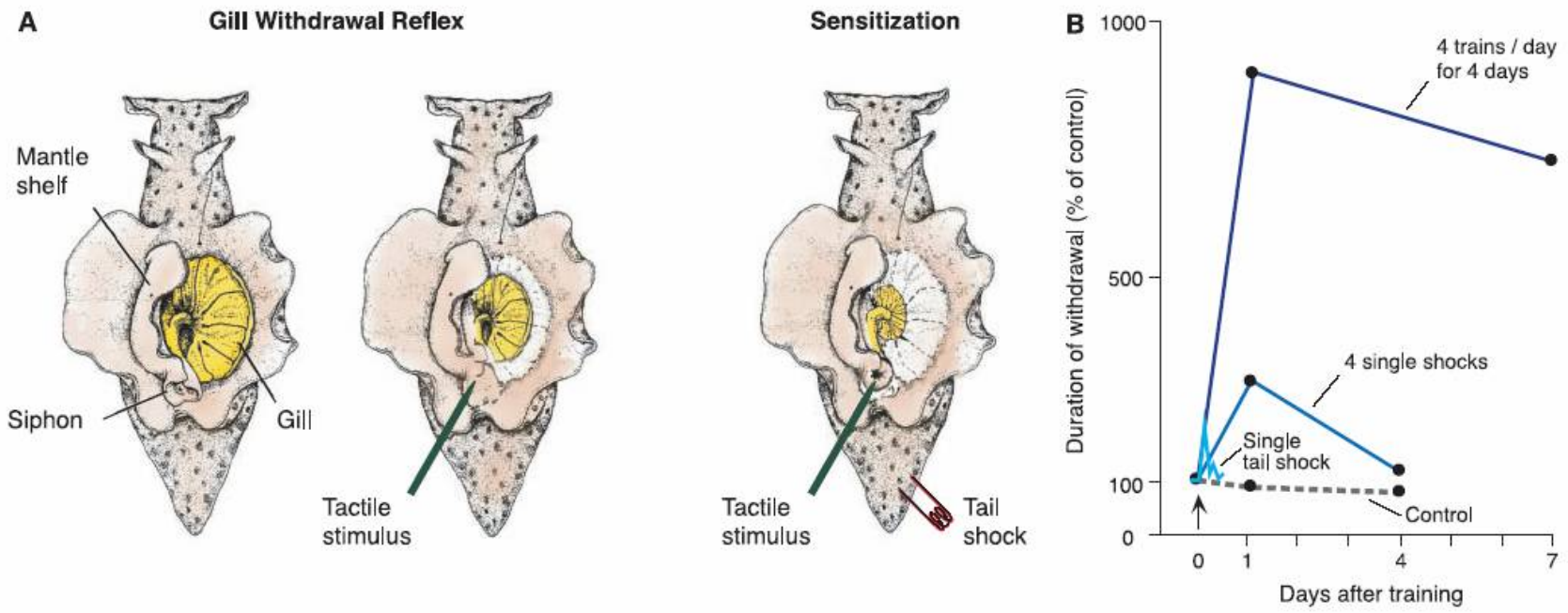
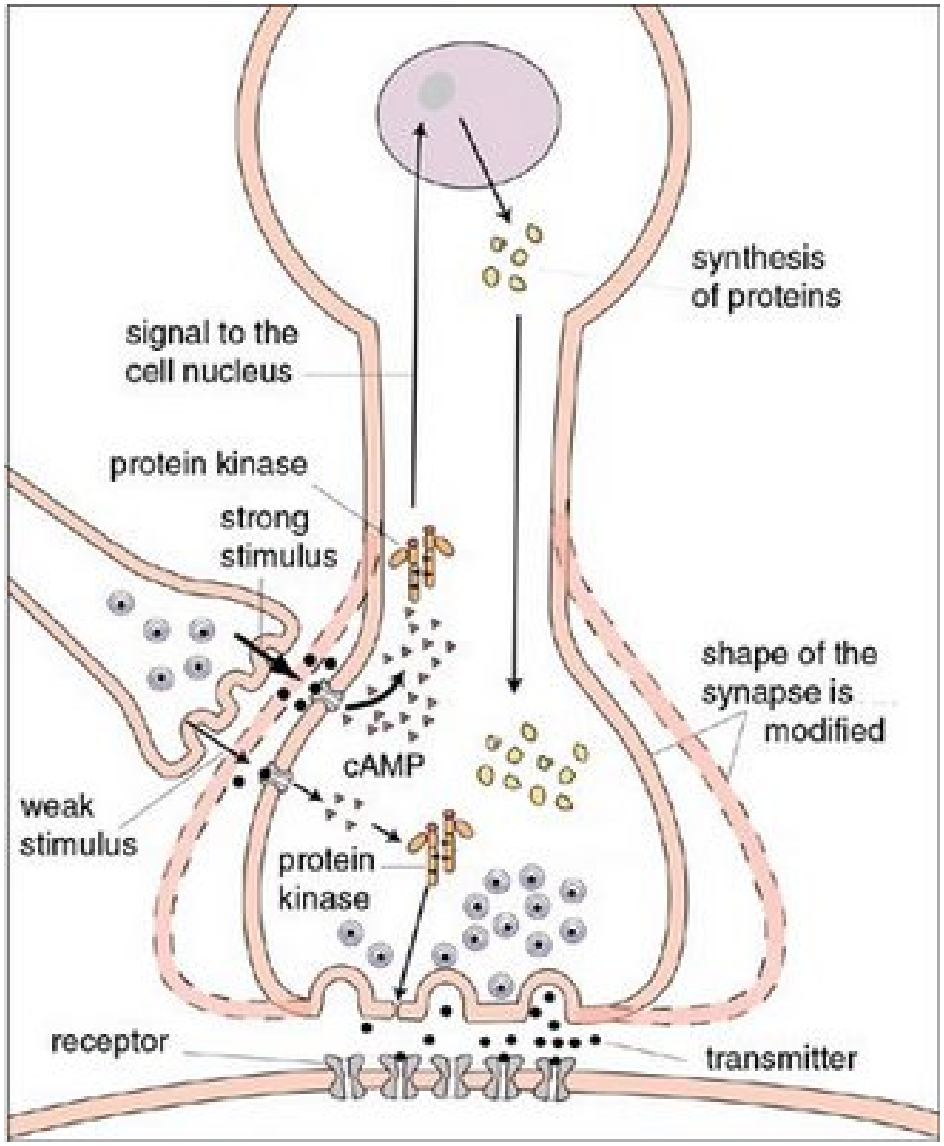
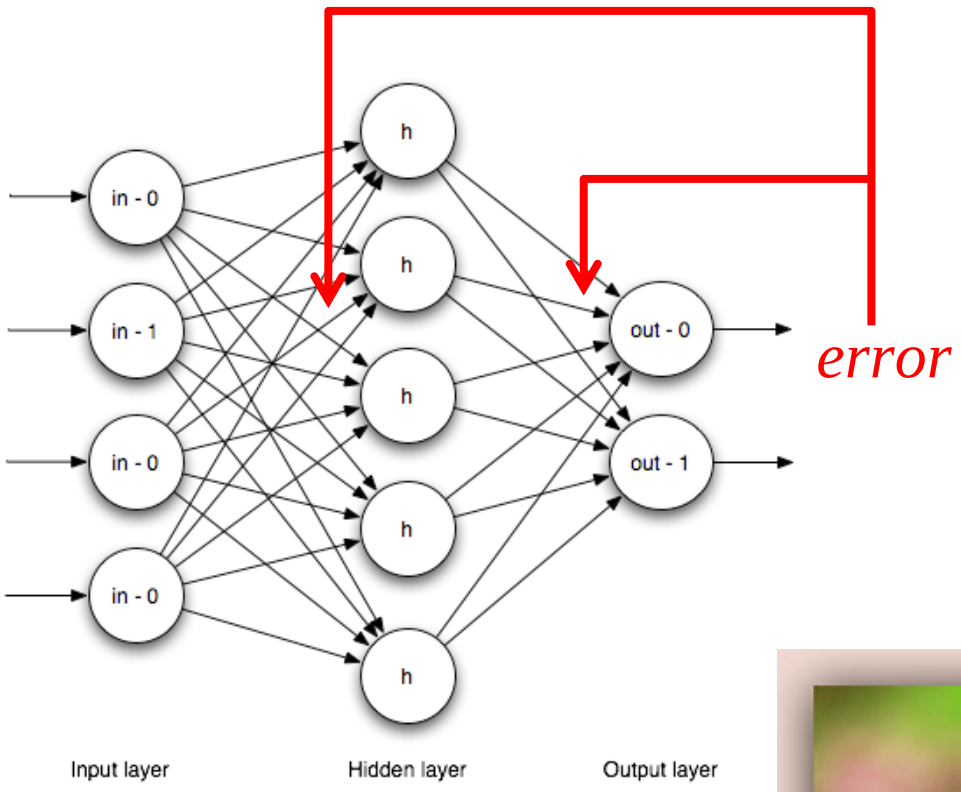
1. learning *vs* plasticity
2. supervised learning *vs* reinforcement learning
3. circuits: VOR & OKR
4. open vs. closed loop controllers
5. motor learning: adjusting the FF controller
6. cerebellar LTD & VOR gain adaptation


A
Gill Withdrawal Reflex
Mantle shelf
Siphon
Gill
Tactile stimulus
Sensitization
Tactile stimulus
Tail shock
B
1000
500
100
0
Duration of withdrawal (% of control)
4 trains / day for 4 days
4 single shocks
Single tail shock
Control
0
1
4
7
Days after training


synthesis
of proteins
signal to the
cell nucleus
protein kinase
strong
stimulus
shape of the
synapse is
modified
cAMP
weak
stimulus
protein
kinase
receptor
transmitter

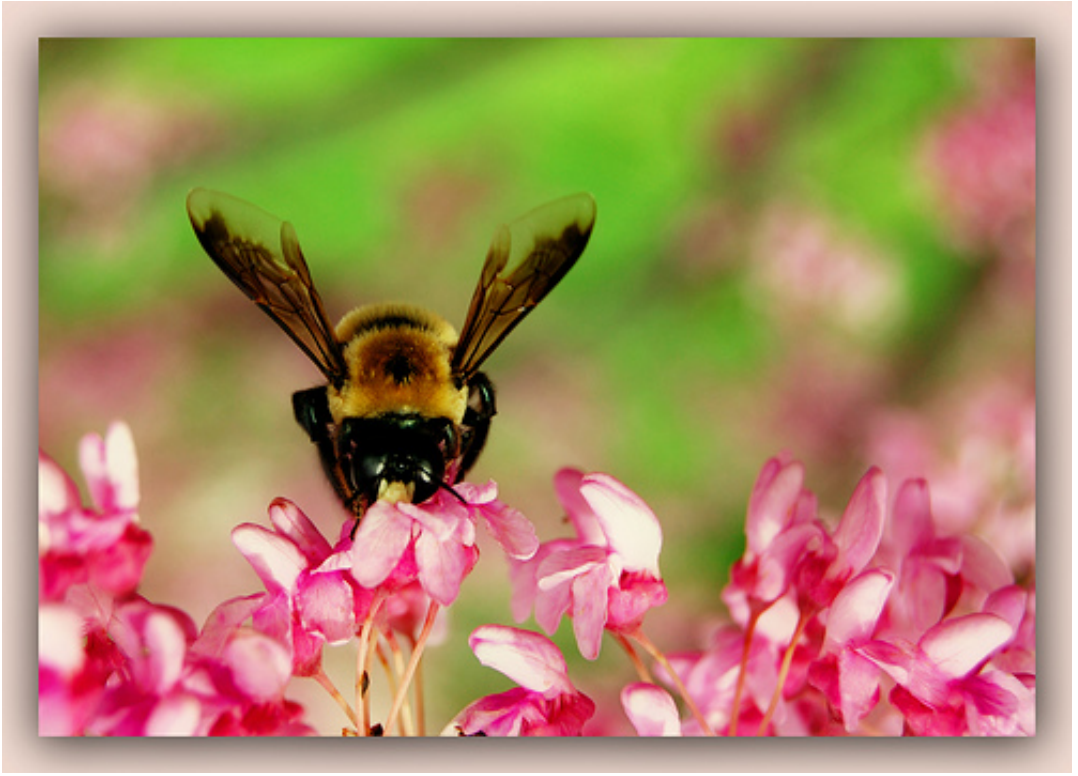


supervised learning
- learning from examples
- knowledgeable external supervisor
- feedback: instructive
  (What should have been done.)

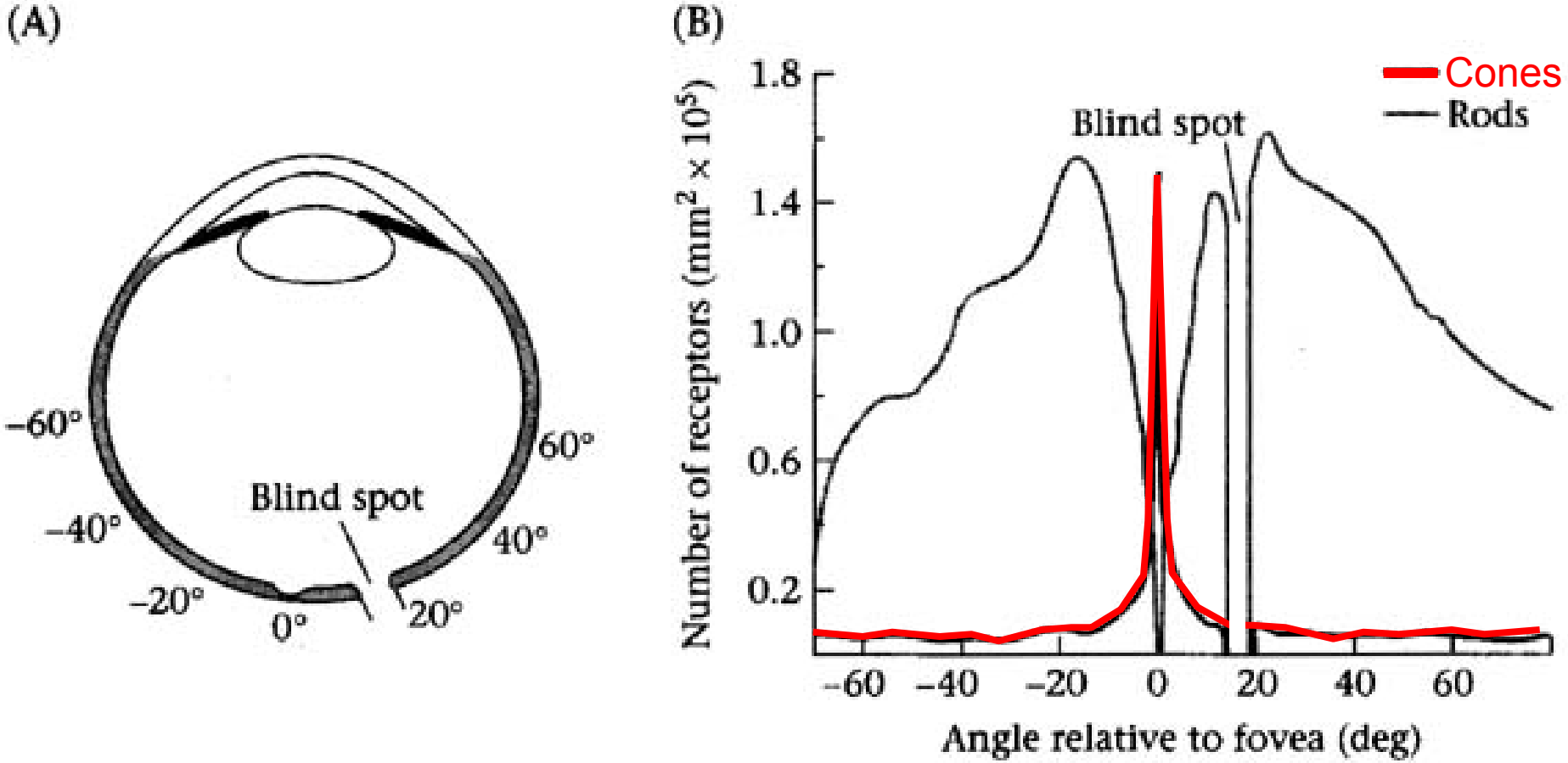
reinforcement learning
- trial-and-error search
- delayed reward
- feedback: evaluative
  ("warmer" or "cooler")

Rescorla-Wagner learning rule

$$\Delta P_n = (R_{n-1} - P_{n-1}) \cdot \alpha$$



Fovea & Acuity



Test your acuity: hold fixation on the red ‘e’

“The muscles were of necessitie provided and given to the eye, that so it might move on every side: for if the eye stoode fast, and immoveable, we should be constrained to turne our head and necke (being all of one peece) for to see: but by these muscles it now moveth it selfe with such swiftnes and nimblenes, without stirring of the head, as is almost incredible …”

Andreas Laurentius (1599)

“A Discourse of the Preservation of Sight: of Melancholike Diseases; of Rheumes, and of Old Age”

Basic Types of Eye Movements

Get the fovea onto a target.

Saccades (“jerk” or “yank”)

Keep it there . . .

Vestibulo-Ocular Reflex (VOR)

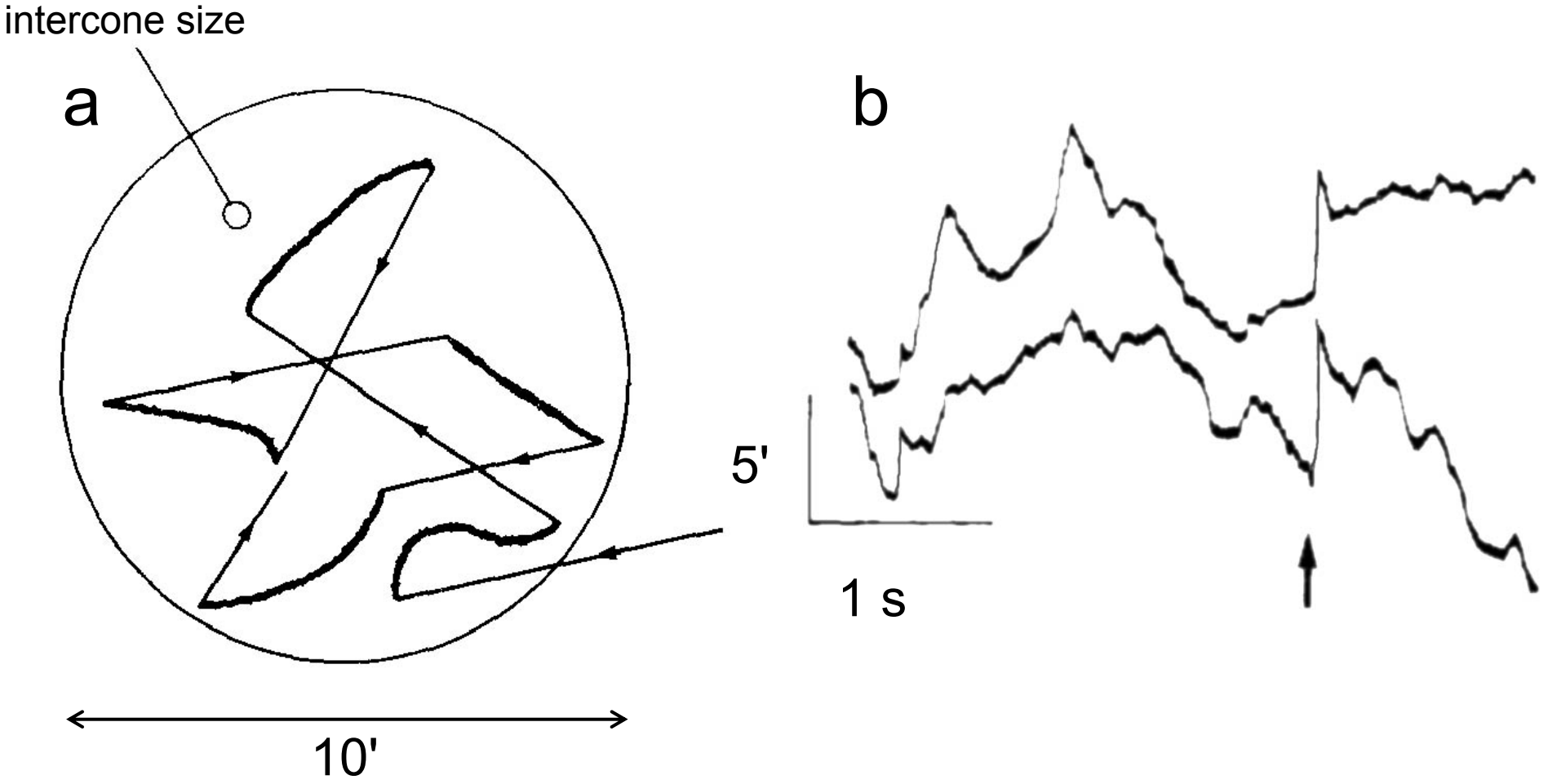
Optokinetic

Smooth Pursuit

. . . but not too well.

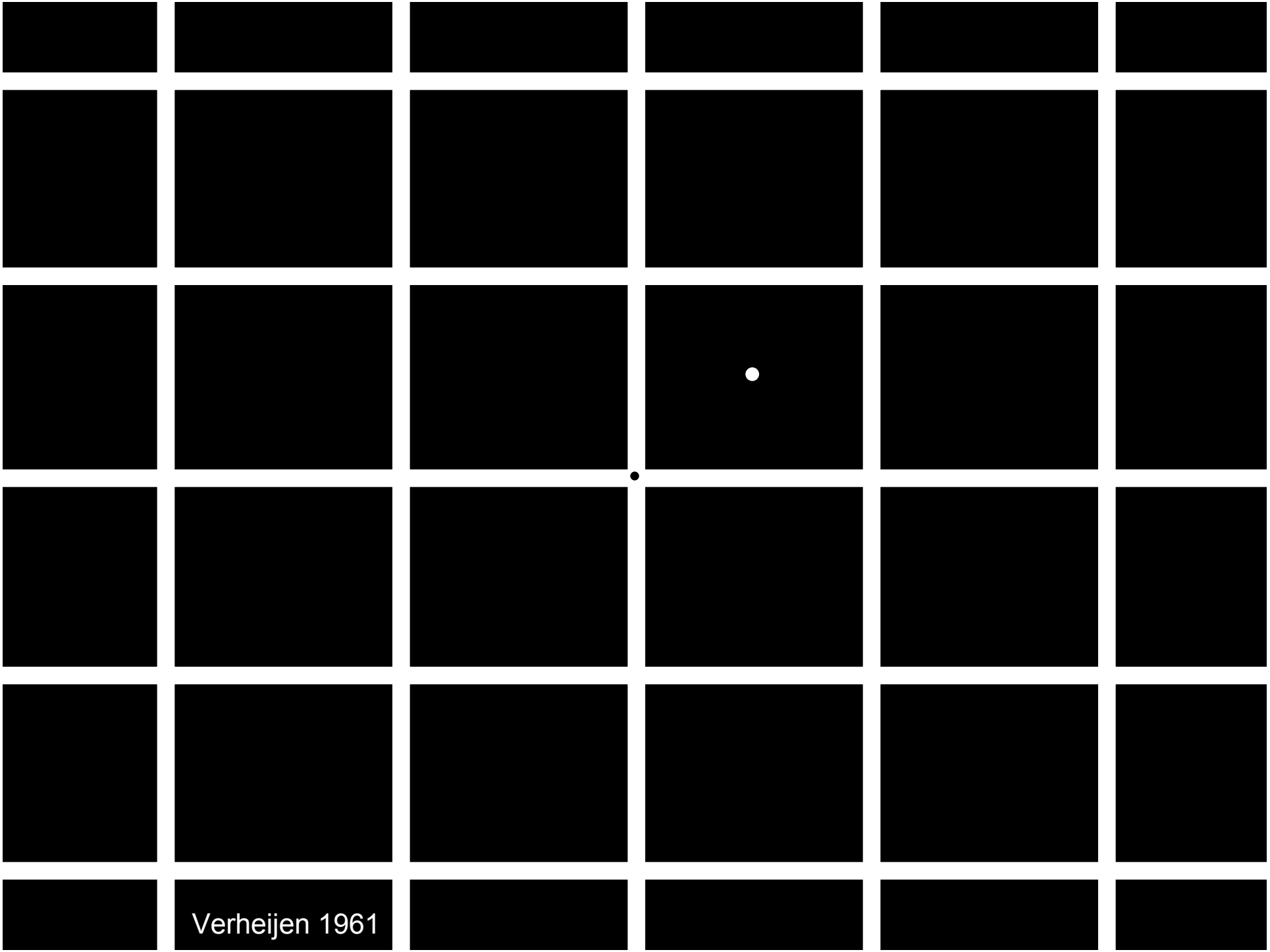
miniature eye movements

Miniature Eye Movements

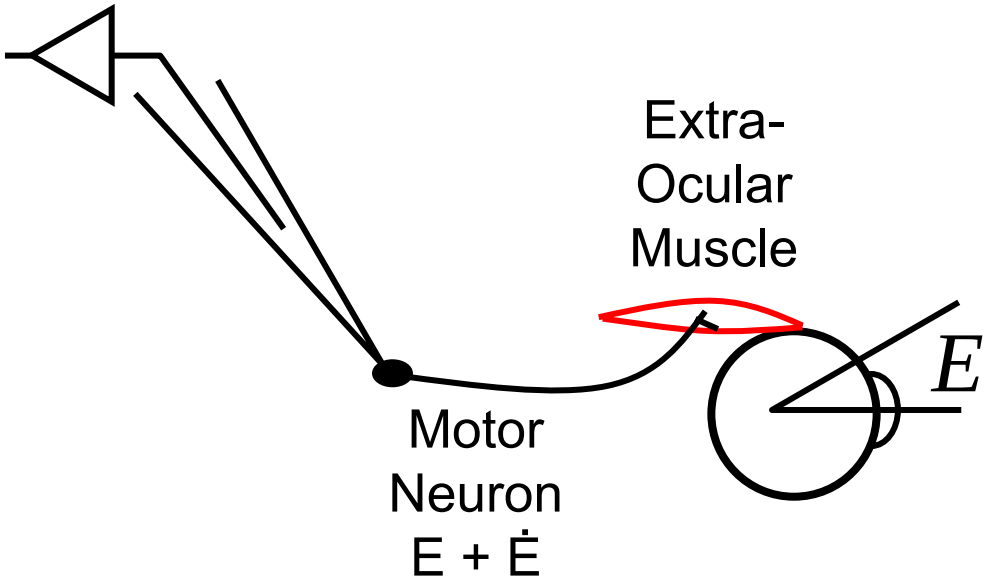


Pritchard 1964

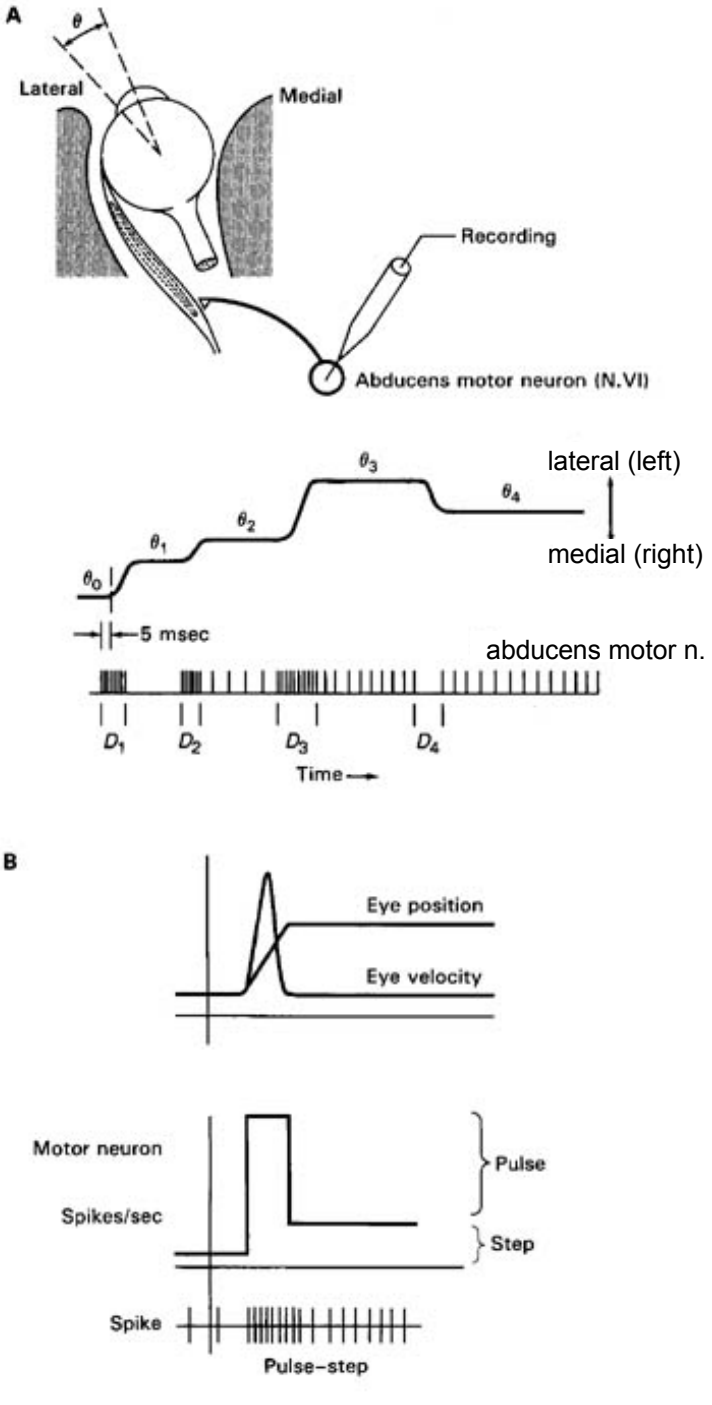
Yarbus 1967


Verheijen 1961

Final Motor Pathway: Motor Neuron

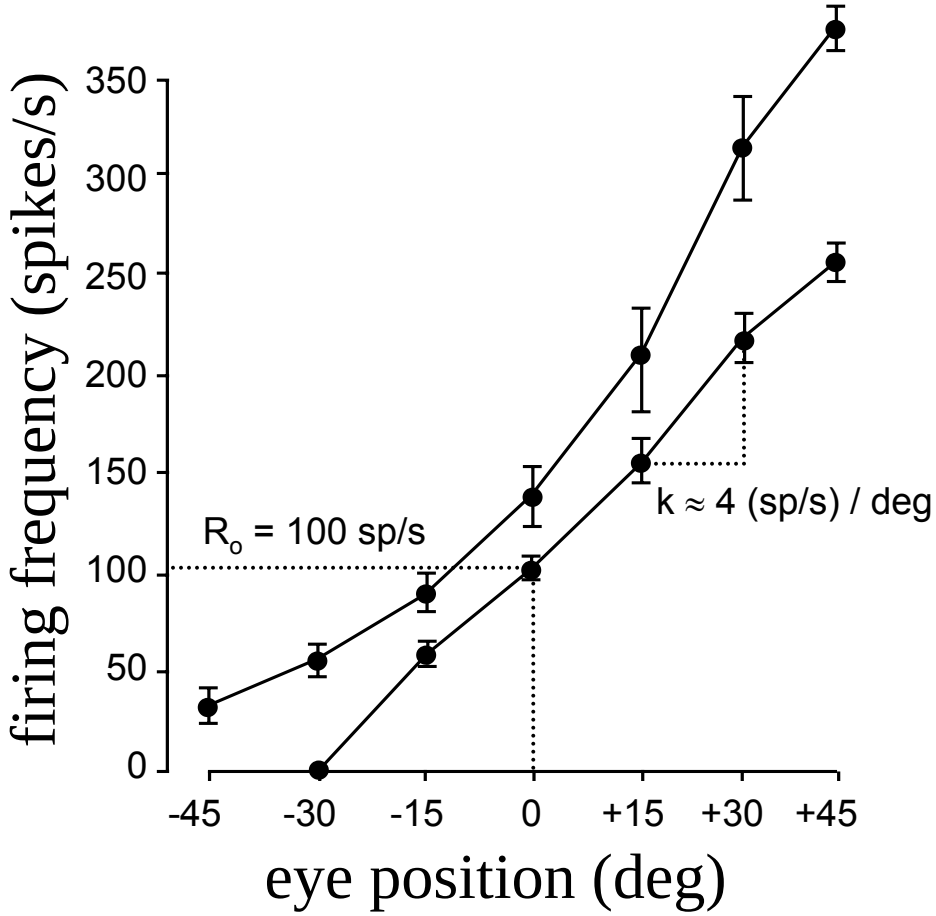


Pulse-Step Firing of Motor Neurons

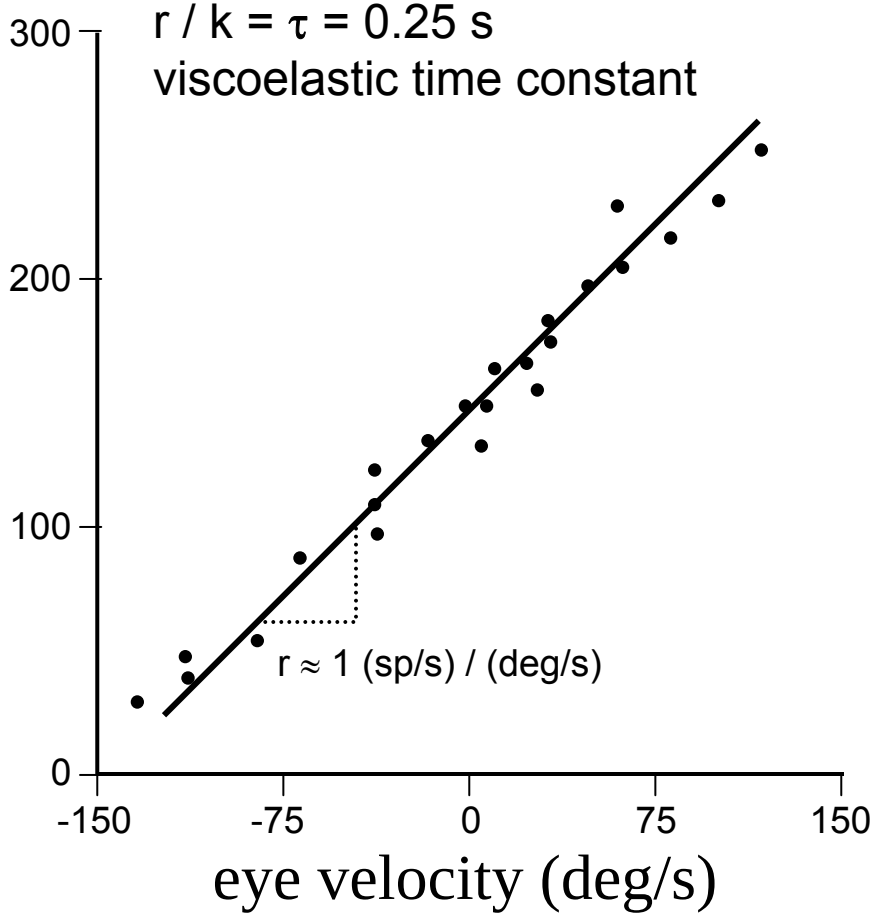


Motor Neurons

$$R_m = R_o + kE + r\dot{E}$$

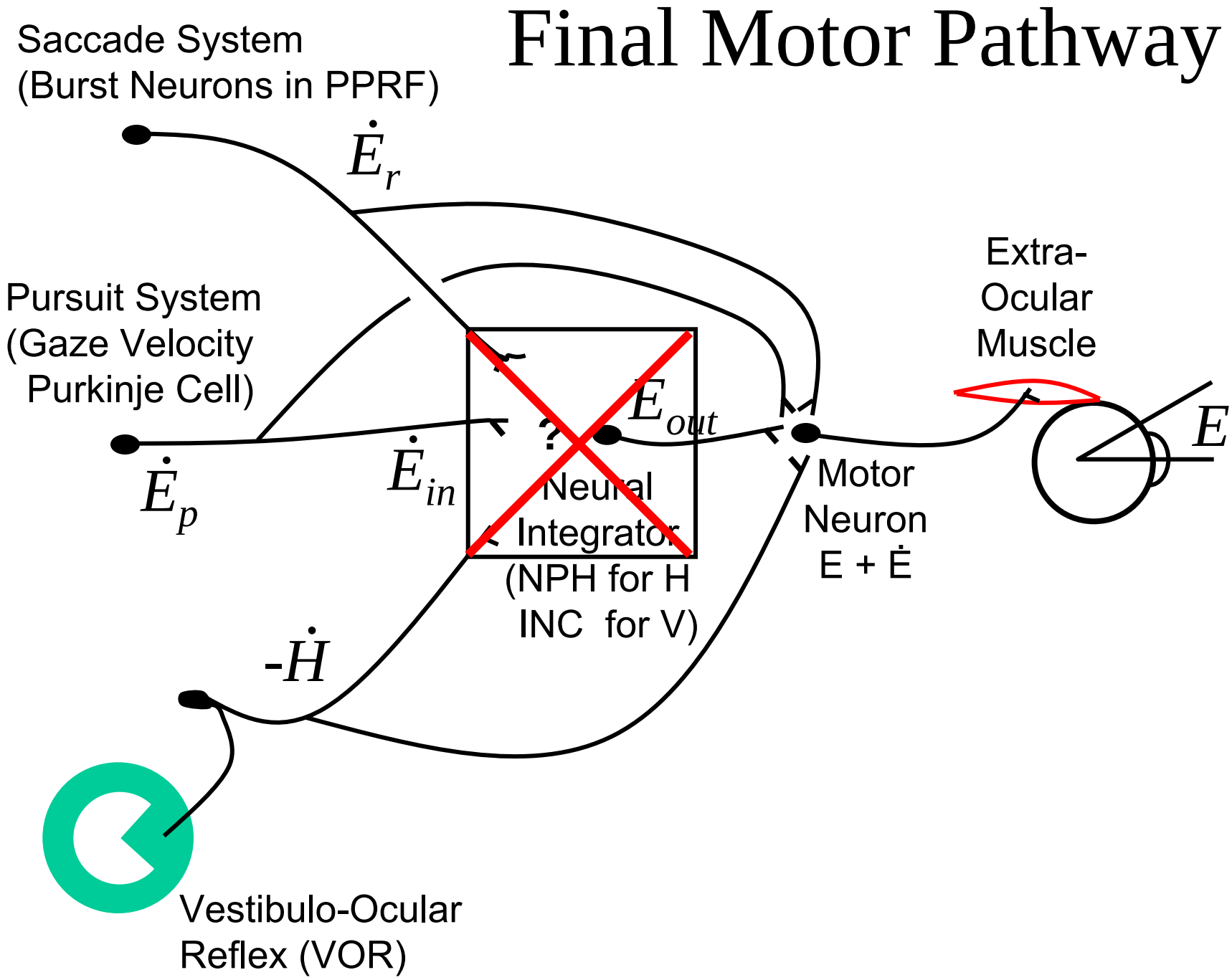


From Fuchs & Leschei 1970

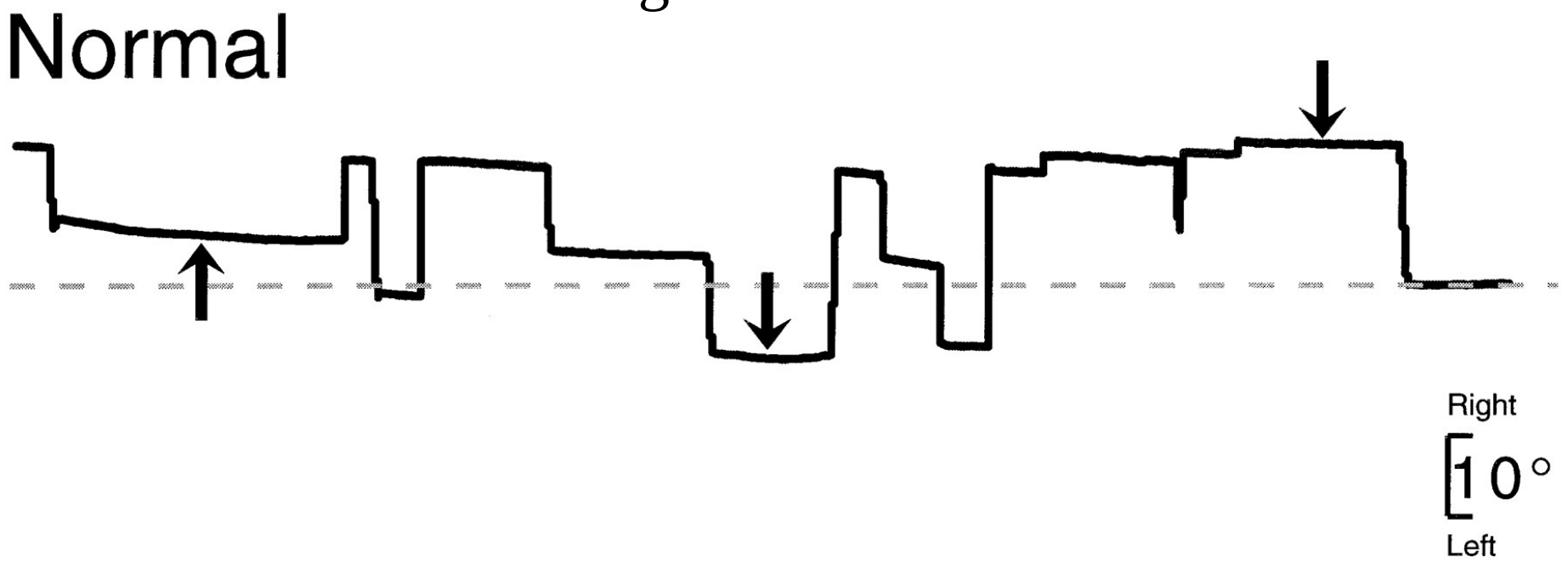


From Robinson & Keller 1972

Final Motor Pathway

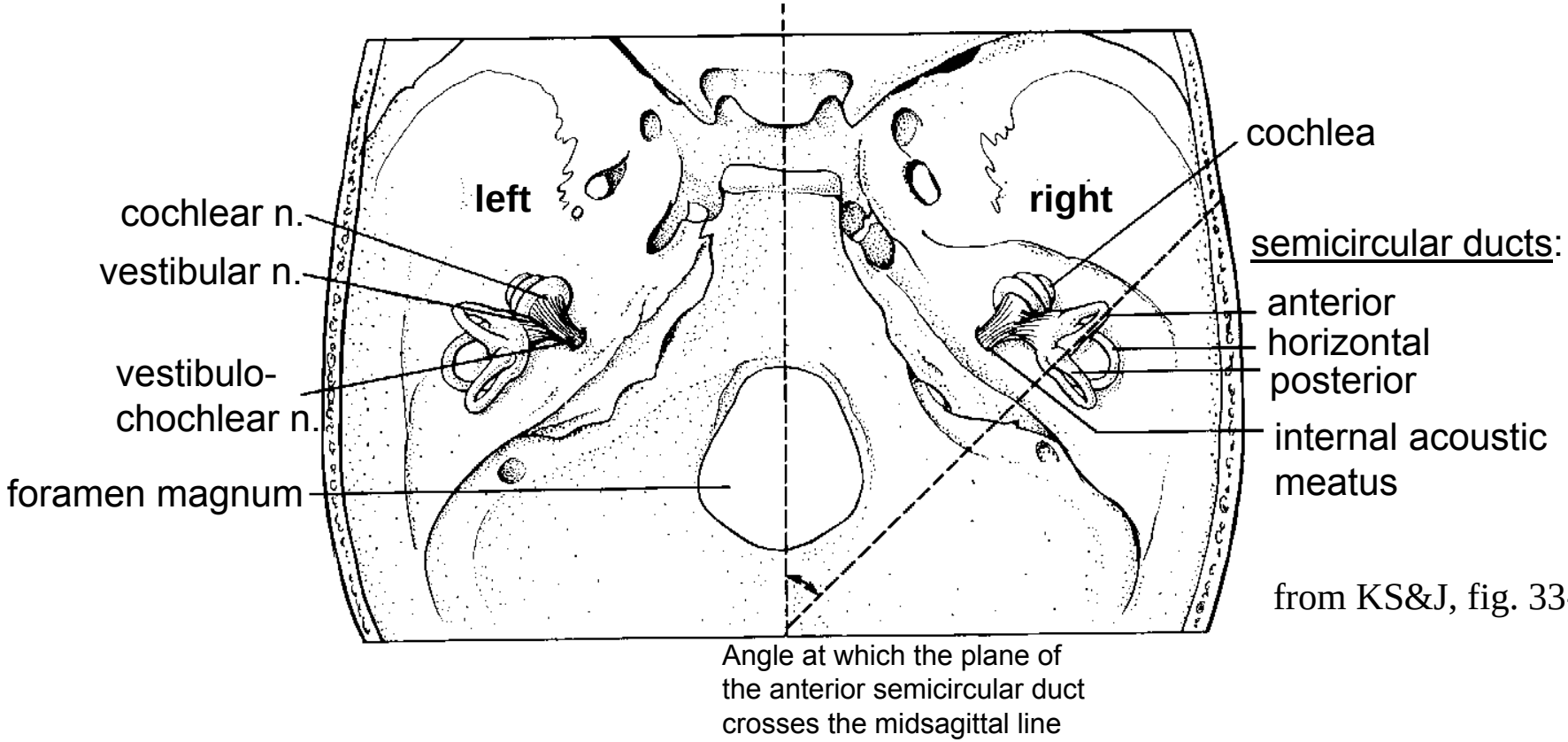


Integrator Lesion: Effects



Cannon & Robinson 1987

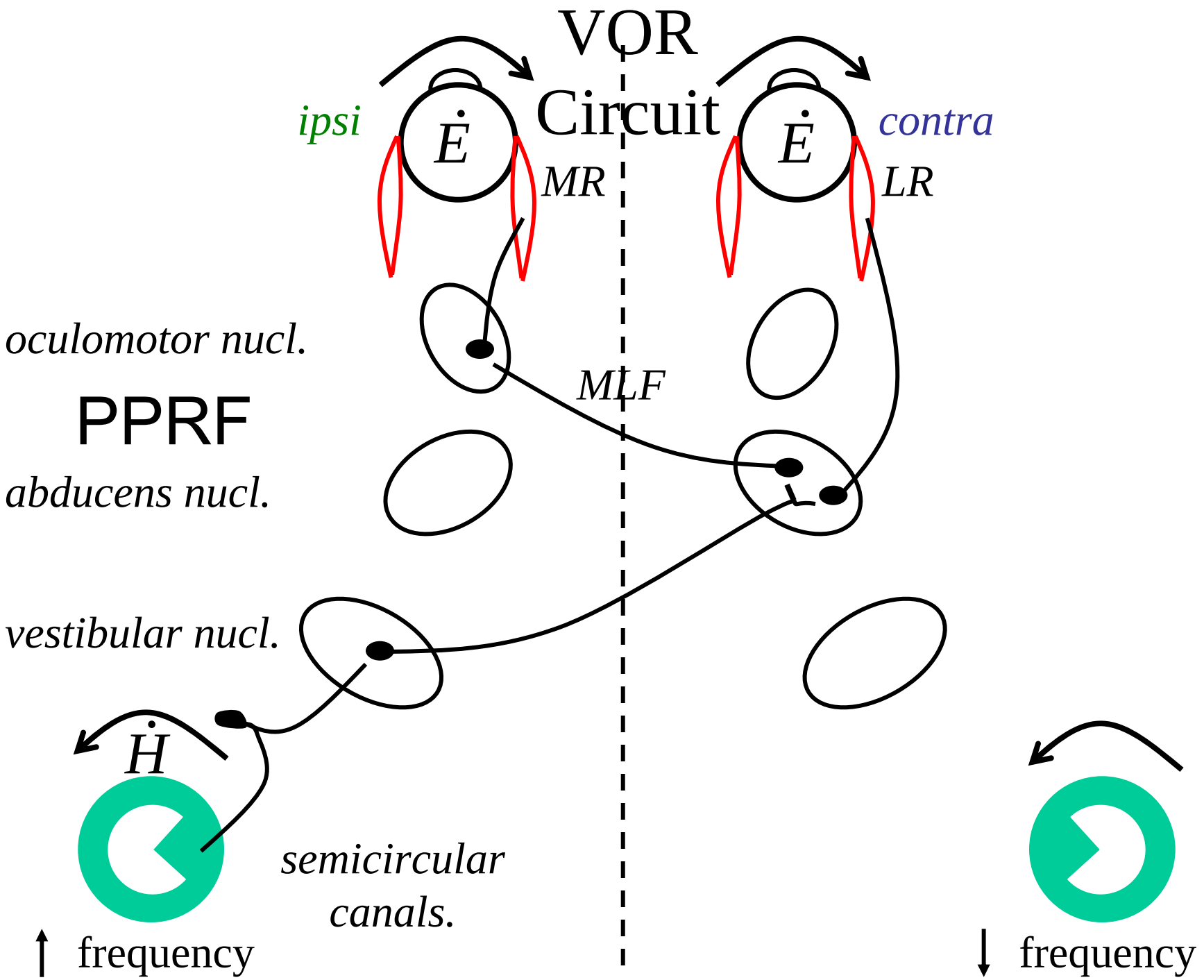
Planes of the Semi-Circular Canals



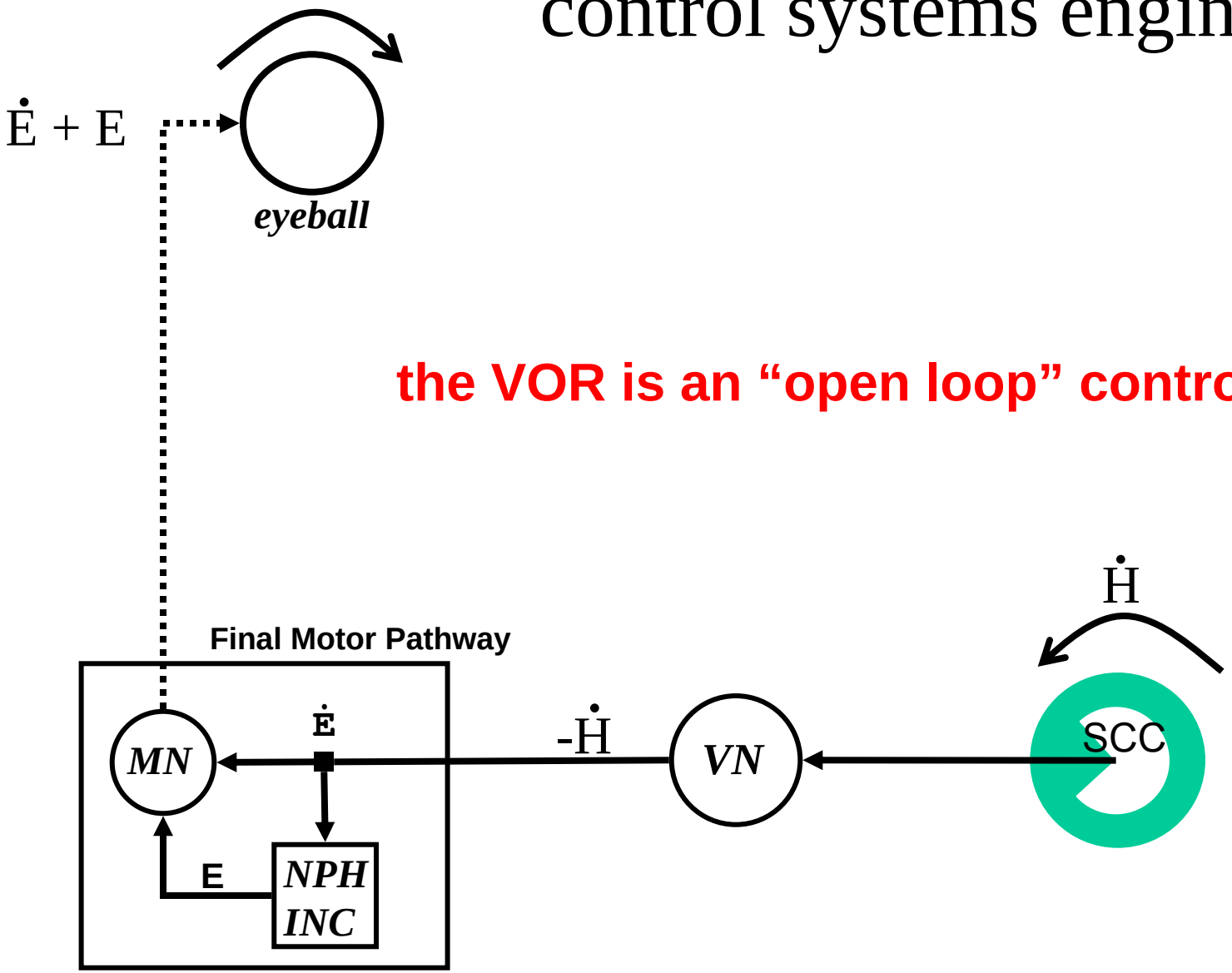
from KS&J, fig. 33-9

Excitatory Motions for the SCC's on the **left**.

from Carpenter, fig. 2.7

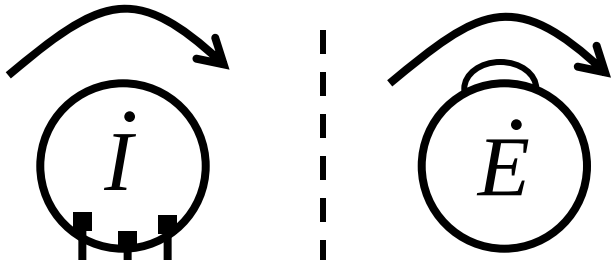

VOR
Circuit
ipsi
contra
$\dot{E}$
$\dot{E}$
MR
LR
oculomotor nucl.
MLF
PPRF
abducens nucl.
vestibular nucl.
$\dot{H}$
semicircular
canals.
frequency
frequency

VOR through the eyes of a control systems engineer

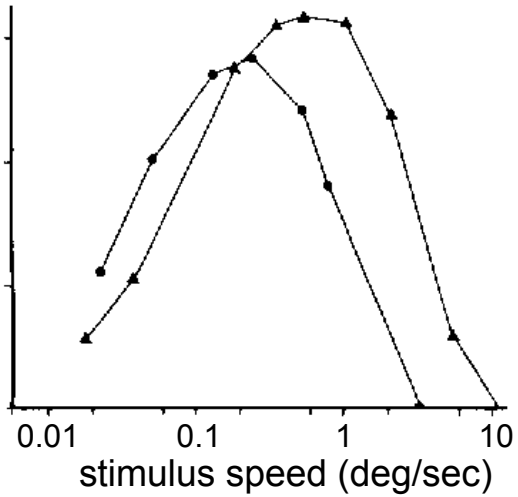


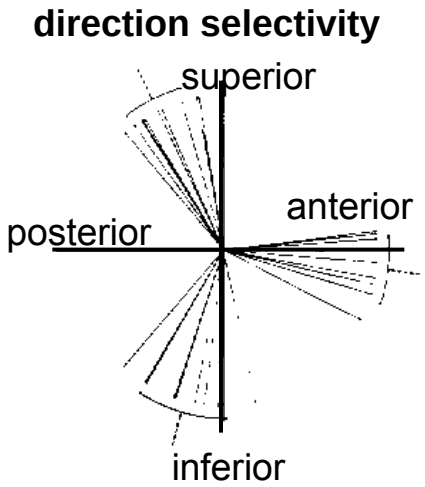
the VOR is an “open loop” controller

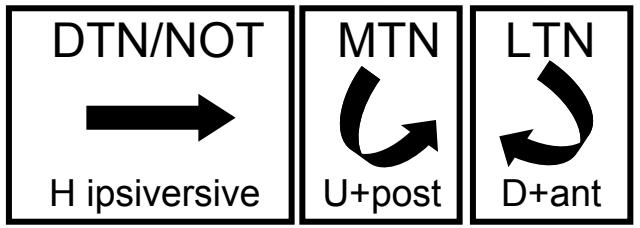
Rabbit OK (Afferents)



Accessory Optic System

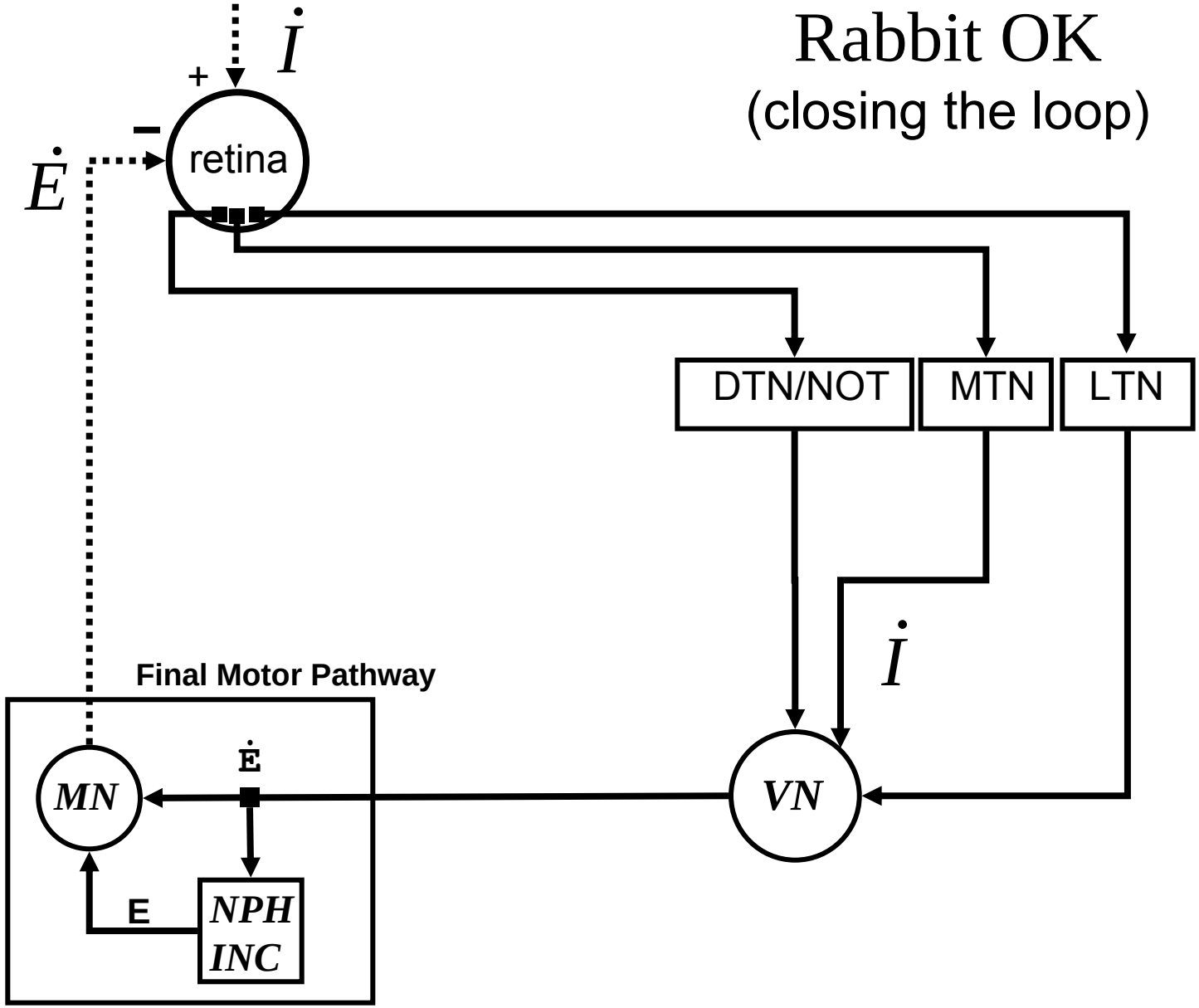




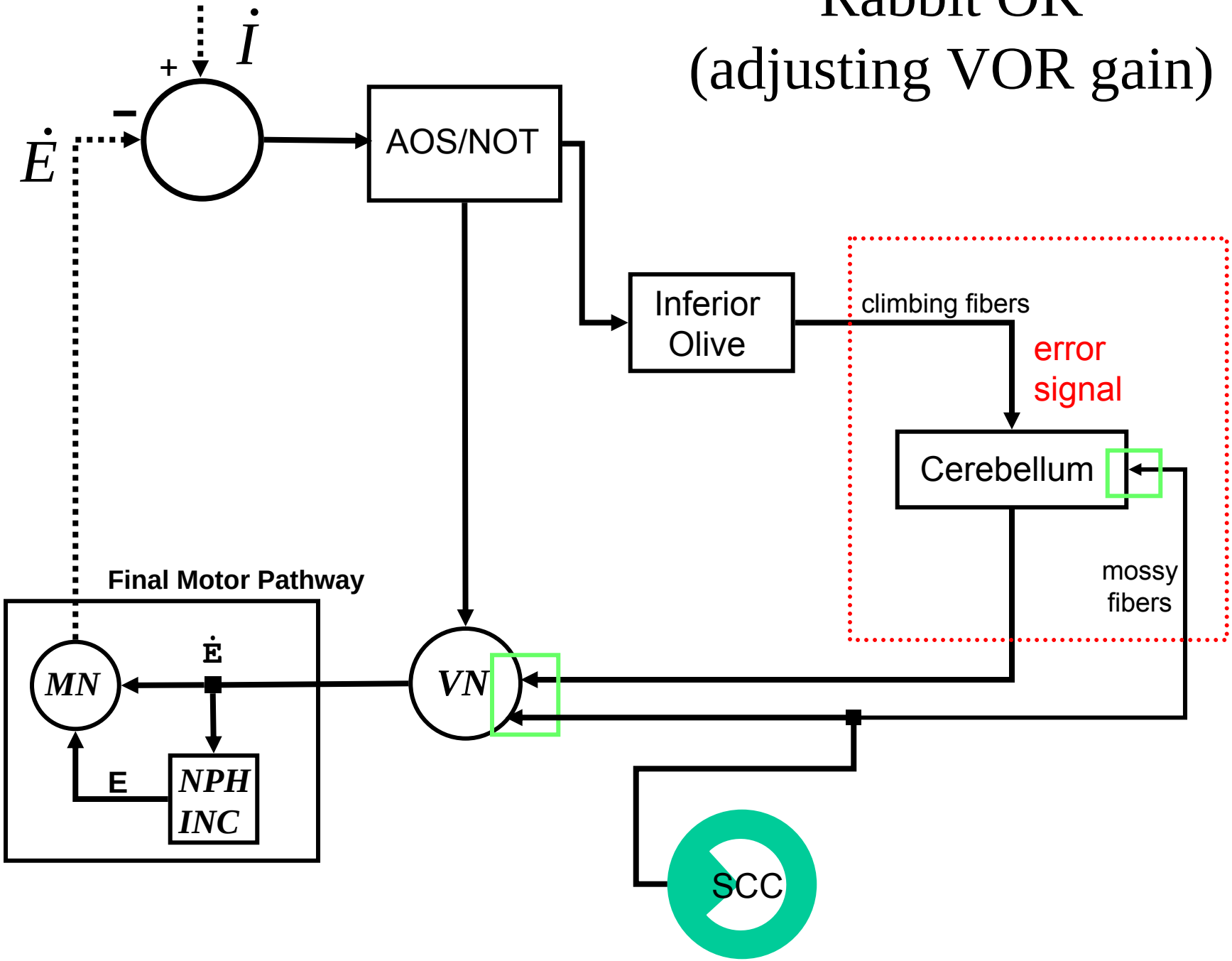


canal: *horizontal* *anterior* *posterior*

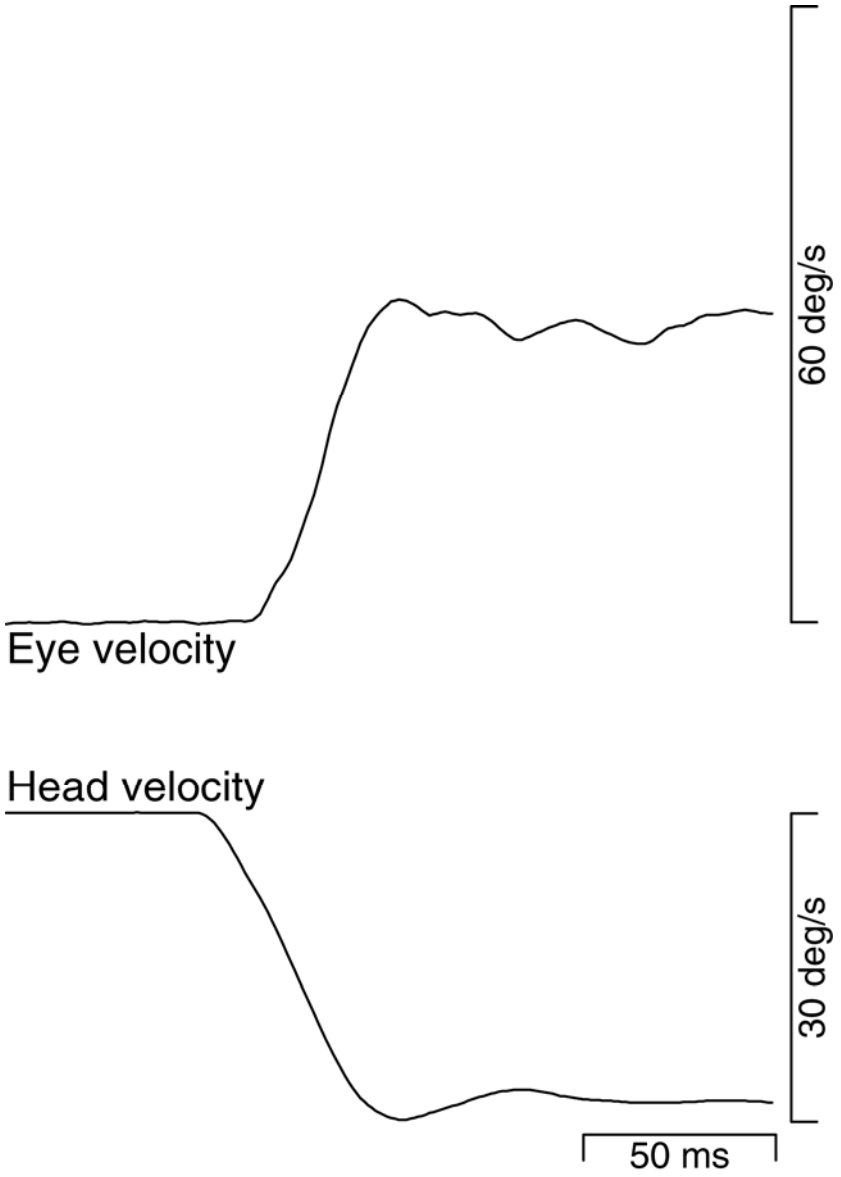
data from Simpson 1984


Rabbit OK
(closing the loop)
$\dot{I}$
+
−
$\dot{E}$
retina
DTN/NOT
MTN
LTN
$\dot{I}$
Final Motor Pathway
$\dot{E}$
MN
VN
E
NPH
INC

Rabbit OK
(adjusting VOR gain)



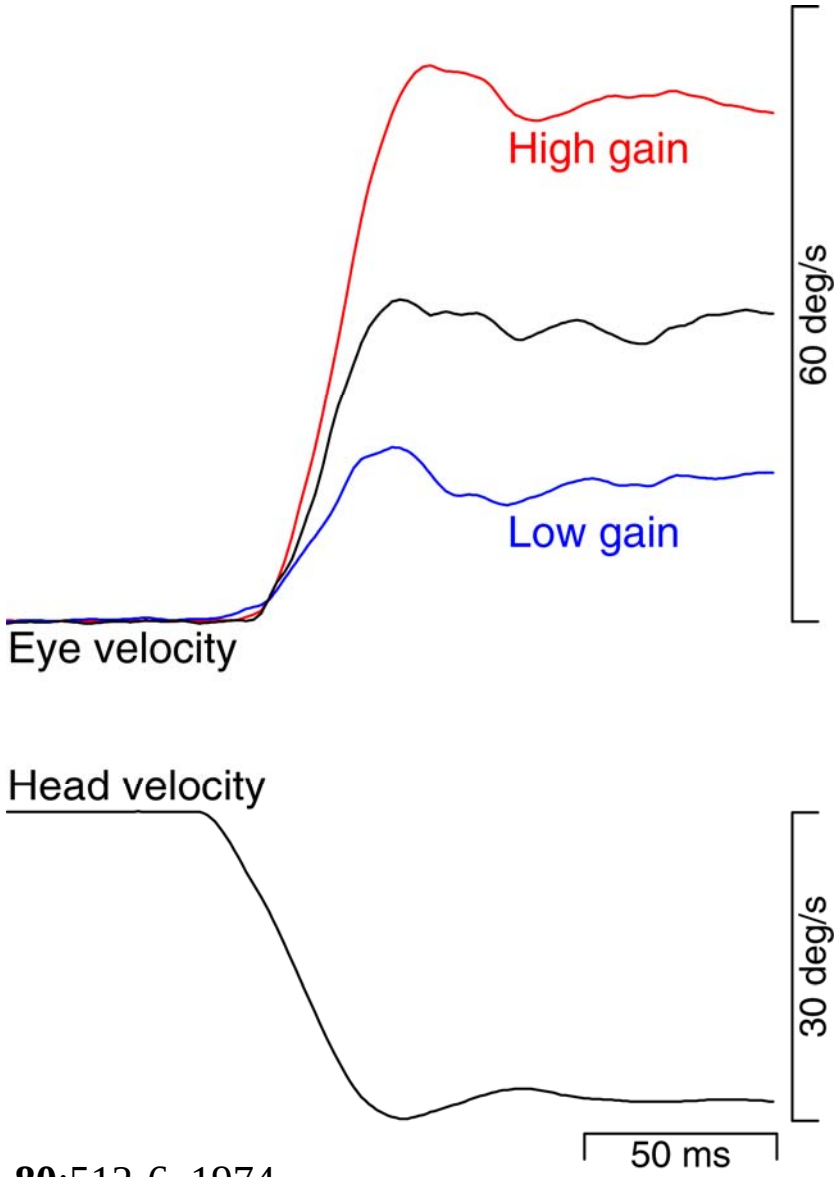
The normal VOR



Spectacles to change VOR gain

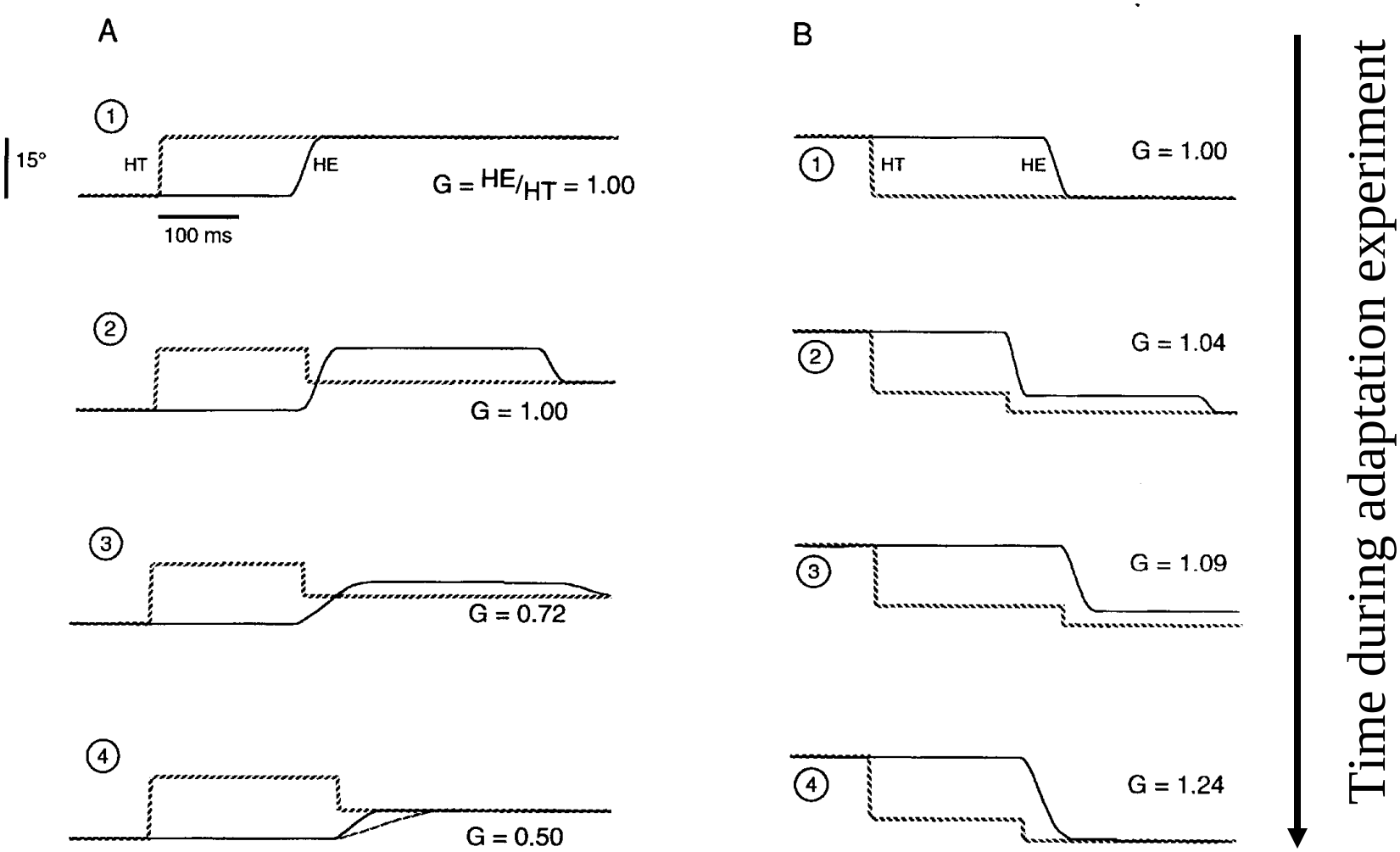
Steve Lisberger

VOR before and after learning



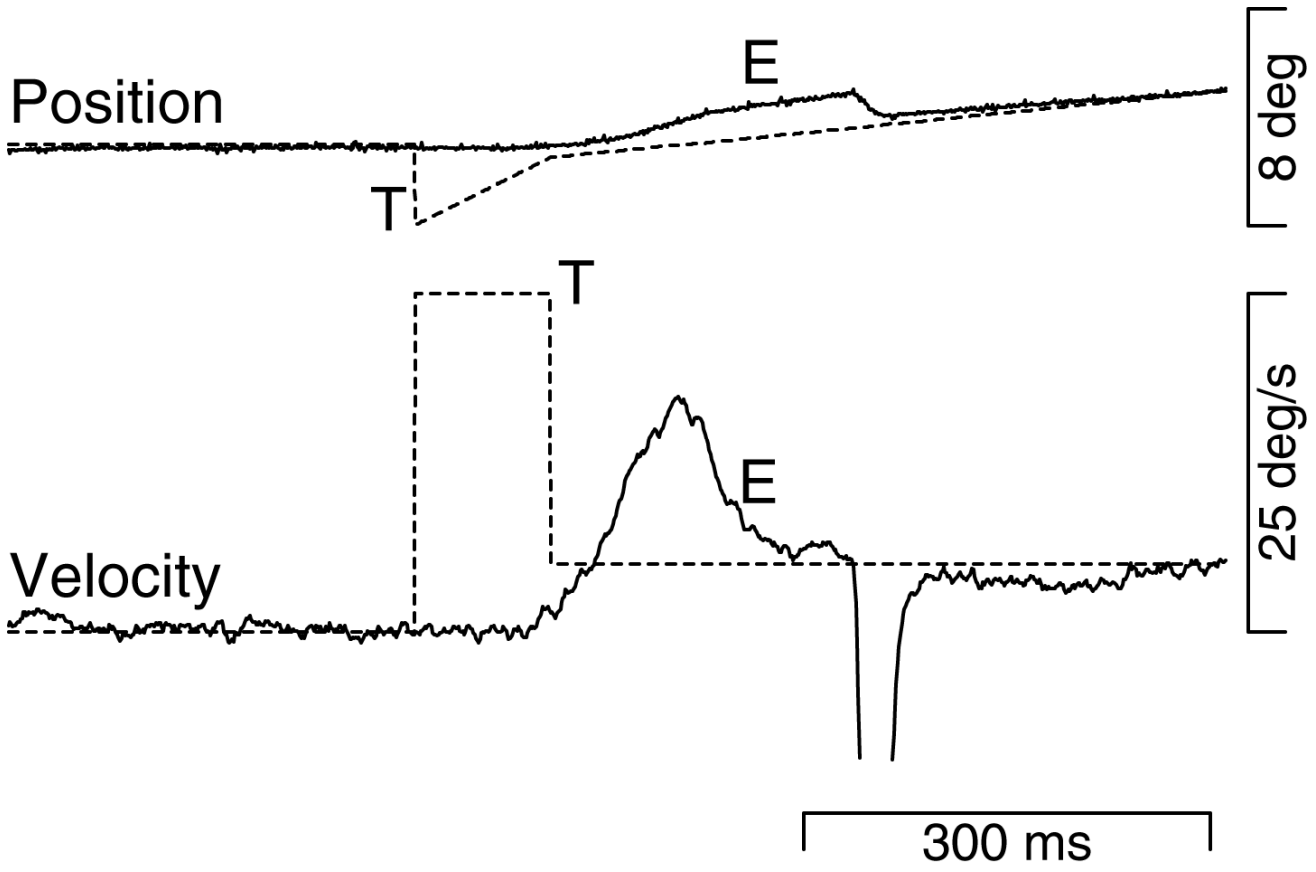
Miles & Fuller, *Brain Res.* **80**:512-6, 1974

Learning in the feedforward controller for saccades



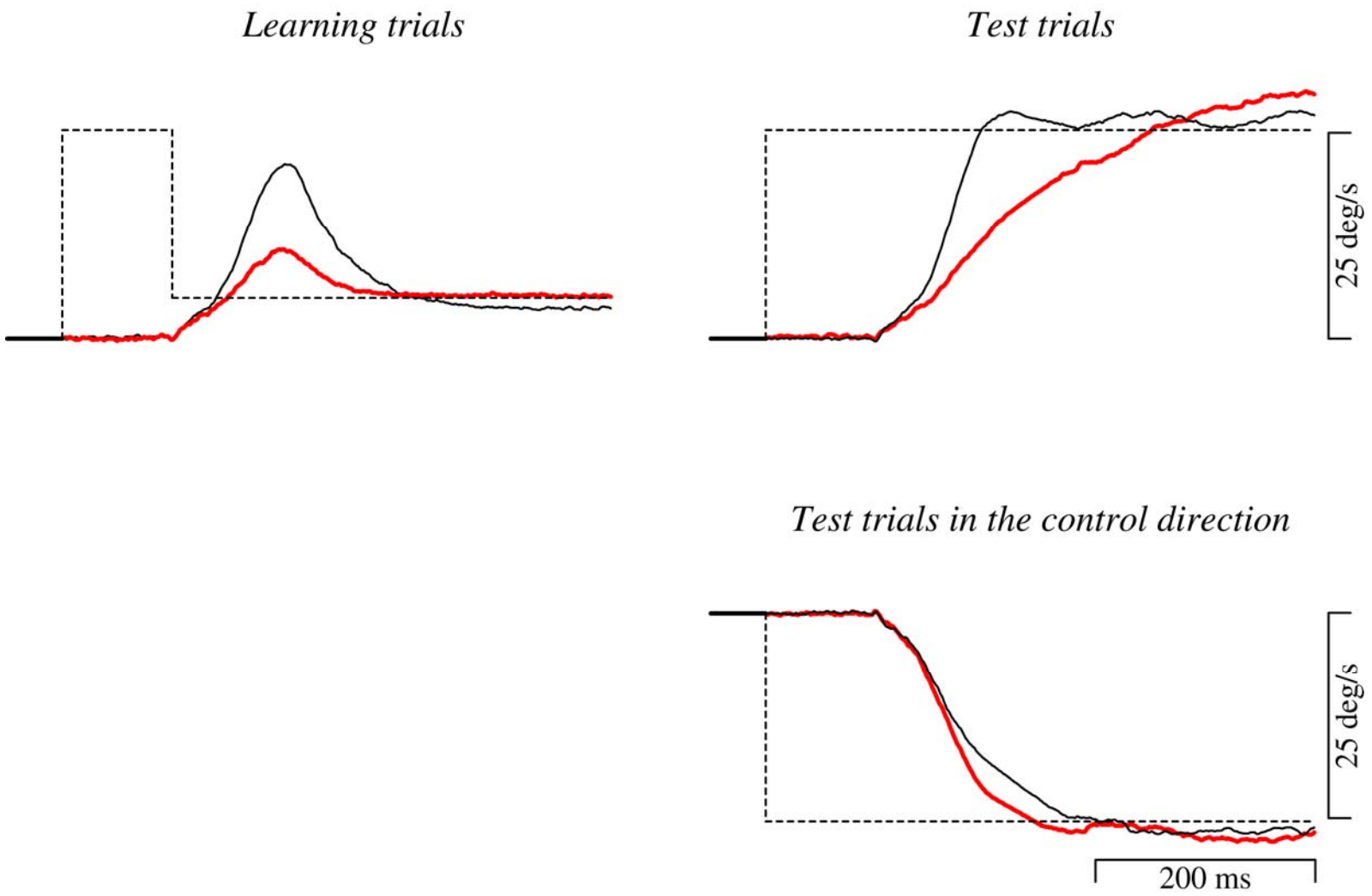
Straube et al. *J. Neurophysiol.* **77**: 874-895, 1997.

Double steps of target speed for studying learning in the feedforward controller for pursuit



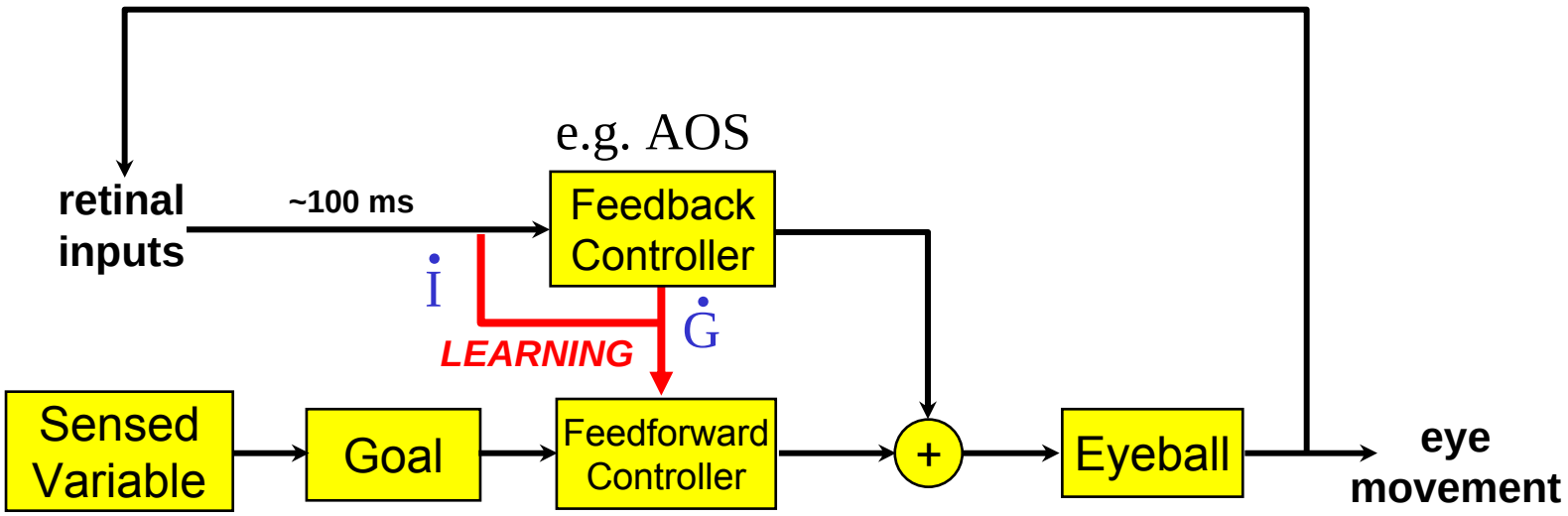
Kahlon & Lisberger, *J. Neurosci.* **16**: 7270-7283, 1996.

Sequence of a pursuit learning experiment

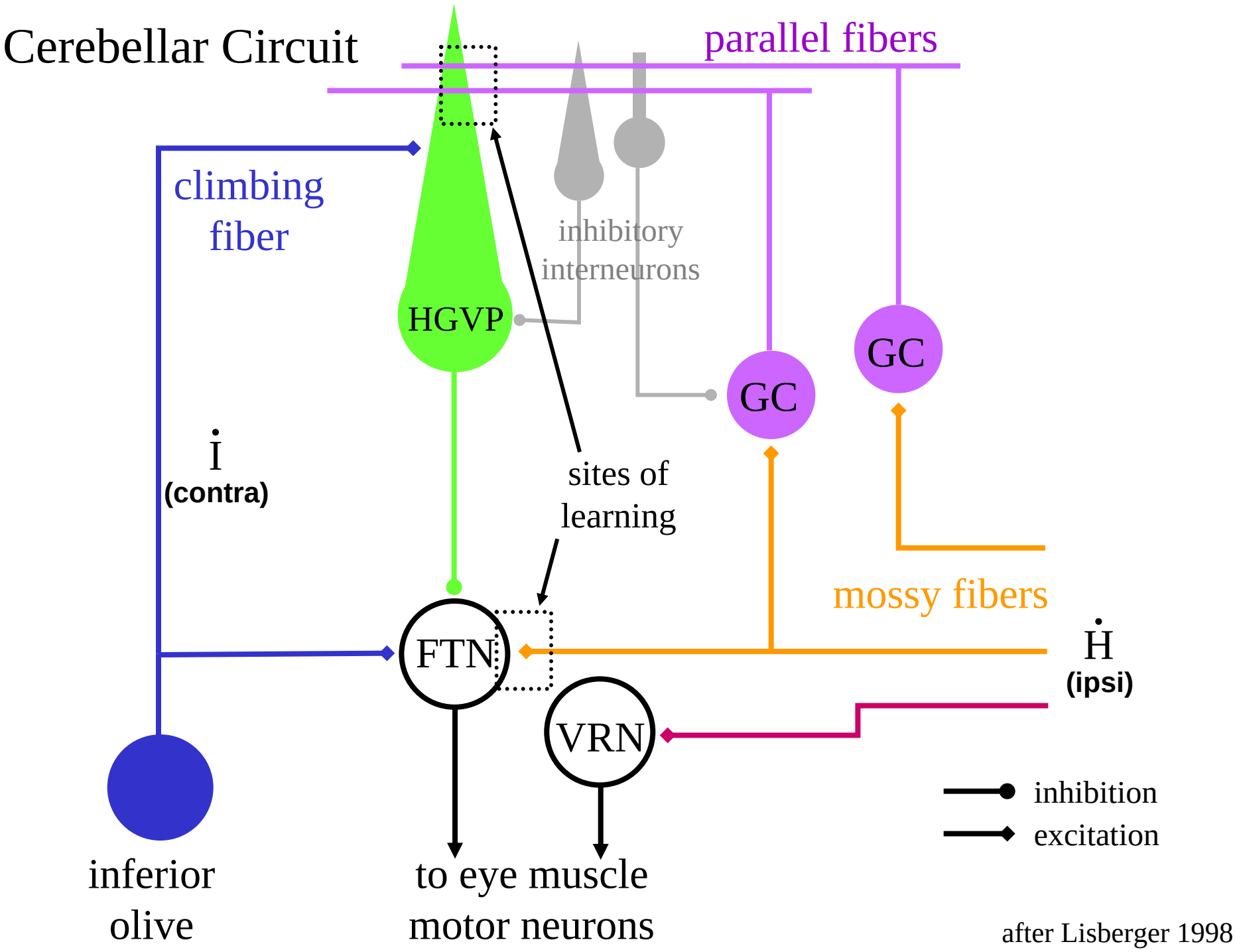


Kahlon & Lisberger, *J. Neurosci.* **16**: 7270-7283, 1996.

General Scheme for Motor Learning



VOR	$\dot{H}$	$-\dot{E}$	VN	
Saccades	ΔI	ΔI	SC, PPRF	FMP
Pursuit	$\dot{I}$	$\dot{I}$	MT, DLPN	


Cerebellar Circuit
parallel fibers
climbing fiber
inhibitory interneurons
HGVP
GC
GC
İ
(contra)
sites of learning
mossy fibers
Ḣ
(ipsi)
FTN
VRN
inhibition
excitation
inferior olive
to eye muscle motor neurons
after Lisberger 1998

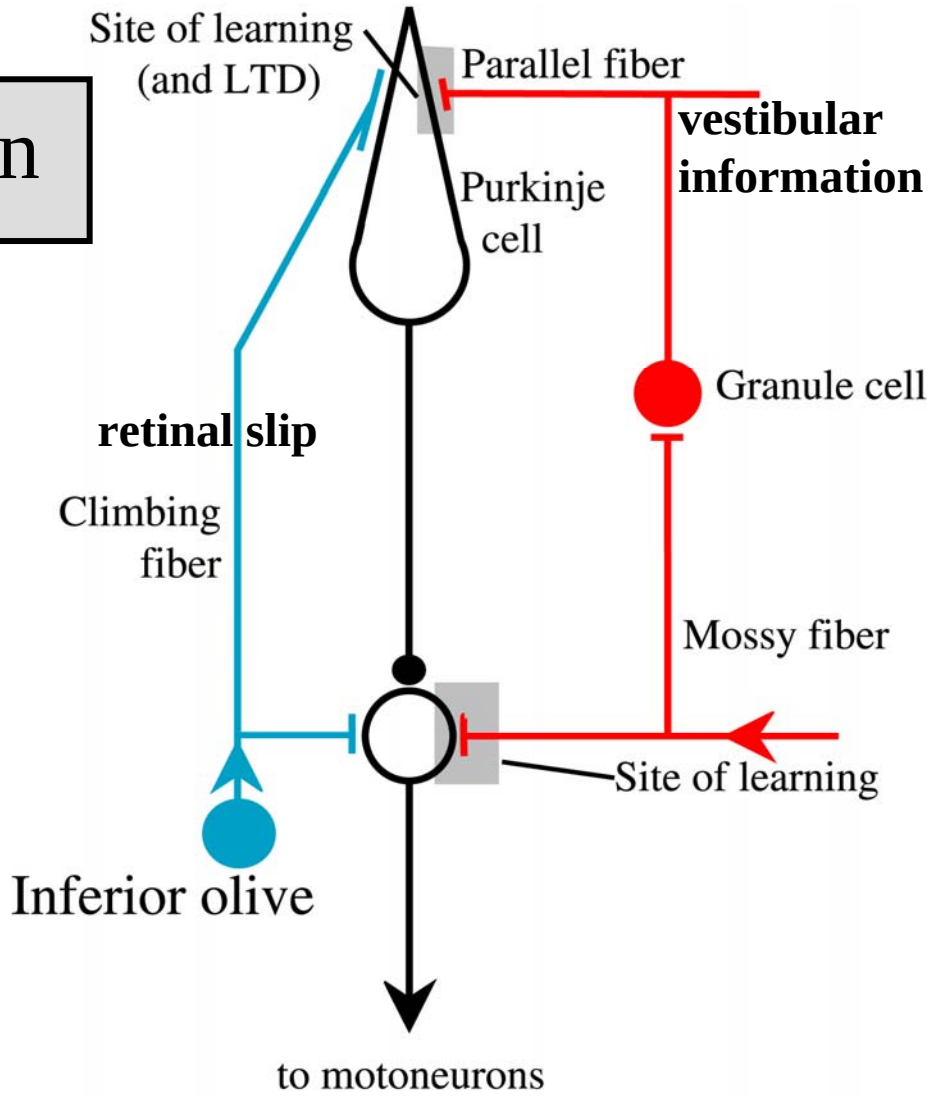
The learning rule:
"Marr-Albus-Ito" or "Floccular" Hypothesis

Version 1: operational

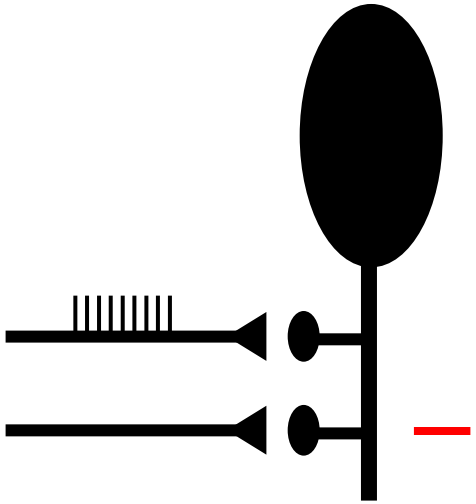
ipsi $\dot{H}$ + contra $\dot{I}$ ⟶ ↑gain

Version 2: synaptic plasticity

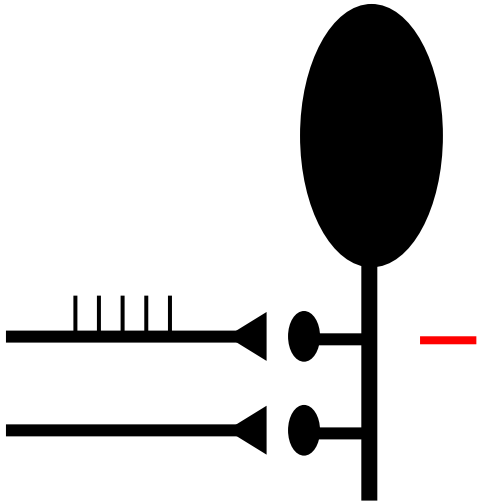
↑CF + ↑PF ⟶ LTD



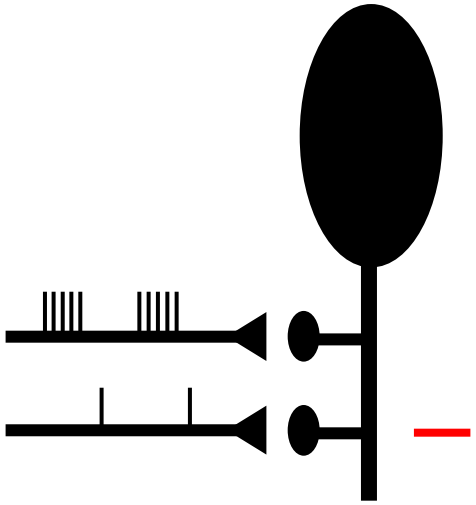
Long Term Depression



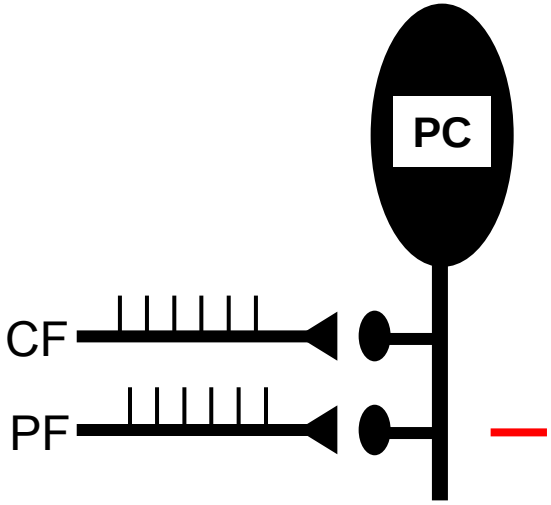
heterosynaptic LTD



homosynaptic LTD



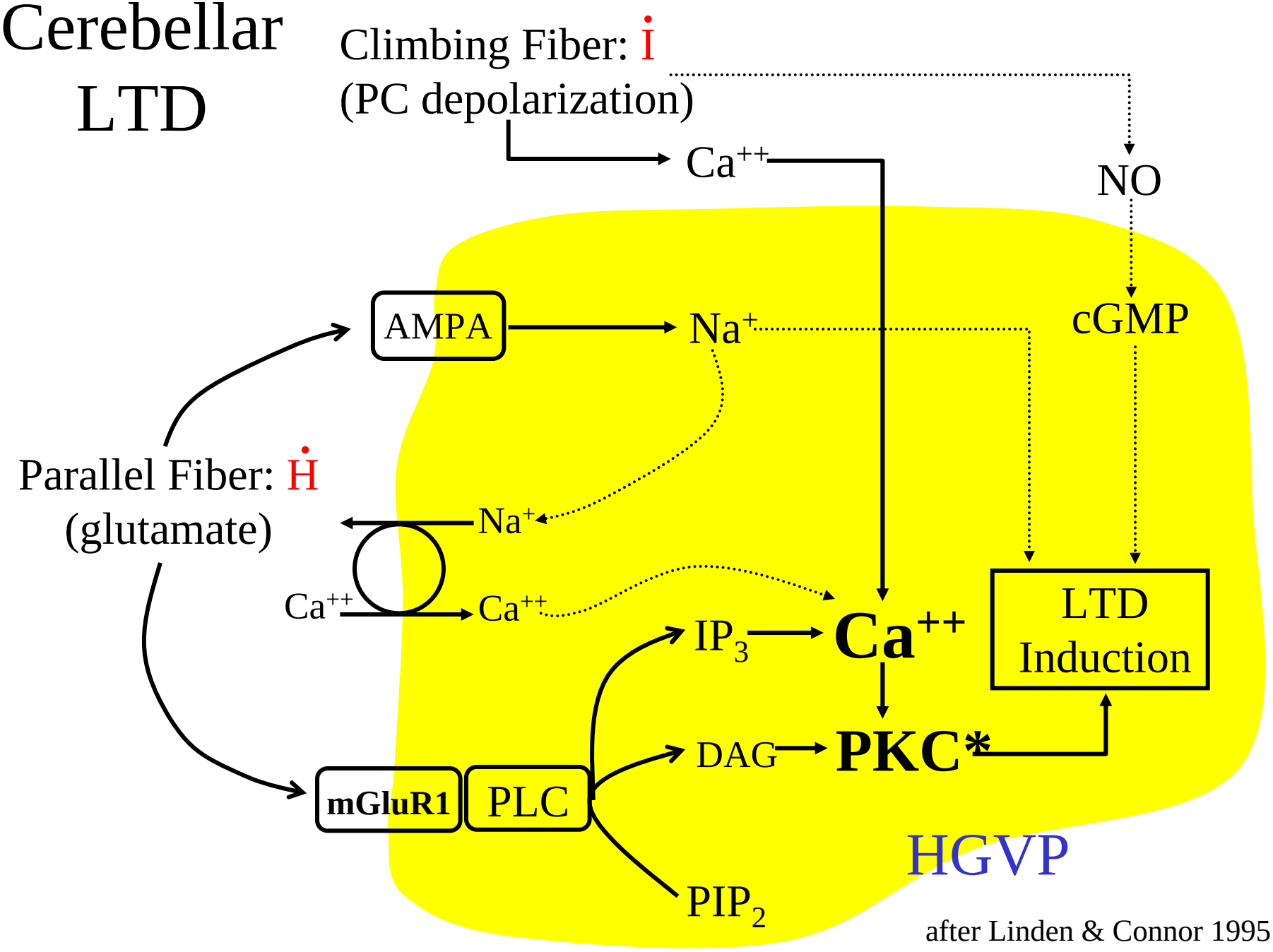
associative LTD



cerebellar LTD

after Linden & Connor 1995

Cerebellar LTD



after Linden & Connor 1995