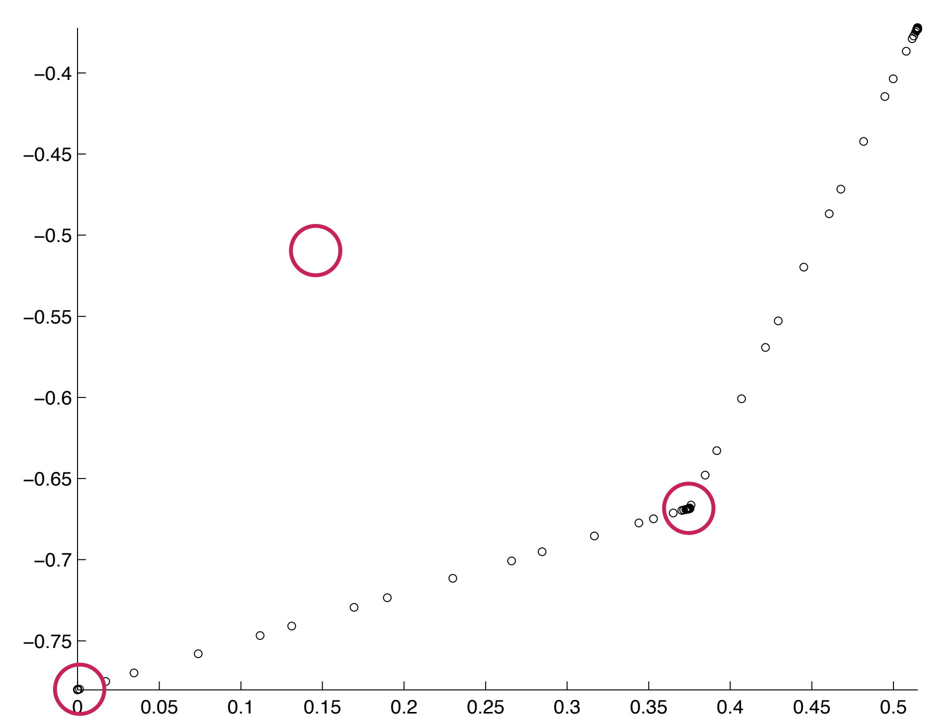
Camera movement



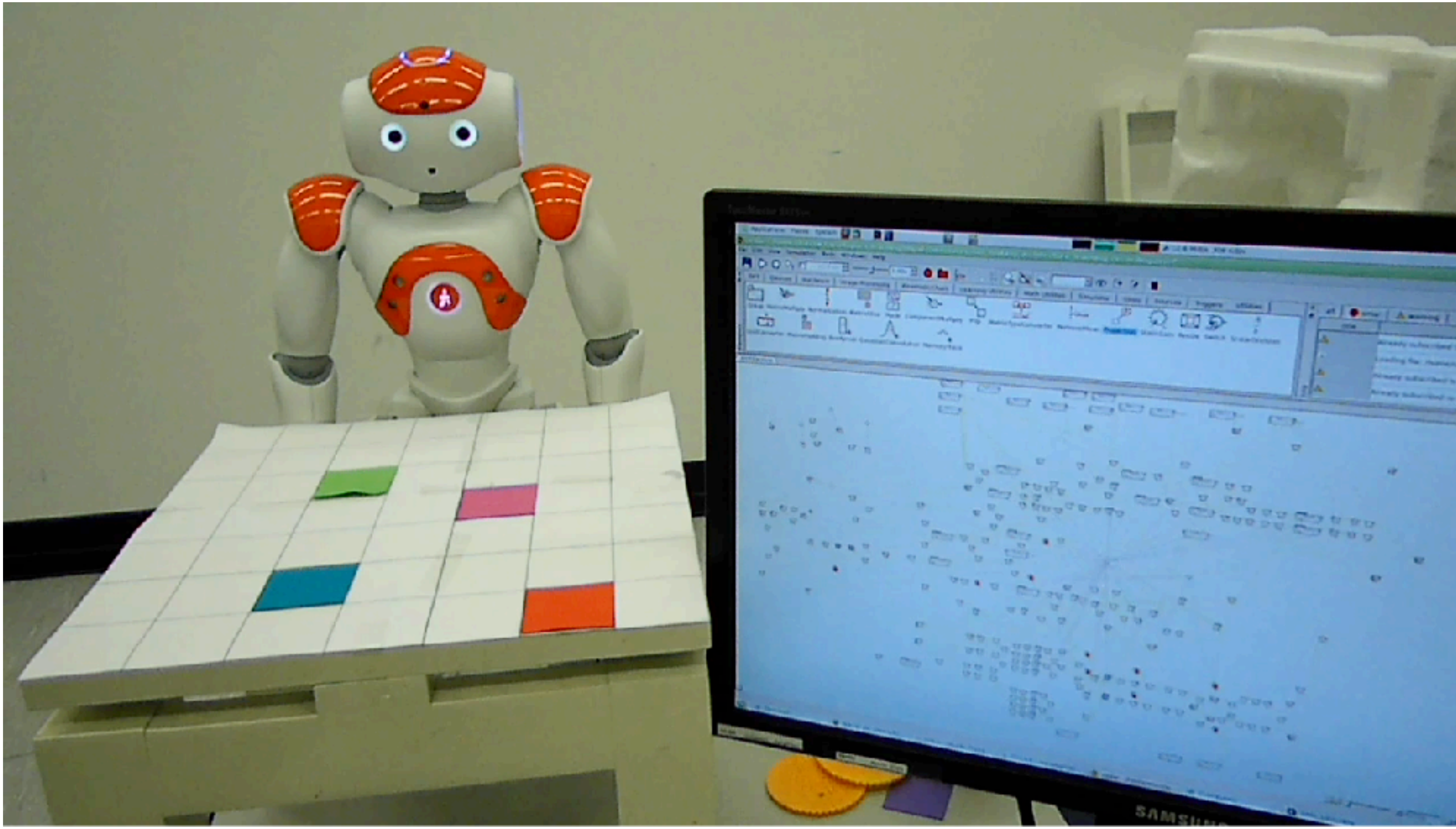
Gaze-based target representation



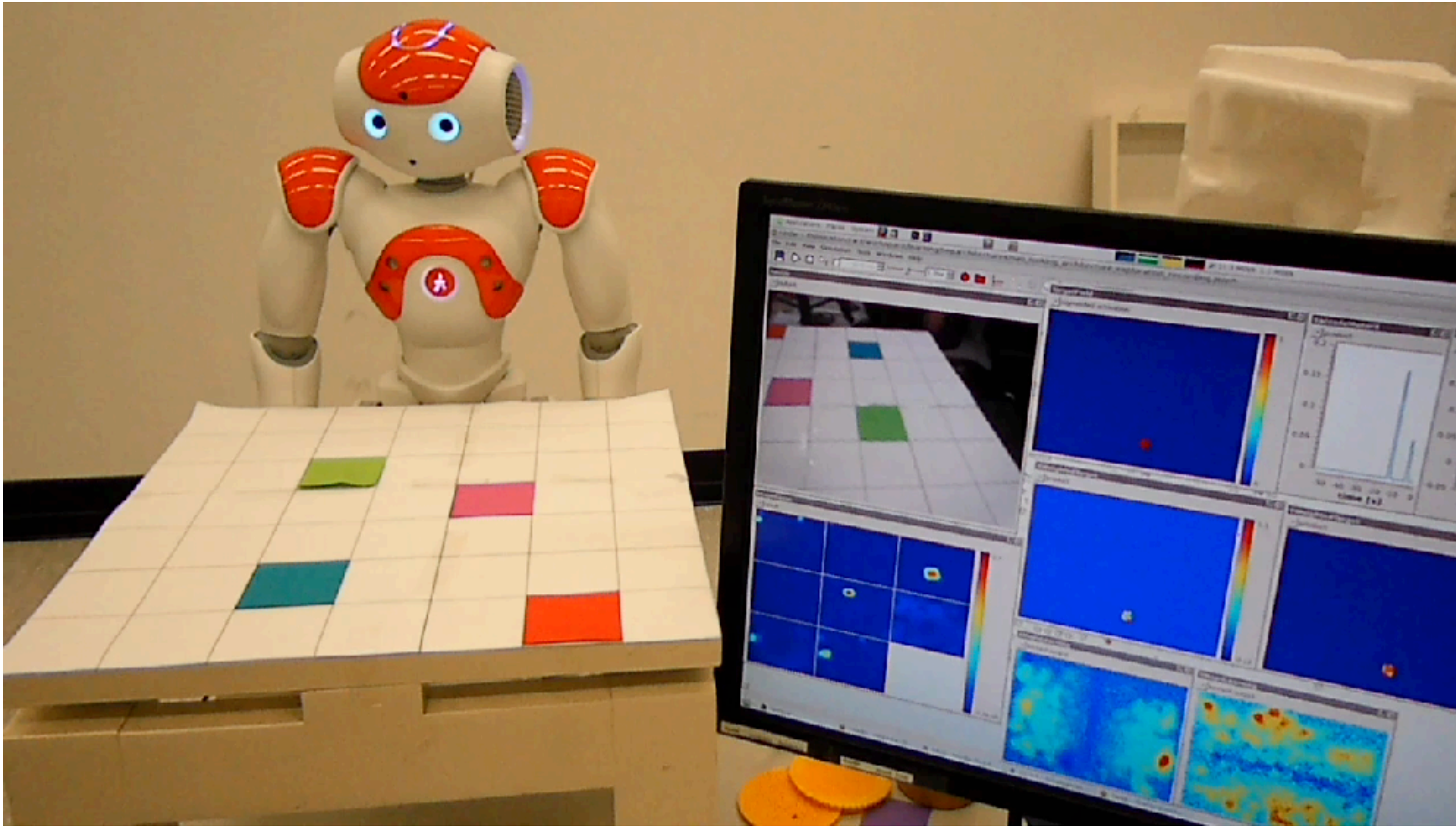
Retinotopic target representation



Learning to look on a robot

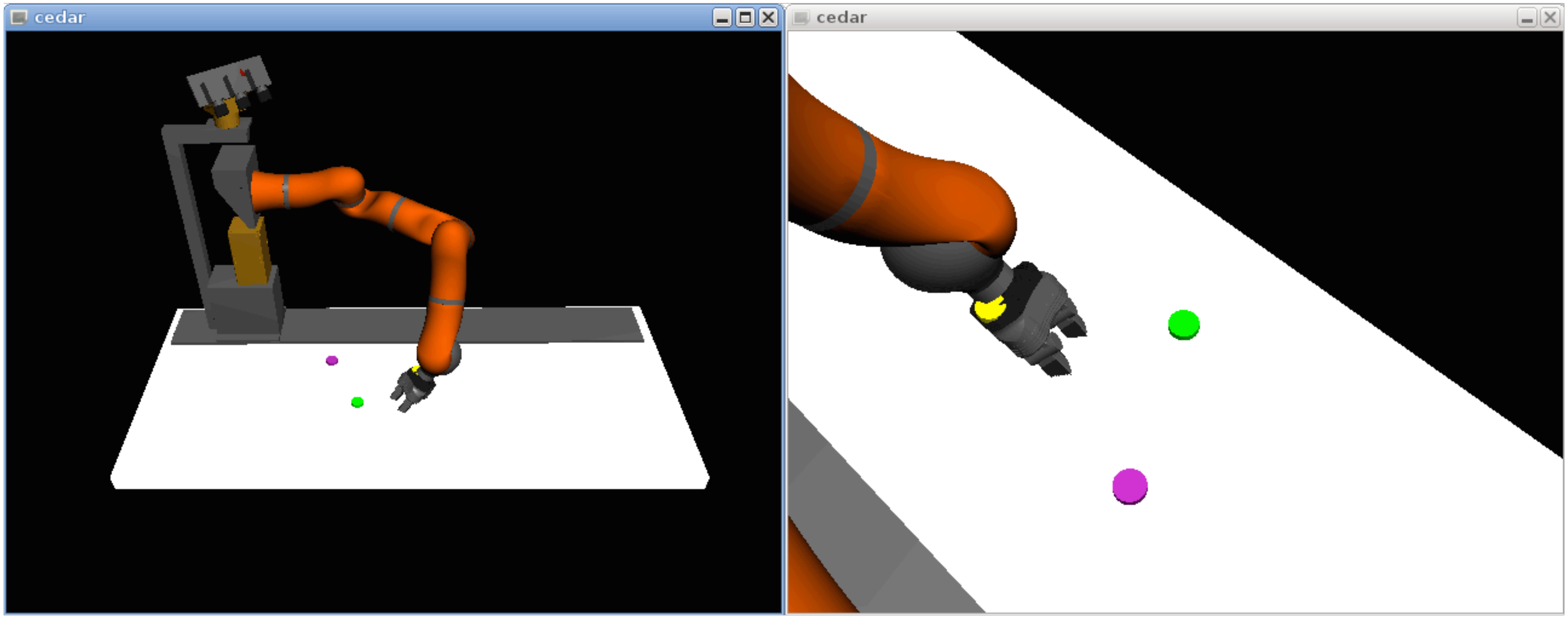


Exploring a scene on a robot



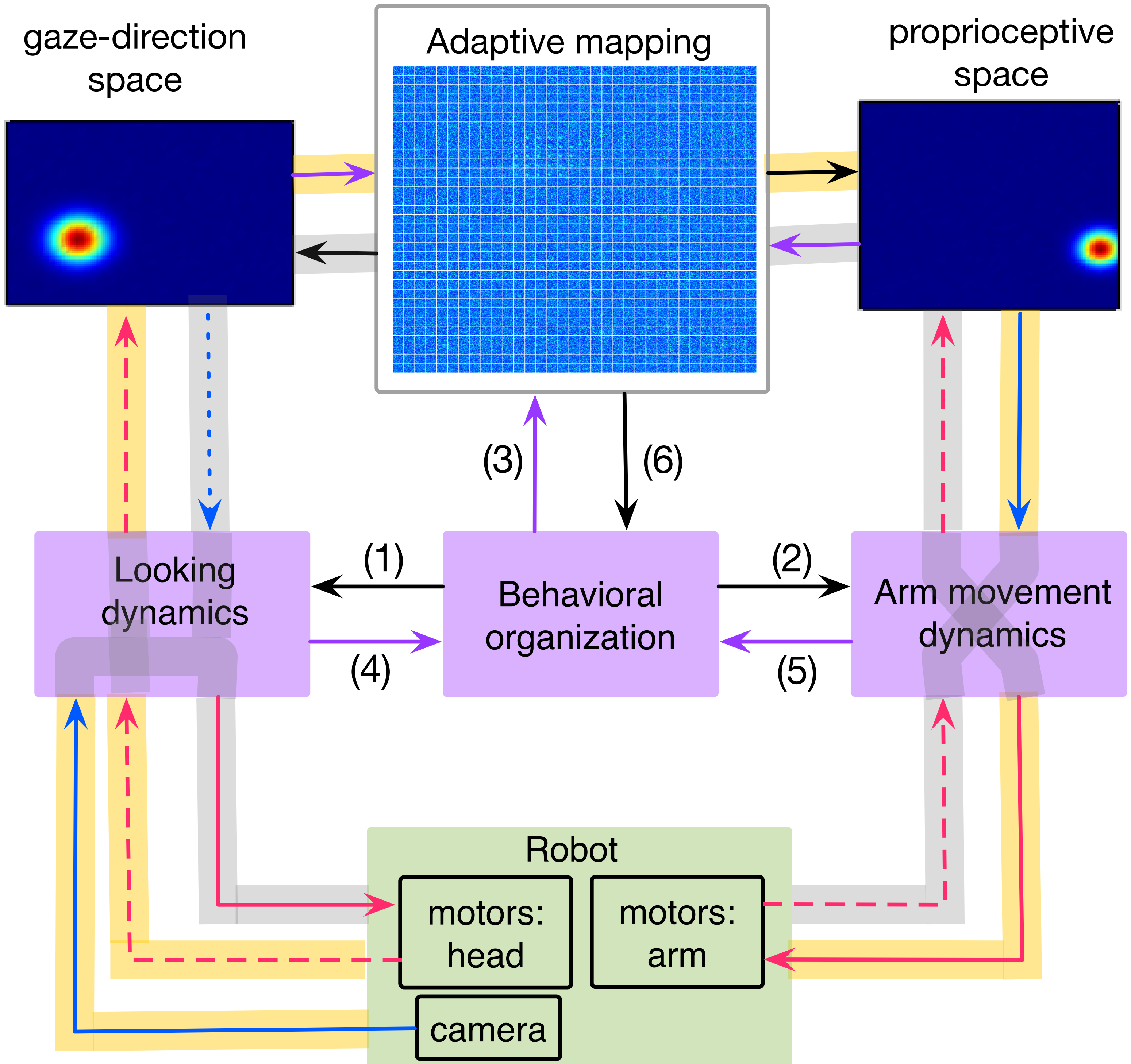
Storck et al, 2014a,b

Learning to reach

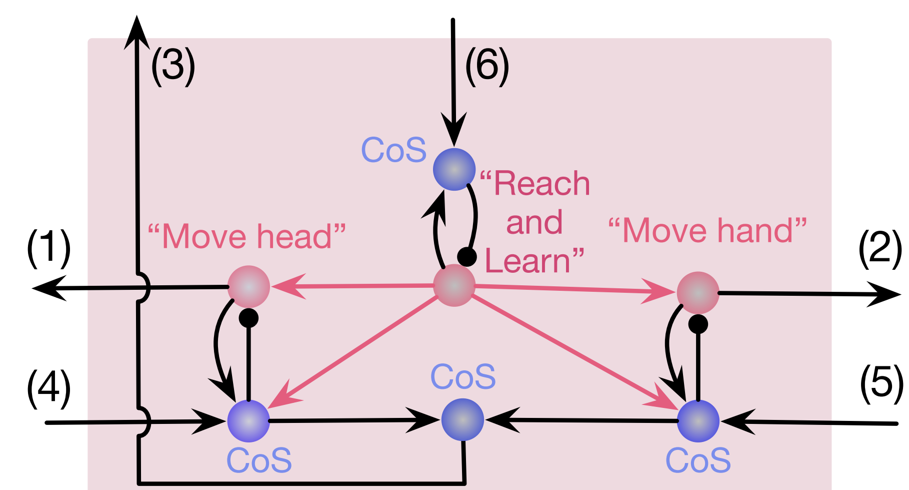


- learning the mapping between the gaze-based and body-centred coordinates

Architecture for Learning to reach



Behavioral organisation



More topics…

- ➡forward and inverse models, tasks vs. operational space
- ➡uncontrolled manifold
- ➡redundancy
- ➡coordination, timing
- ➡motor primitives, synergies
- ➡skill learning, habit formation

Take home message

- understanding motor control in biological neural systems is key to understanding the brain and to development of new generation of AI
- our understanding of motor control in biological neural systems is currently very limited
- it is hard to study because it requires the whole loop from perception to parameter estimation and representation to cognition and actual low-level (but adaptive) control, and learning
- understanding low-level MC led to many insights and technical innovations (prostheses, compliant actuators, soft robotics, force control)