Architecture and models of the brain eye saccadic movement circuitry

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Plan

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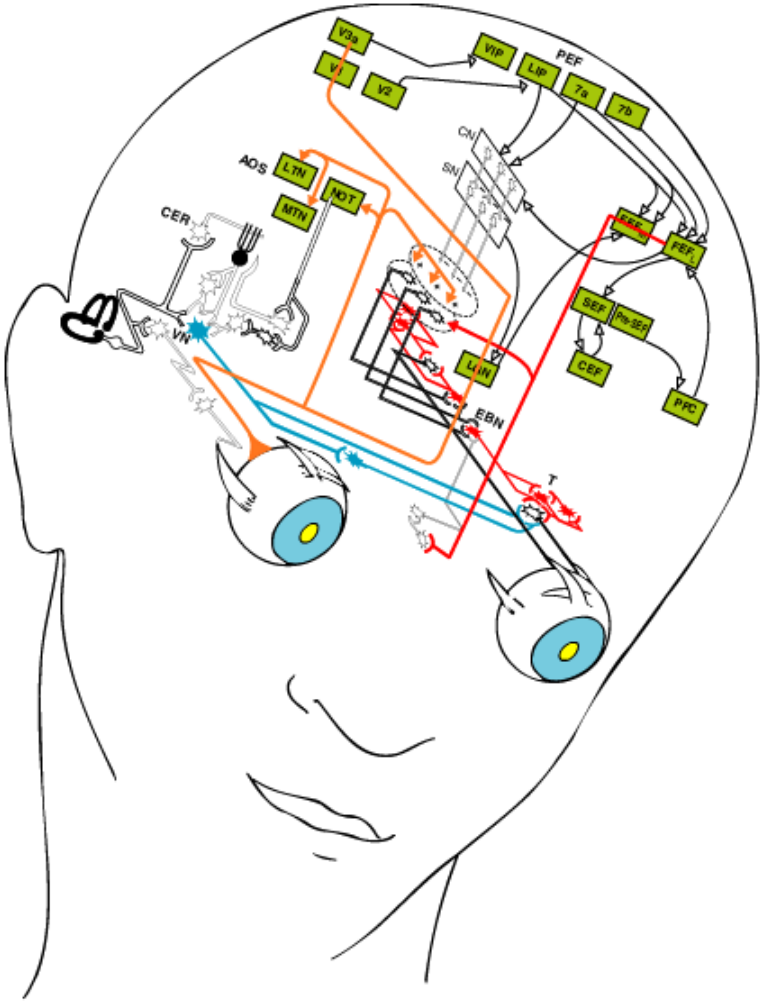
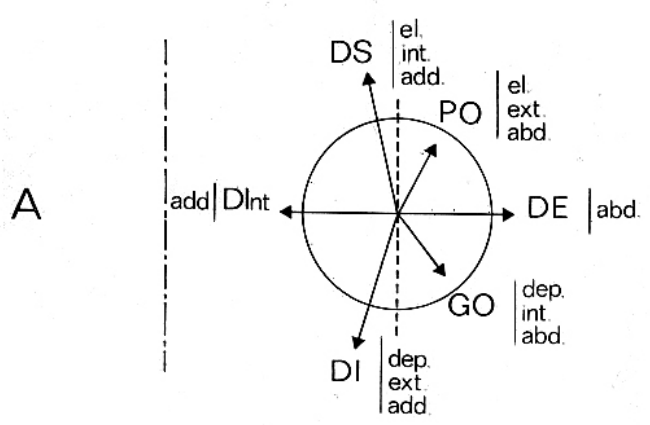
Oculomotor Movements

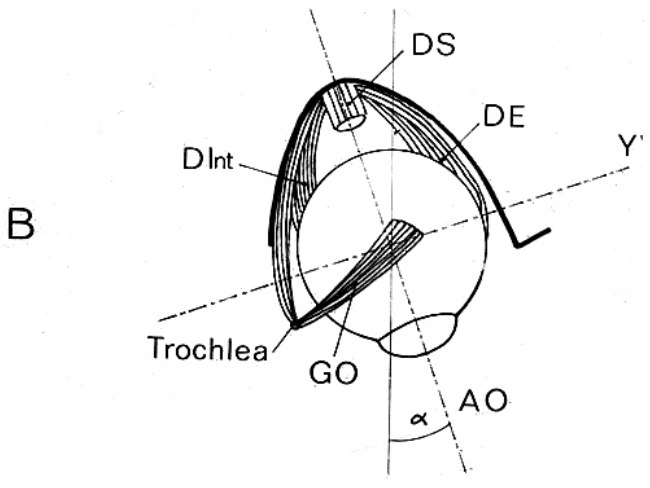


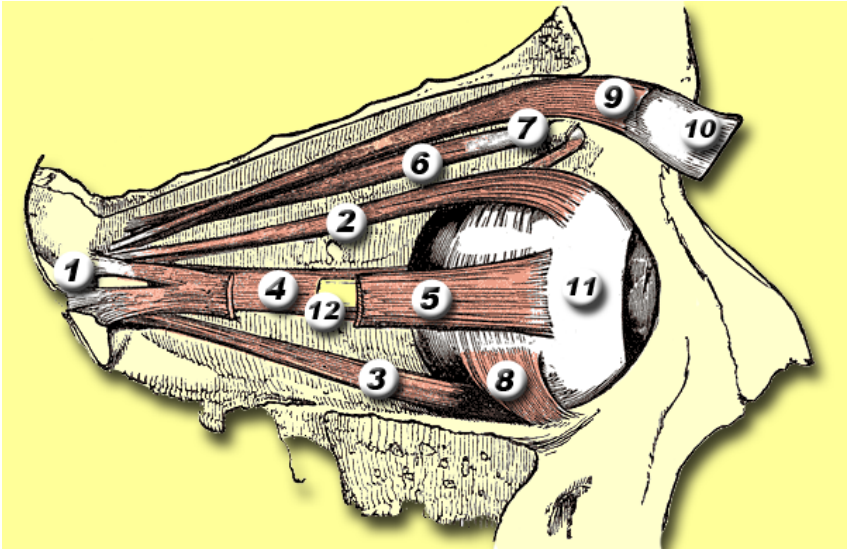
Numerous circuits, at all the levels of the CNS.
Repertoire of movements / repertoire of (relatively) distinct systems :

- Stabilization :
  - Vestibulo-ocular reflex (VOR),
  - Opto-kinetic reflex/nystagmus (OKN).
- Fovea-specific :
  - Saccades,
  - Smooth pursuit.
- Vergence.

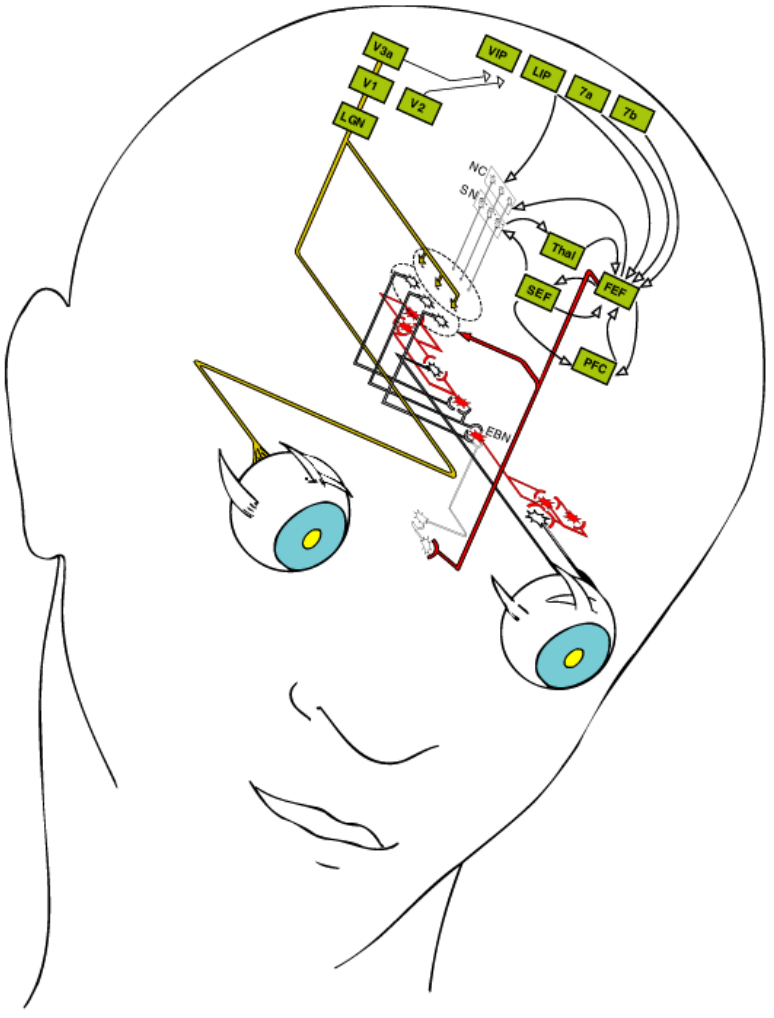
Extra-ocular muscles organization

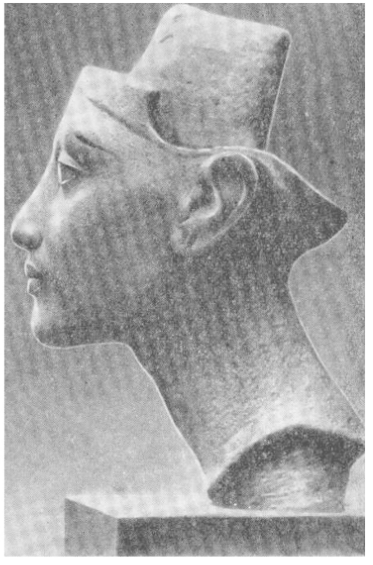






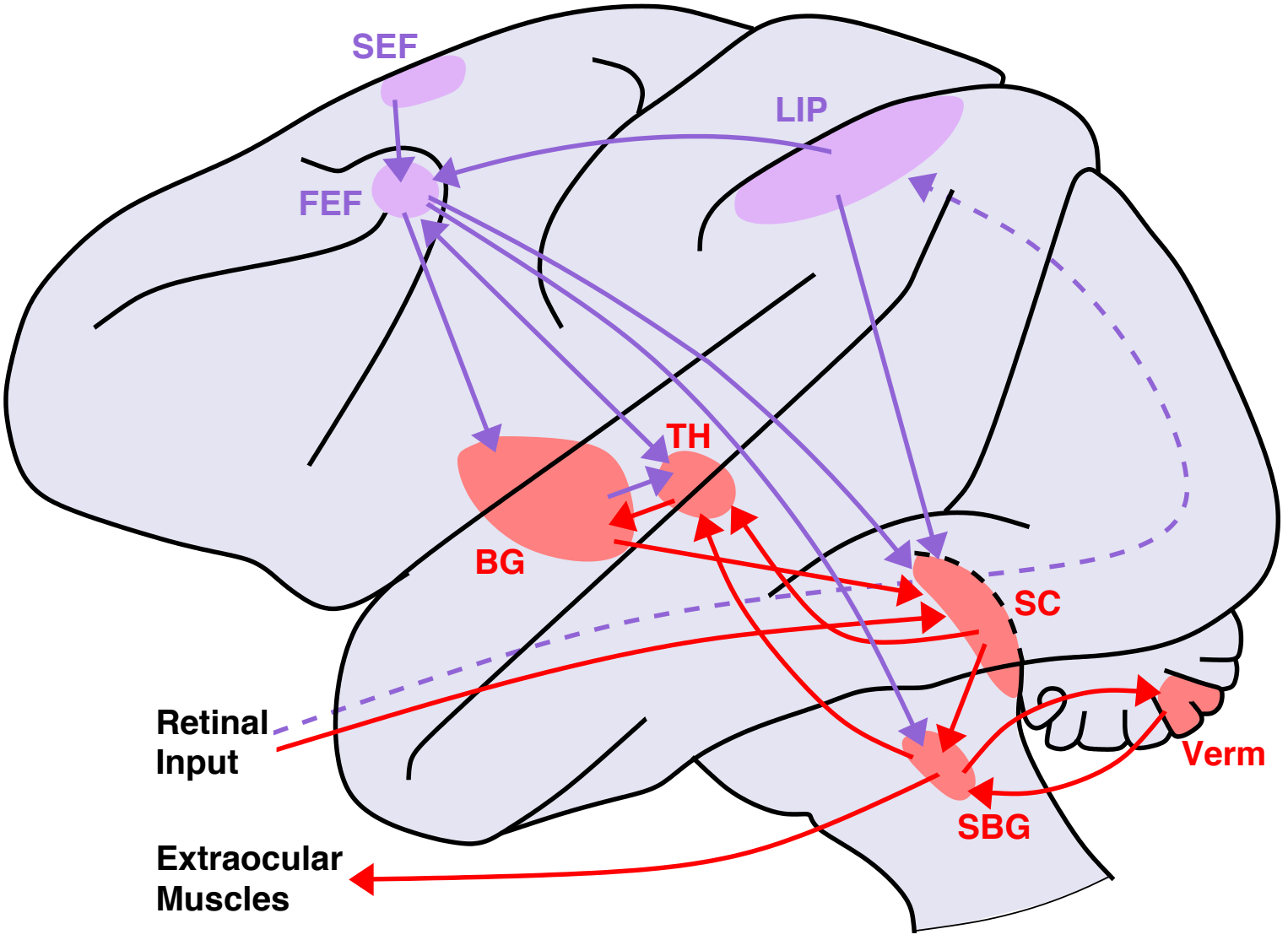
Saccades



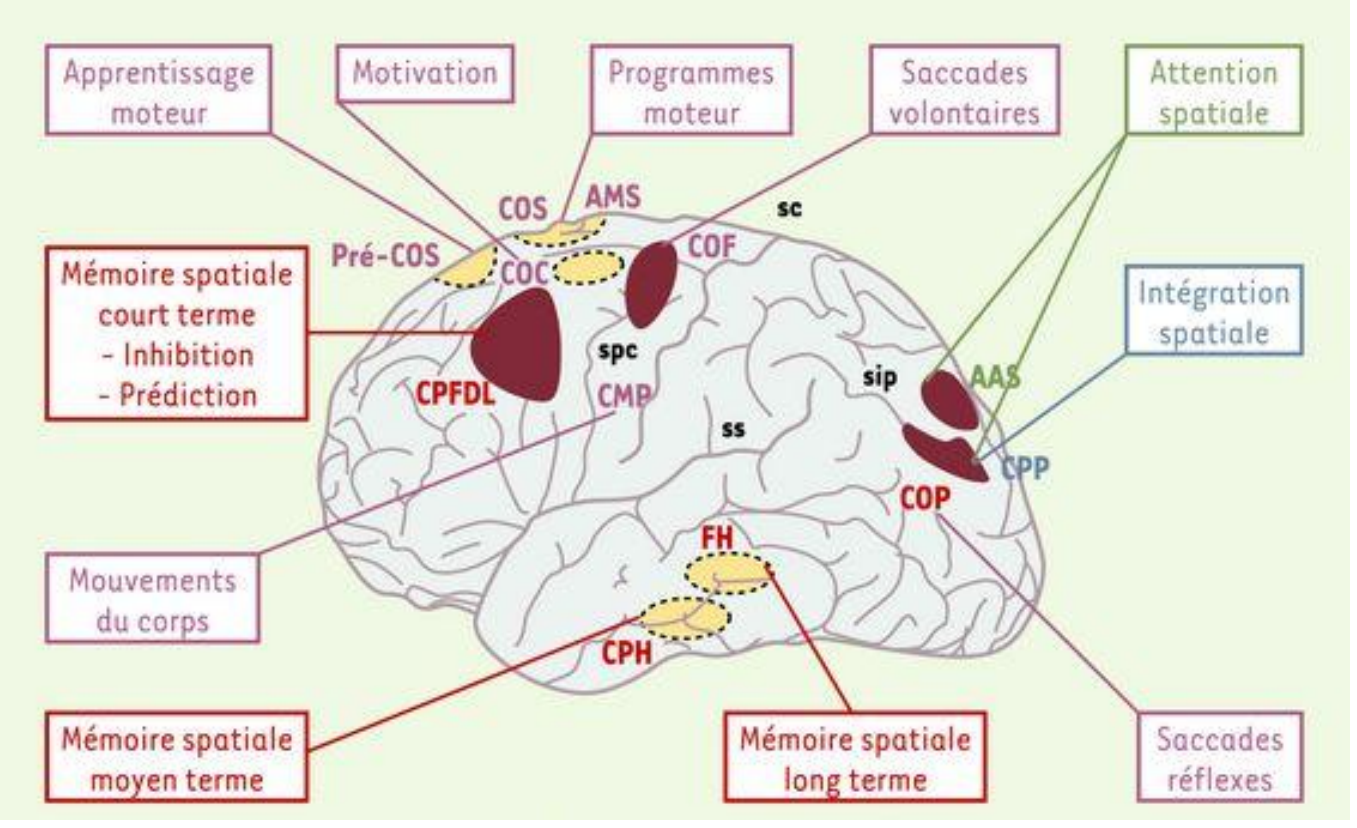


(Yarbus, 1967)

Neural Substrate



Neural Substrate



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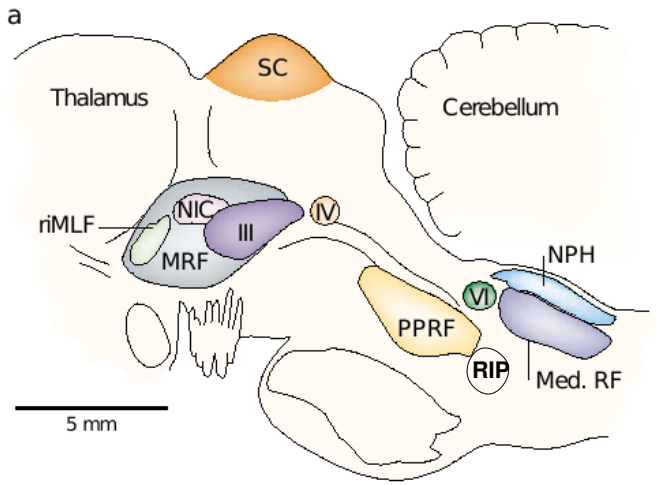
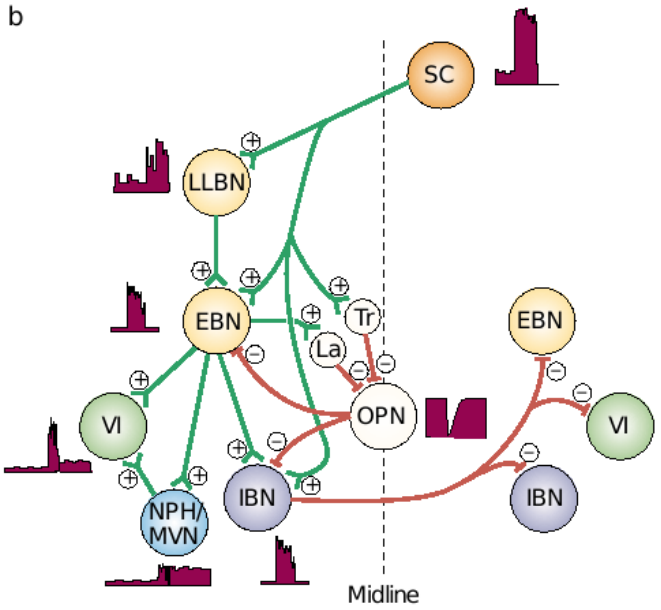
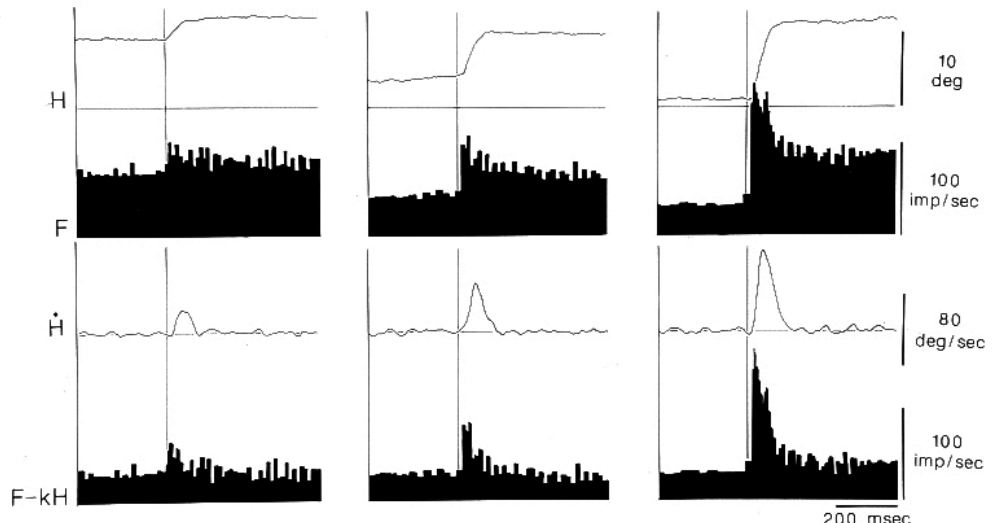




- MN : oculomotor (III), trochlear (IV) and abducens (VI) nuclei
- EBN , IBN :
  - H : paramedian pontine reticular formation (PPRF), medular reticular formation (Med. RF)
  - V : Rostral interstitial nucleus of medial longitudinal fasciculus (riMLF), nucleus of the posterior commissure (nPC)
- TN :
  - H : nucleus prepositus hypoglossi (NPH), medial vestibular nucleus (MVN),
  - V : nucleus interstitial of Cajal (NIC)
- OPN : nucleus raphe interpositus (nRIP)



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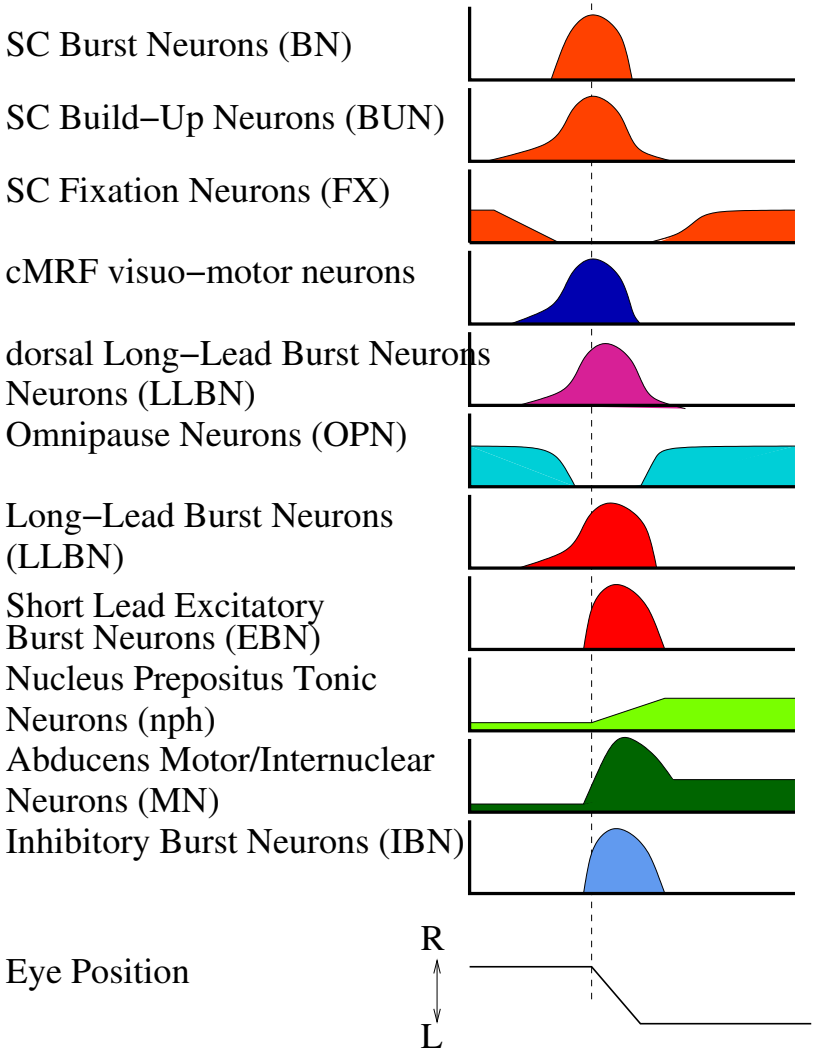
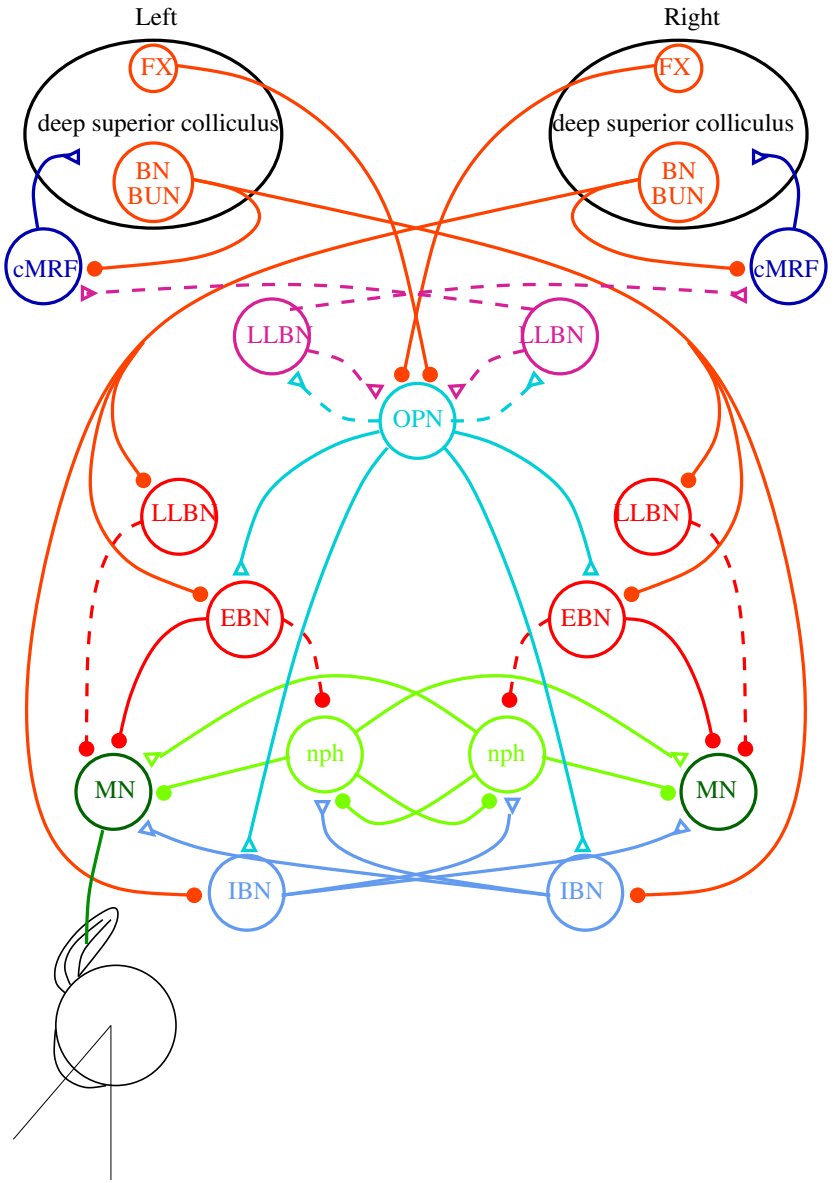
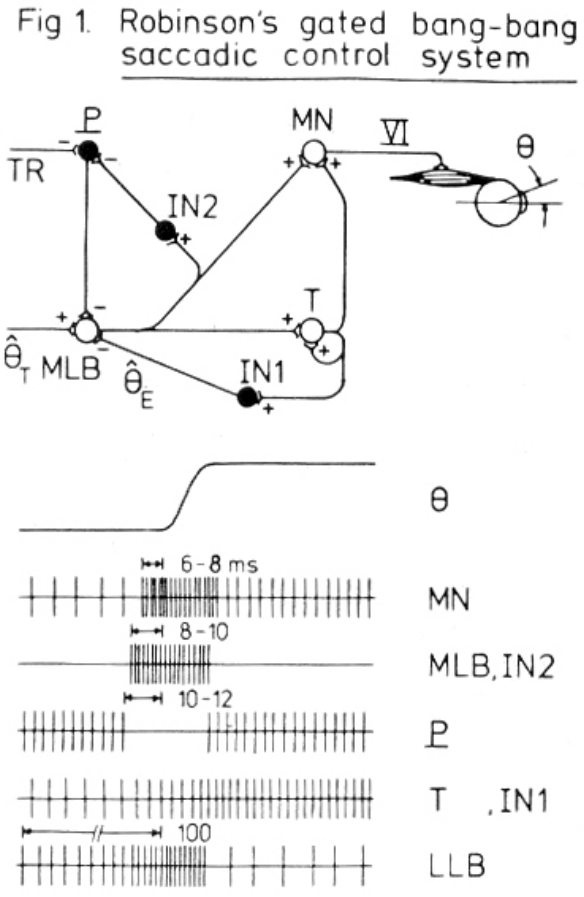
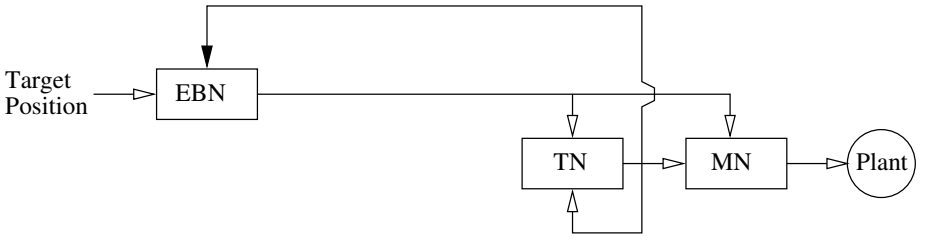




(Robinson, 1975)

Feedback control of the saccade (as pertubed saccades have correct metrics).



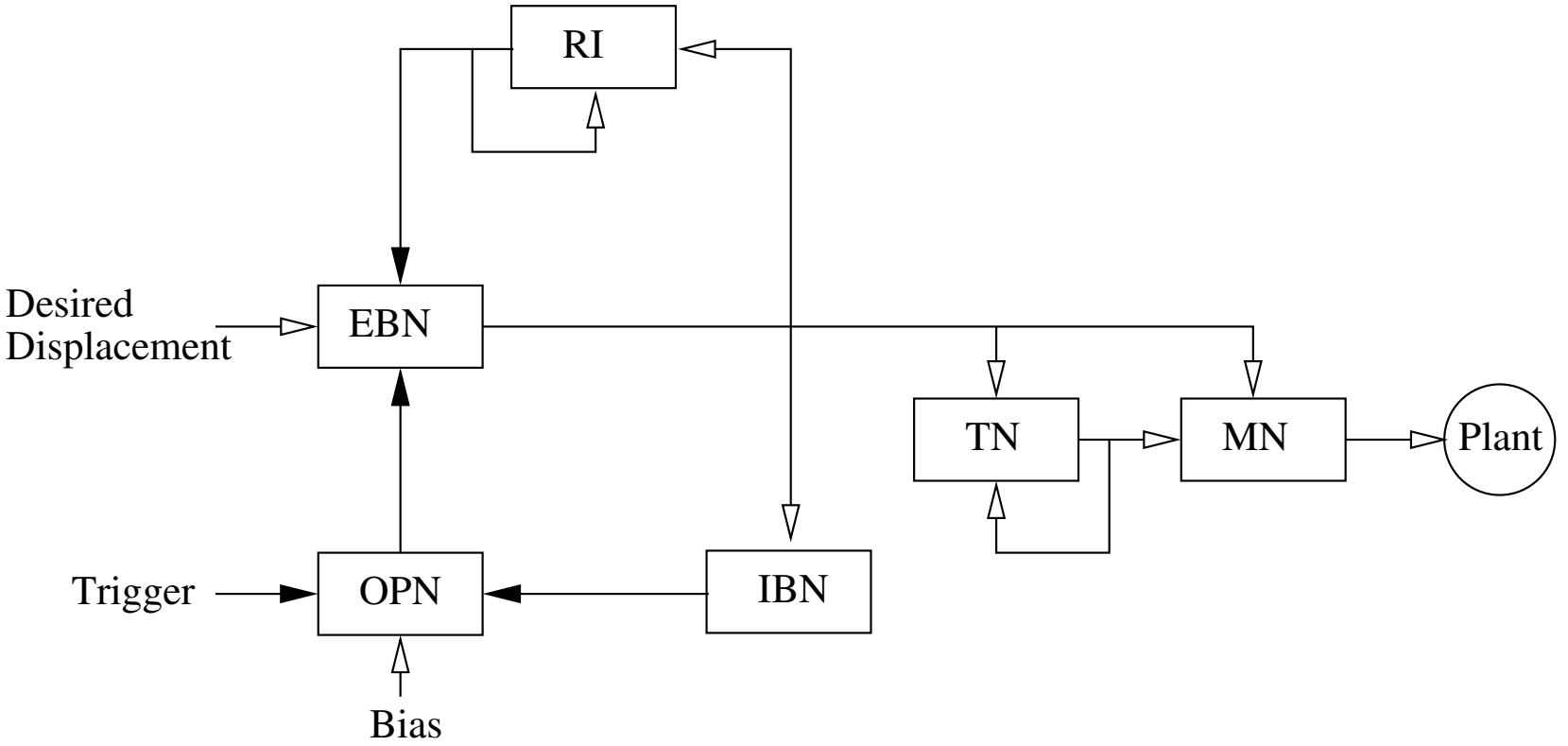


Problems :

- Cranio-centric coordinates,
- Oblique saccades.

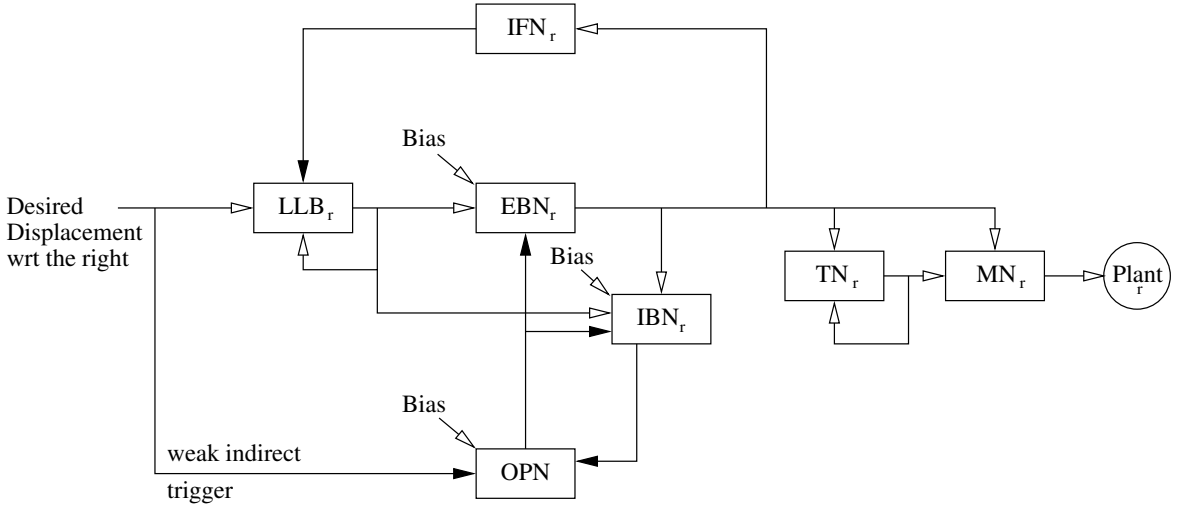
(Jürgens et al., 1981)

Retino-centric coordinates : resettable integrator



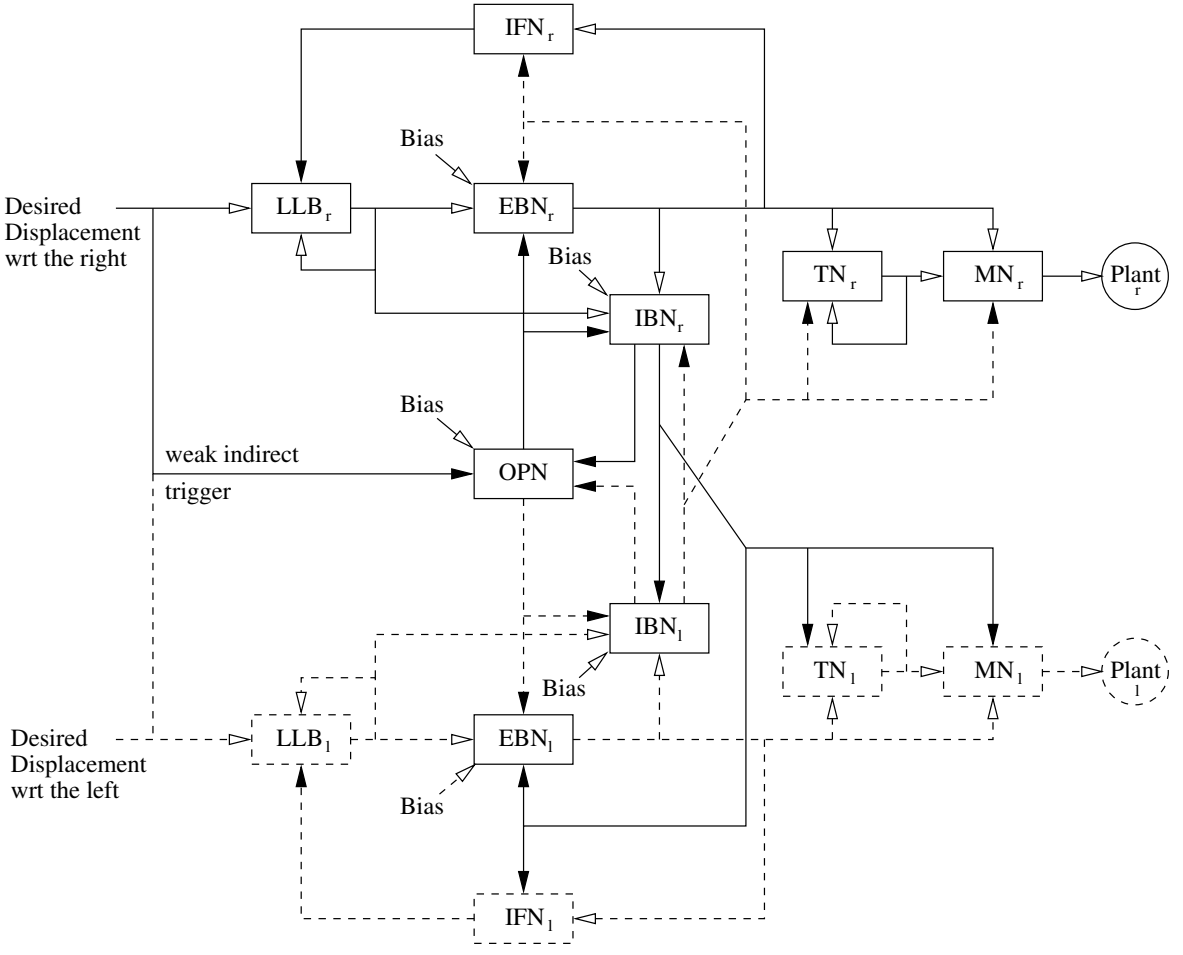
Where is the RI ?

(Scudder, 1988)



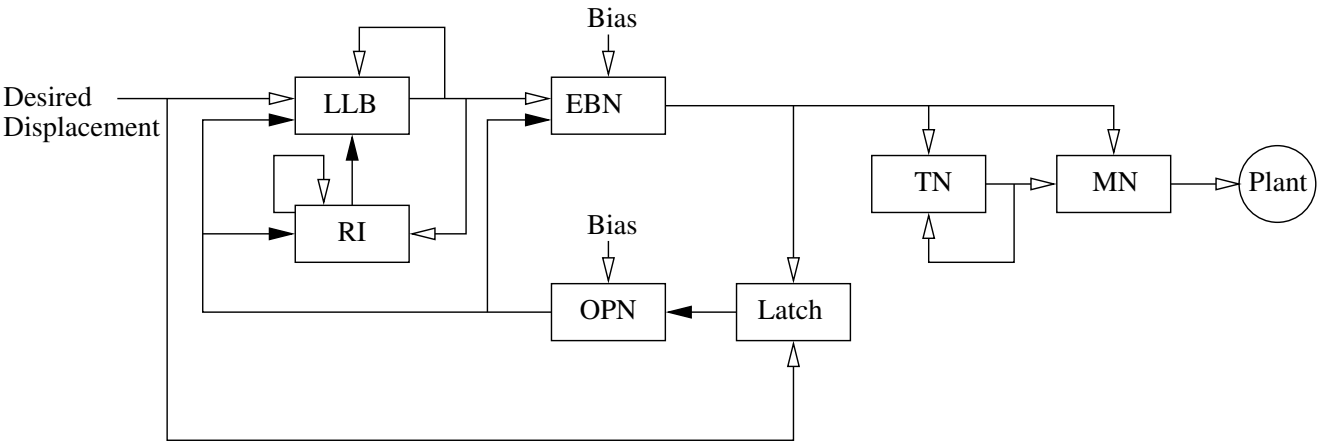
- Changed order of operations (integration in LLB and substraction)
- RI changed in IFN
- Resumed saccades after OPN stimulation
- Straight oblique saccades
- Pb with staircase saccades

(Scudder, 1988)



- Antagonist control

(Moschovakis, 1994)



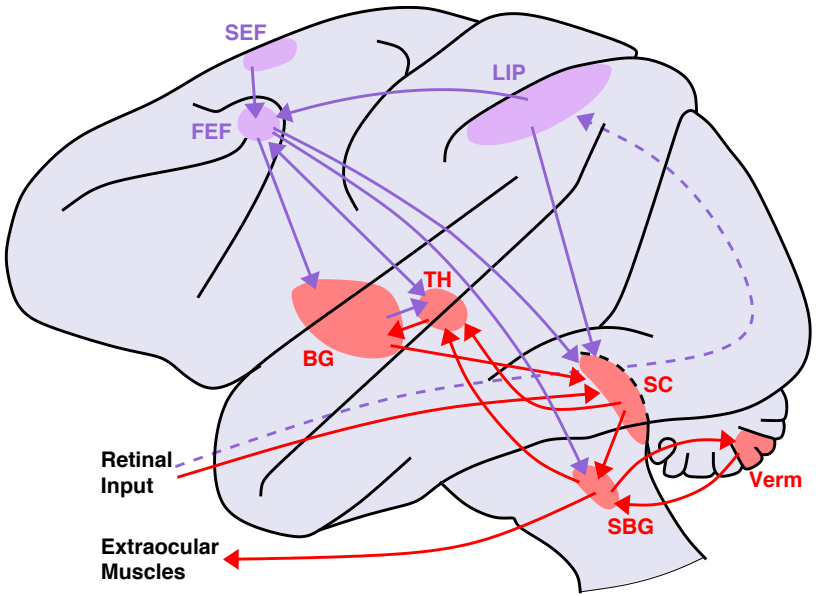
- Upward generator : RI !
- Reset specified (OPN),
- Keeps Scudder's model good properties.

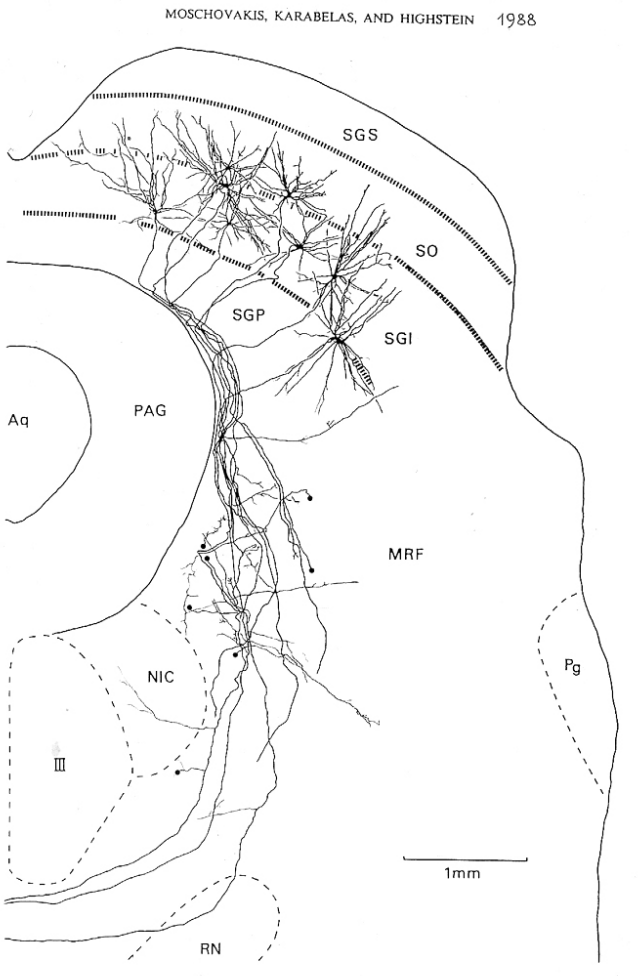
What if the feedback was somwhere else ?

- Where are the RI ? Are there RI ?
- The SC could be part of the feedback mechanism (we'll discuss that soon).
- The Cerebellum could play a role in the feedback control of saccades ! (Lefèvre et al., 1998)

Plan

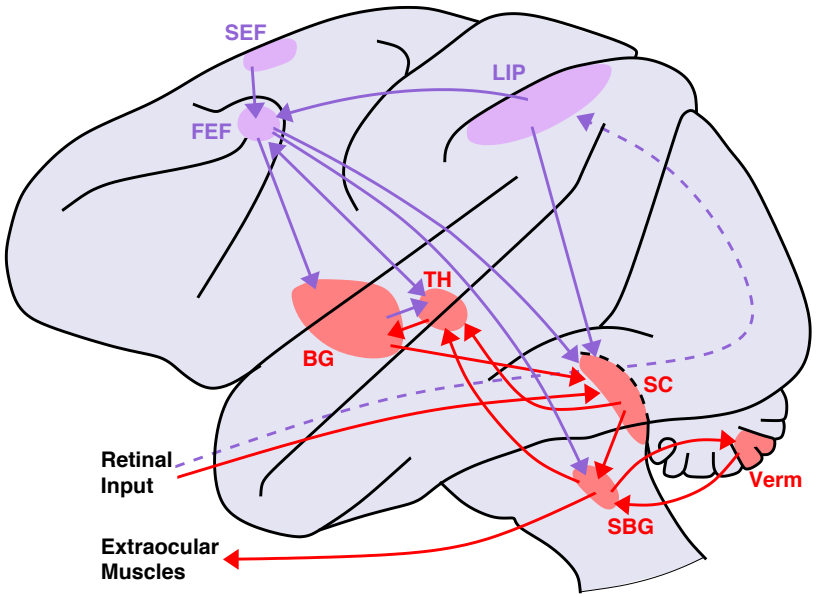
Layers

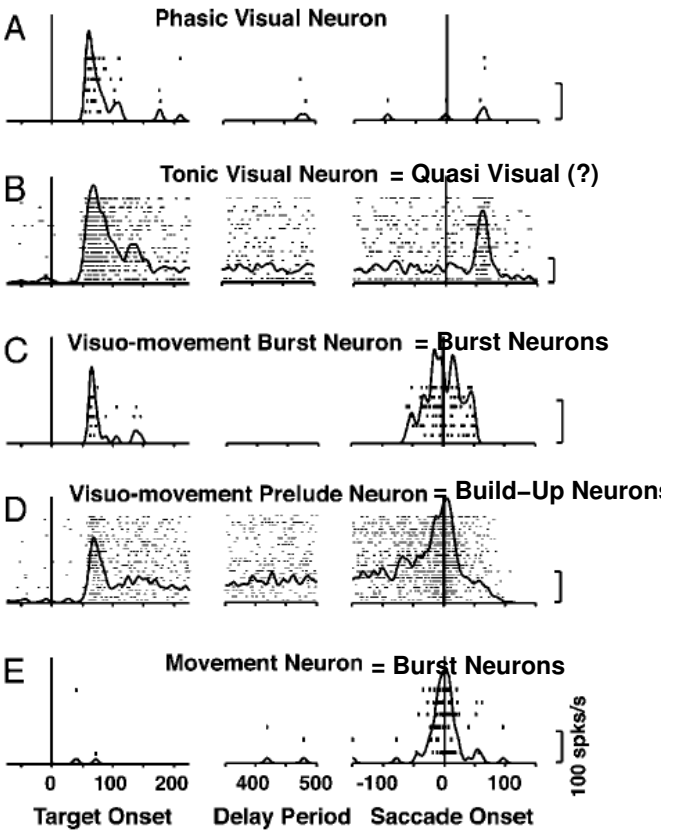




- Visual neurons (V),
- Quasi-visual neurons (QV) : memory,
- Visu-motor neurons (VMB/VMP)
- Motor neurons (M)
- Fixation neurons (FIX)

Layers

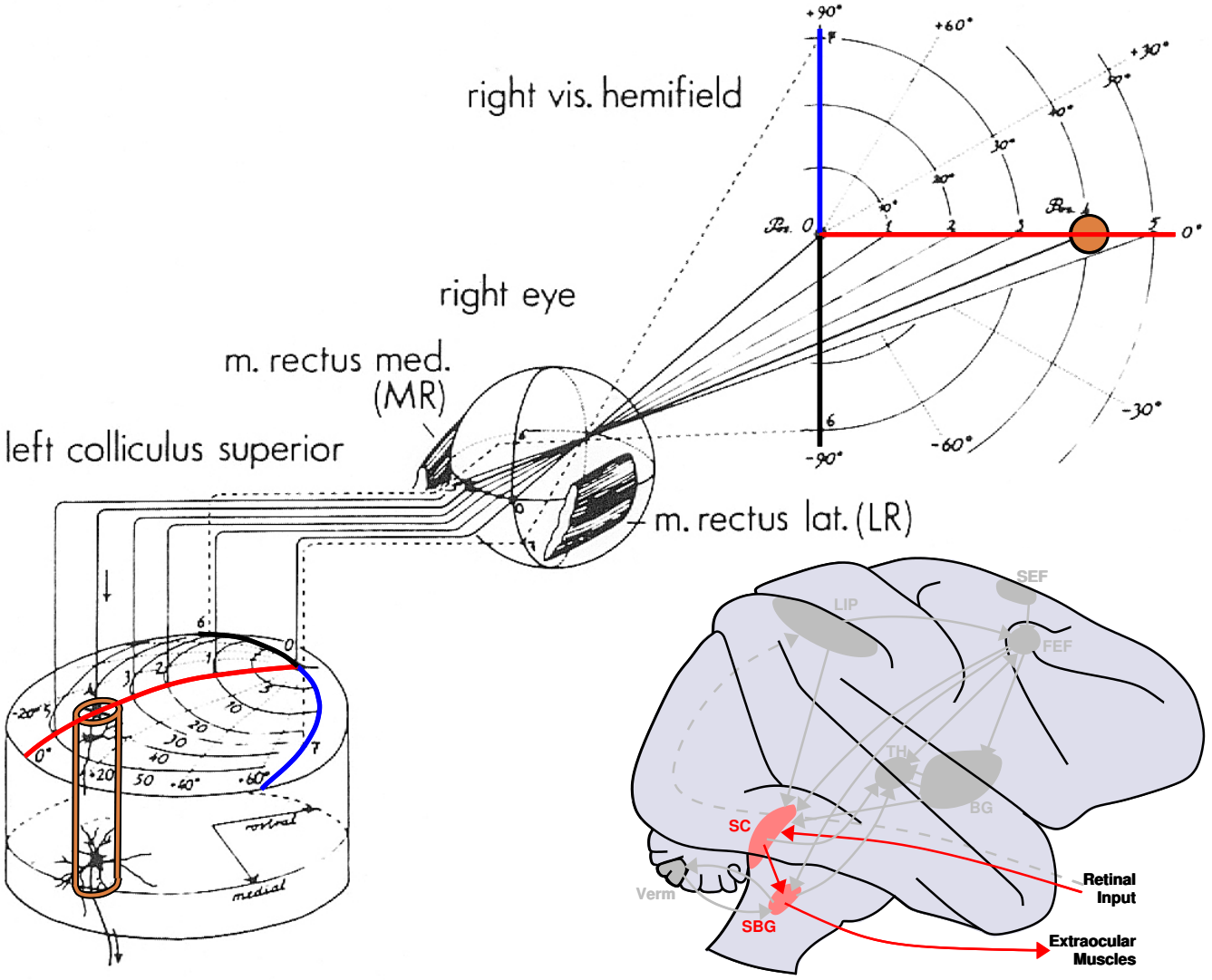




F : Arm Movement Neurons (Werner, 1993)

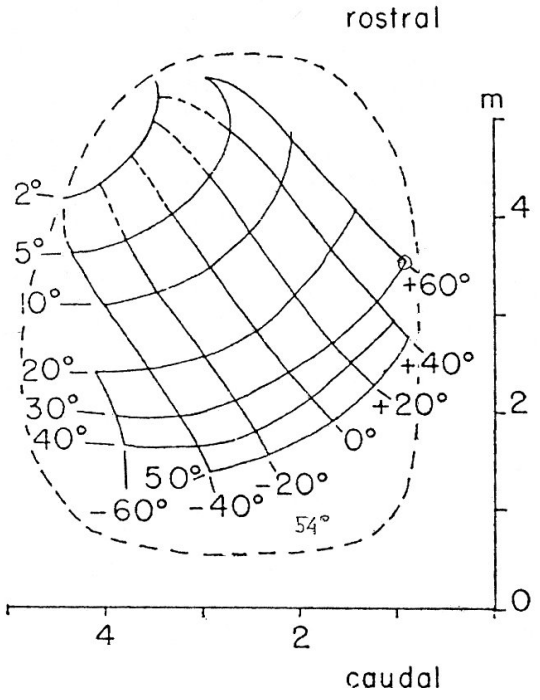
- Visual neurons (V),
- Quasi-visual neurons (QV) : memory,
- Visu-motor neurons (VMB/VMP)
- Motor neurons (M)
- Fixation neurons (FIX)

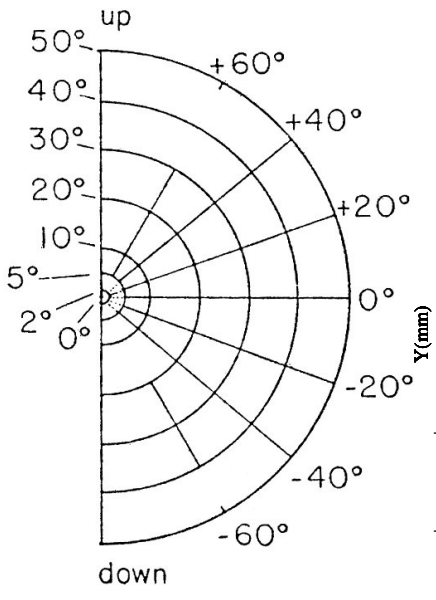
Maps

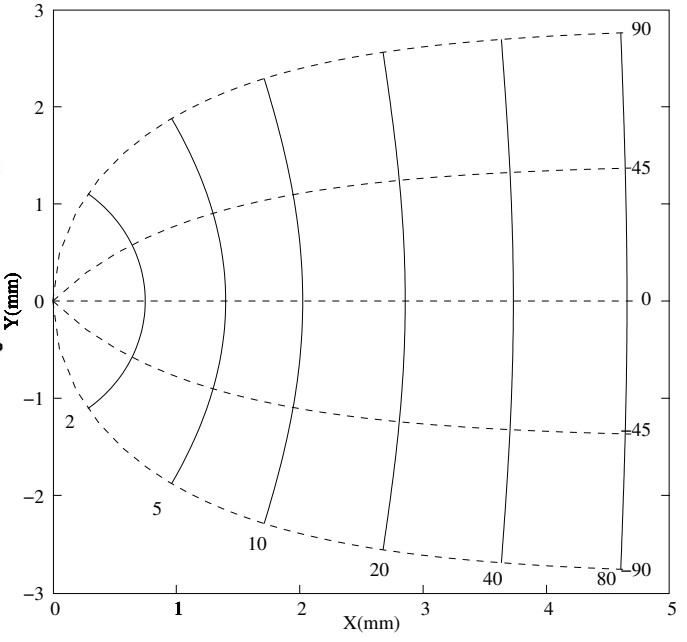

right vis. hemifield
right eye
m. rectus med. (MR)
left colliculus superior
m. rectus lat. (LR)
+90°
+60°
+30°
0°
-30°
-60°
-90°
SEF
LIP
FEF
TH
BG
SC
SBG
Verm
Retinal Input
Extraocular Muscles

Logarithmic maps

Macaque (Robinson, 1972 ; Ottes et al., 1986)



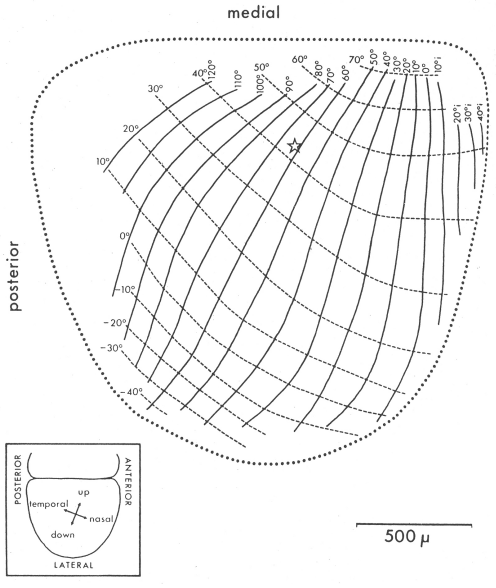


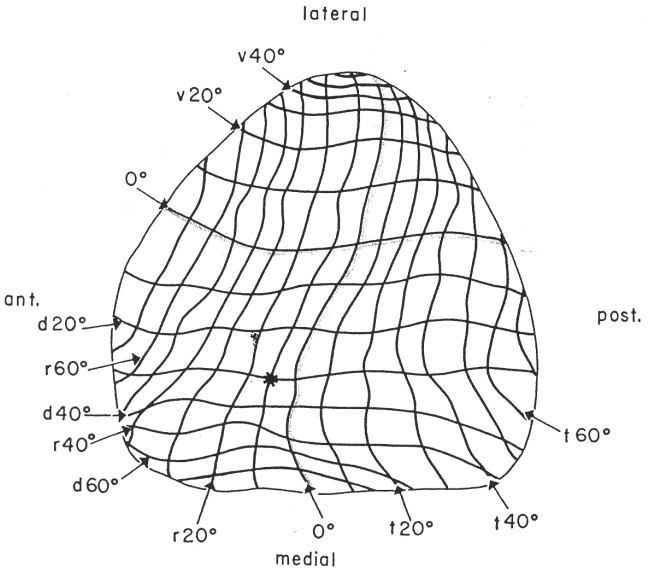


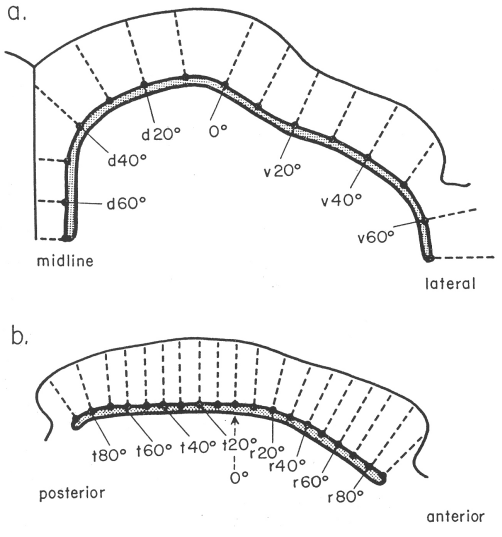
$$\frac{X}{B_X} + i\frac{Y}{B_Y} = \ln\left(\frac{z+A}{A}\right), \text{ with } z = \alpha + i\beta$$

Linear maps

Mouse (Dräger & Hubel, 1976), Rat (Siminoff et al., 1966)

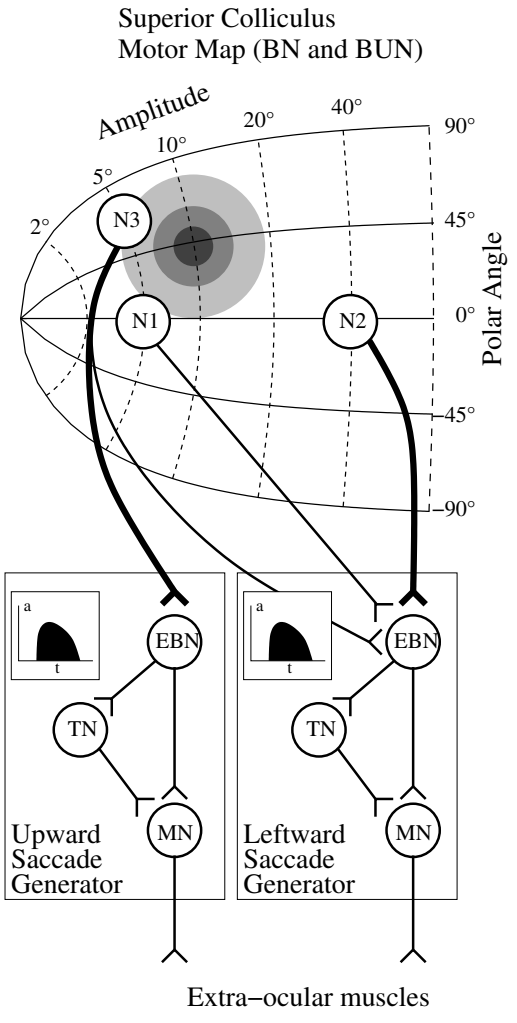






$$\alpha = X/b_X \text{ and } \beta = Y/b_Y$$

Spatio-temporal transformation : the problem



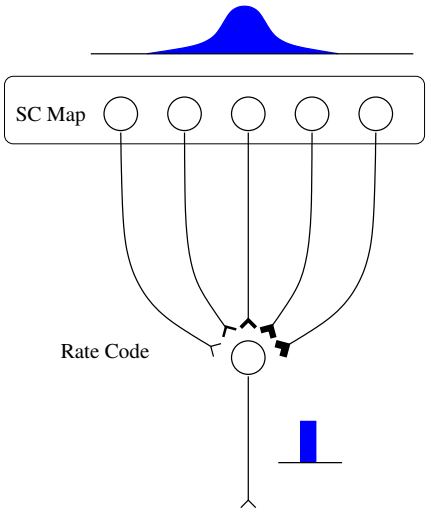
Saccade encoded as :

- SC map : a (stereotyped) bump of activity on a given location,
- SG : two bursts of varying intensities.

STT : How to transform one code into another ?

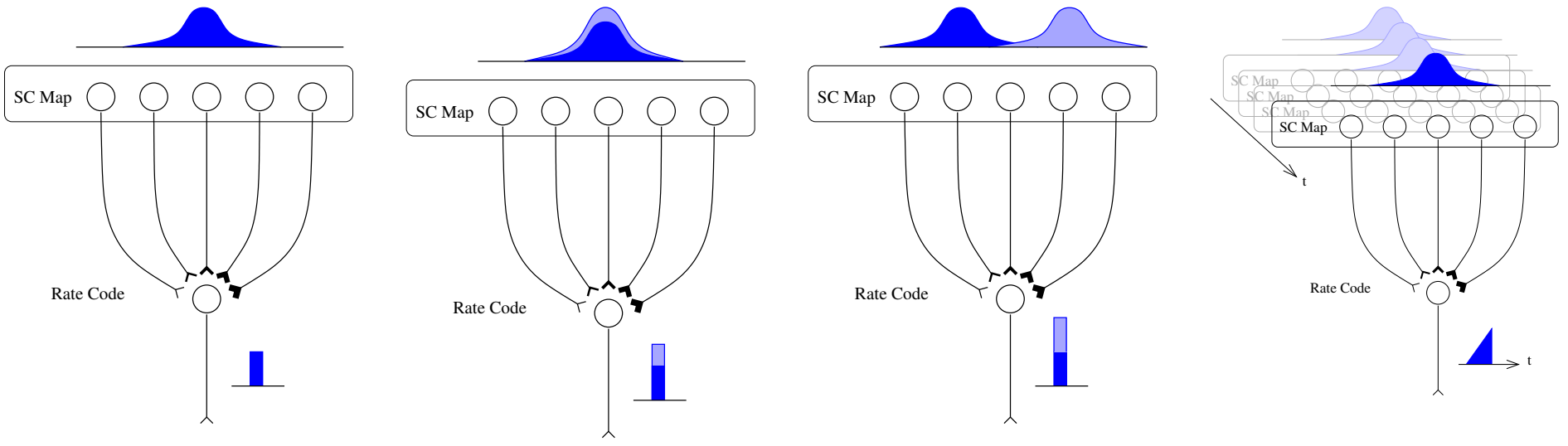
STT : weighted sum

(van Opstal & van Gisbergen, 1987)



STT : weighted sum

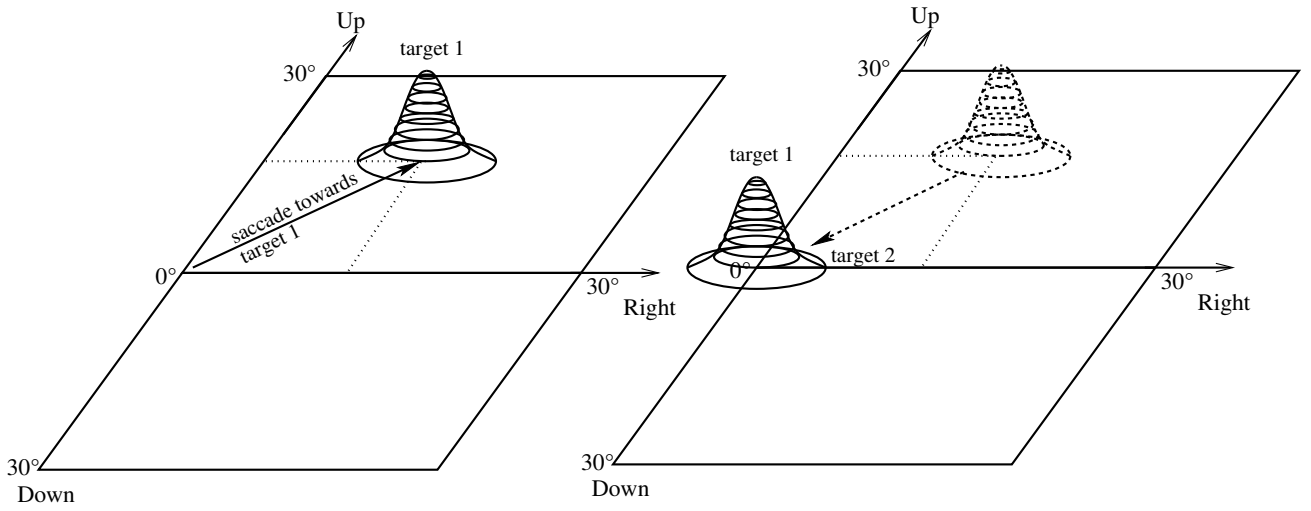
(van Opstal & van Gisbergen, 1987)



SC-in-the-loop

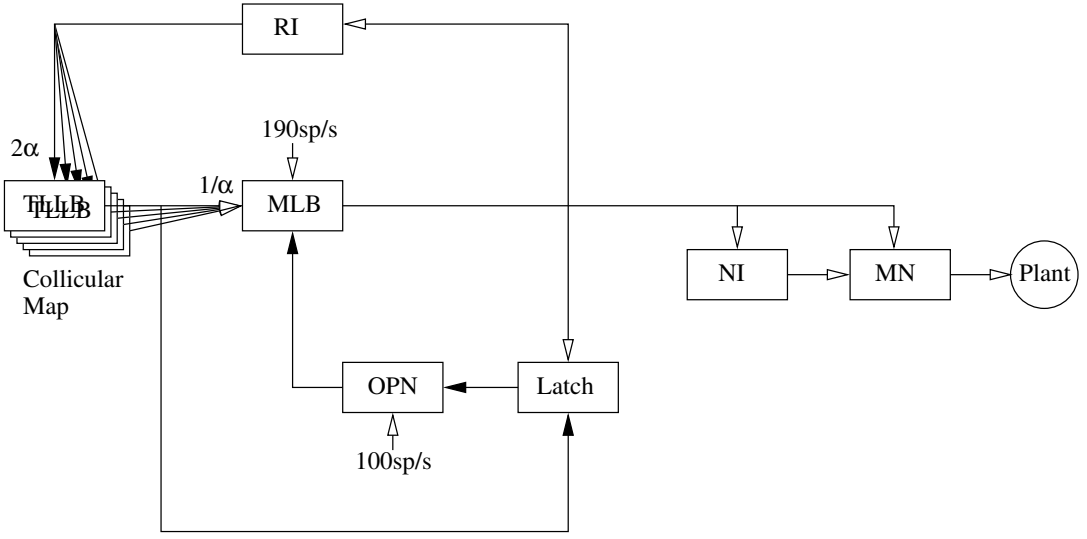
What if the SC was in the feedback loop ?

(Droulez and Berthoz, 1991)



- "Moving Hills" hypothesis

(Waitzman et al., 1991)



- "Stationary Decreasing Hill"
- Inspired by correlation results between BN burst decrease and eye trajectory,
- Very similar to a (Jürgens et al., 1981) model.

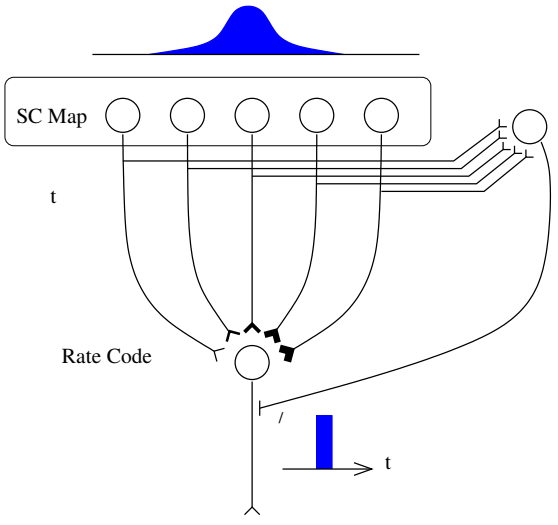
SC-NOT-in-the-loop

Well, it's probably not...

(Kato, Grantyn, Dalezios, Moschovakis, **THE LOCAL LOOP OF THE SACCADIC SYSTEM CLOSES DOWNSTREAM OF THE SUPERIOR COLLICULUS**, Neuroscience, 143 (2006) 319 –337)

STT : normalized weighted sum

(Lee, Rohrer & Sparks, 1988)



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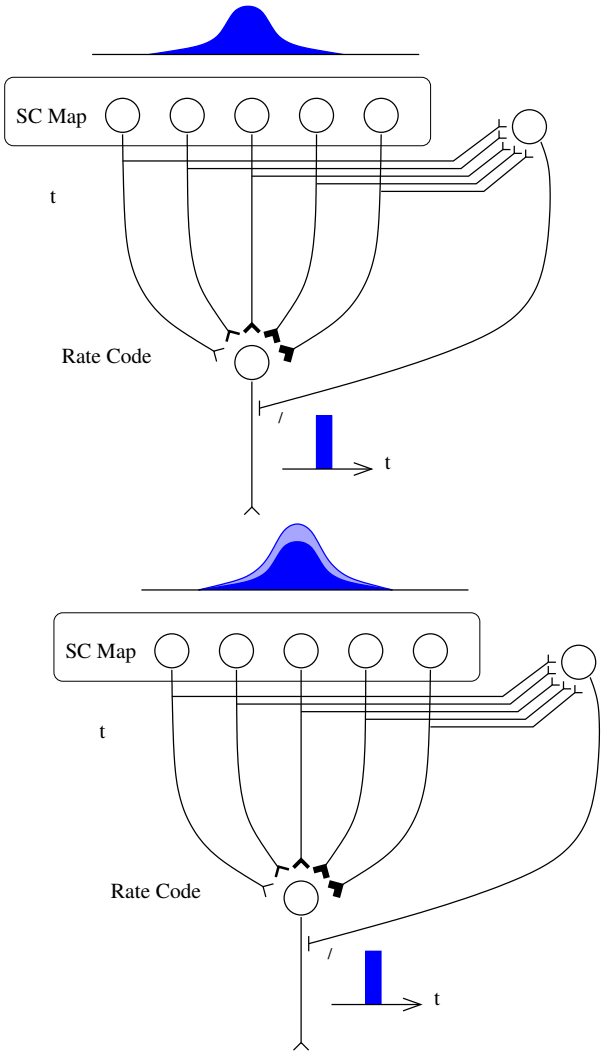

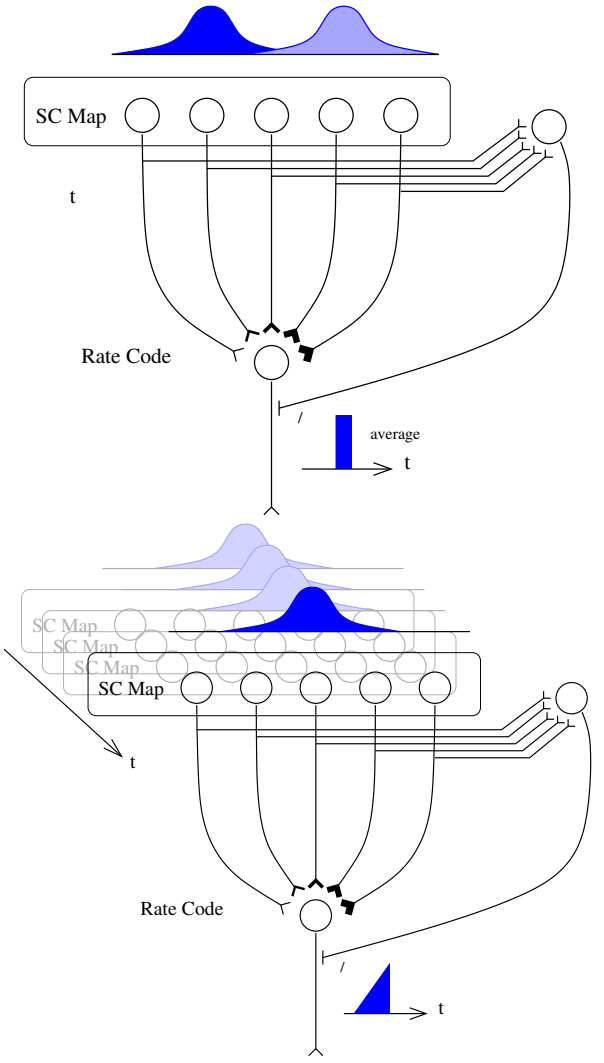

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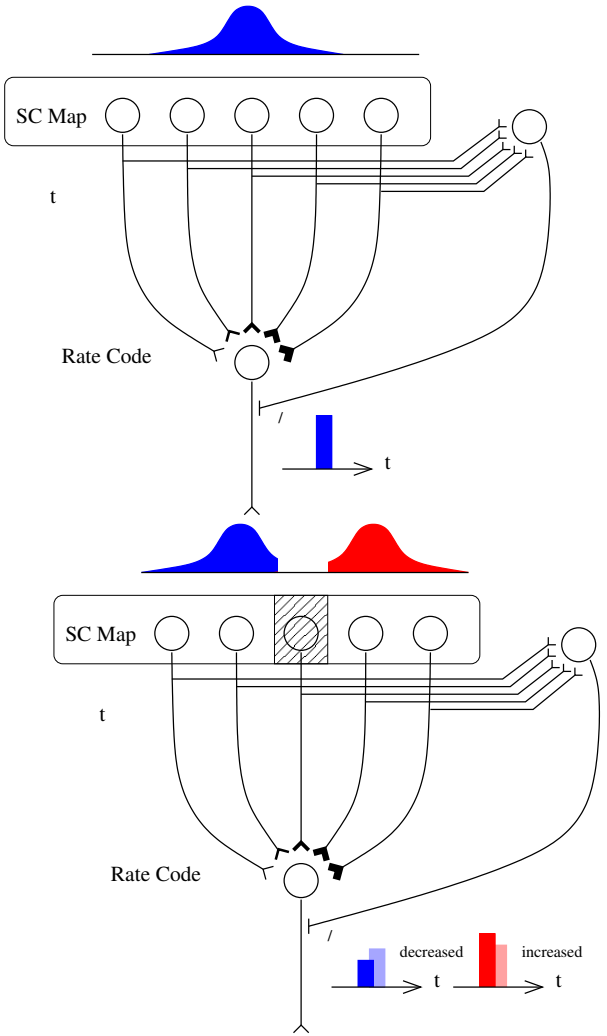
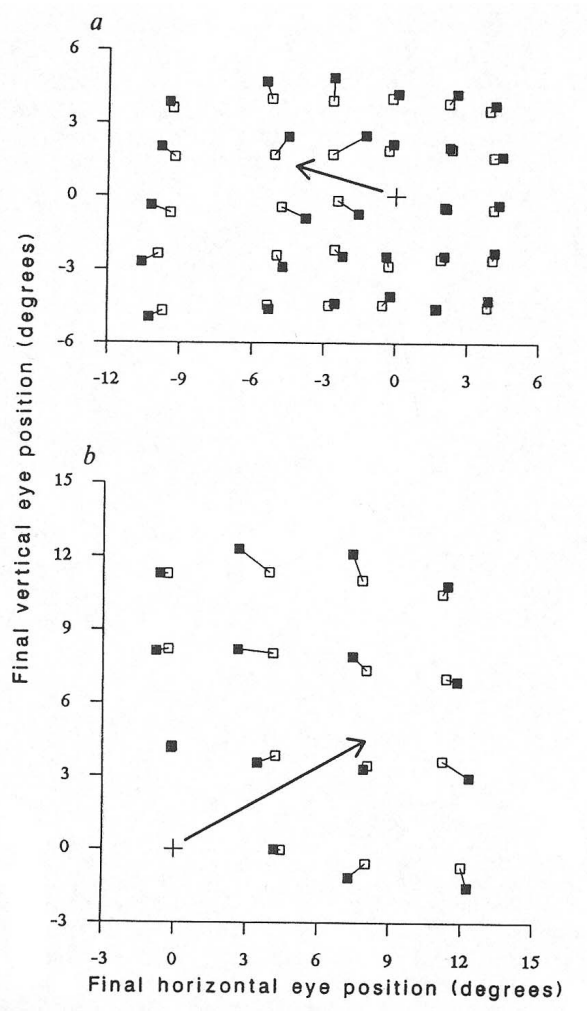
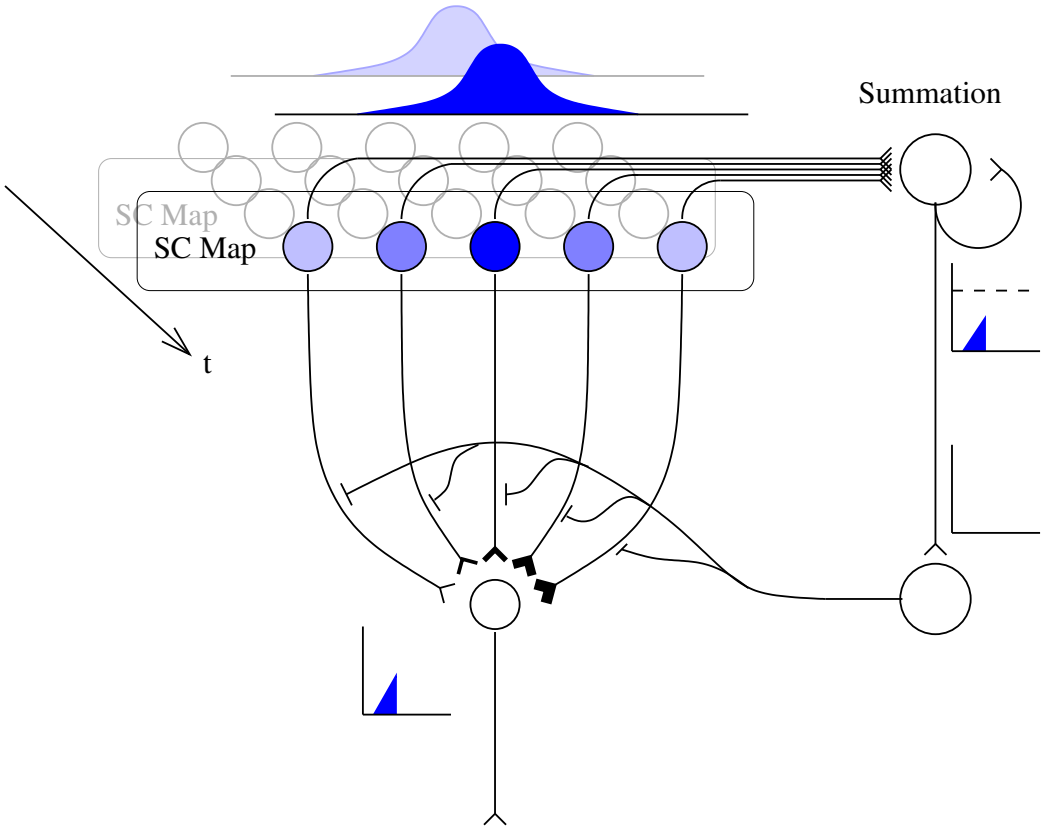




STT : summation & saturation

(Groh, 2001 ; Goossens & van Opstal, 2006 ; Tabareau et al., 2007)



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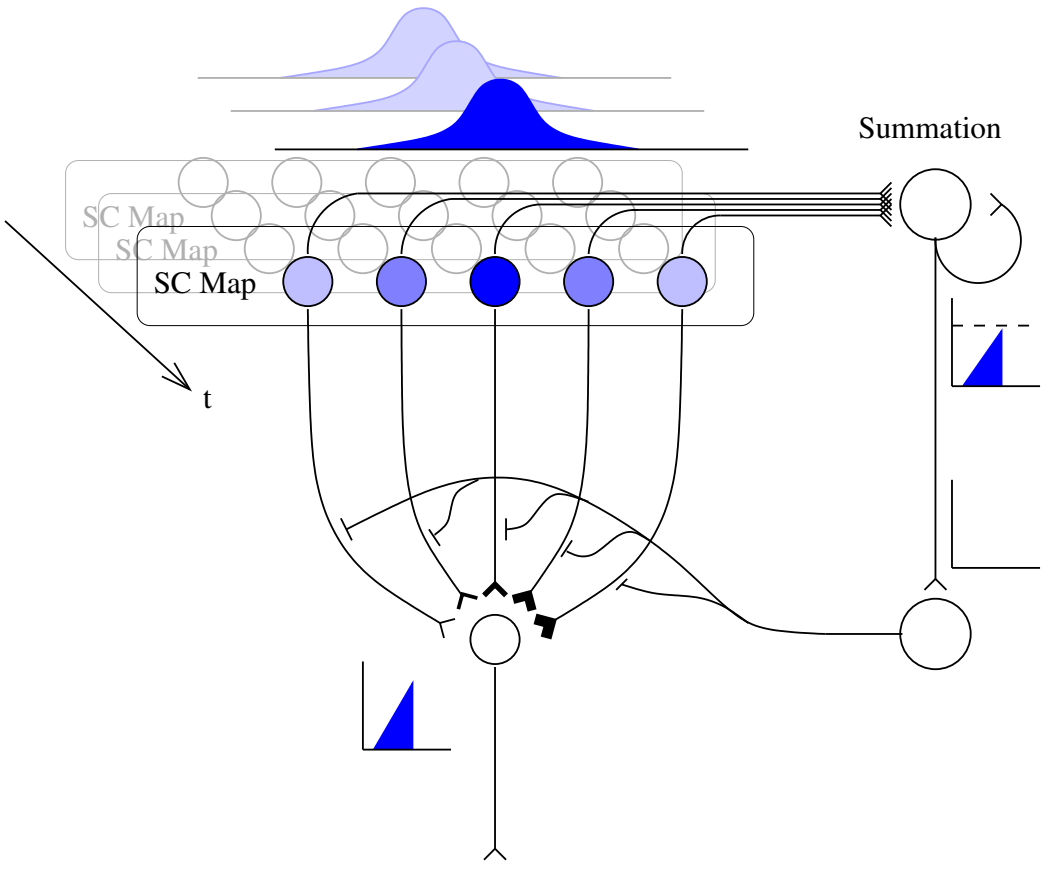

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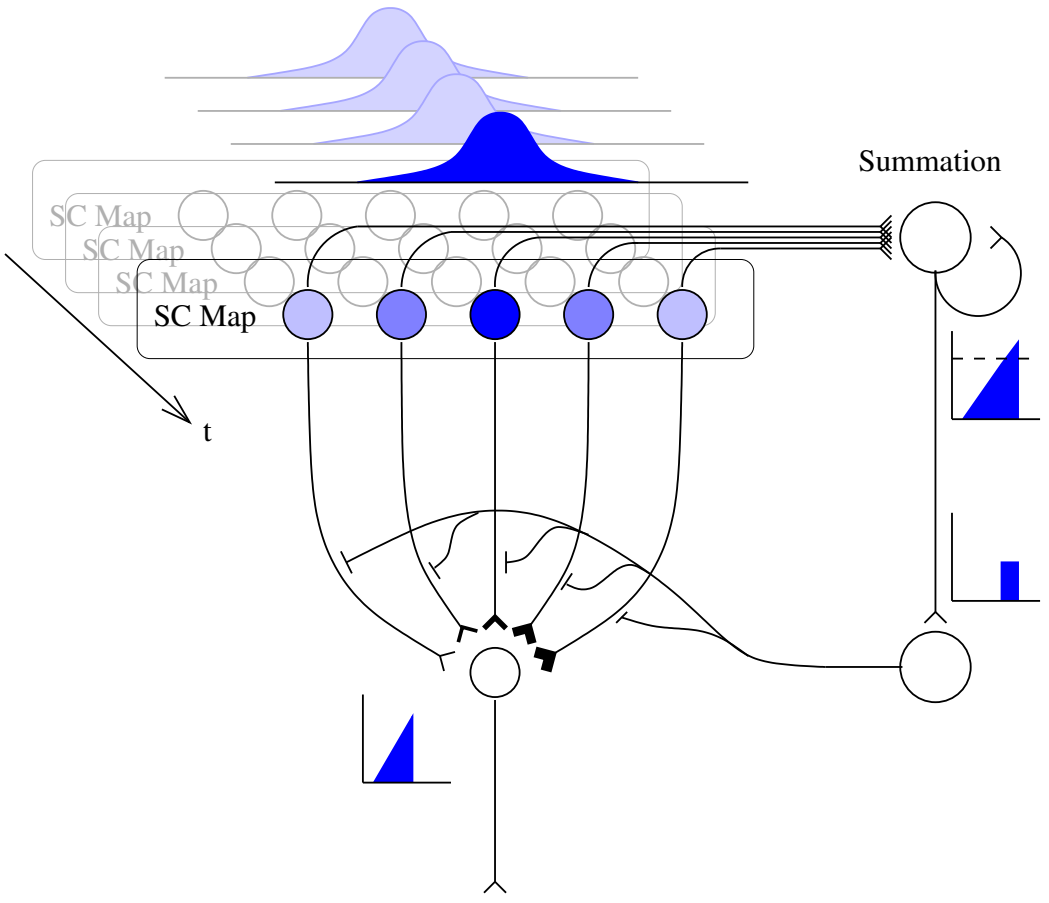

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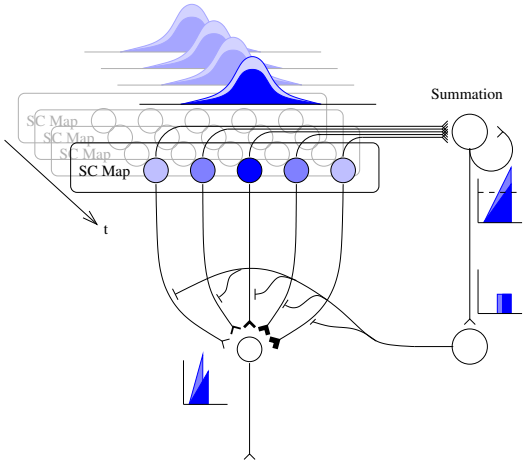

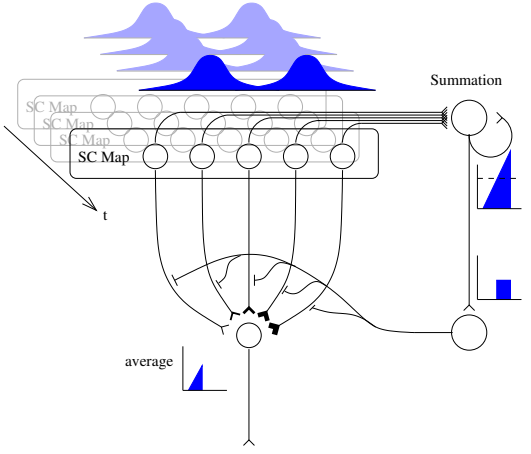

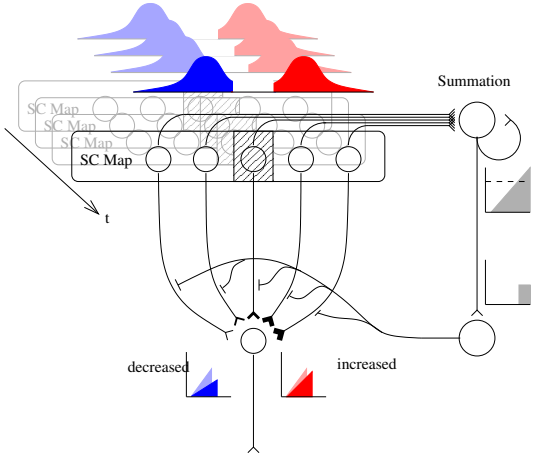

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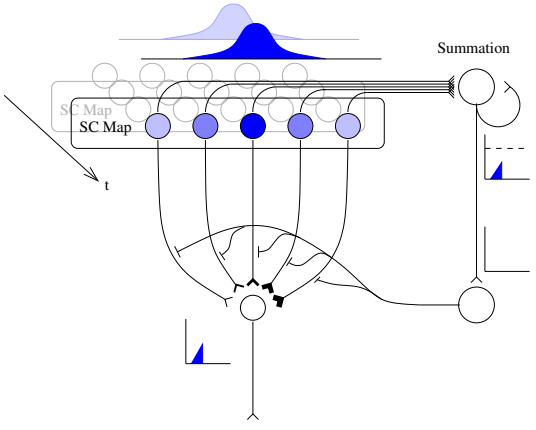
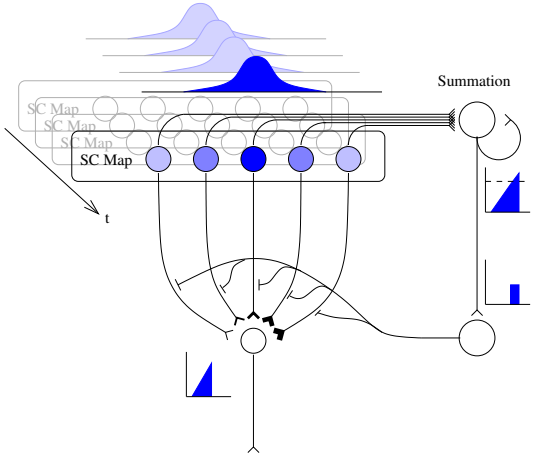
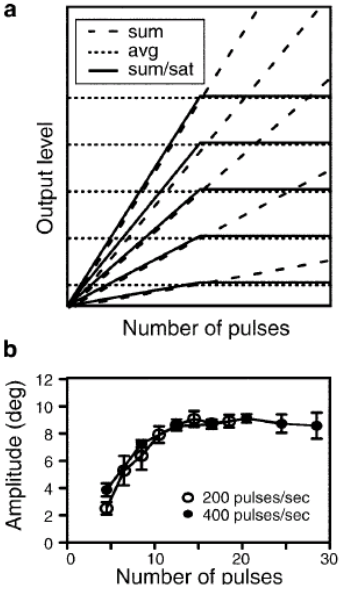
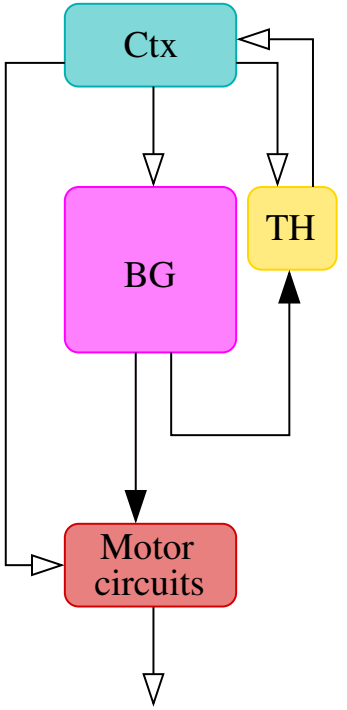




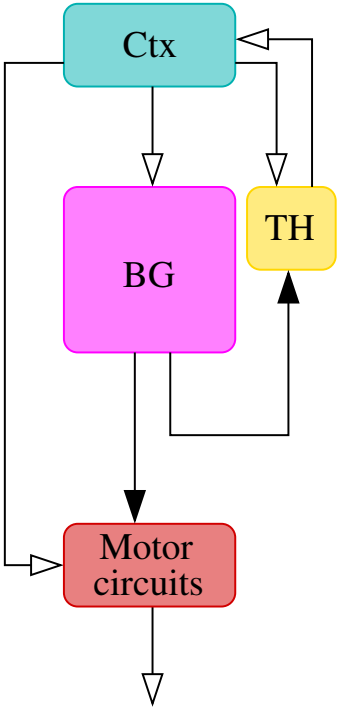


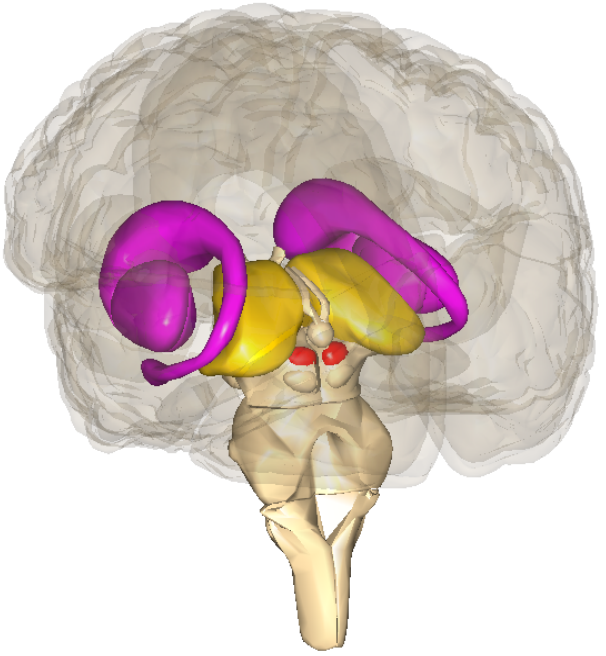
Plan

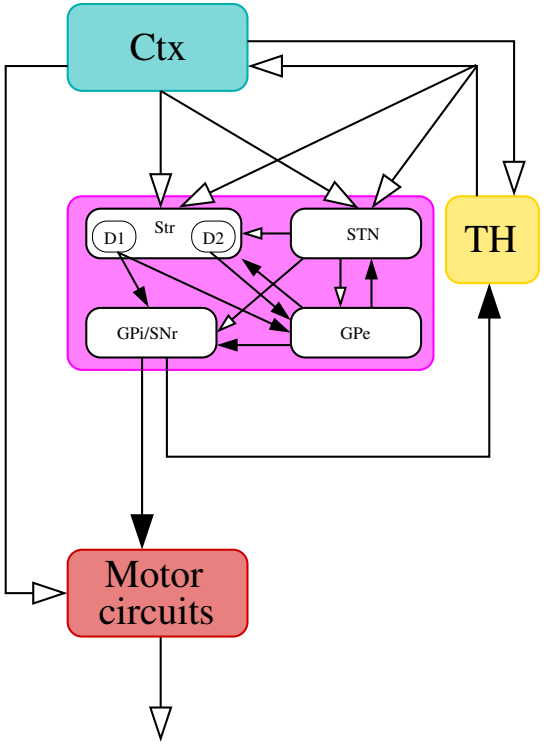
Basal Ganglia - Anatomy



Basal Ganglia - Anatomy







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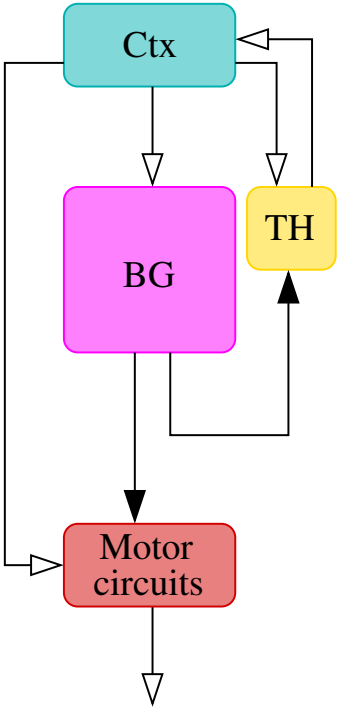

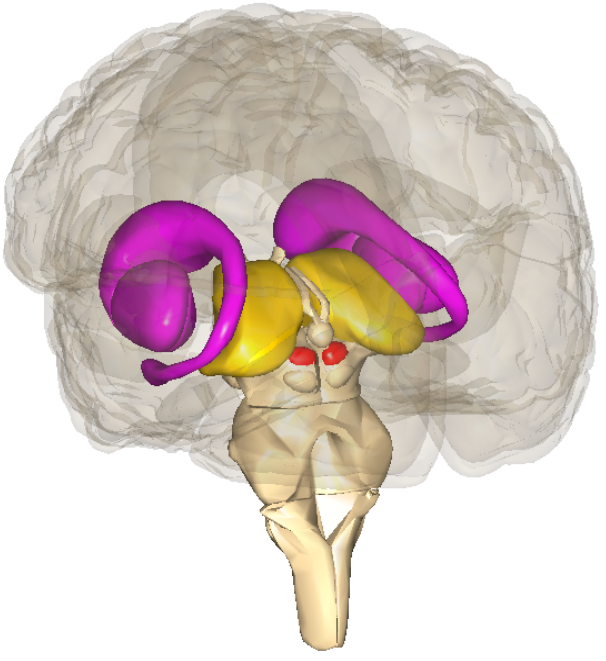

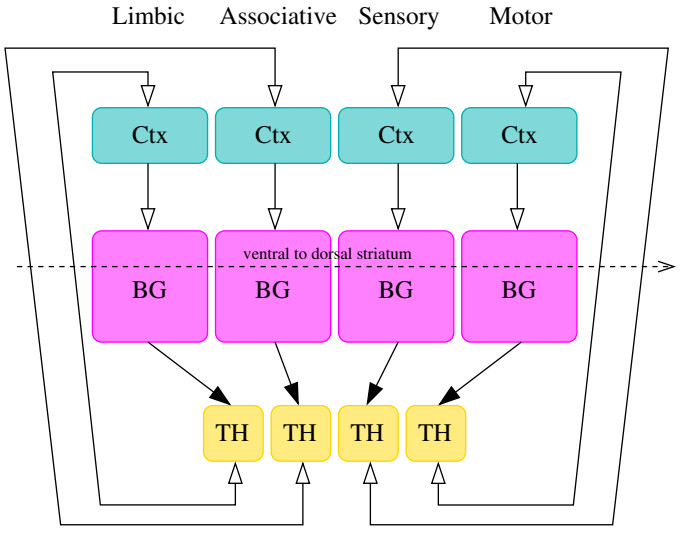

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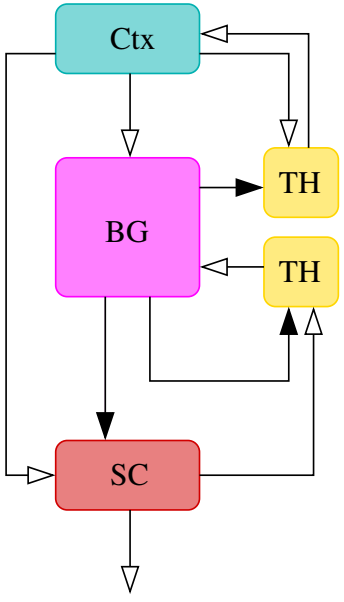

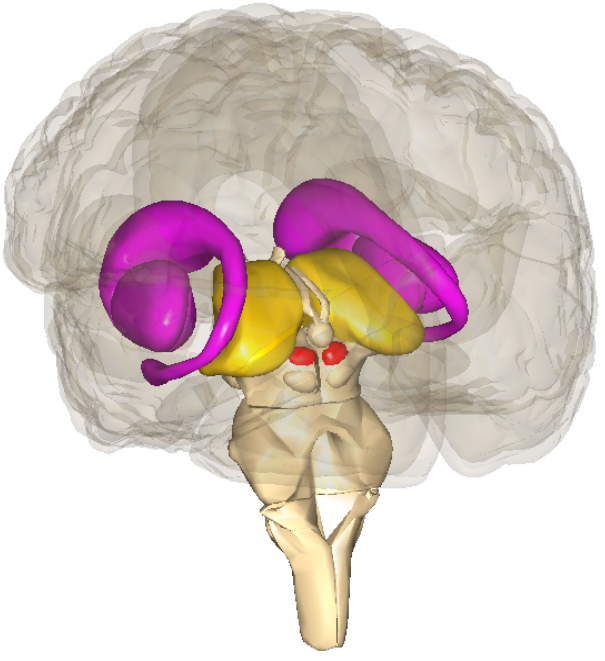

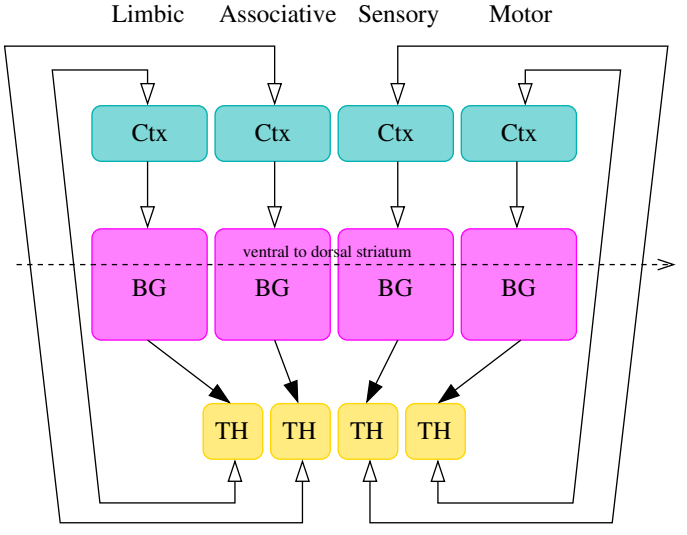

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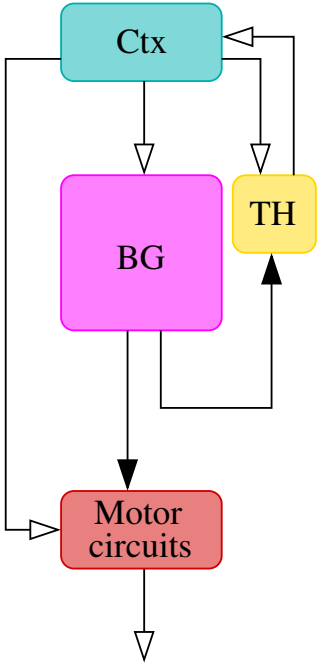
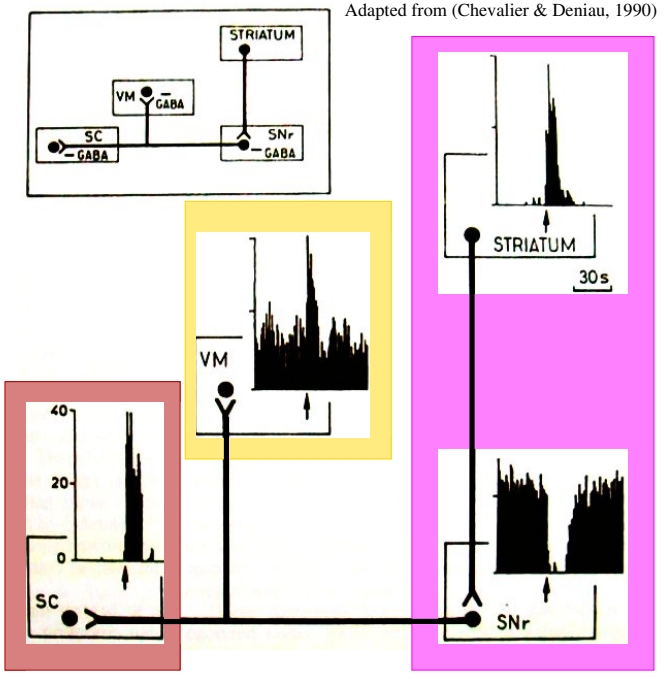
Basal Ganglia - Physiology



Adapted from (Chevalier & Deniau, 1990)



Generic role of selection

- Selection by Disinhibition,
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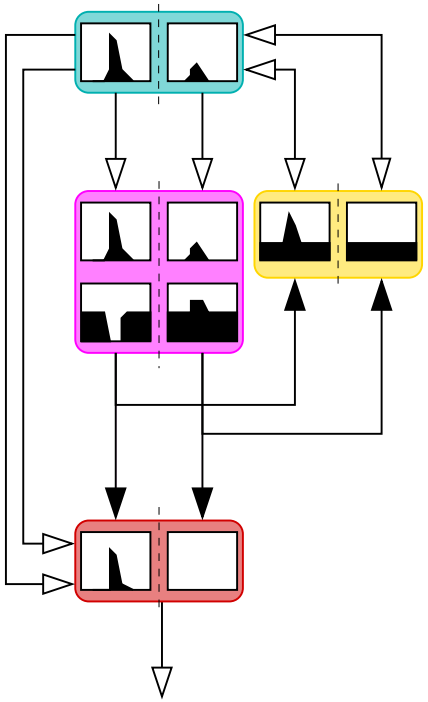
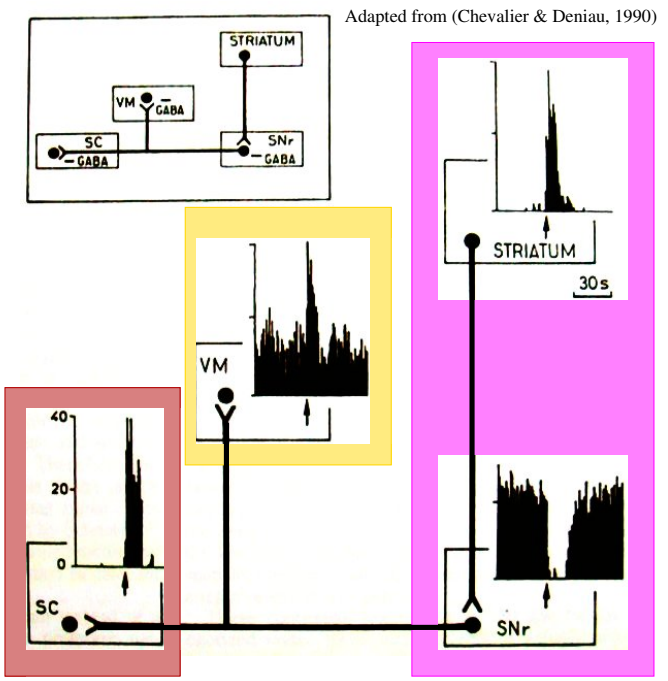
  $\Rightarrow$ Cortico-striatal plasticity, controlled by dopamine

Basal Ganglia - Physiology





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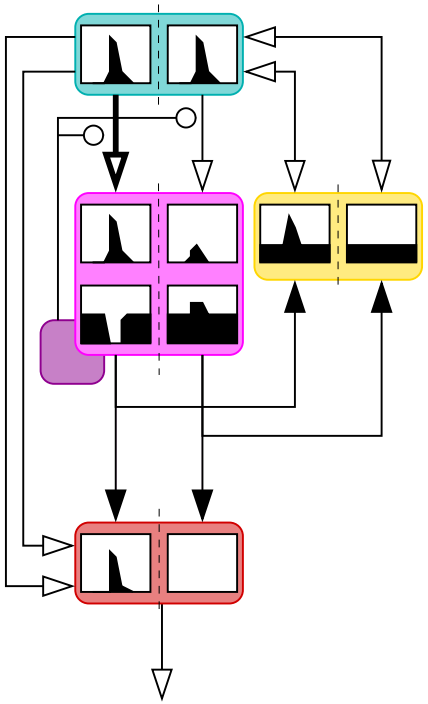

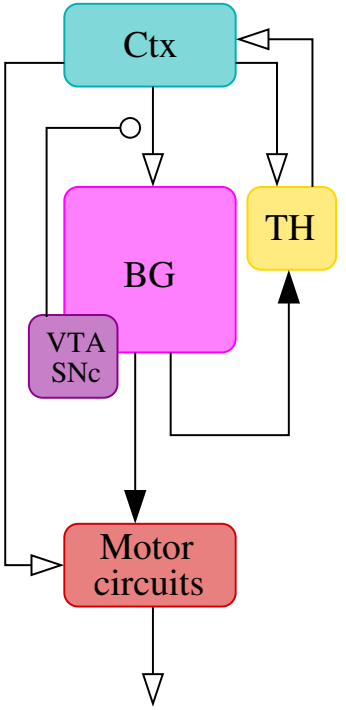

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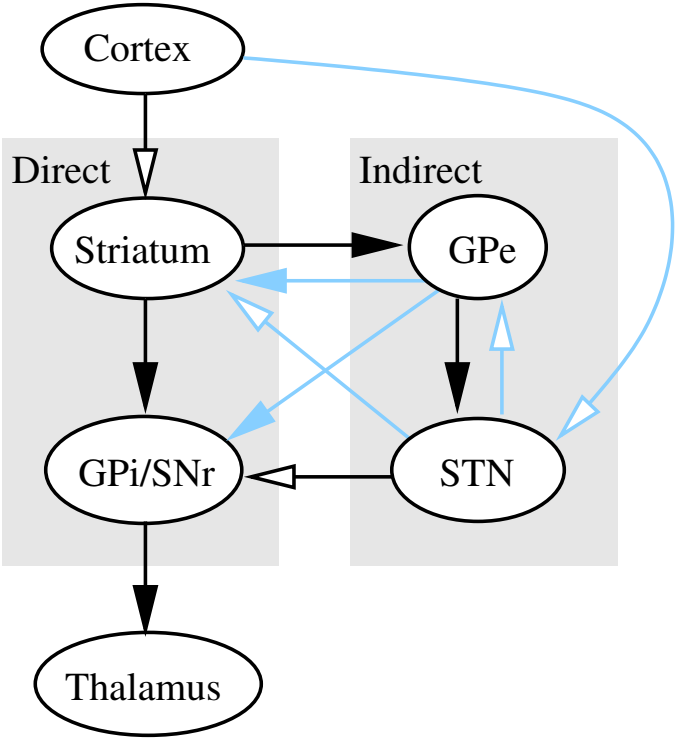
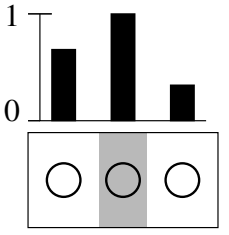
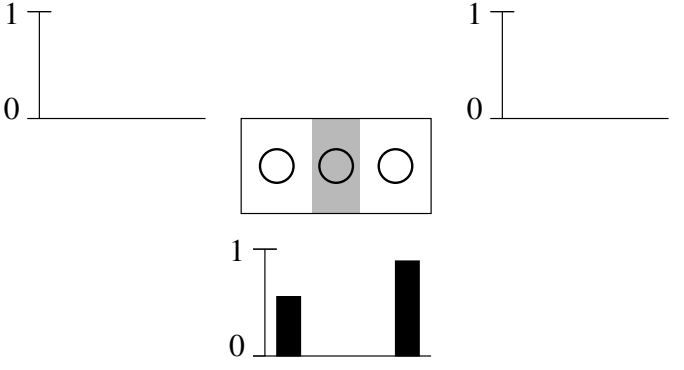
Direct / Indirect Pathways







(Albin et al. 1989)
(Berns & Sejnowski, 1996)
Same off-center on-surround mechanism in recent direct/hyperdirect models (Leblois et al., 2006)

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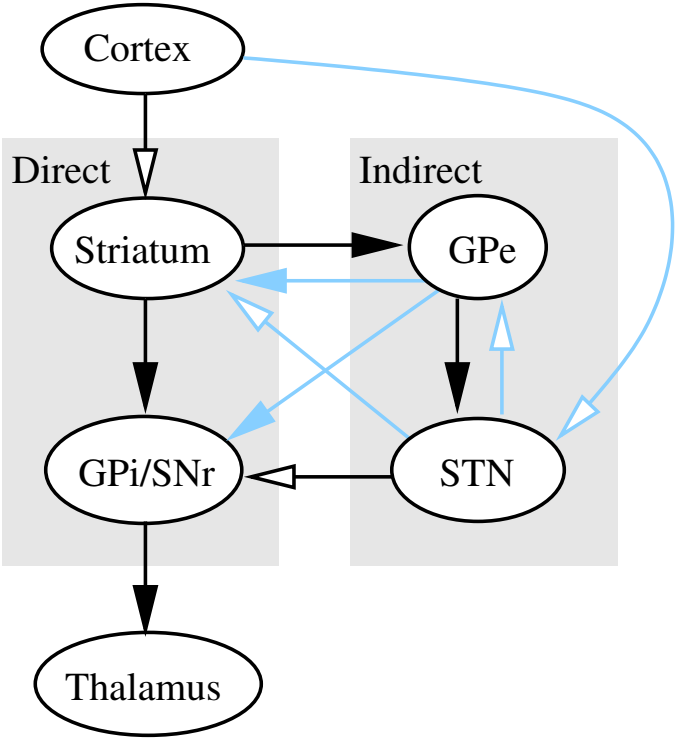

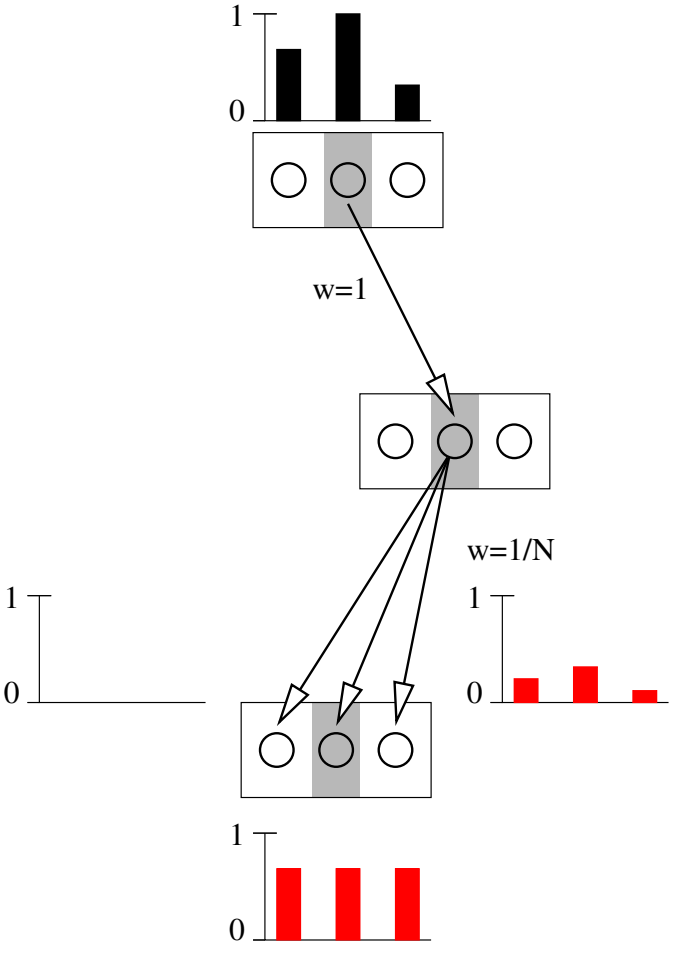

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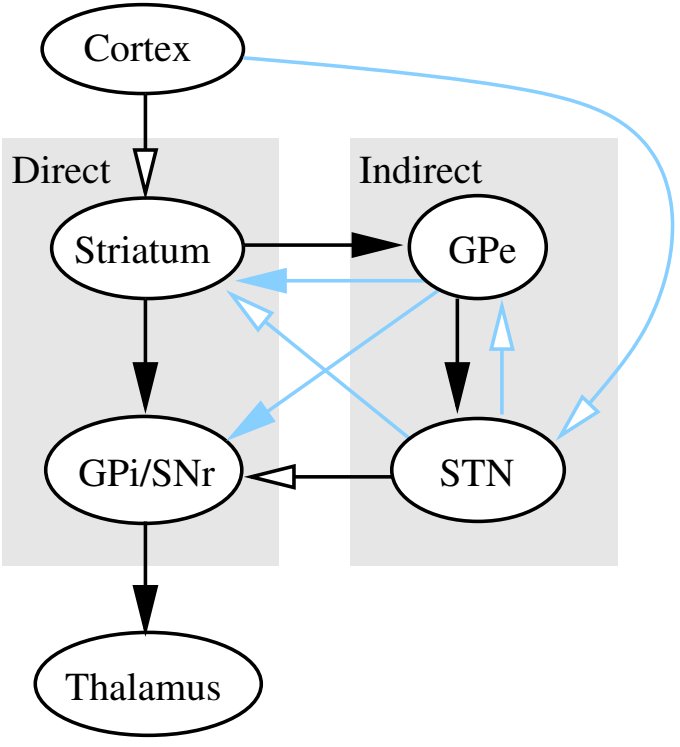

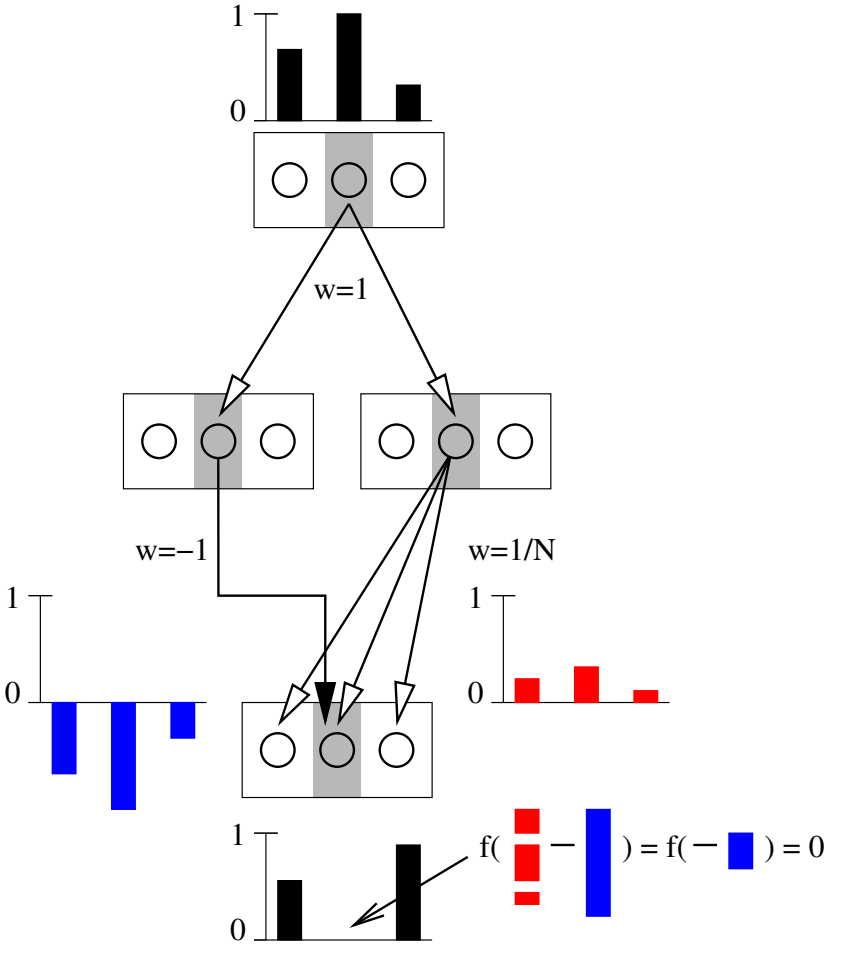

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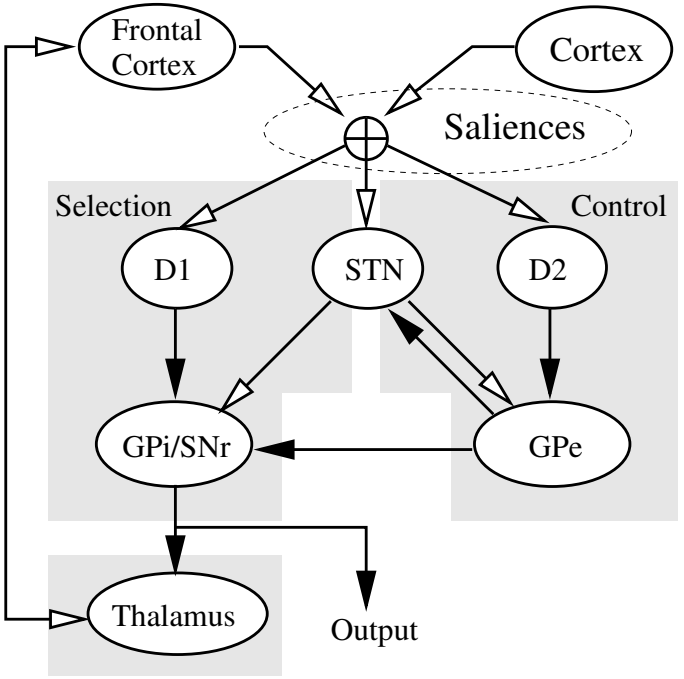
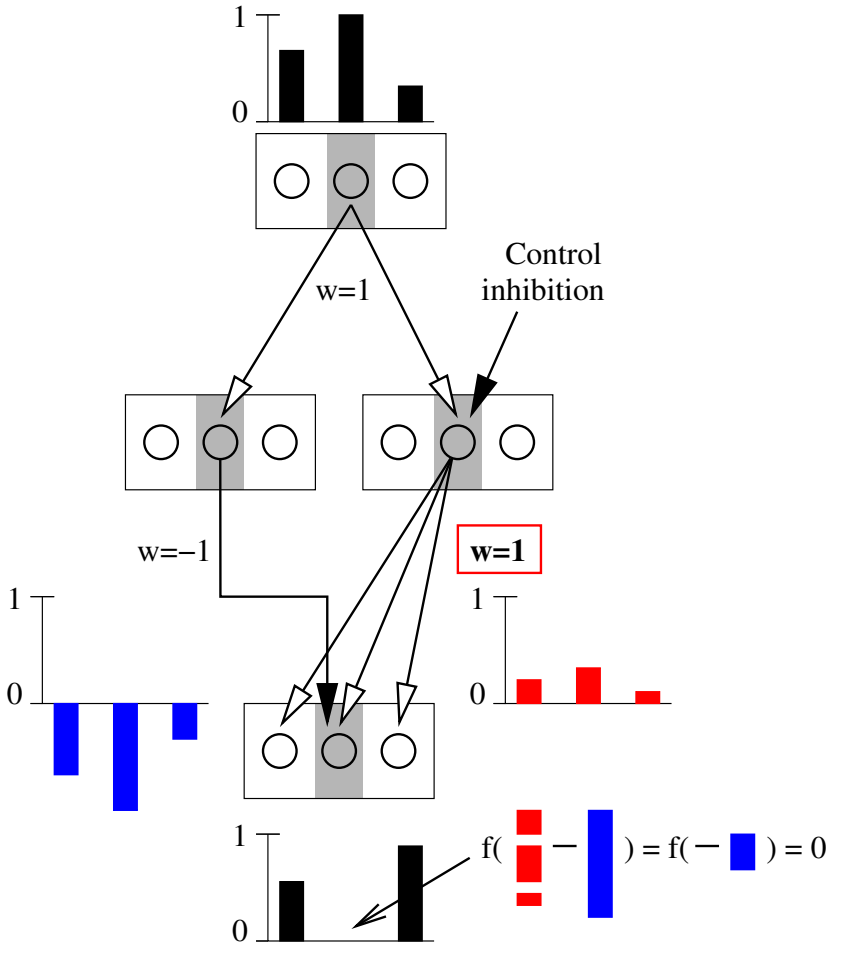
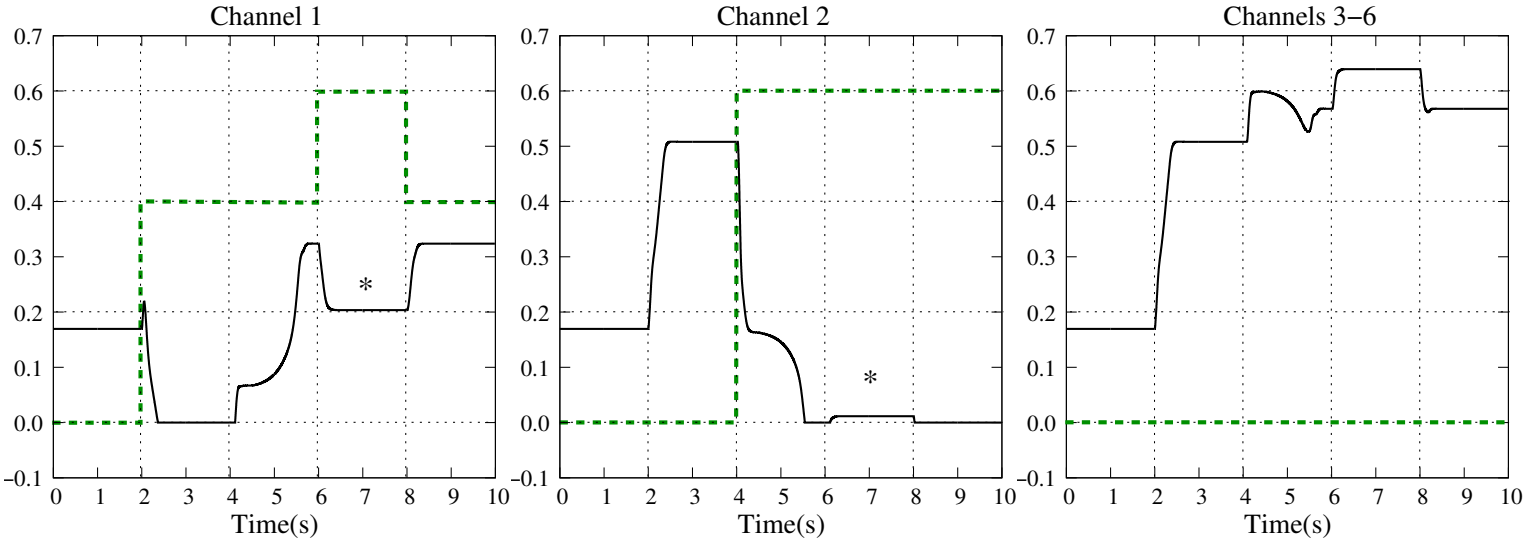
GPR Model (Gurney et al., 2001)





GPR Limitations



* : Instability.

With uniformly drawn inputs :

the ≪ winning ≫ channel is more inhibited than the rest level in 30% of the cases.

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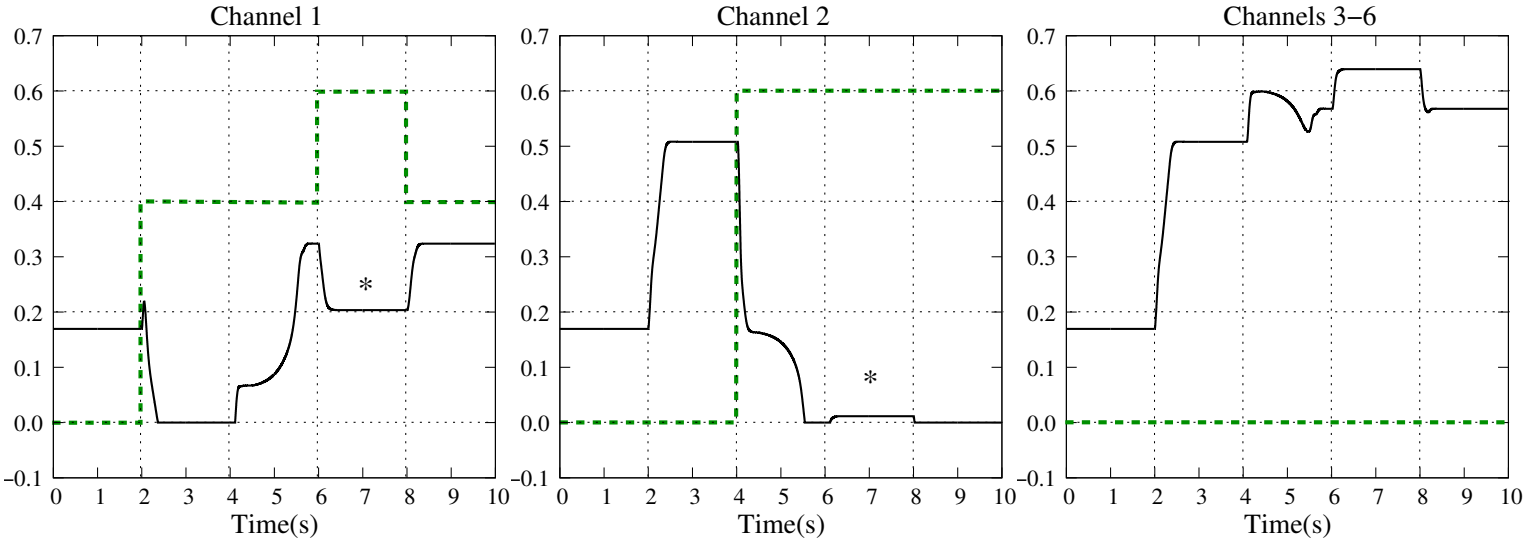

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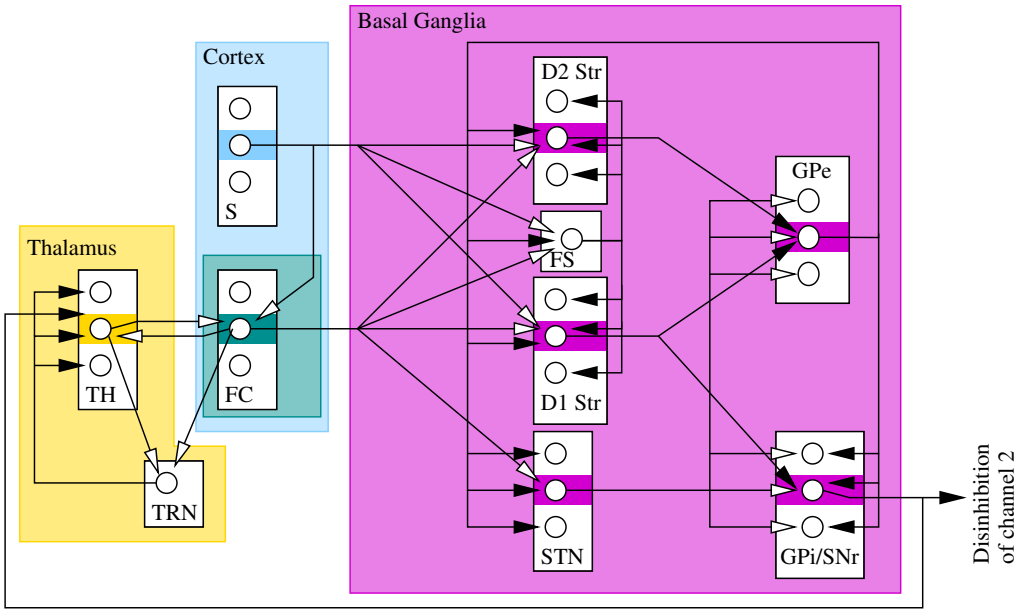
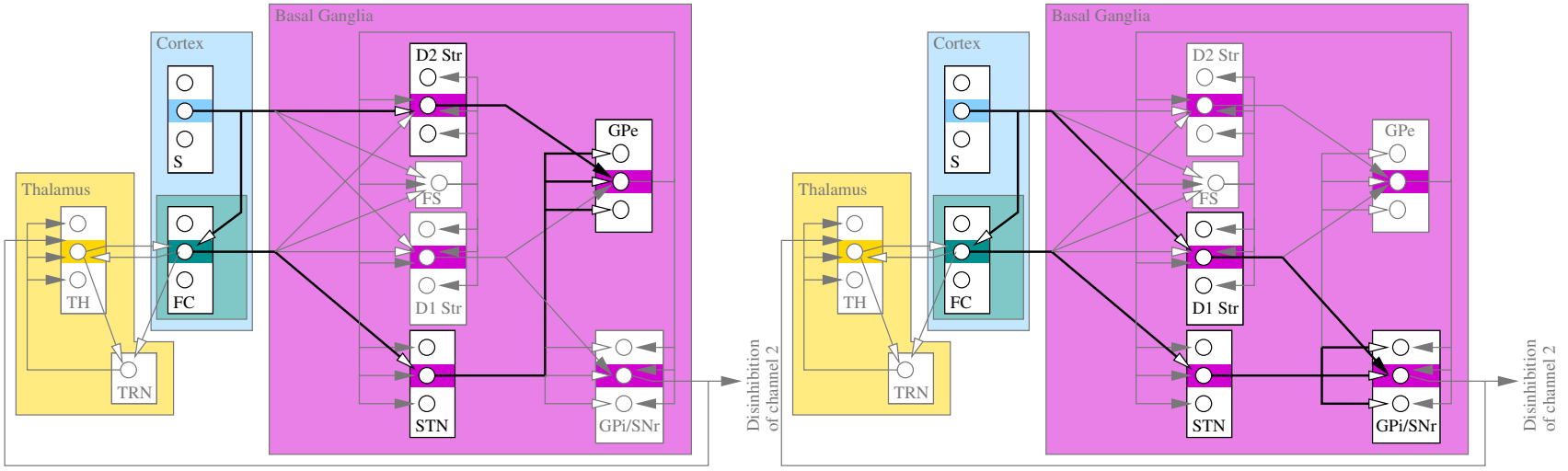
Contracting Basal Ganglia (CBG) Model (Girard et al., 2008)



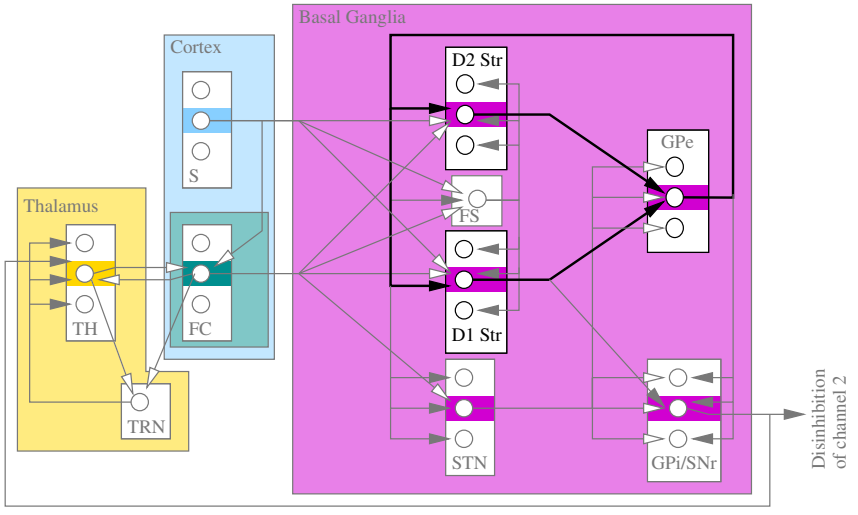
- Includes previously ignored connexions.
- Amplificatory thalamo-cortical loop.
- Selective amplification in the frontal cortex, strict selection of the subcortical targets.
- Numerous internal loops : stability ?

Structure



- Off-center on-surround circuits,
- Negative Feedback to amplify contrast,
- Contraction conditions analytically defined (BG and TC),
- Numerical checking of the contraction of the whole.

Structure



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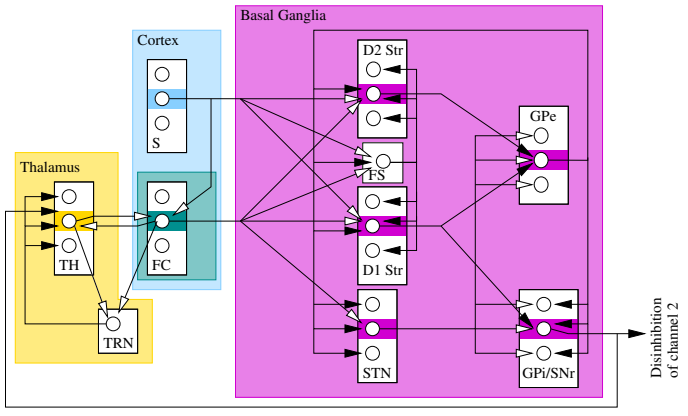
Contraction



BG module :

$$((1+\gamma)w_{D1}^{GPe}w_{GPe}^{D1})^2 + ((1-\gamma)w_{D2}^{GPe}w_{GPe}^{D2})^2 < 1$$

TH-FC module, if $w_{TH}^{TRN} = w_{TRN}^{TH}$:

$$w_{TH}^{FCtx}(w_{FCtx}^{TH} + \sqrt{{w_{FCtx}^{TH}}^2 + N{w_{FCtx}^{TRN}}^2}) < 1$$

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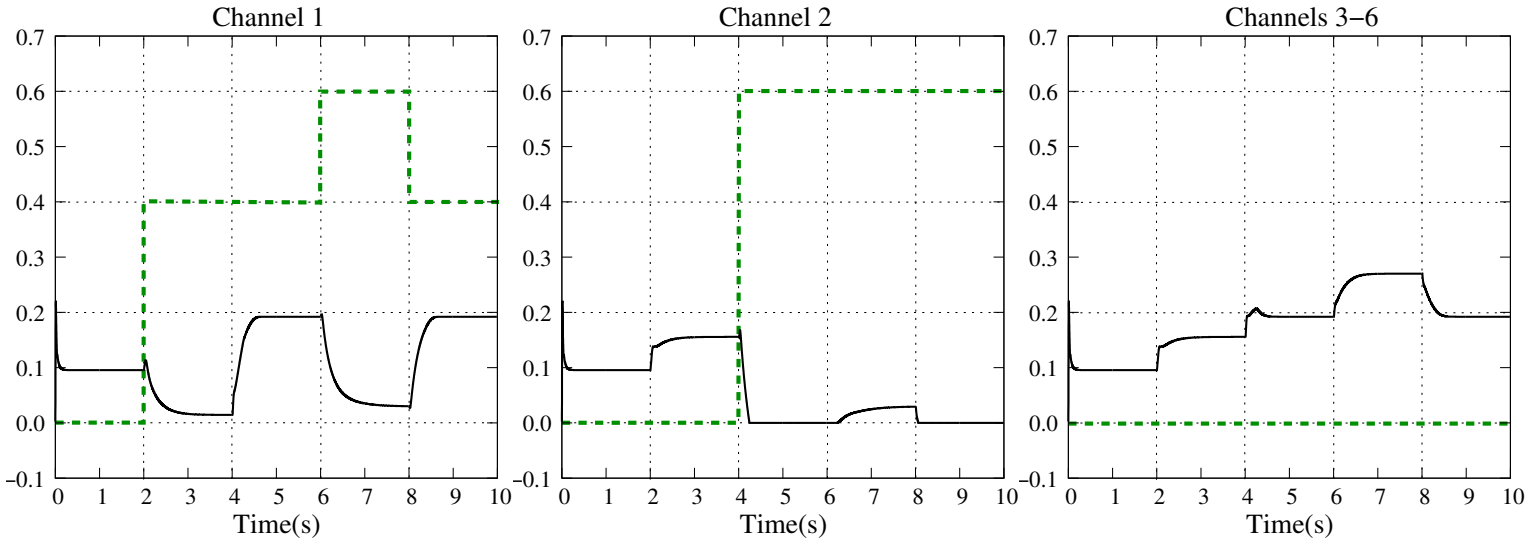
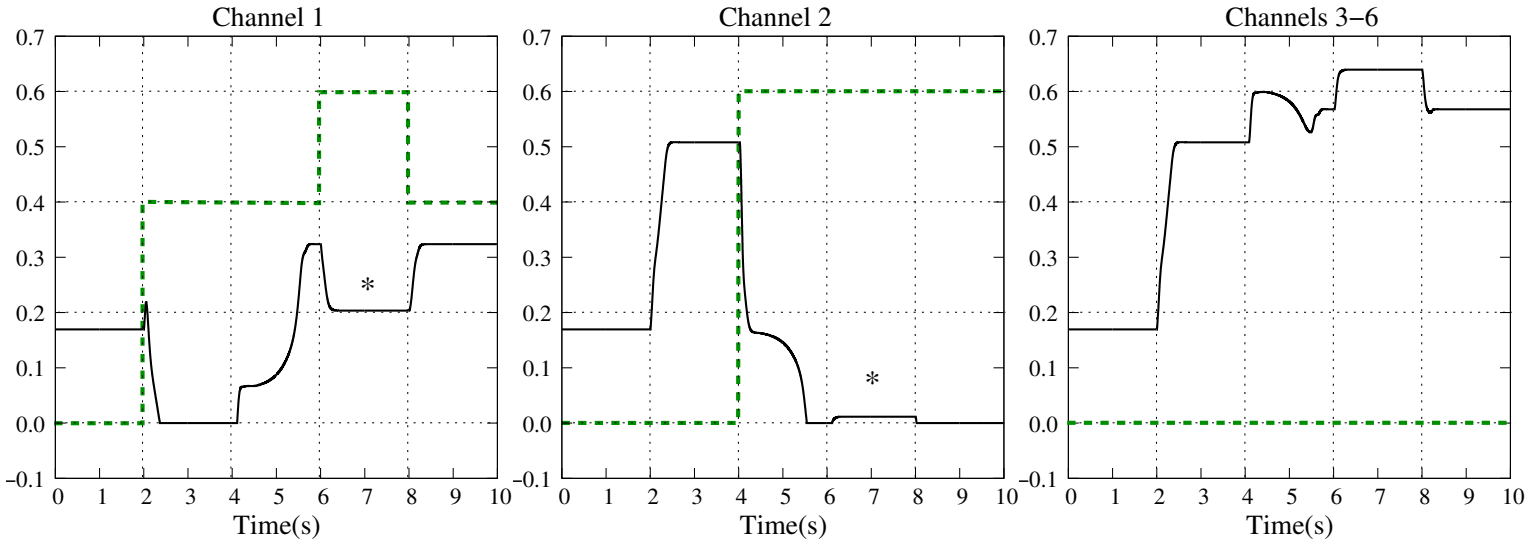
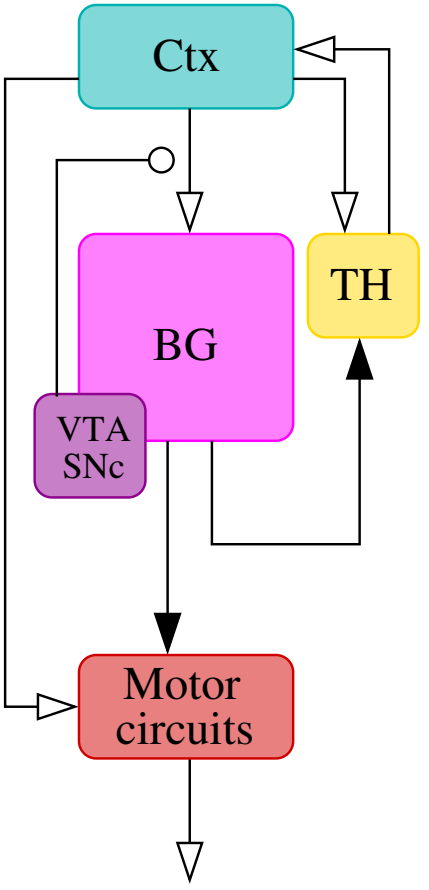
Evaluation of the model





BG & dopaminergic circuit



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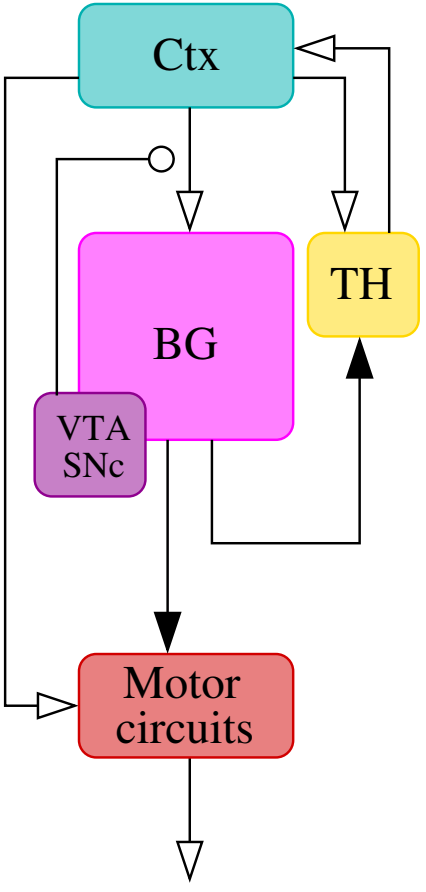

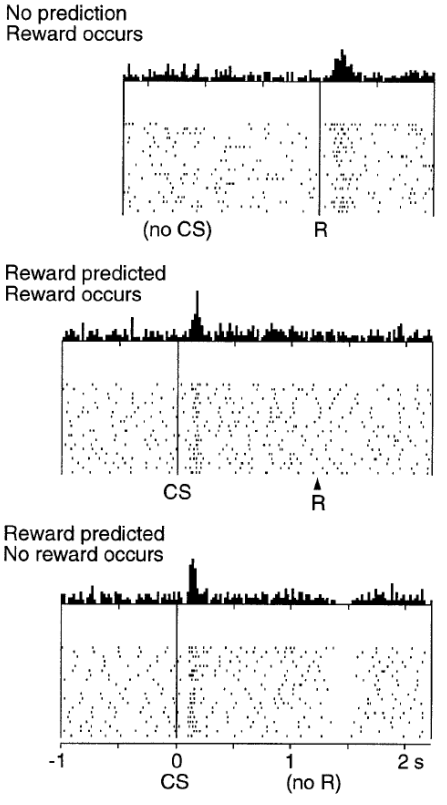

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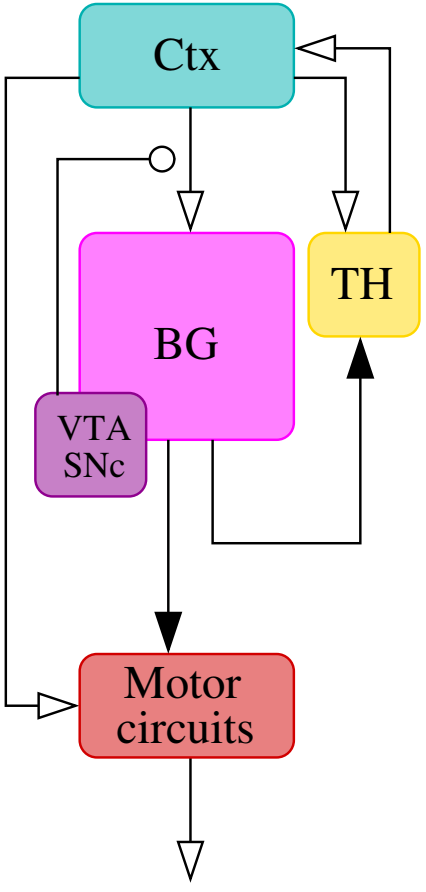
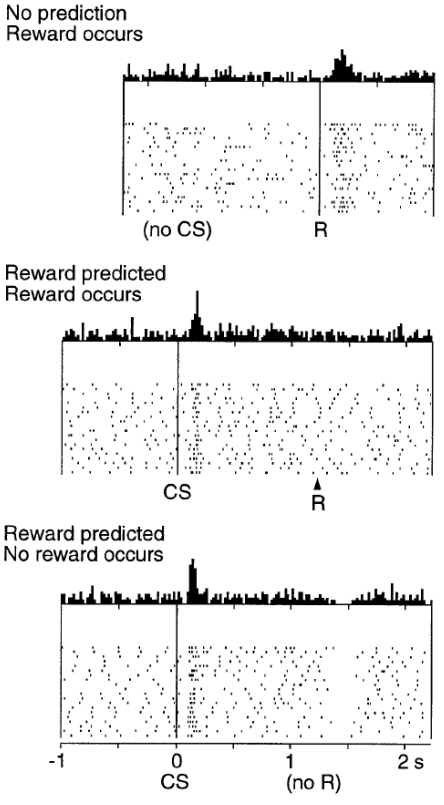
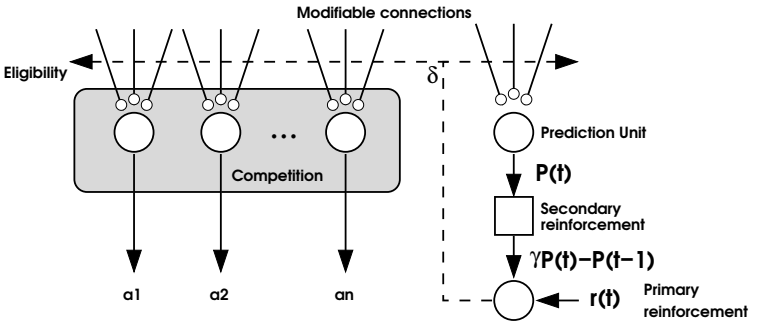


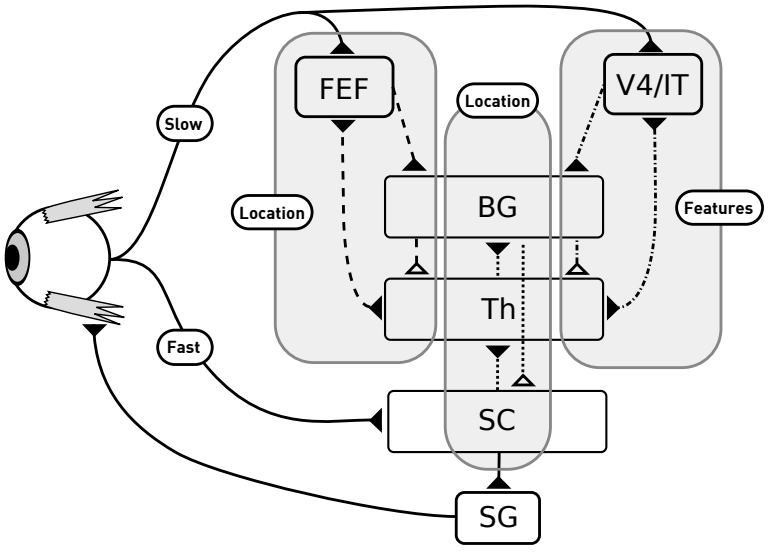


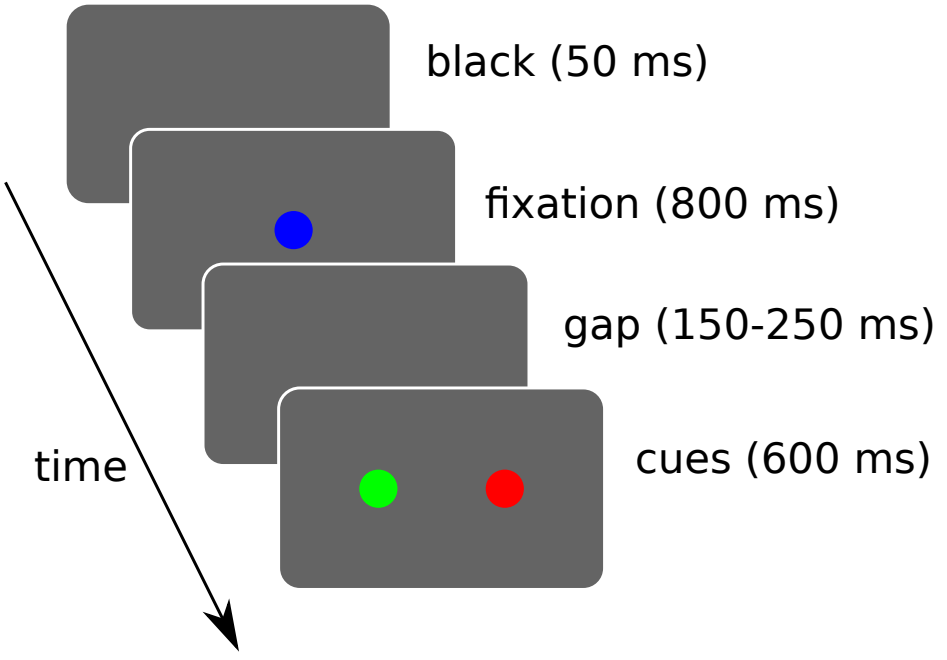


$\delta = r + \gamma P(t-1) - P(t)$

TD-learning algorithms (V, Q, SARSA...)

Learning cortical & sucortical BG loops (N'Guyen et al., 2014)





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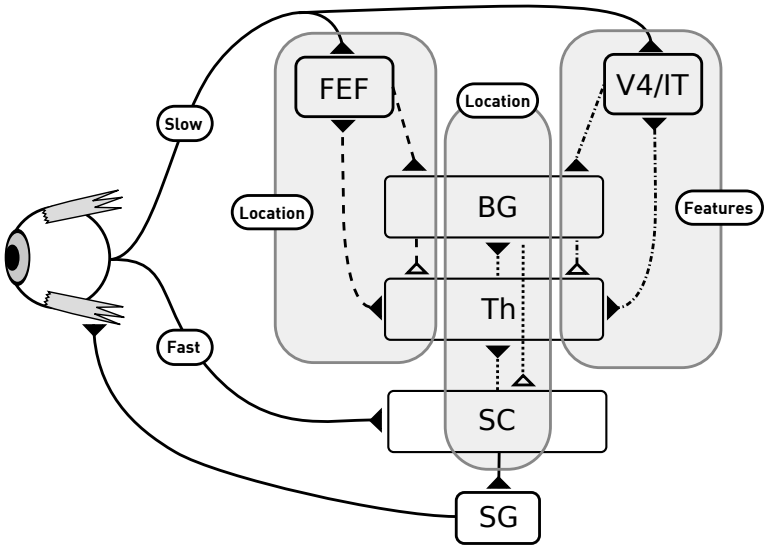
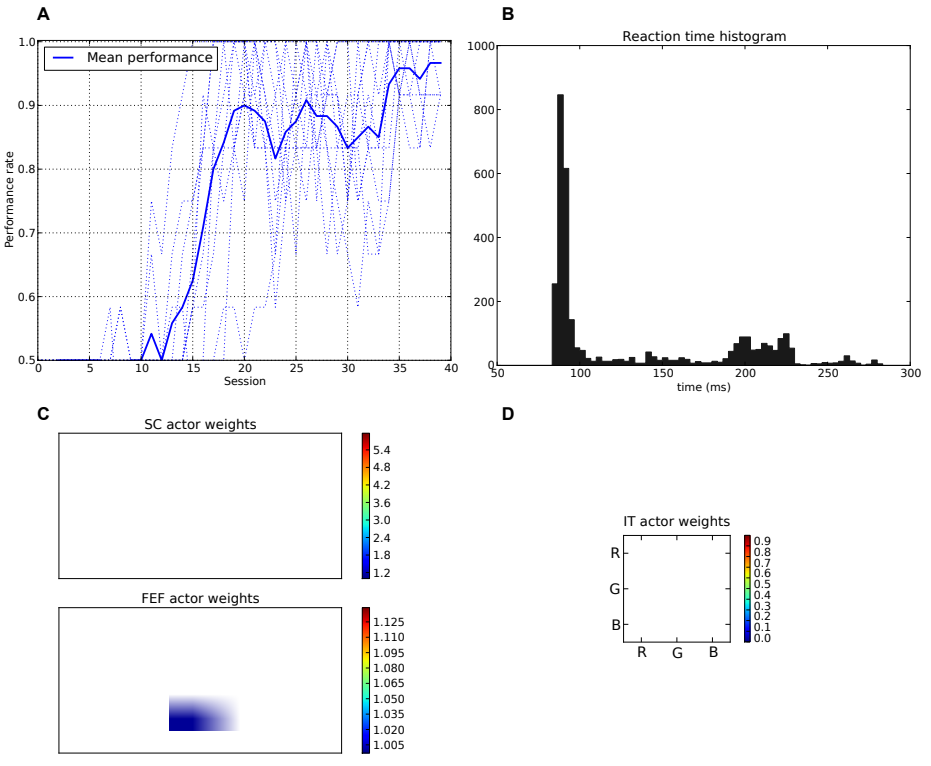


Spatial task :



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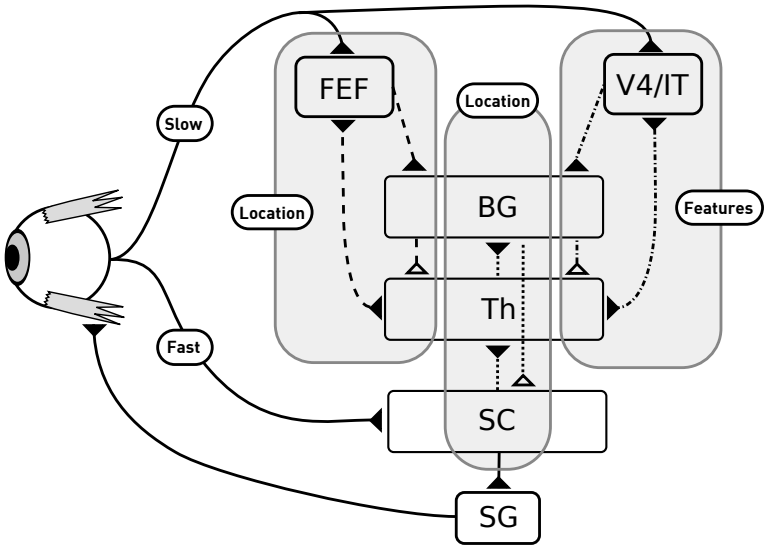

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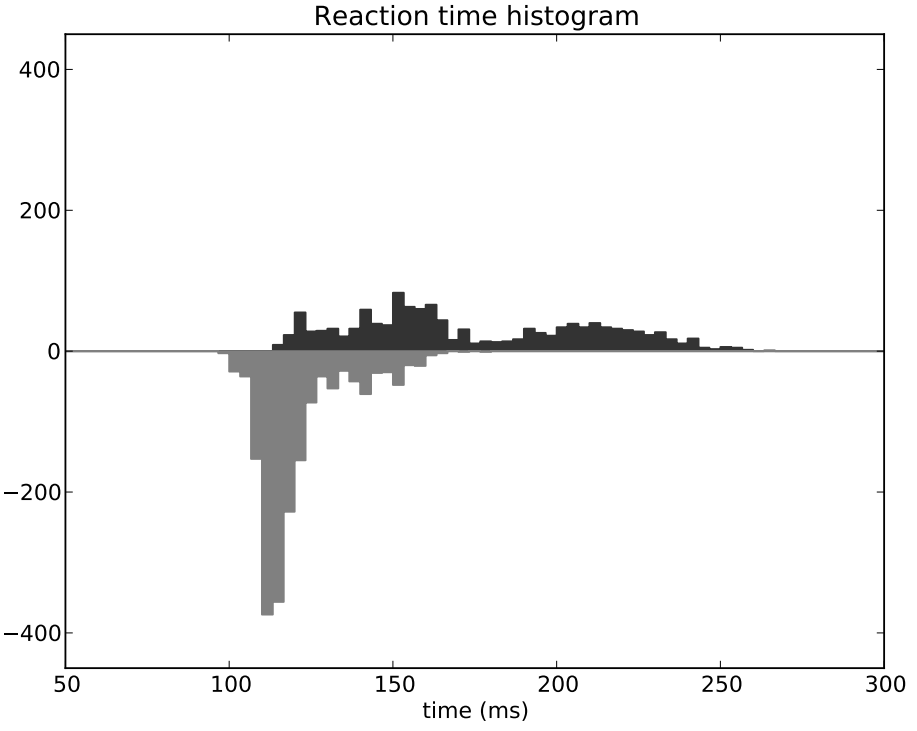

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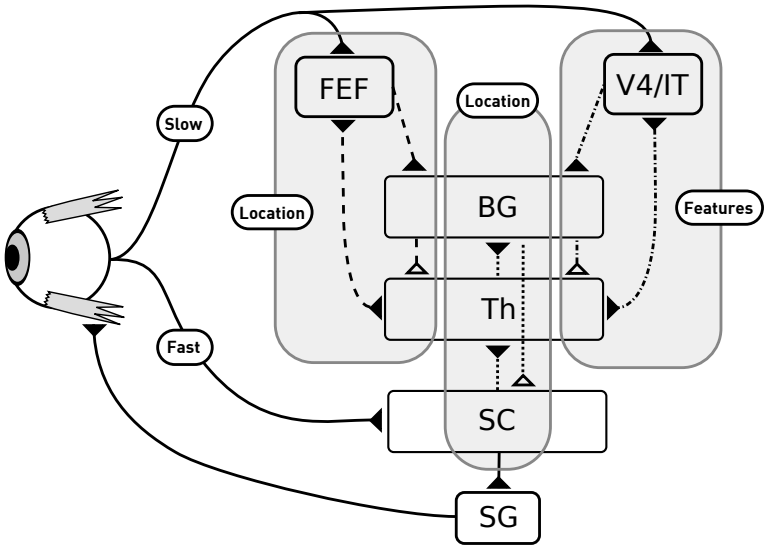

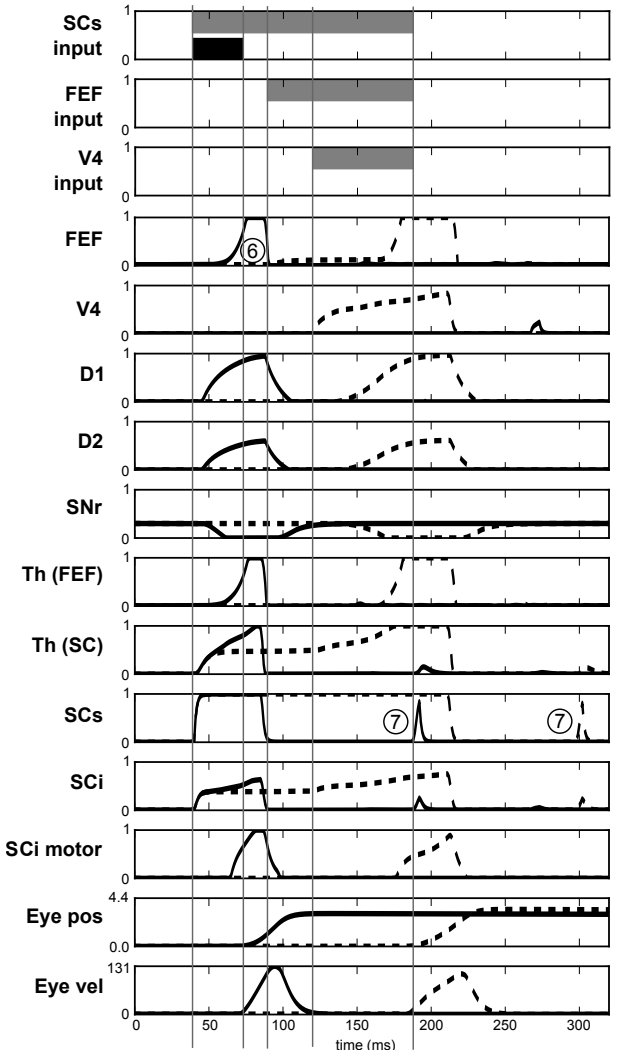

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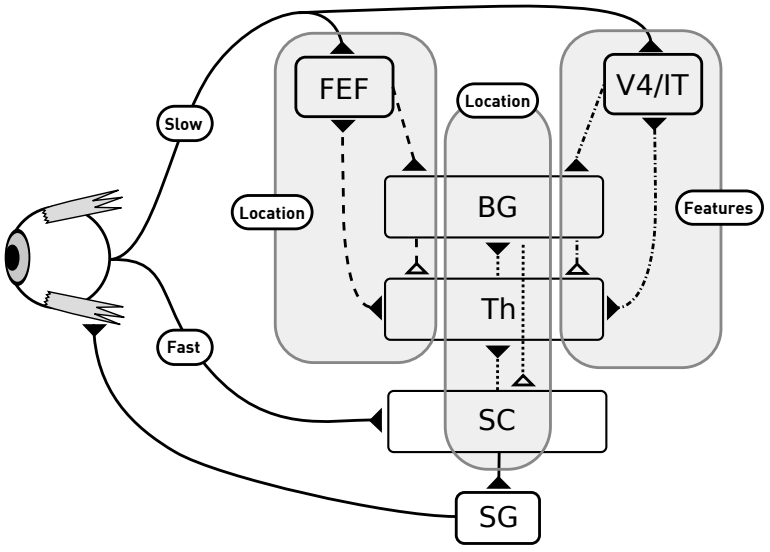
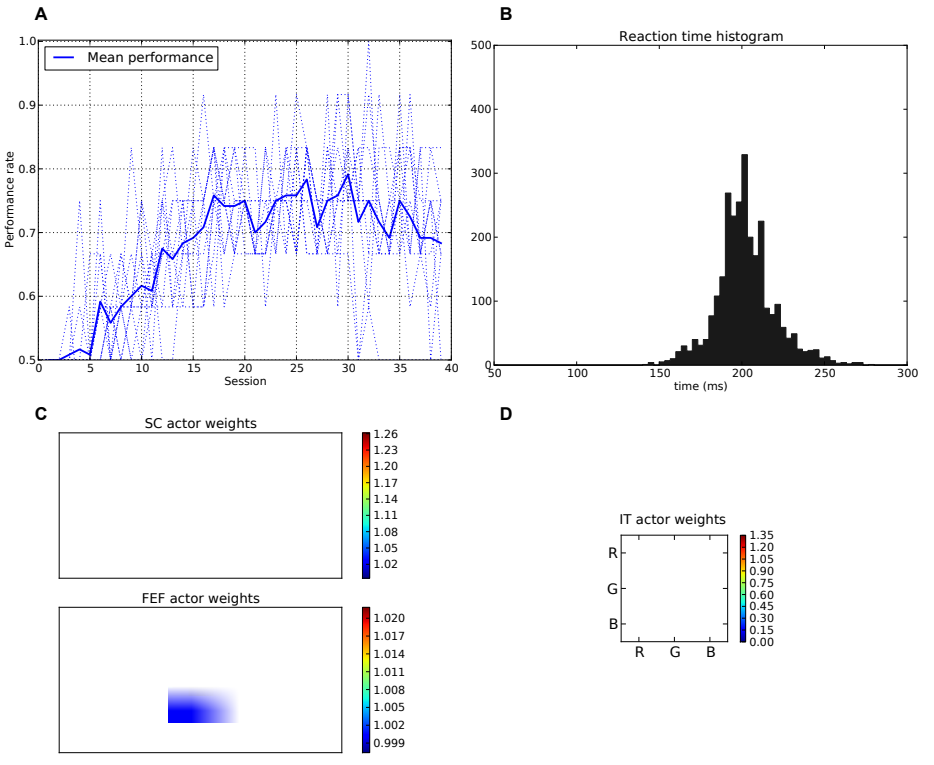


Color task :



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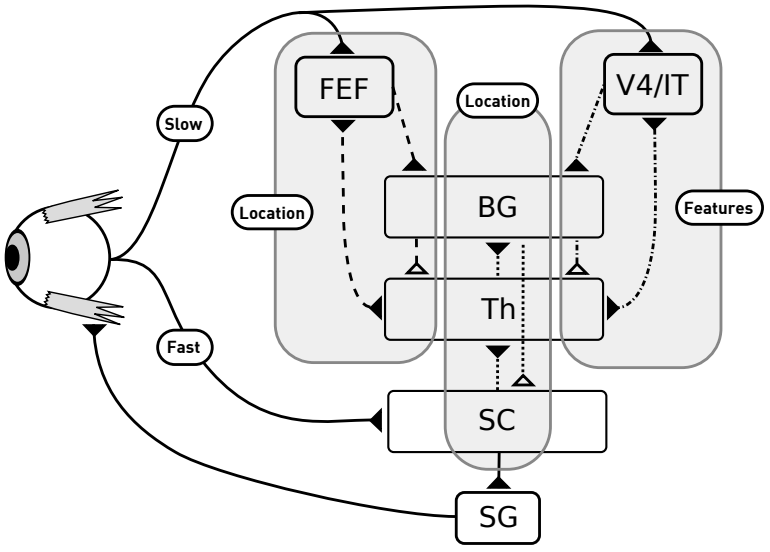
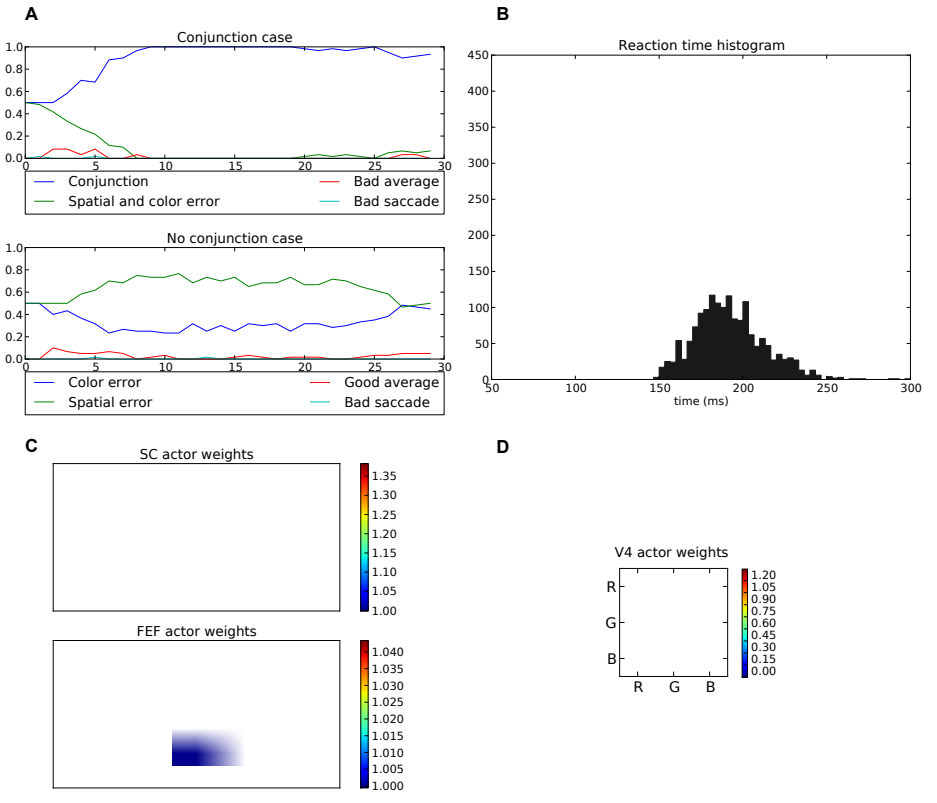
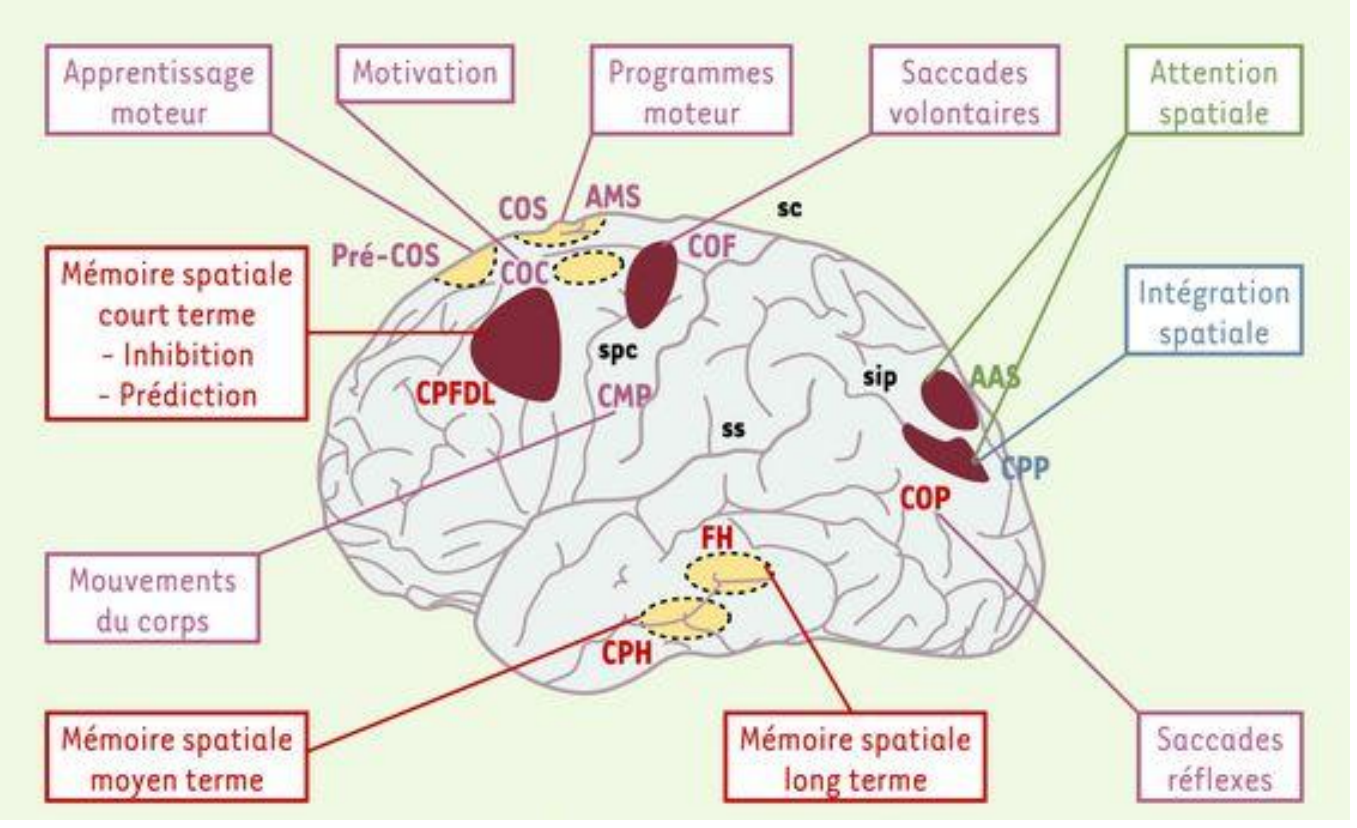


Conjunction task :

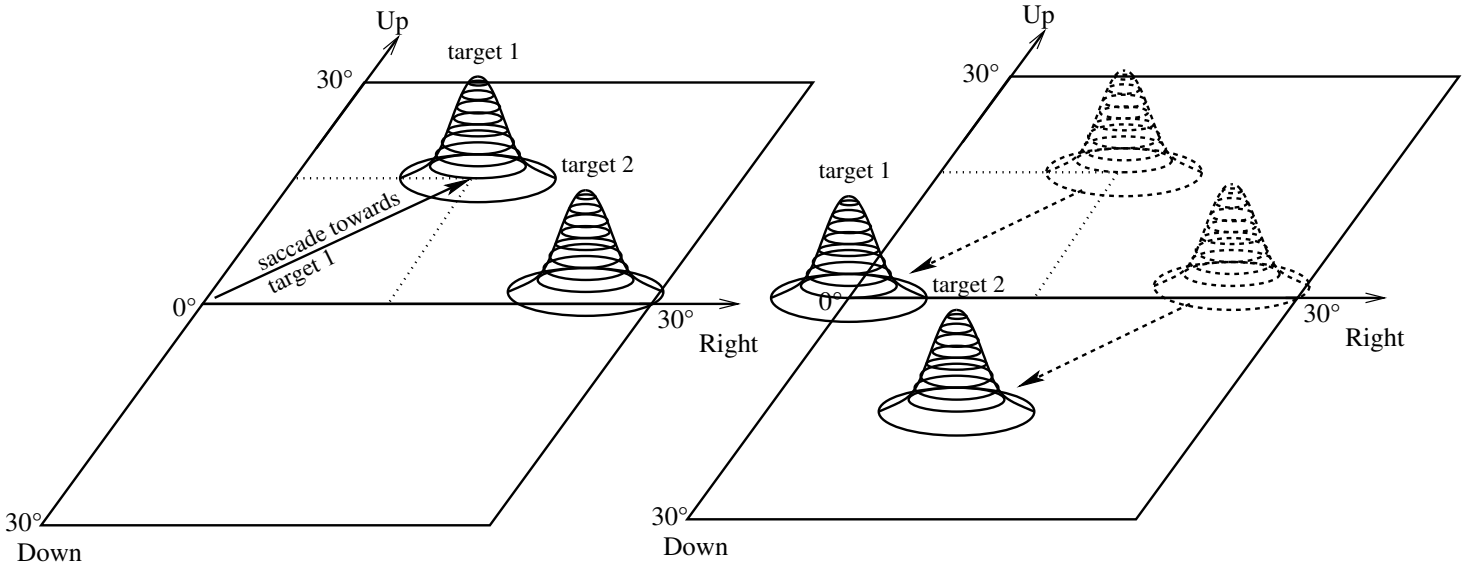


Plan

Multiple cortical regions involved



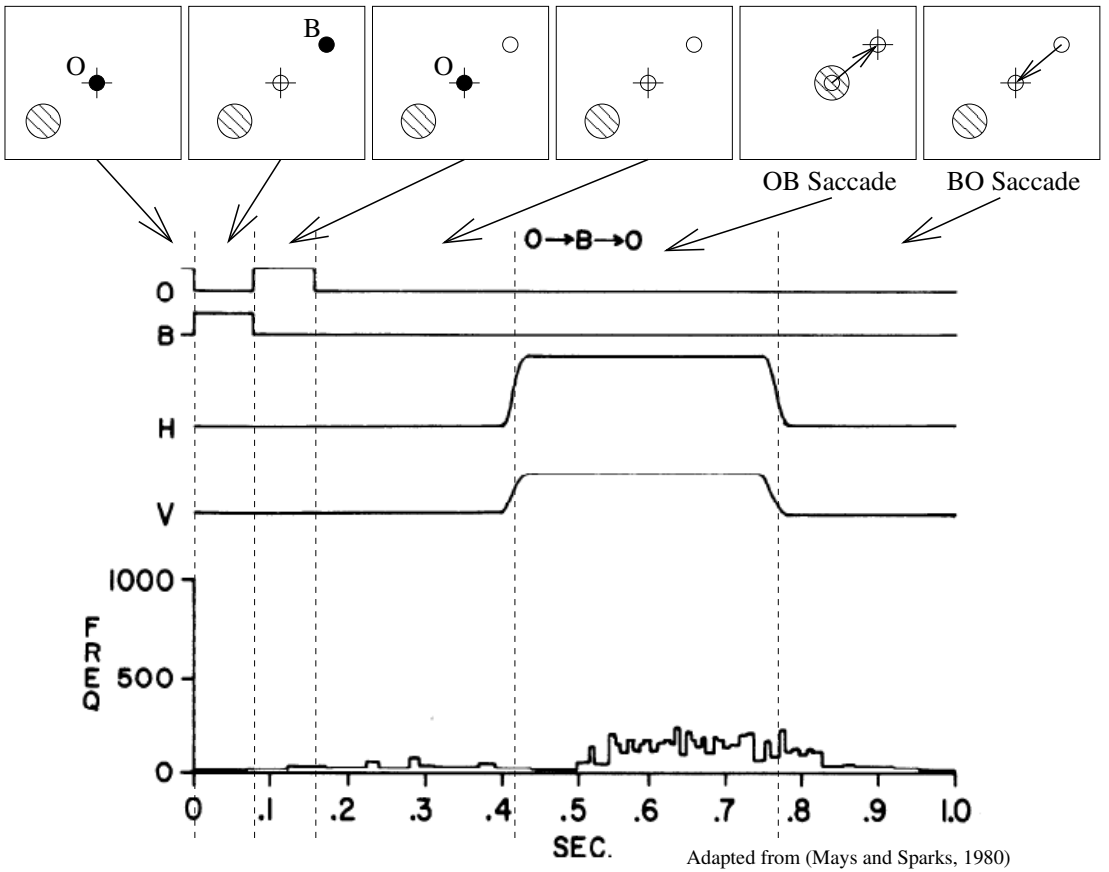
Working Memory and Remapping



Memory of the positions of the targets of the upcoming saccades in :

- Frontal Eye Fields (FEF),
- Lateral IntraParietal sulcus (LIP),

Working Memory and Remapping

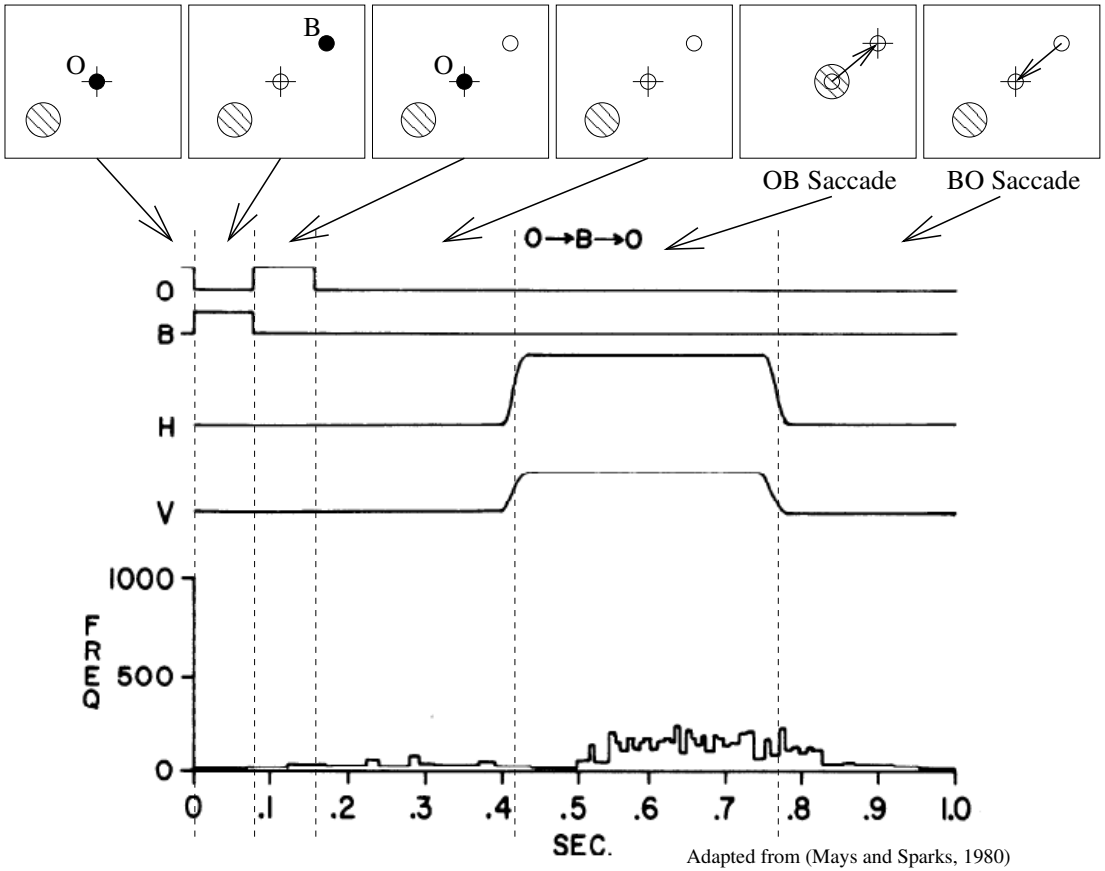


Adapted from (Mays and Sparks, 1980)

Memory of the positions of the targets of the upcoming saccades in :

- Frontal Eye Fields (FEF),
- Lateral IntraParietal sulcus (LIP),

Working Memory and Remapping

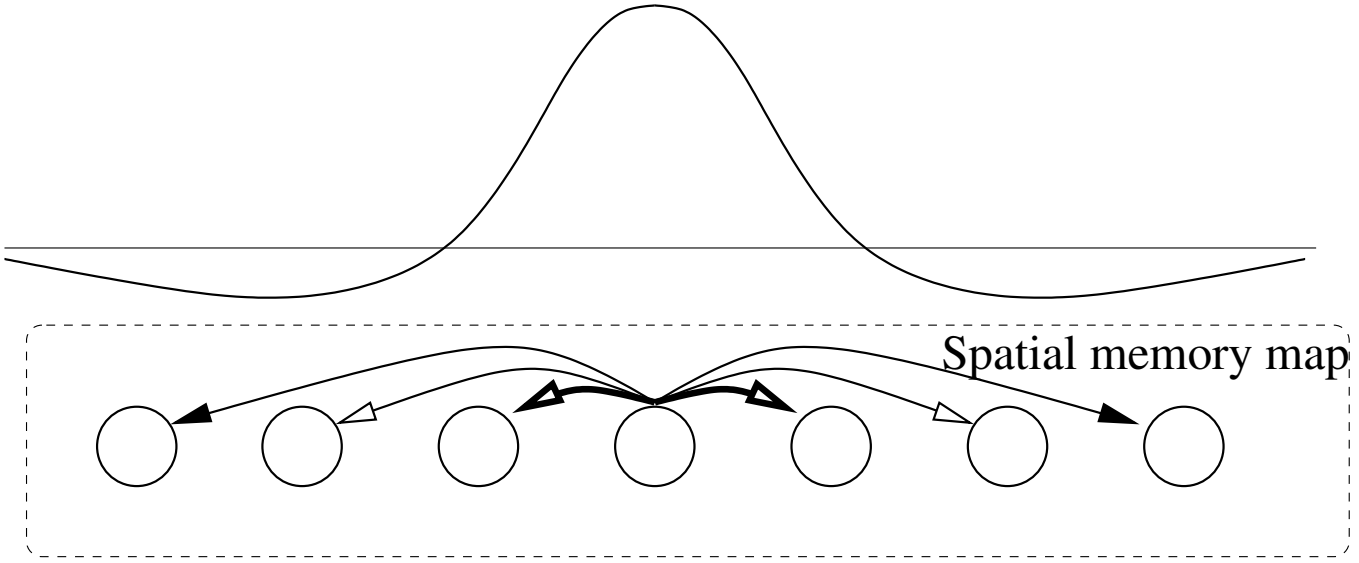


Adapted from (Mays and Sparks, 1980)

Memory of the positions of the targets of the upcoming saccades in :

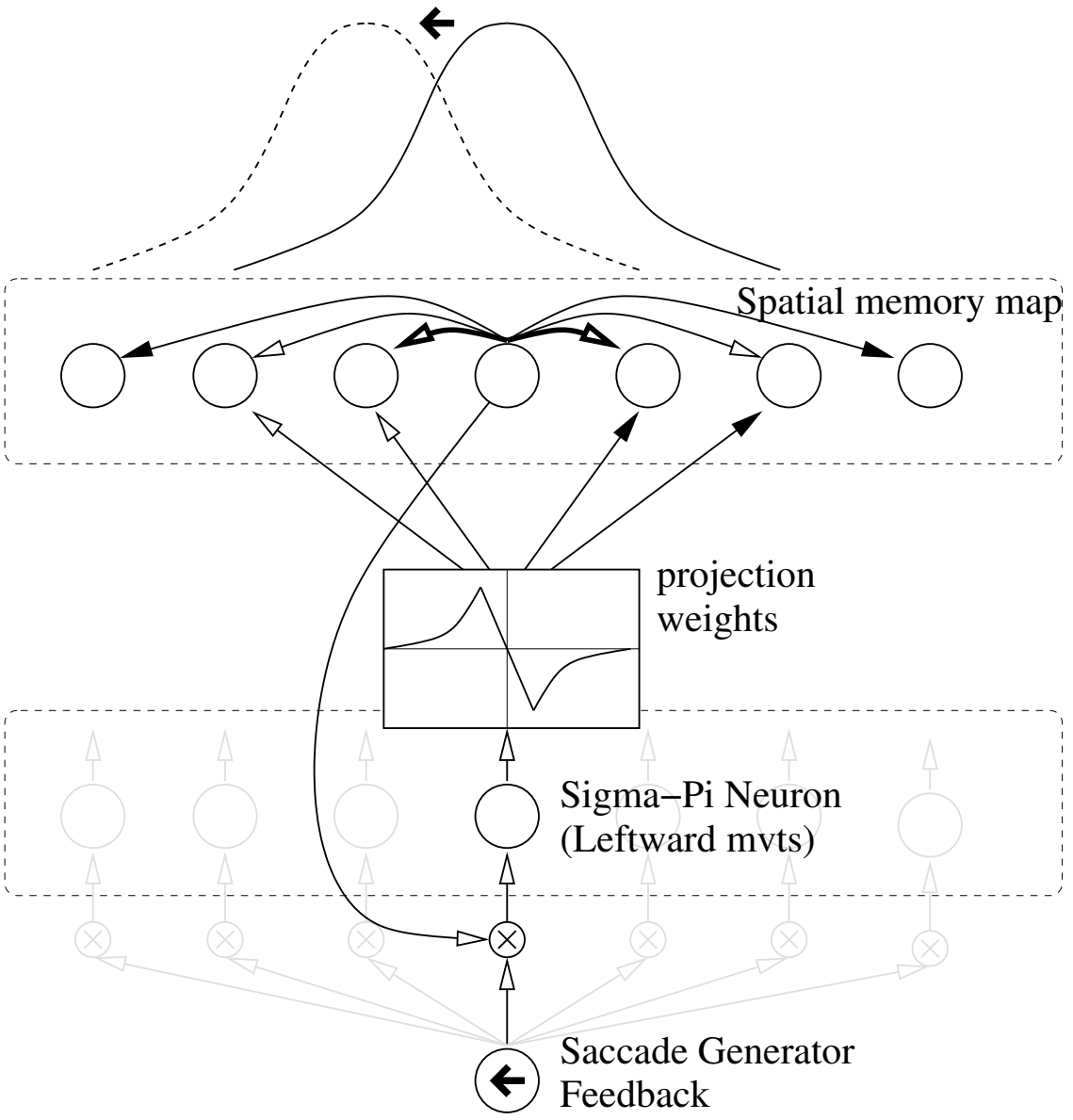
- Frontal Eye Fields (FEF),
- Lateral IntraParietal sulcus (LIP),
- Superior Colliculus ! (SC)

Moving HillS (Droulez & Berthoz, 91)

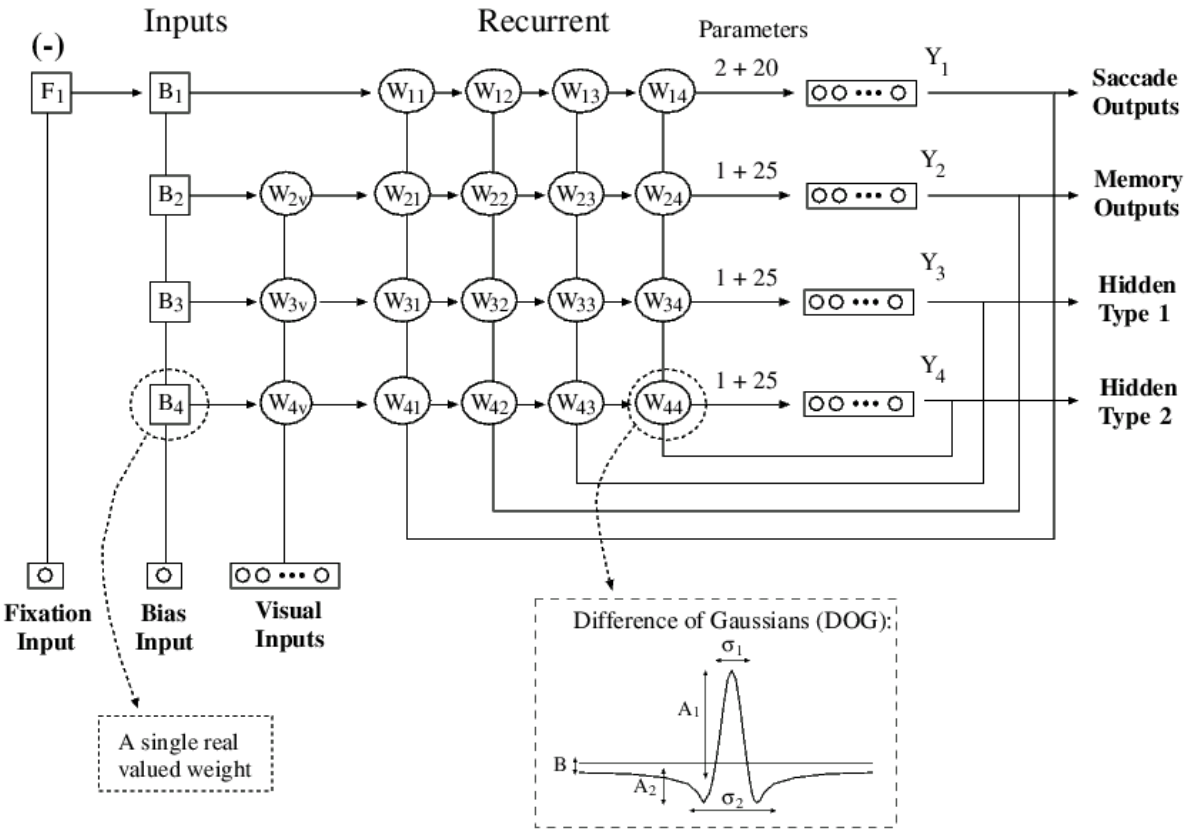


- Memory : Dynamic Neural Field
- Remapping :
  Velocity feedback
  + optimized weight profile
  + multiplicative synapses

Moving HillS (Droulez & Berthoz, 91)

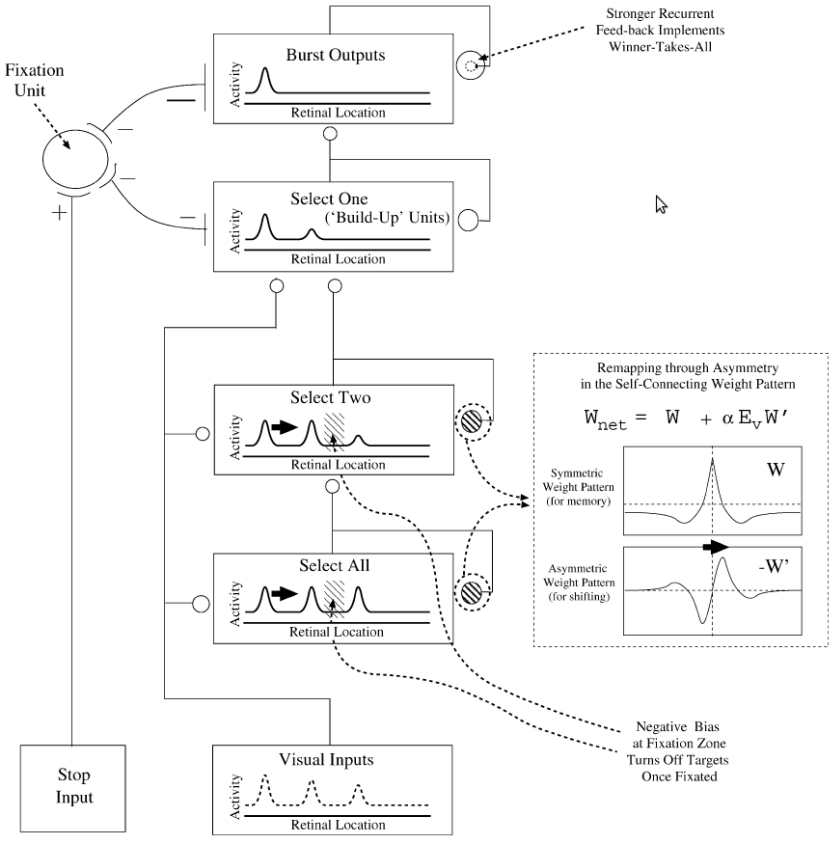


(Mitchell and Zipser, 2003)



- 3 spatial dynamic memories (moving hills), optimized to store in the position of targets and their order of appearance.
- Inhibition of return for free.

(Mitchell and Zipser, 2003)



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