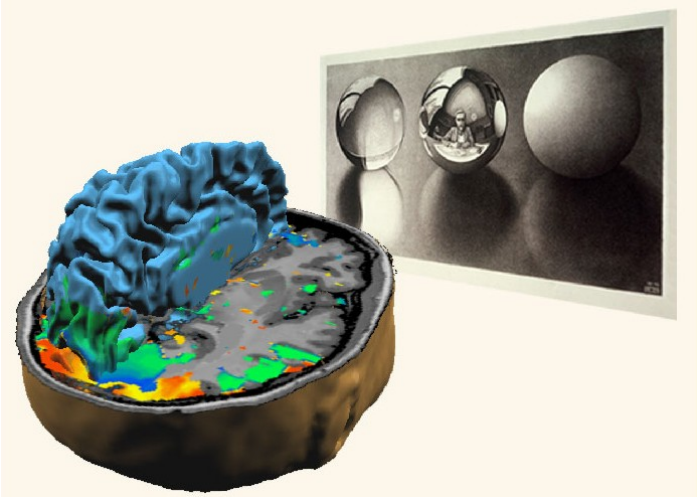
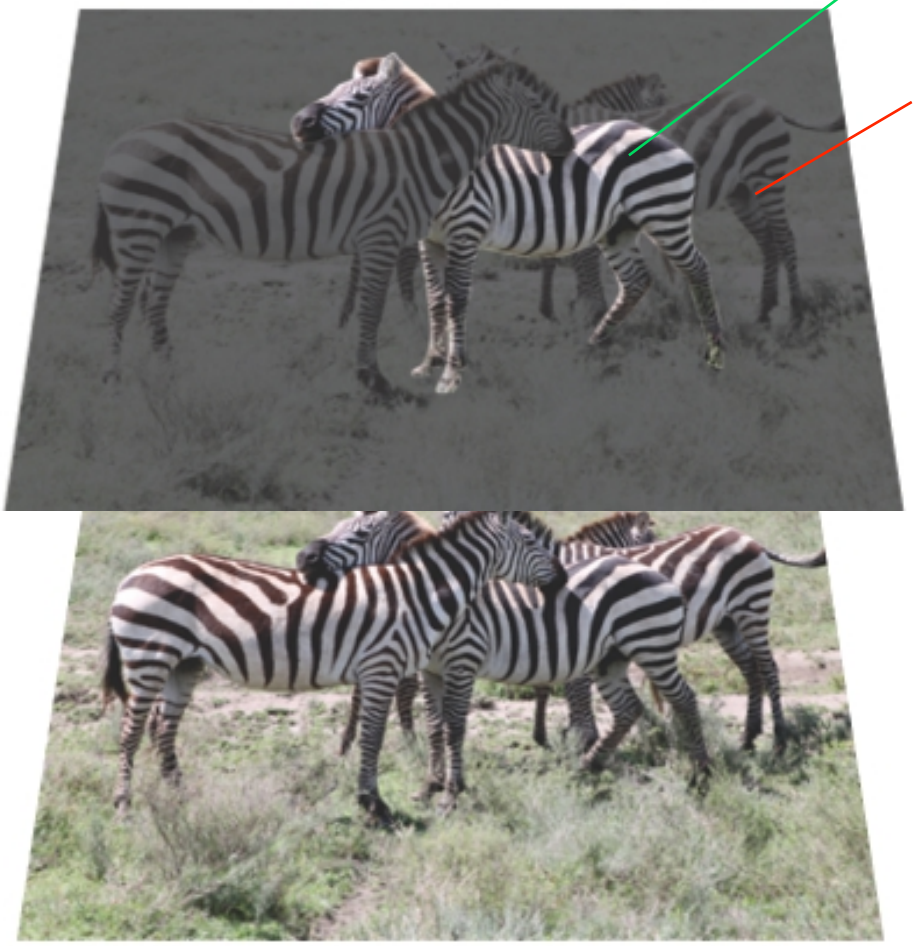
Control of synaptic plasticity in deep cortical networks



NETHERLANDS INSTITUTE FOR NEUROSCIENCE
Master the mind

Pieter R. Roelfsema
Dept. Vision & Cognition, Netherlands Institute for Neuroscience (KNAW)

Incremental grouping theory



Roelfsema, Annu Rev Neurosci, 2006; Roelfsema & Houtkamp, Attent Percept Psychophy 2011

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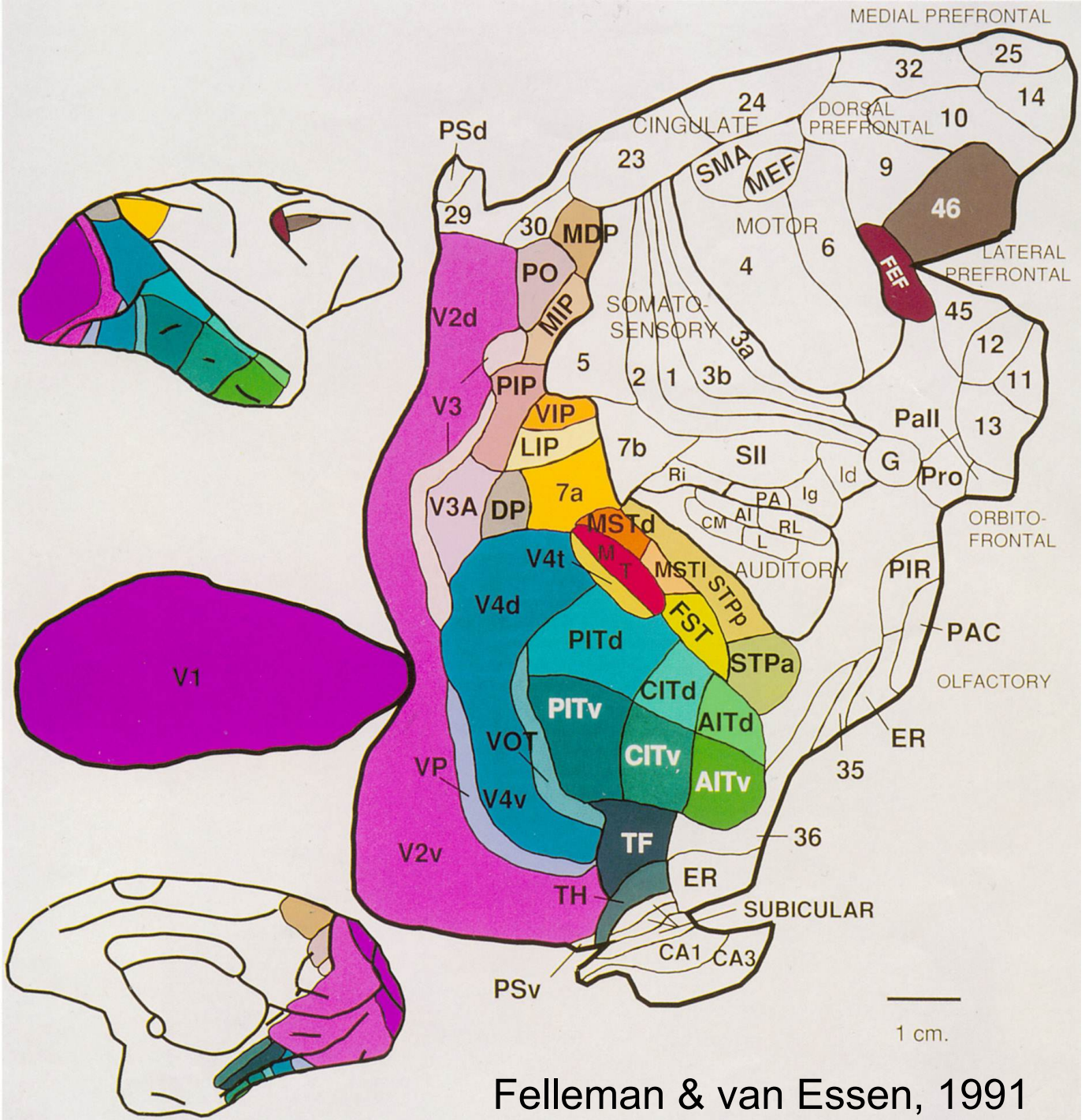
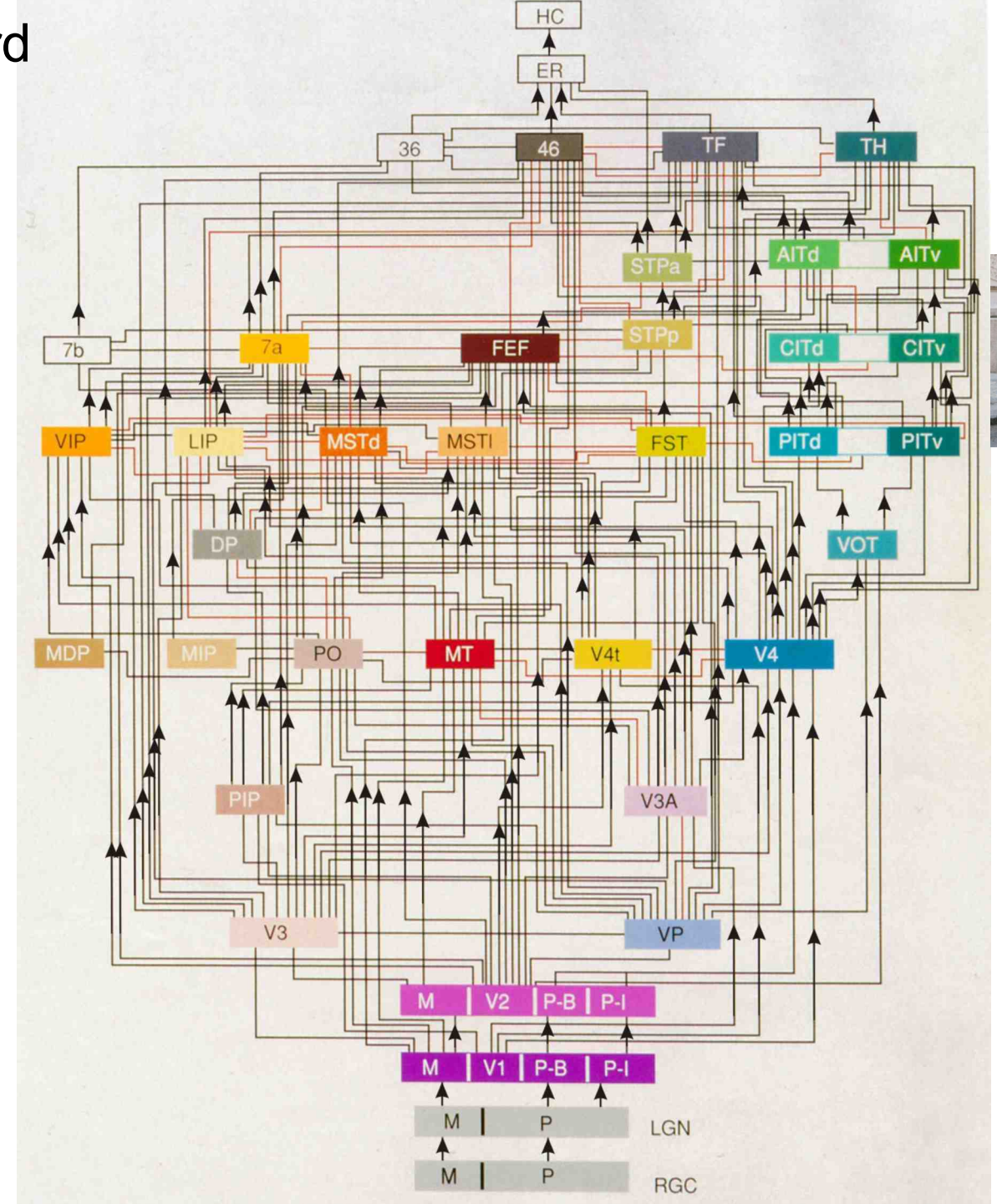


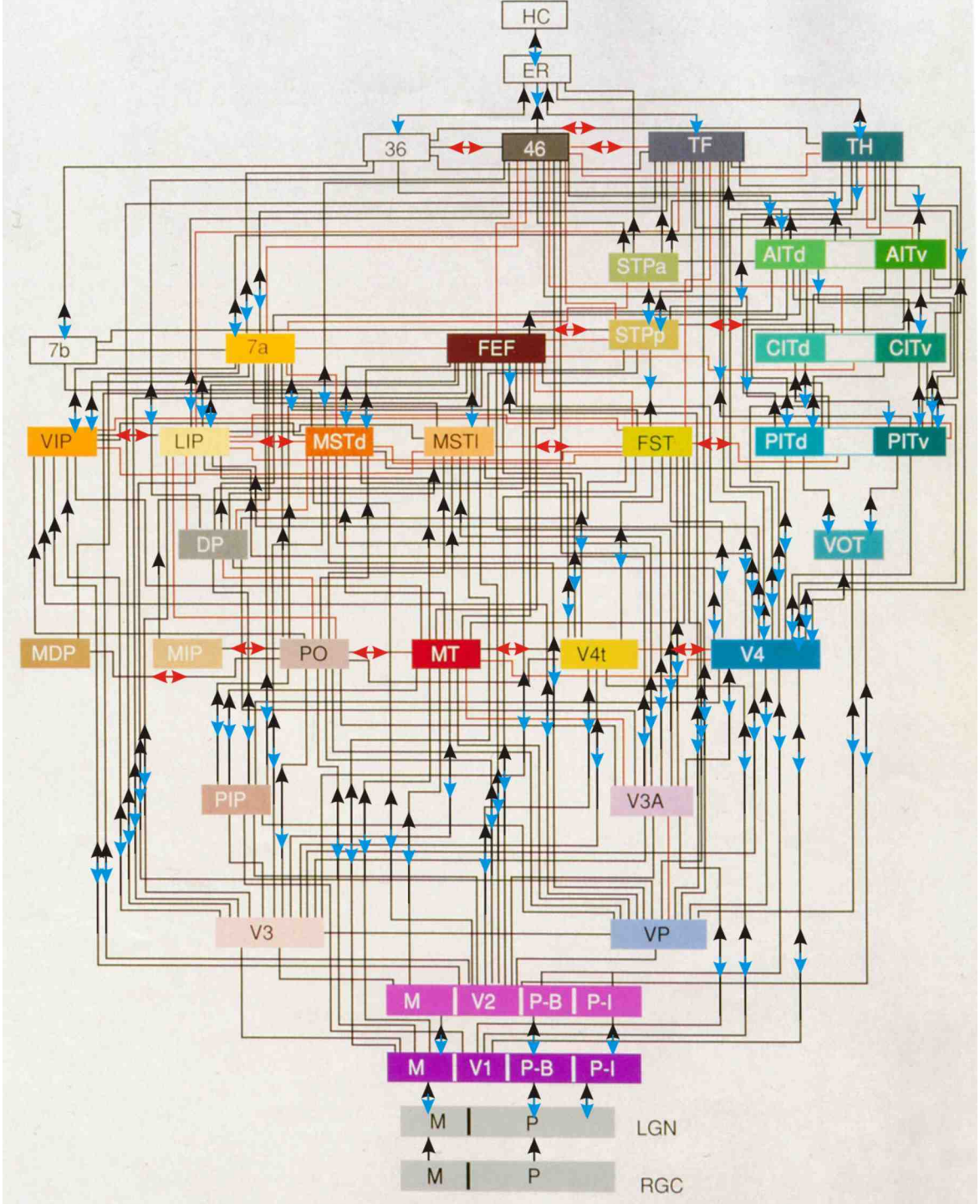
Felleman & van Essen, 1991

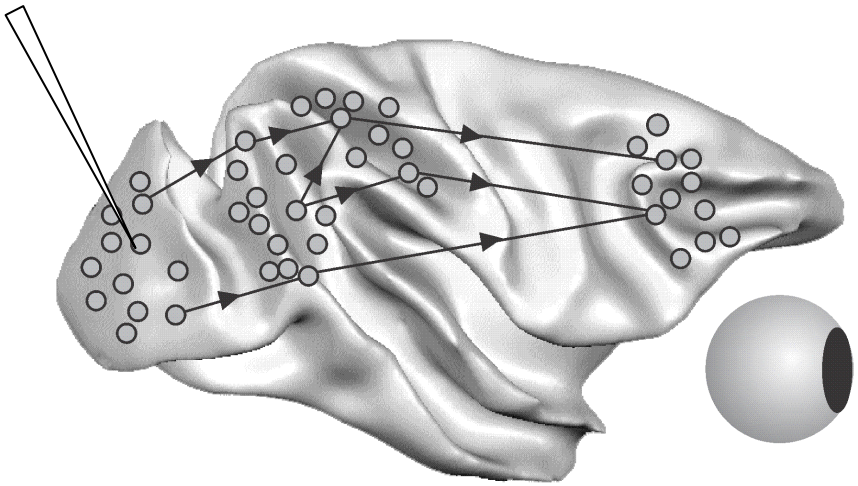
Feedforward

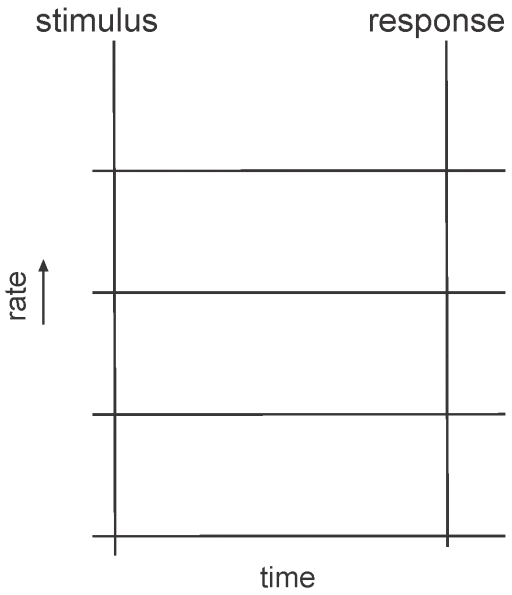


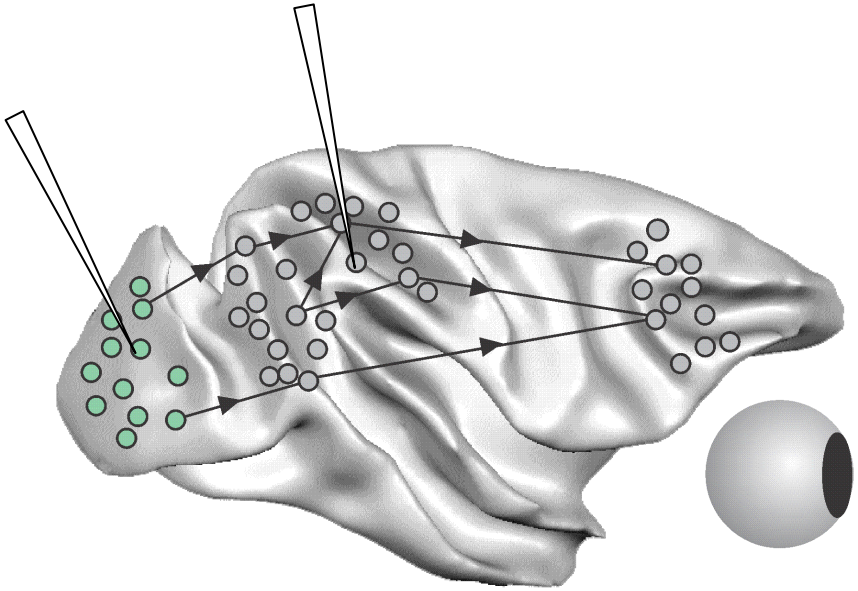
Recurrent

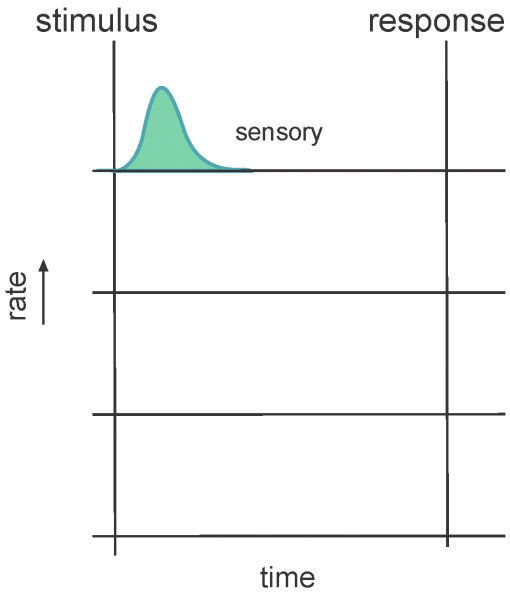
Attention

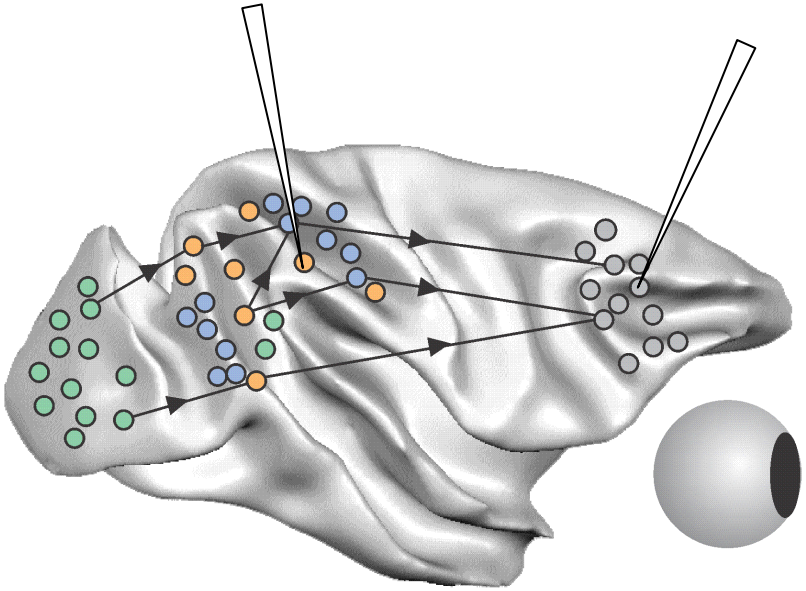


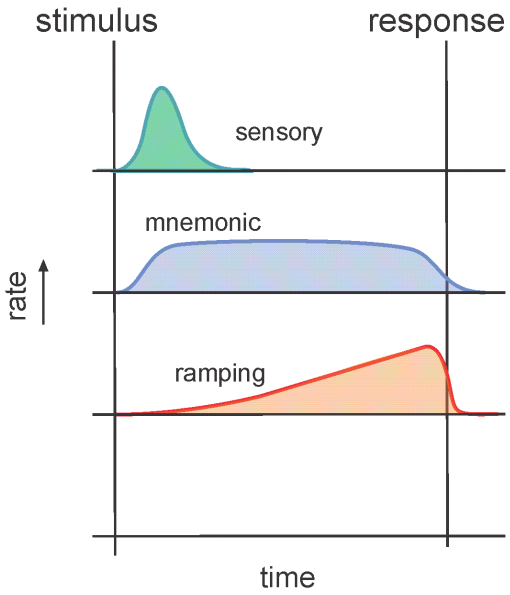


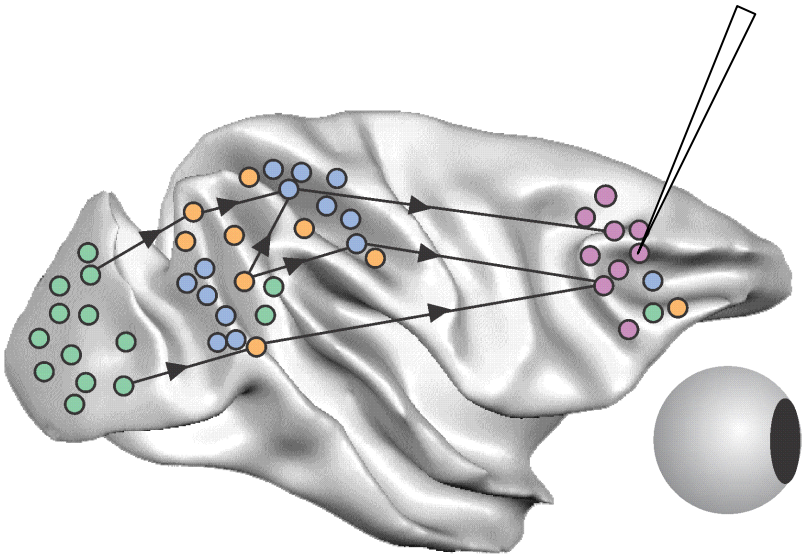

stimulus
response
rate
time

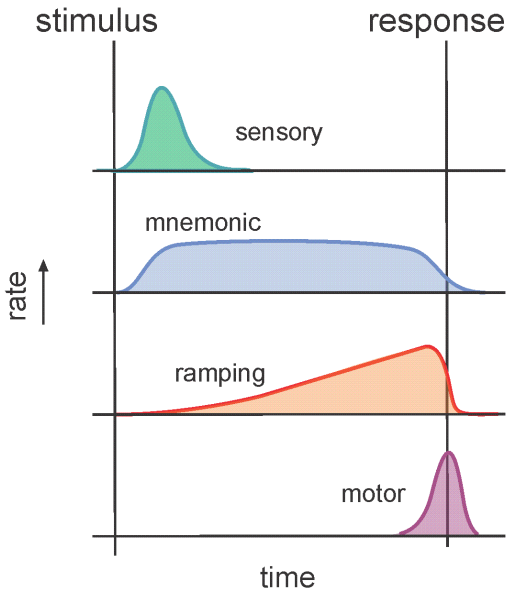



stimulus
response
sensory
rate
time

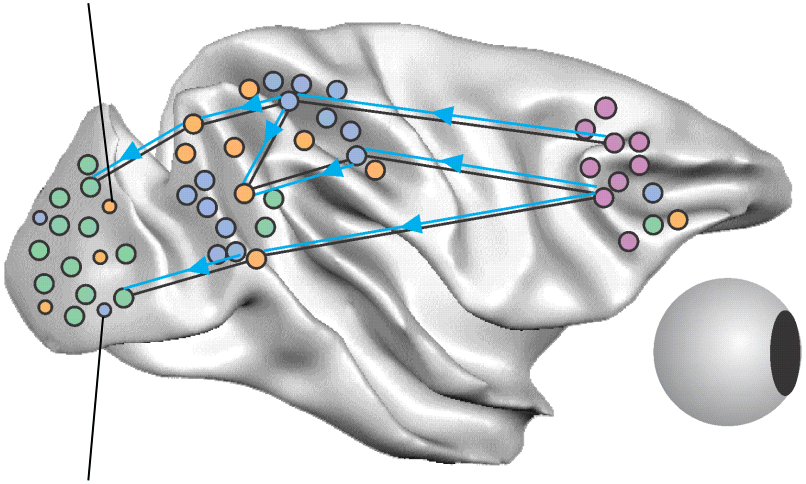



stimulus
response
sensory
mnemonic
rate
ramping
time

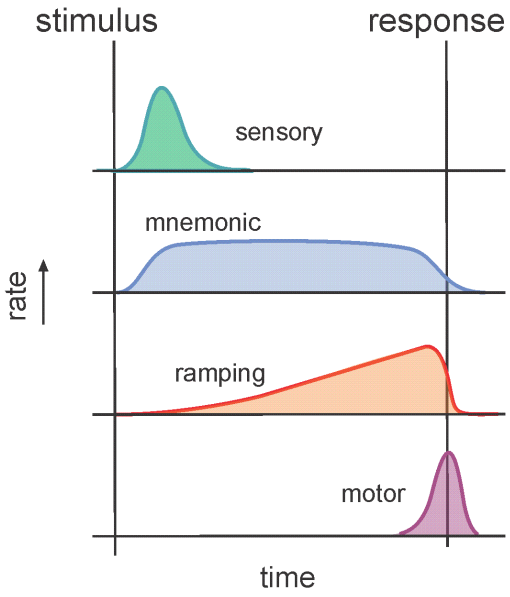


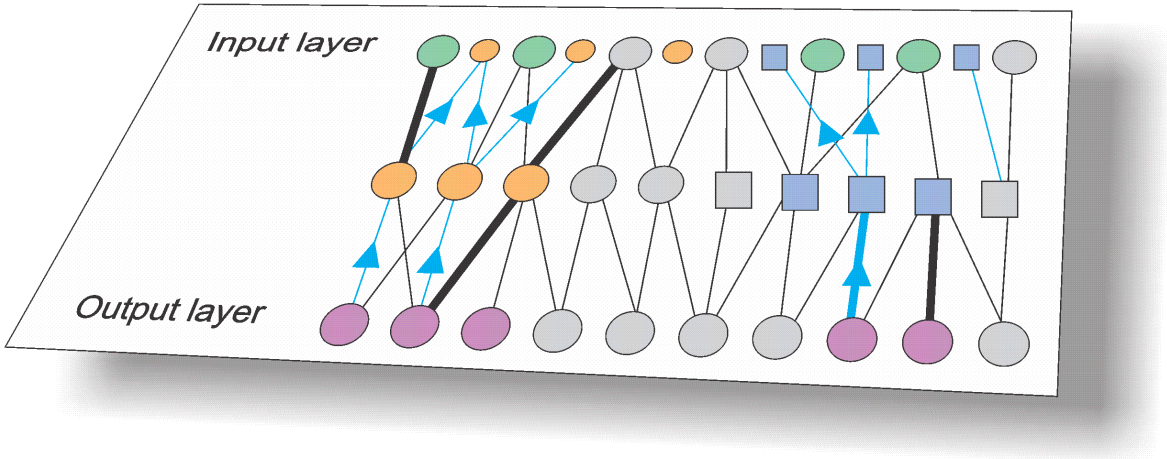

stimulus
response
sensory
mnemonic
rate
ramping
motor
time

Selection signals (attention)

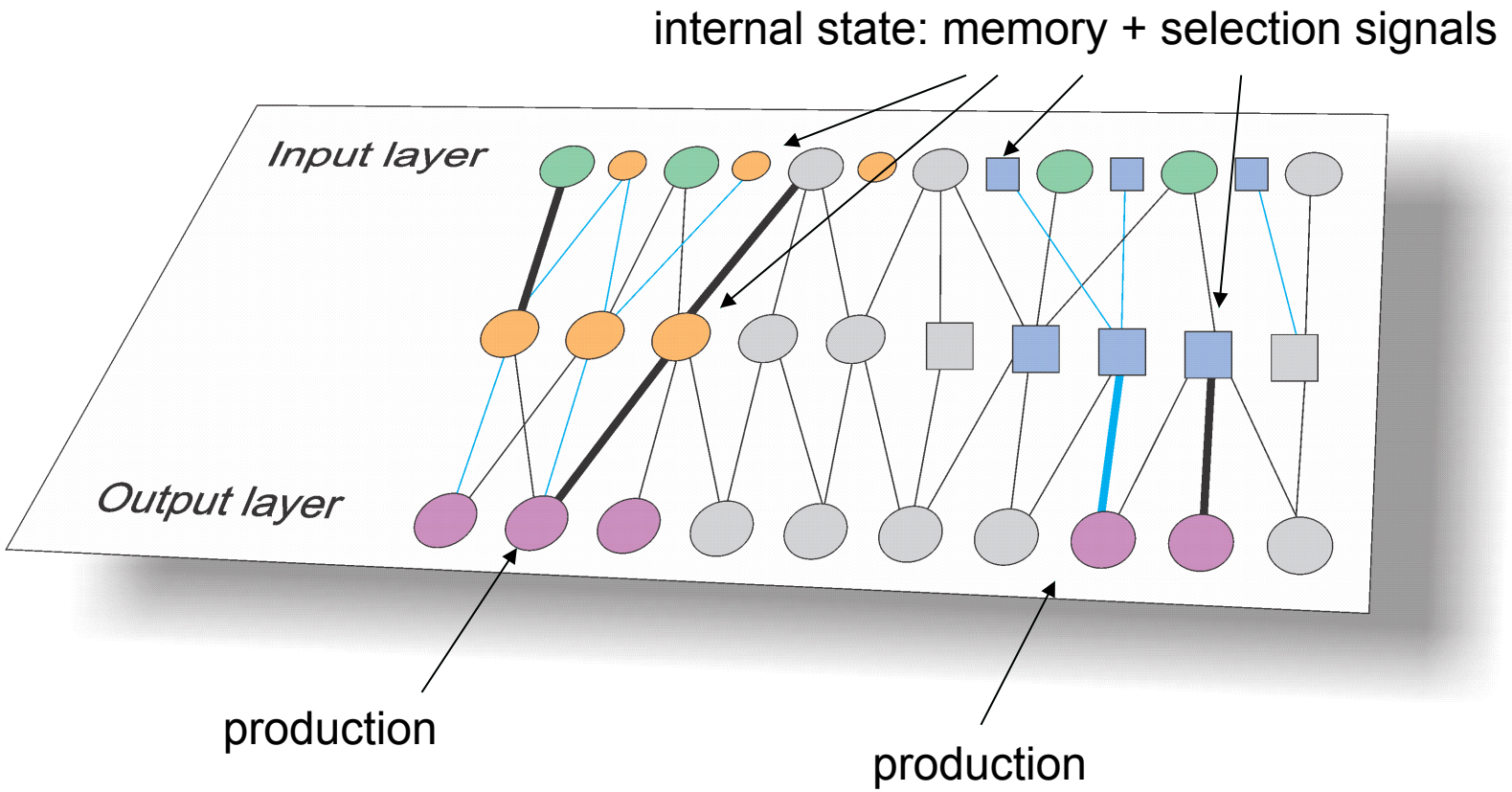


Working memory





Primate Turing Machine



Zylberberg, Dehaene, Roelfsema & Sigman, TiCS, 2011

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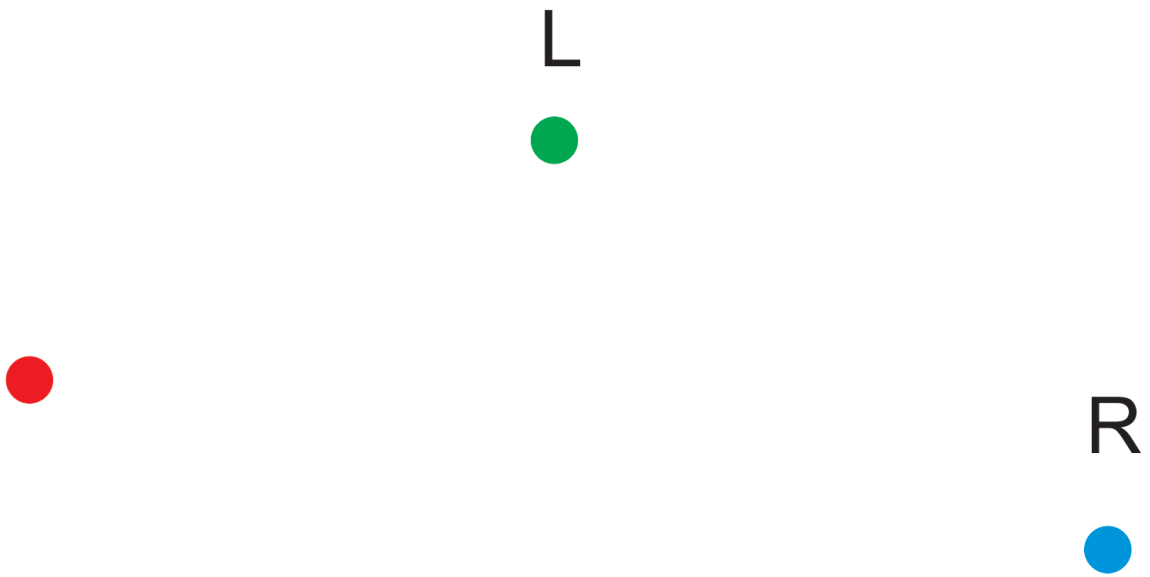
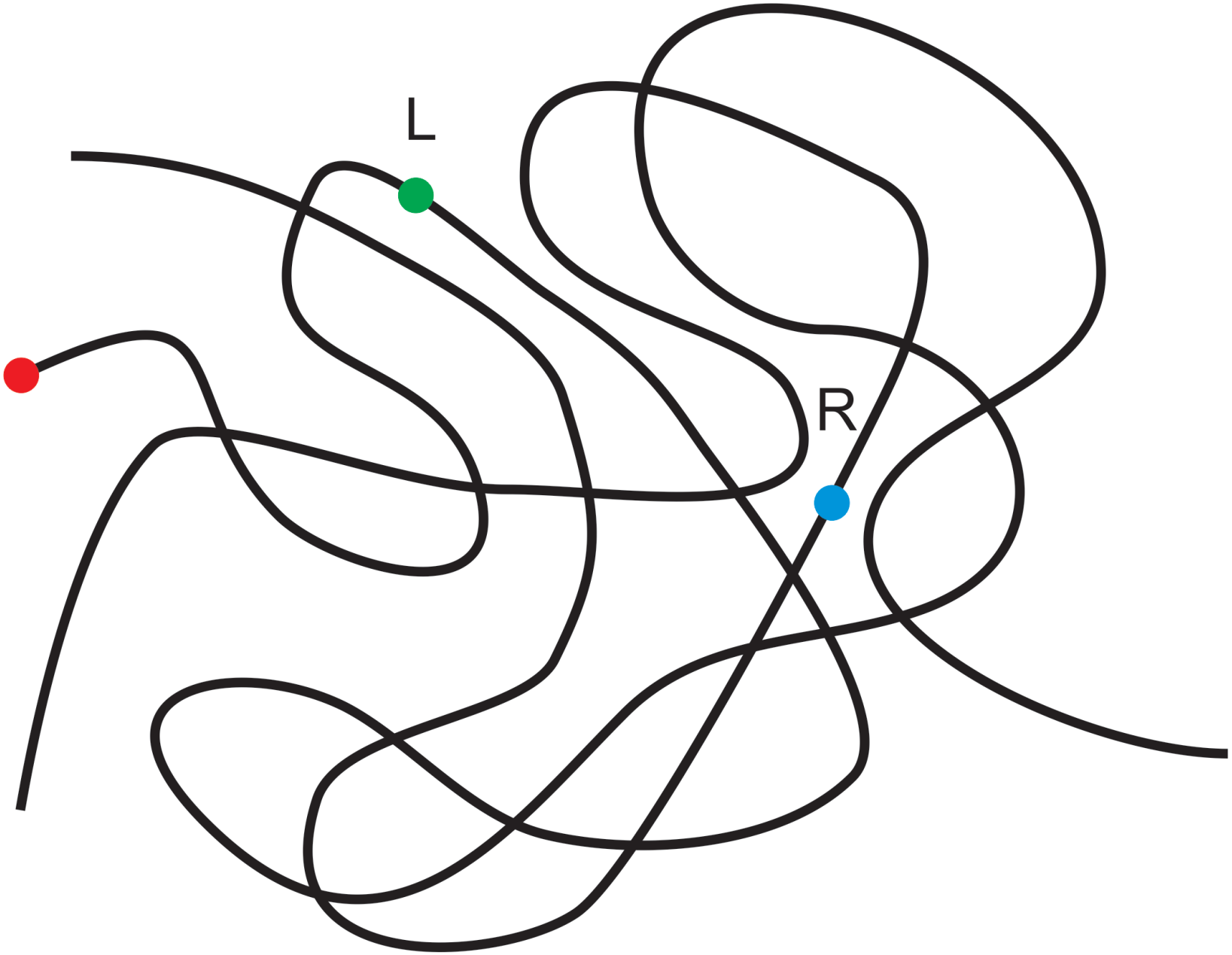
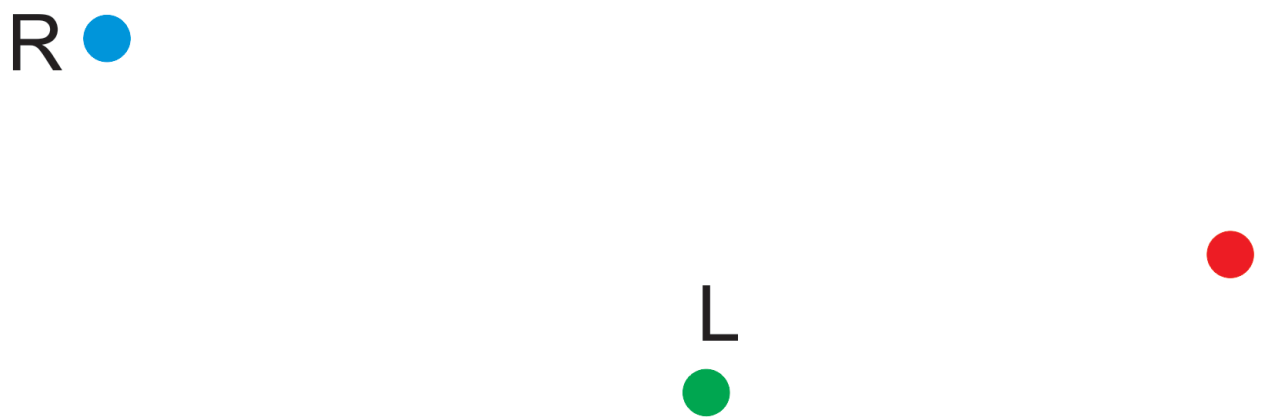
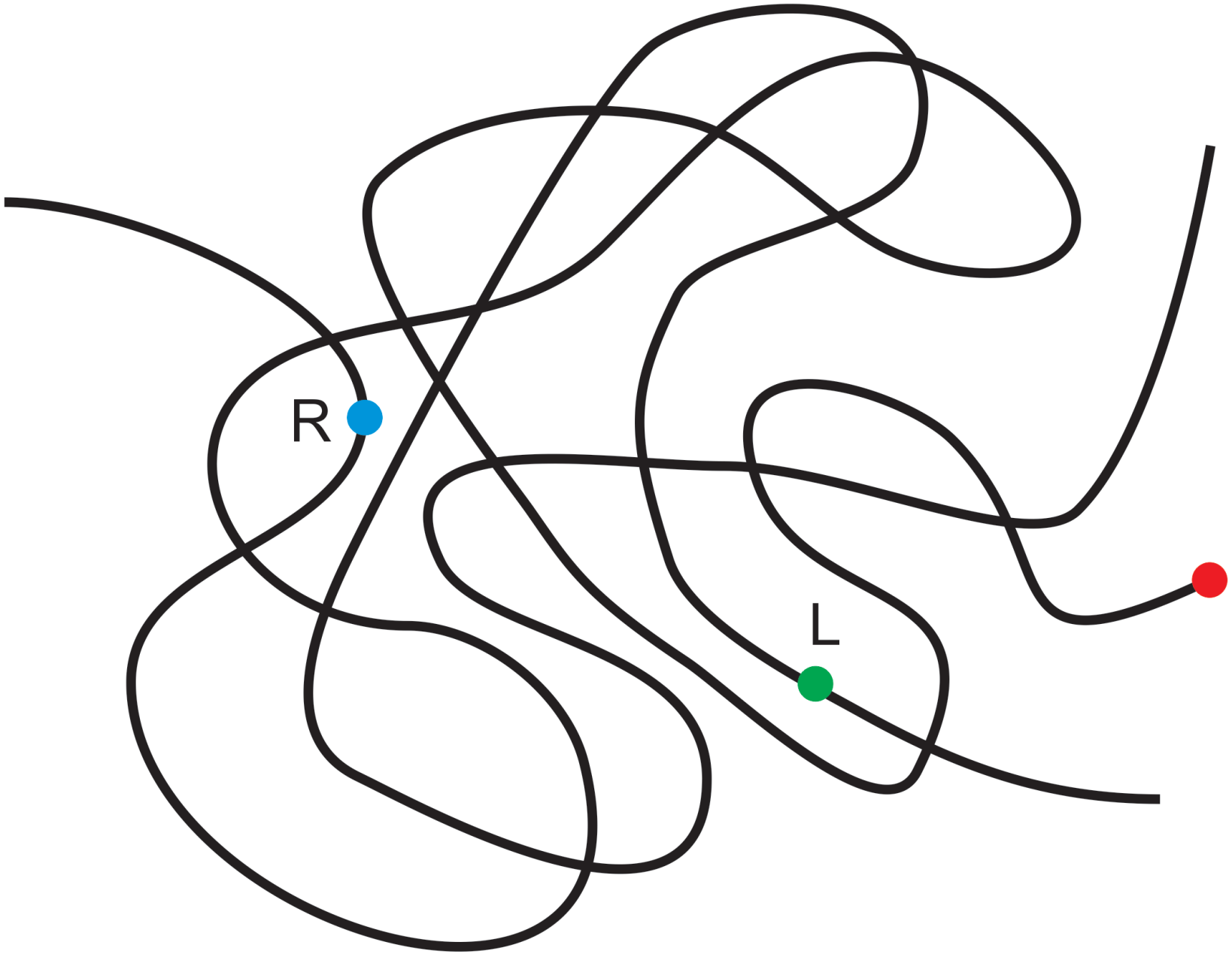
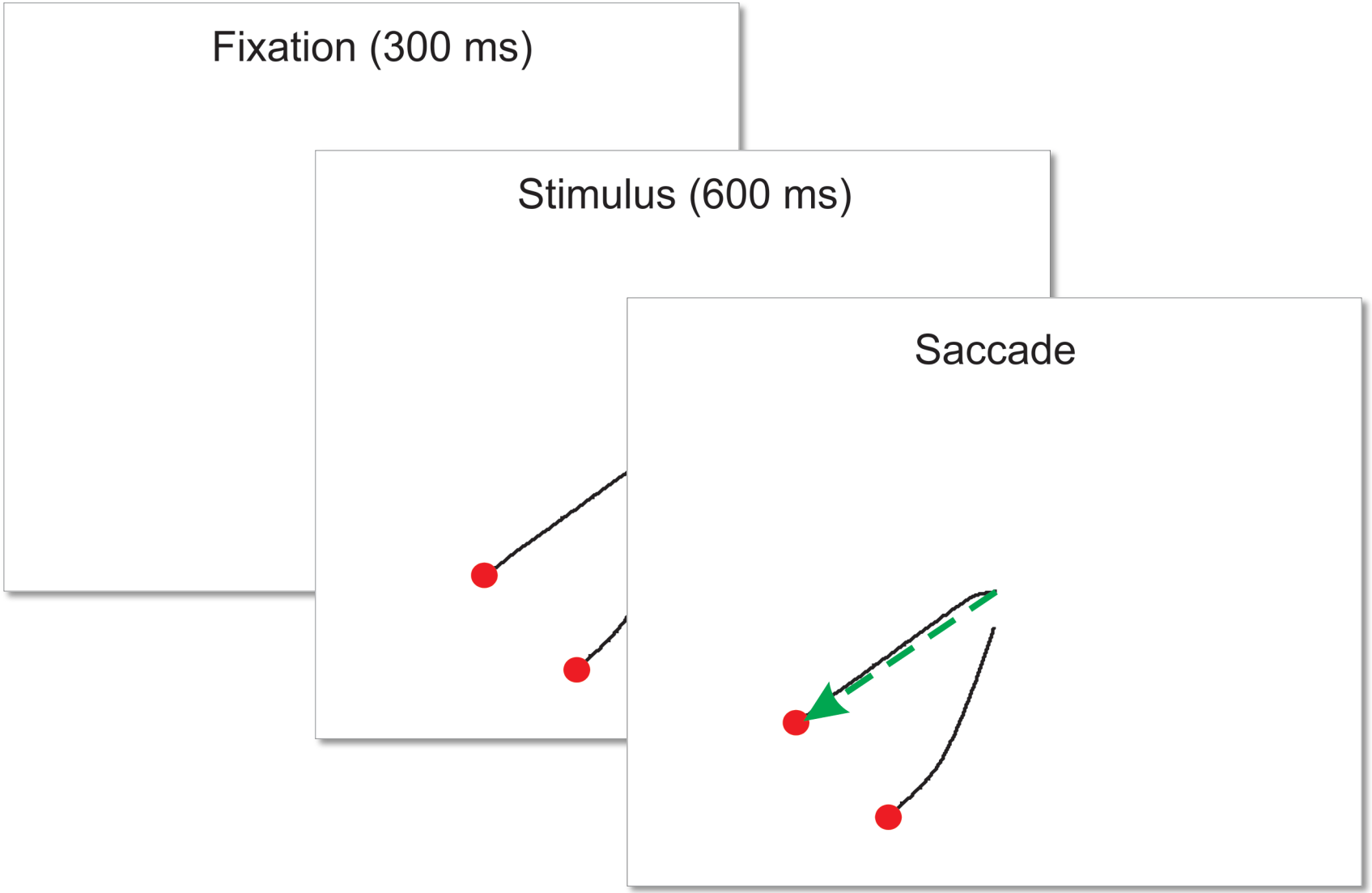

L
R

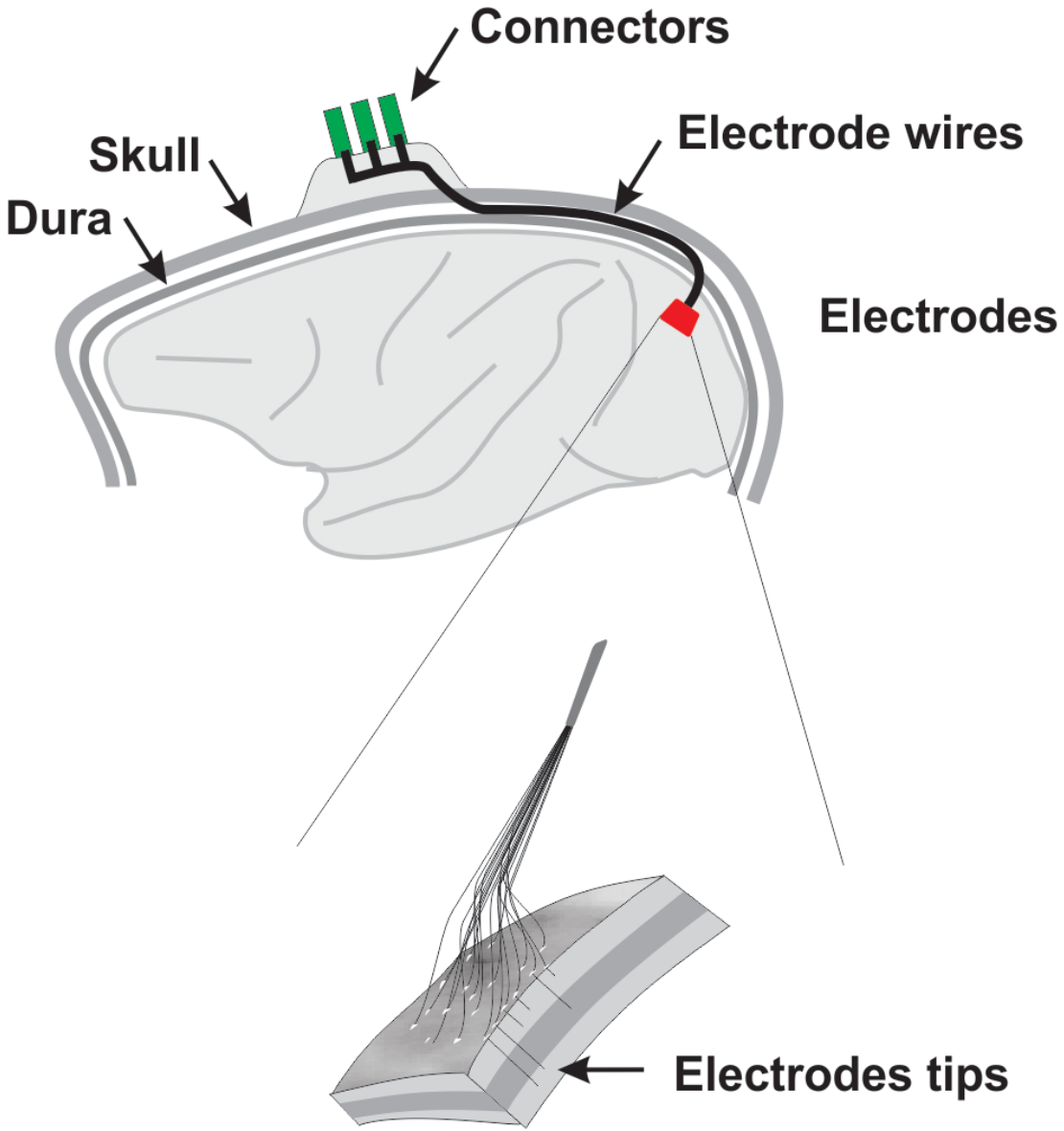

L
R


R
L

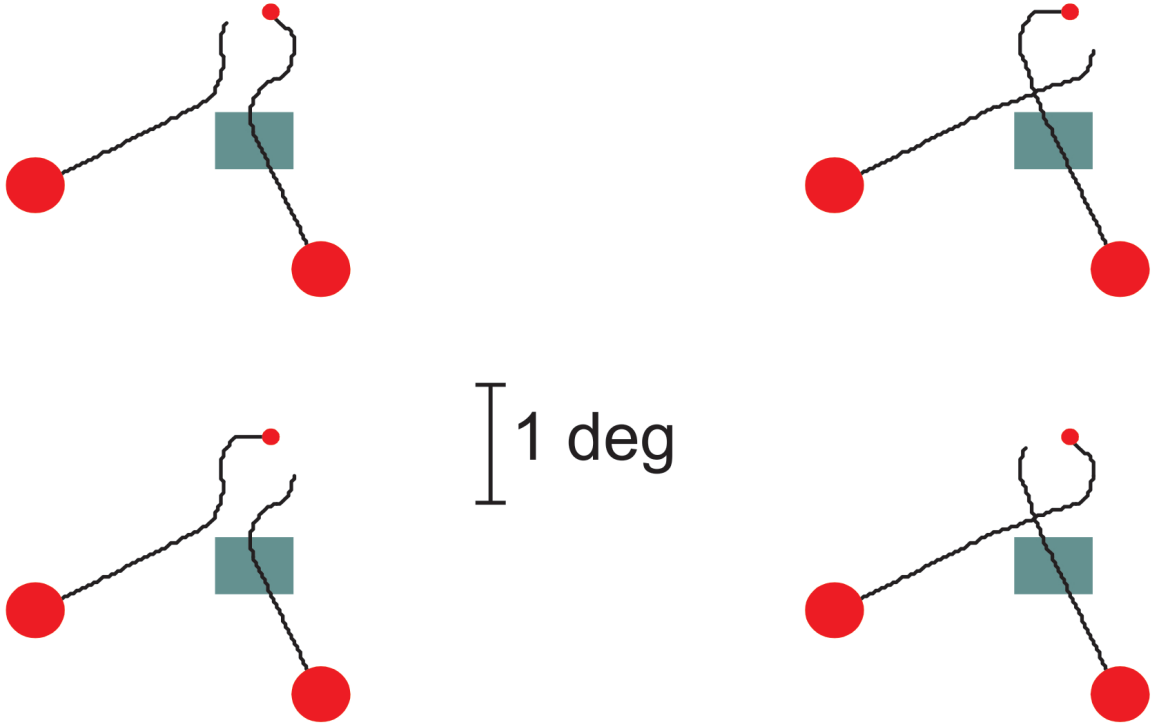

R
L

The task: a saccade to a target connected to the fixation point

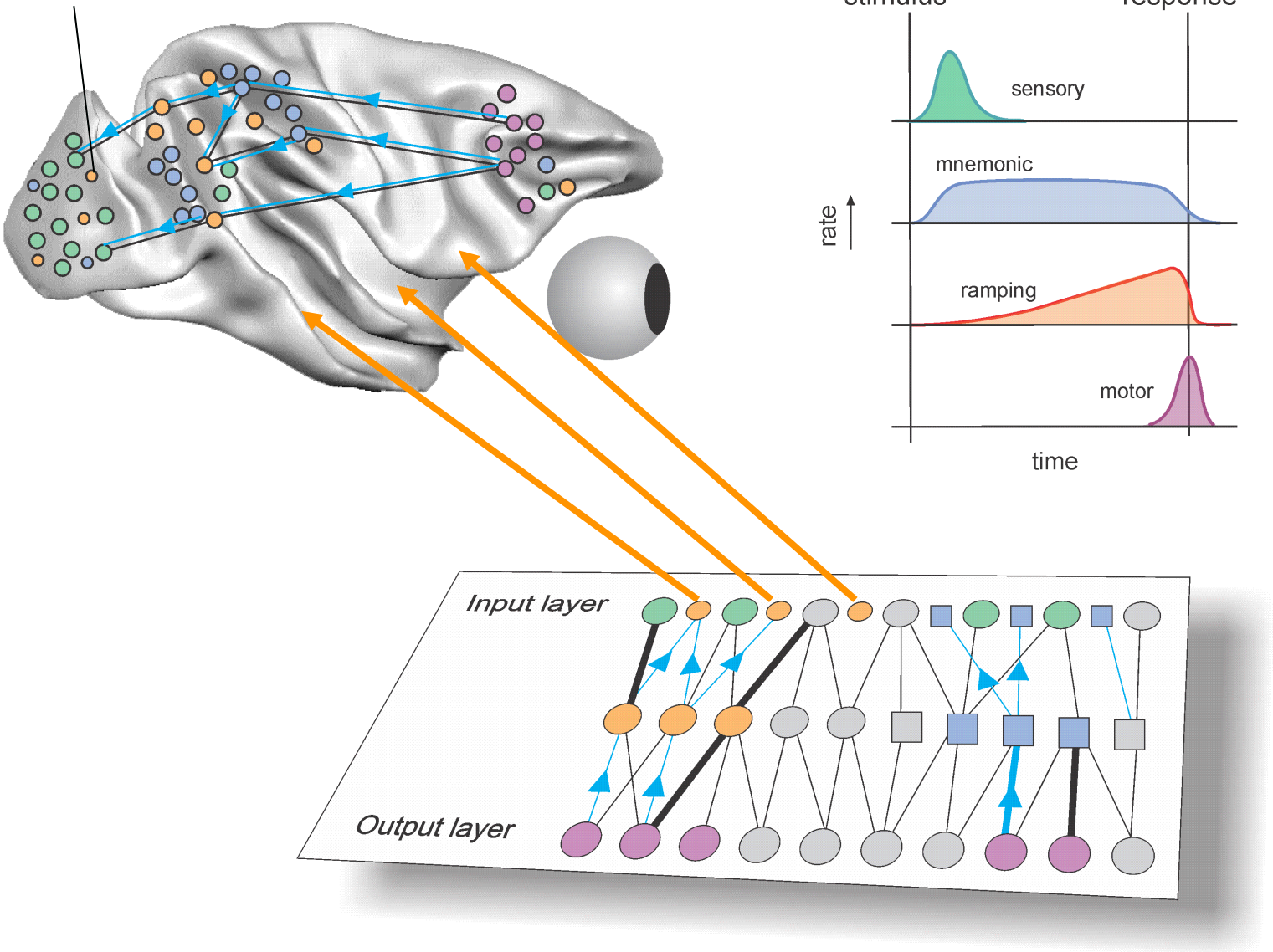




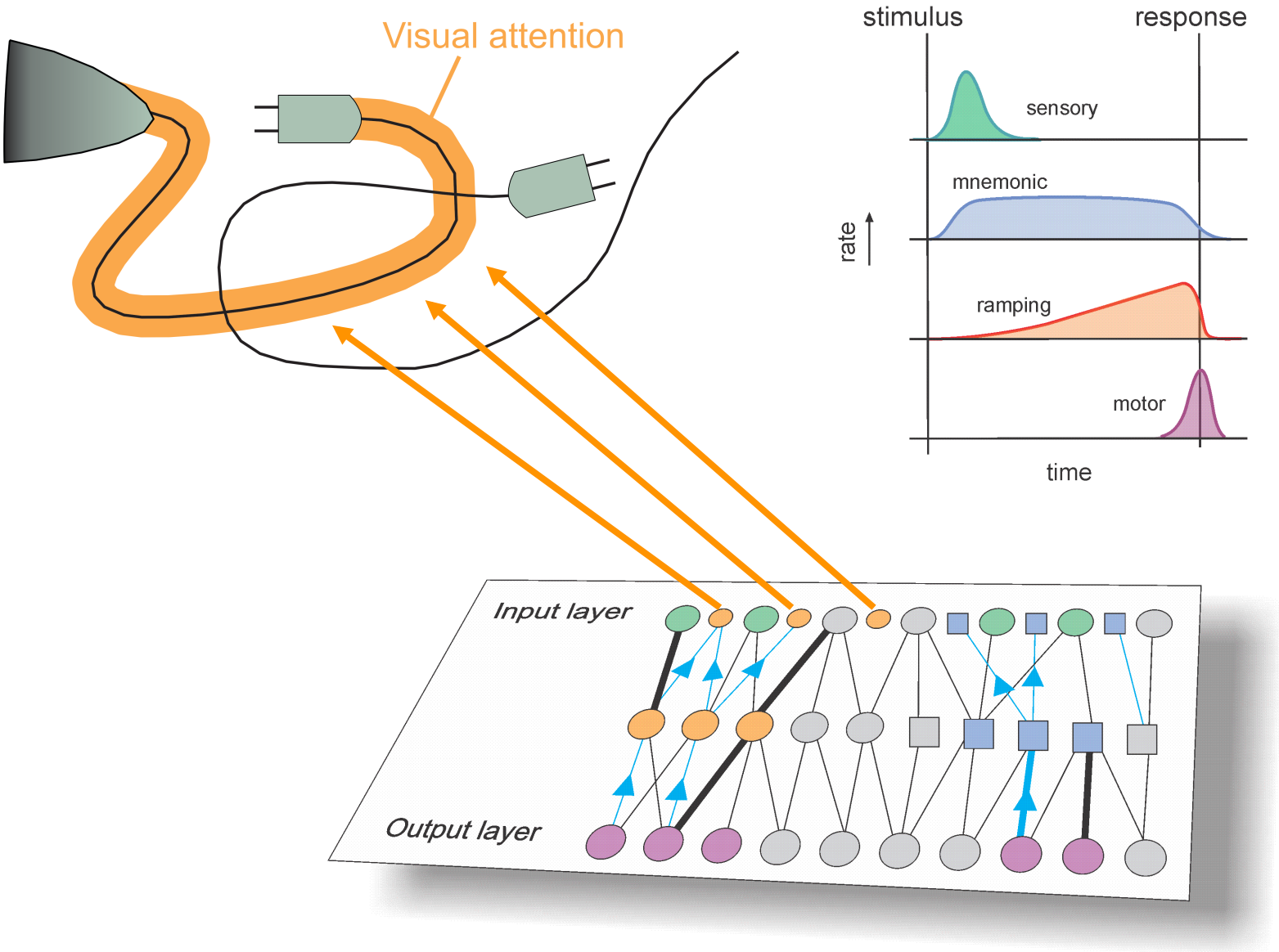
Supèr & Roelfsema, 2005


1 deg

Selection signals (attention)



Primate Turing Machine



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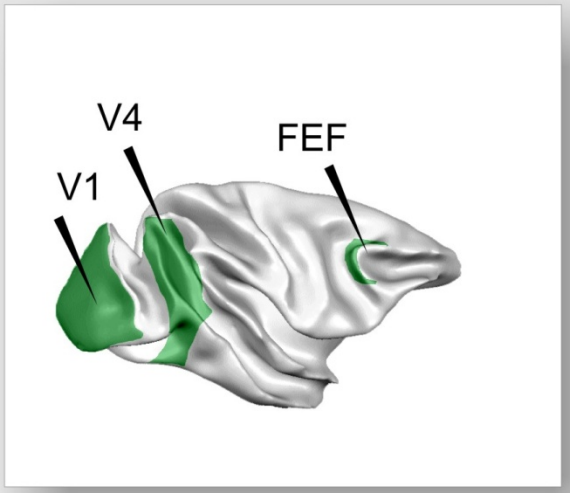
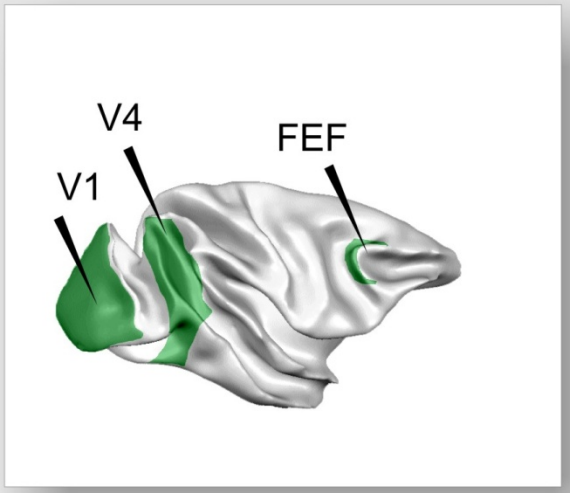
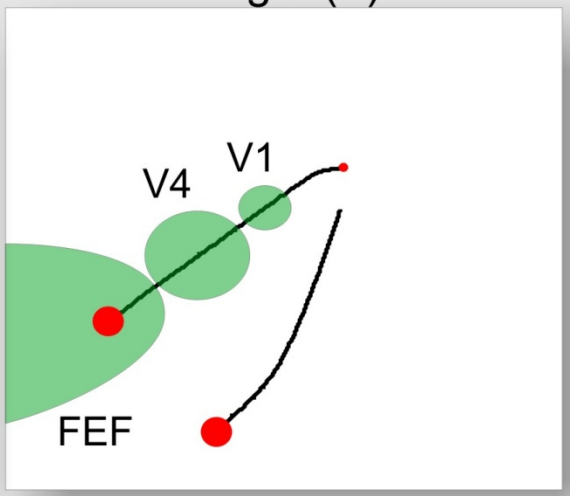


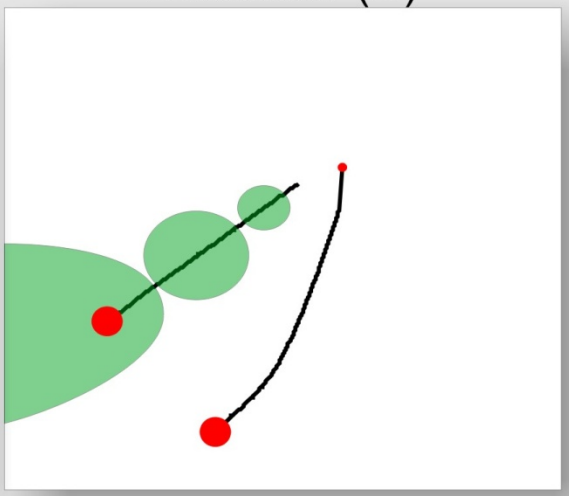
Pooresmaeili, Poort & Roelfsema, *PNAS* 2014



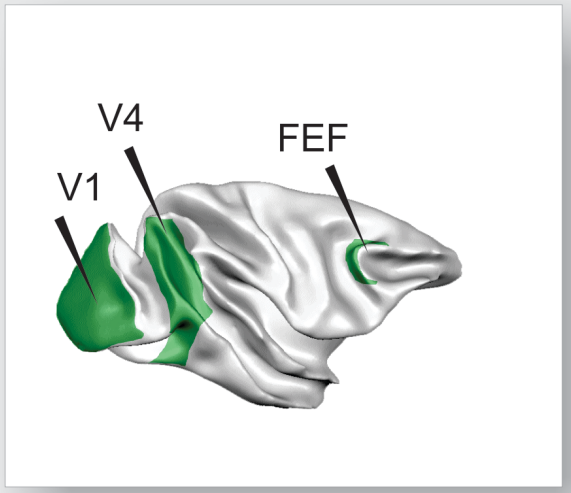
Target (T)



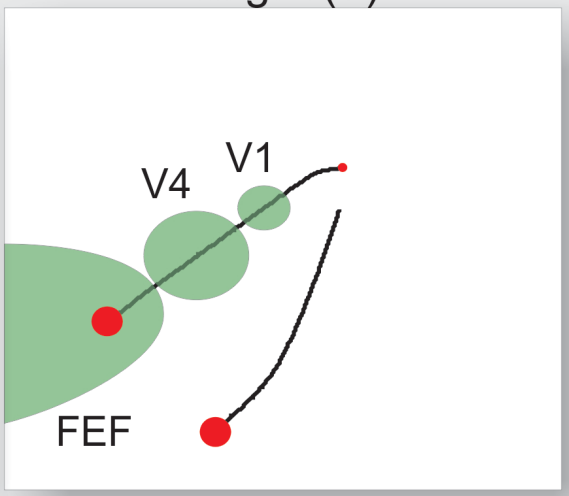
Distractor (D)



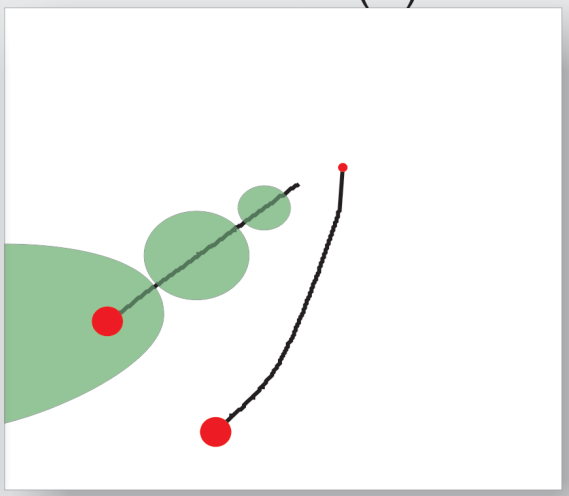
Pooresmaeili, Poort & Roelfsema, *PNAS* 2014



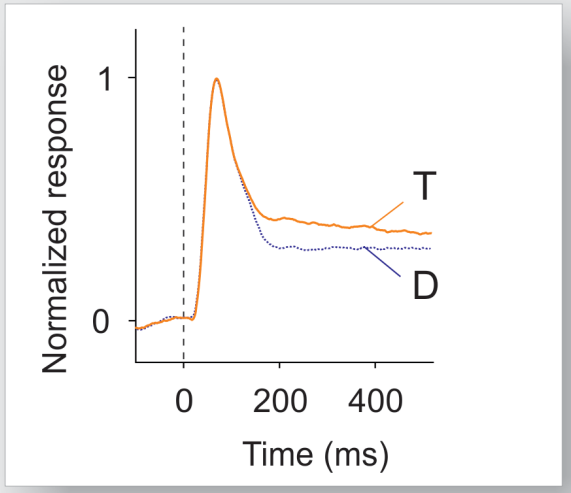
Target (T)



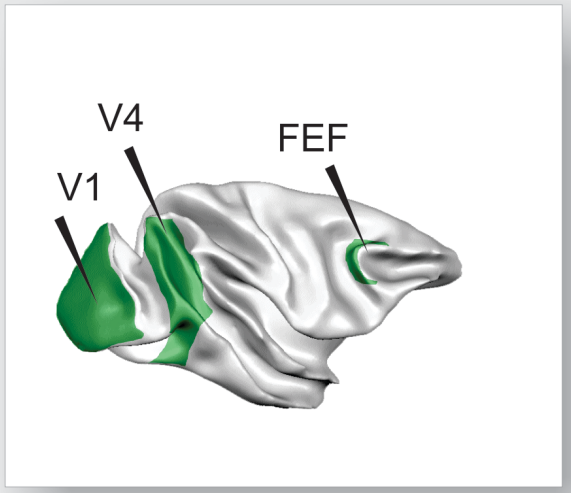
Distractor (D)



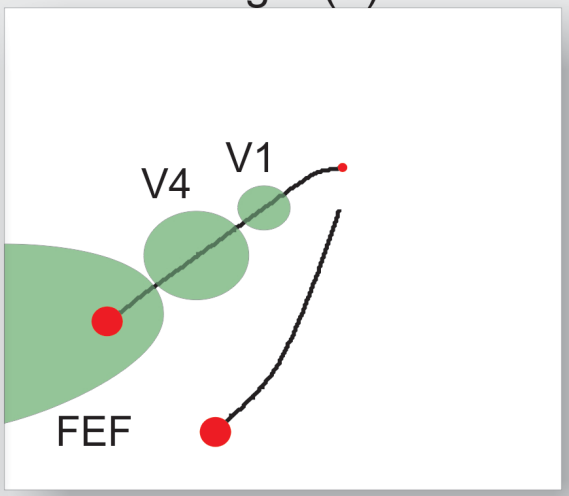
Area V1



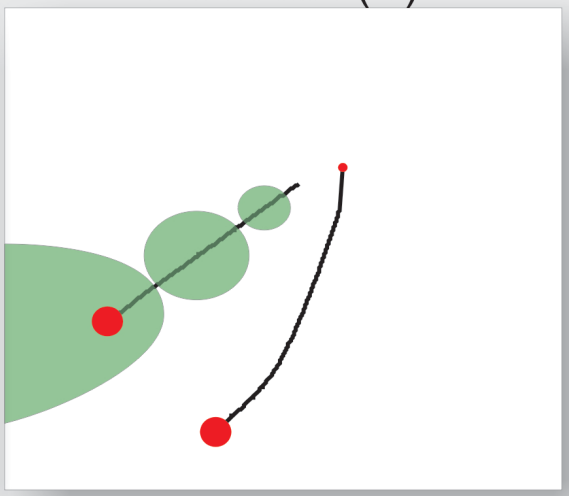
Pooresmaeili, Poort & Roelfsema, *PNAS* 2014



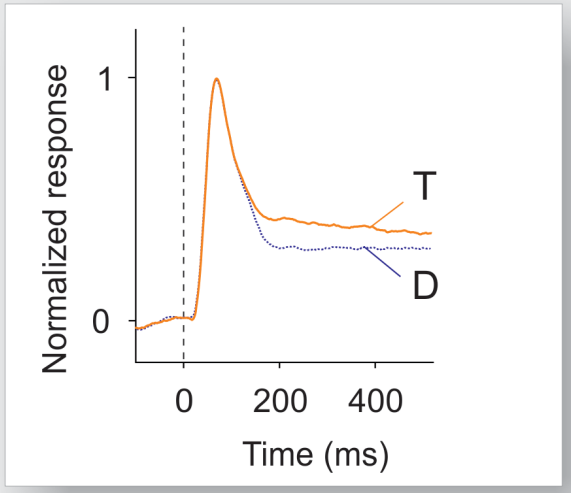
Target (T)



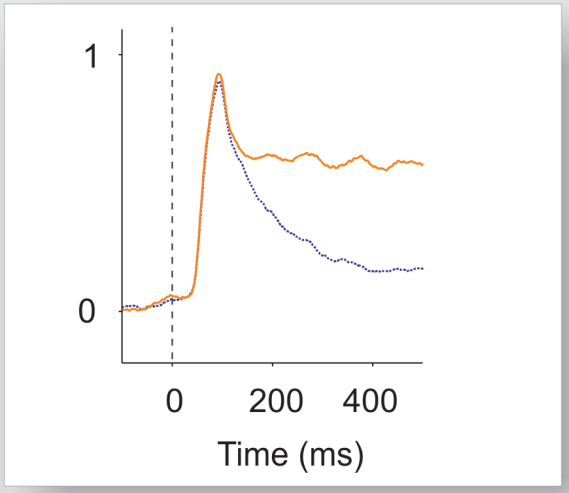
Distractor (D)



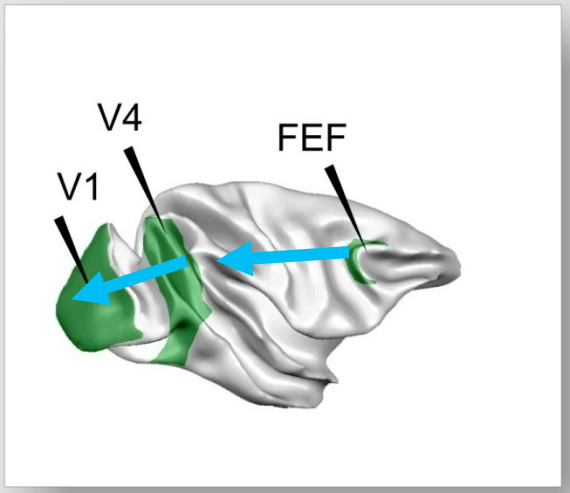
Area V1



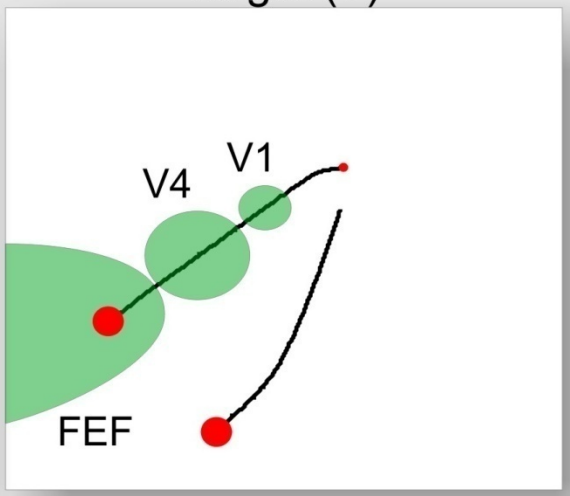
Area V4



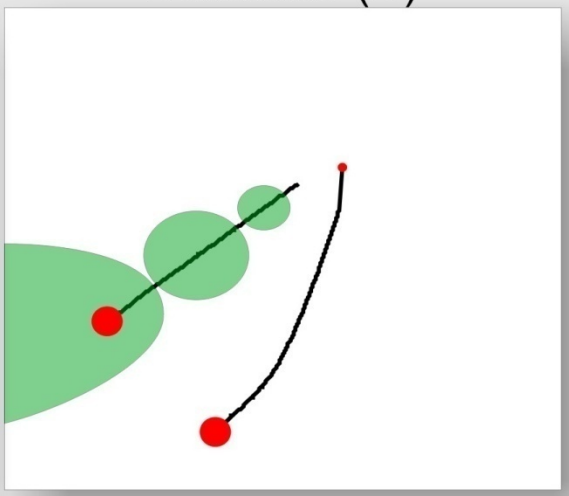
Pooresmaeili, Poort & Roelfsema, *PNAS* 2014



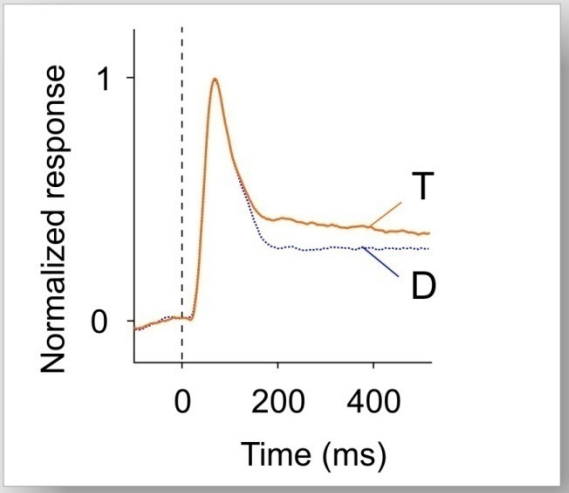
Target (T)



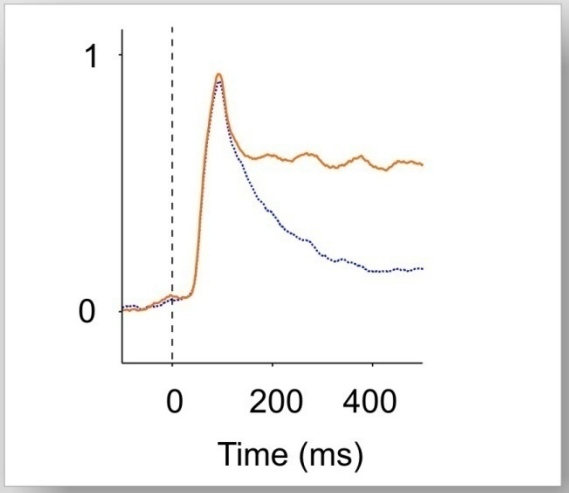
Distractor (D)



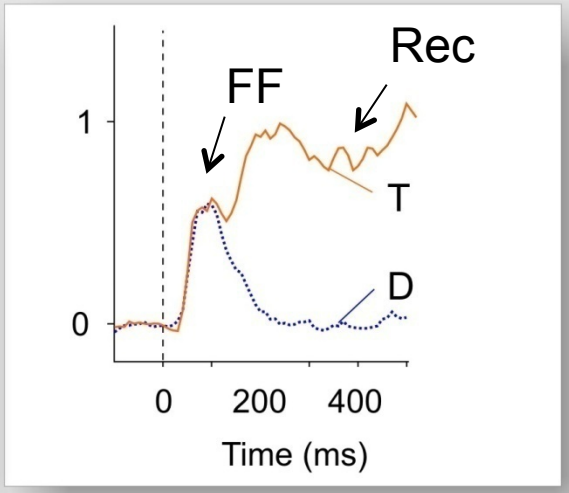
Area V1



Area V4

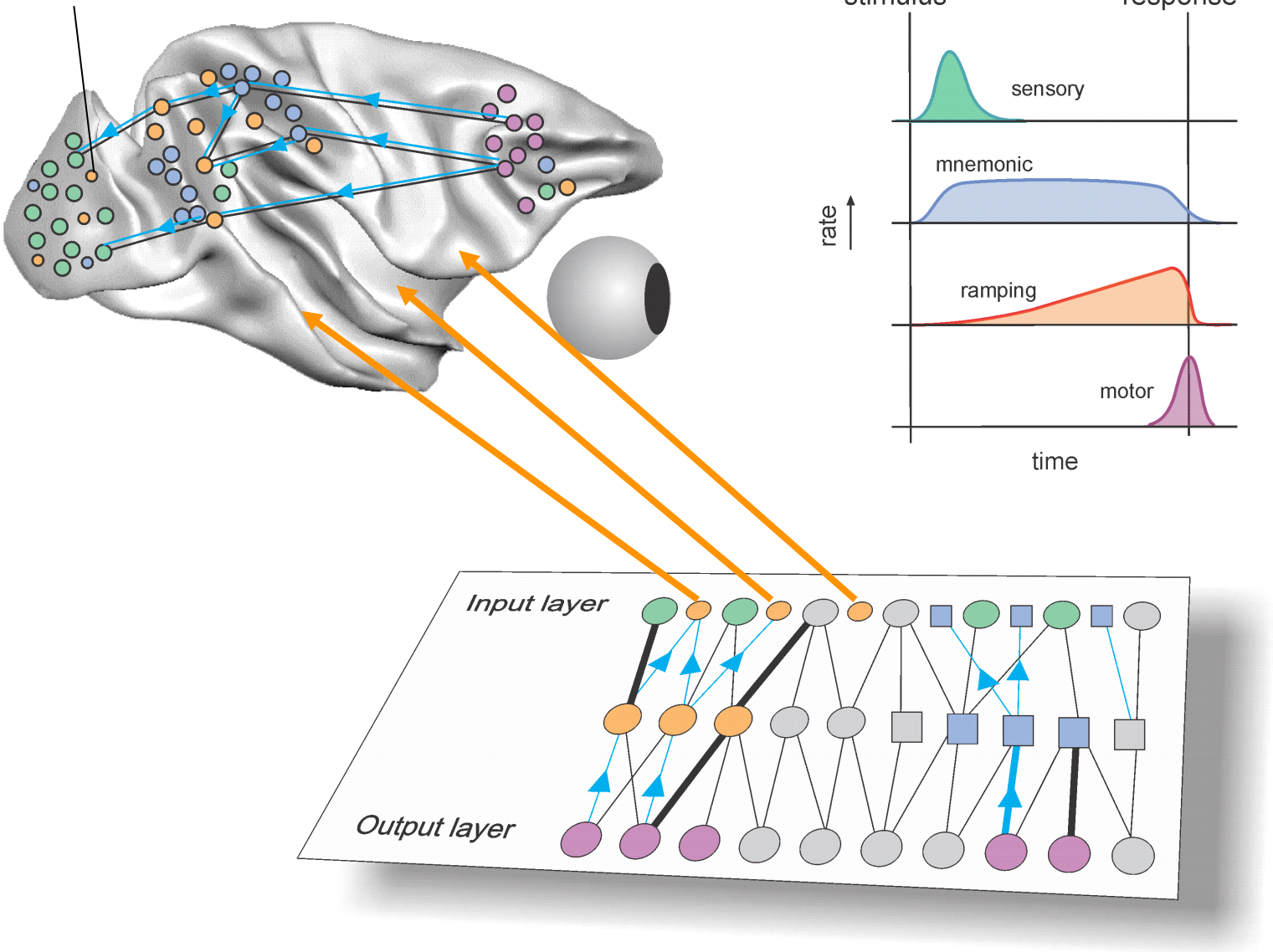


Area FEF



Pooresmaeili, Poort & Roelfsema, *PNAS* 2014

Selection signals (attention)



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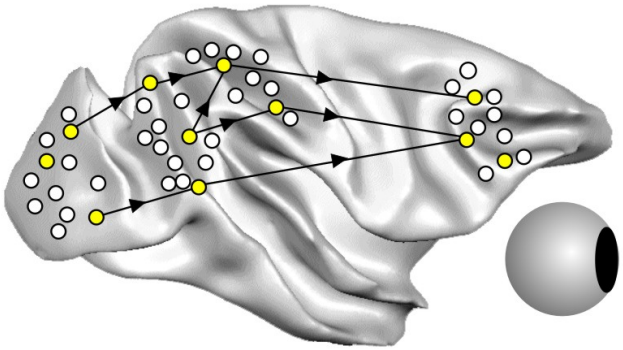
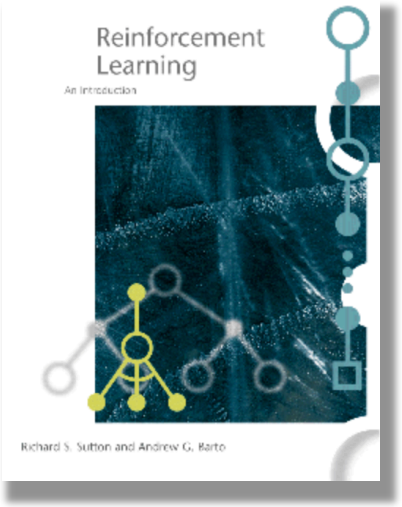
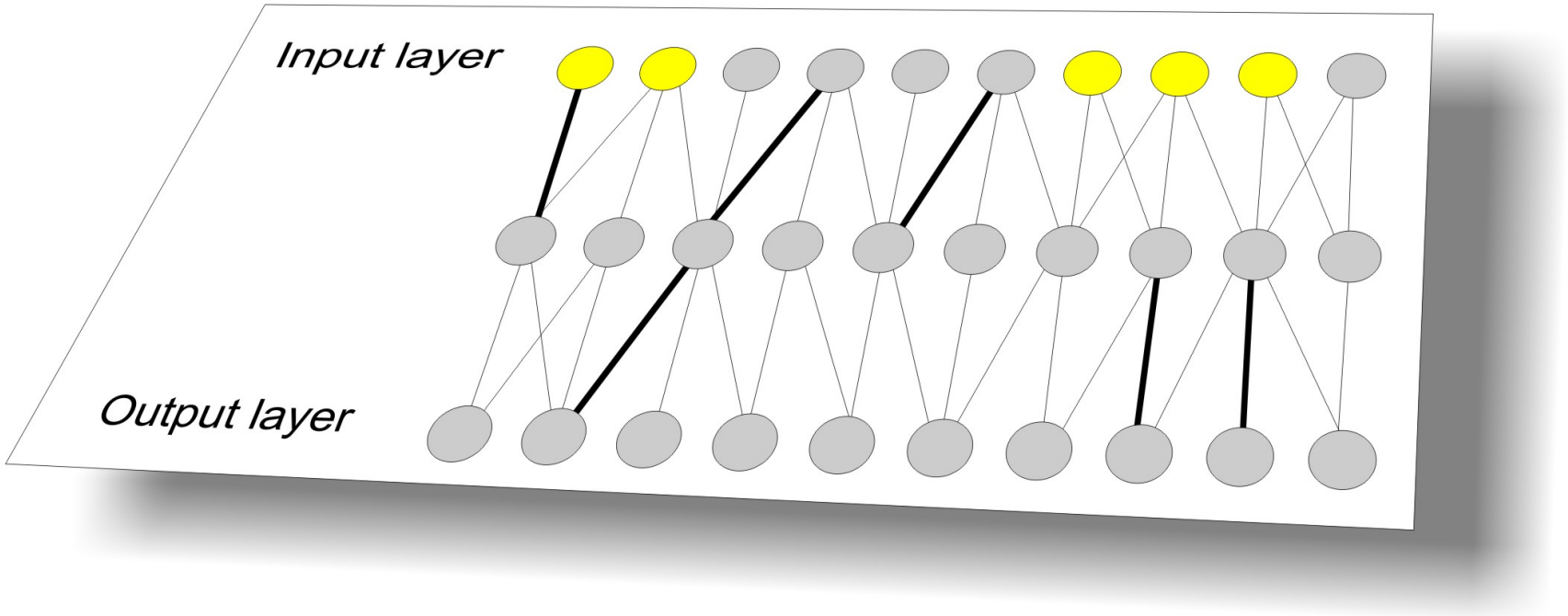
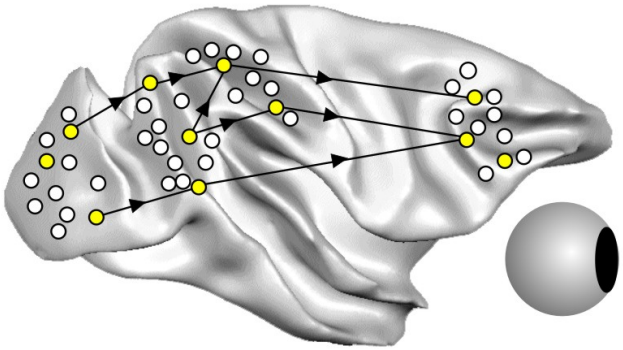


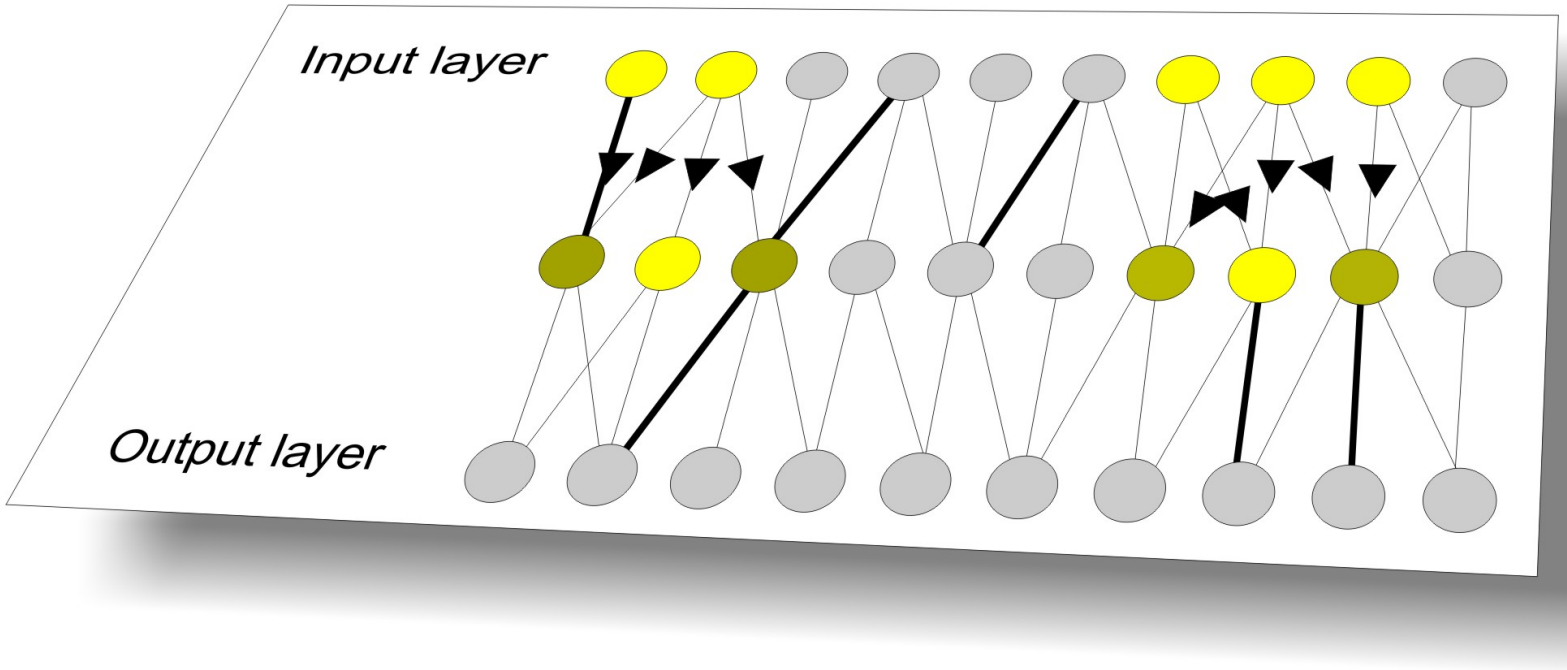




Action values (e.g. in striatum)

(Samejima, Science 2005)

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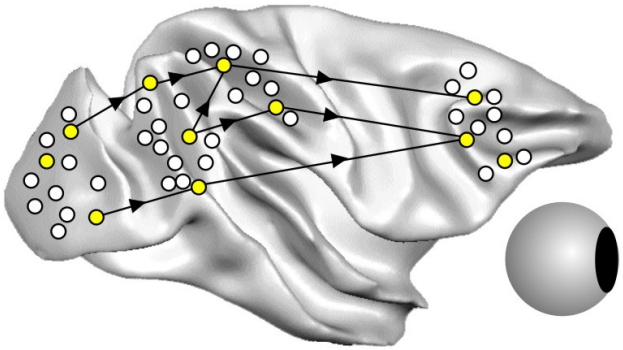
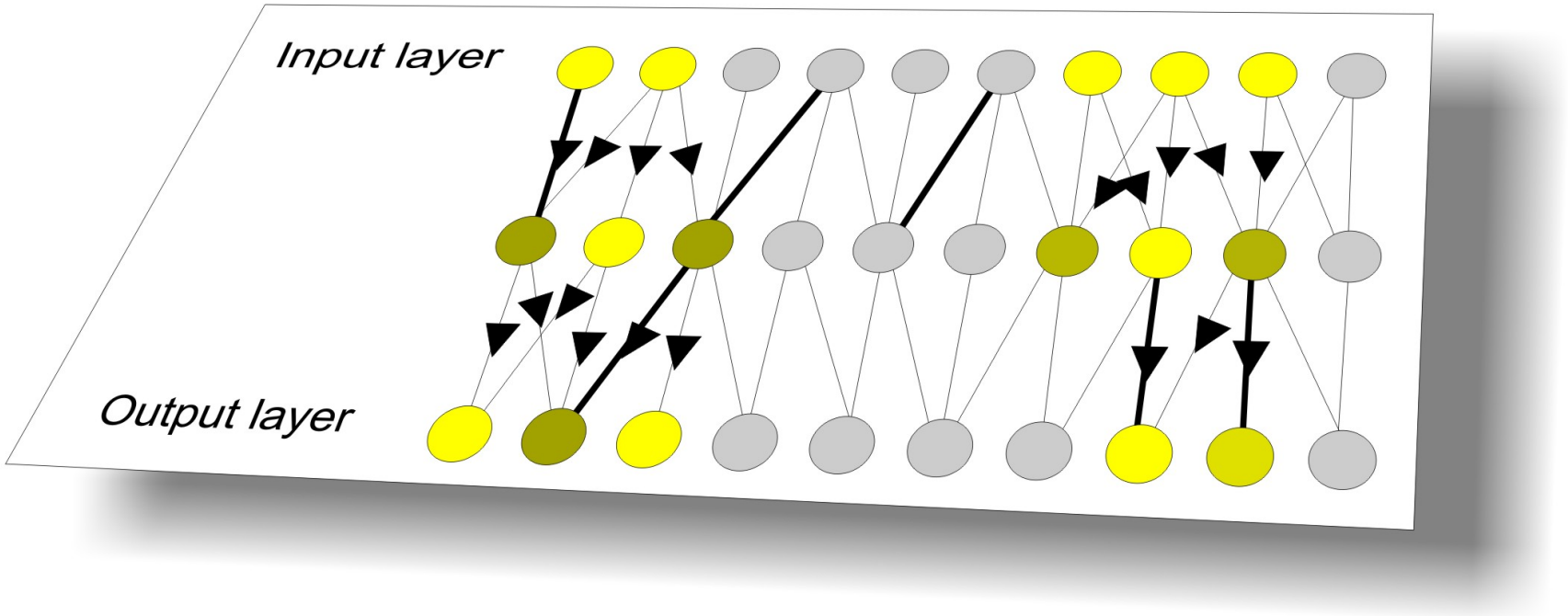
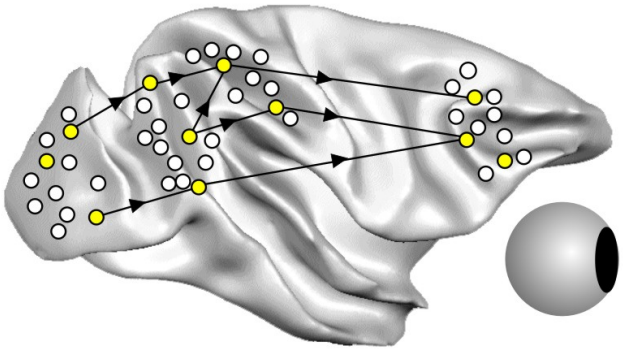
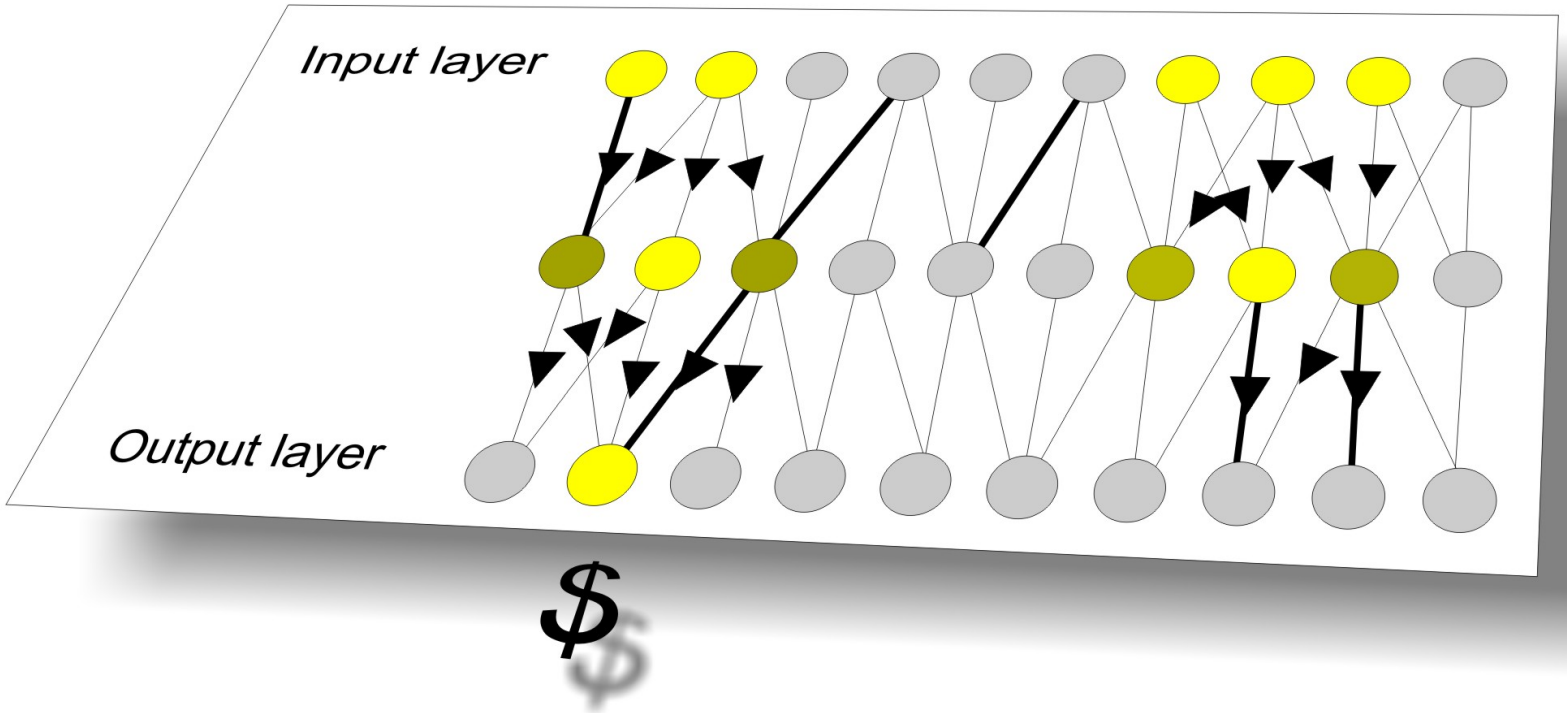
Output layer



Stochastic action selection



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Output layer
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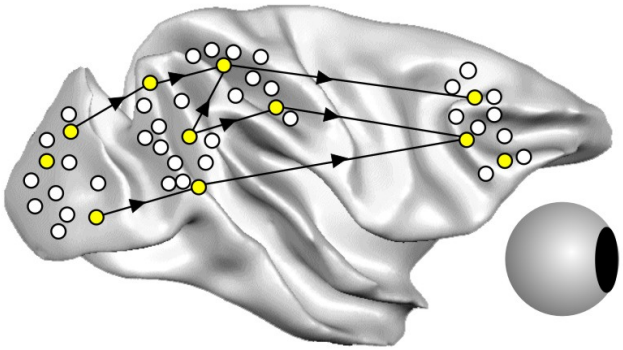

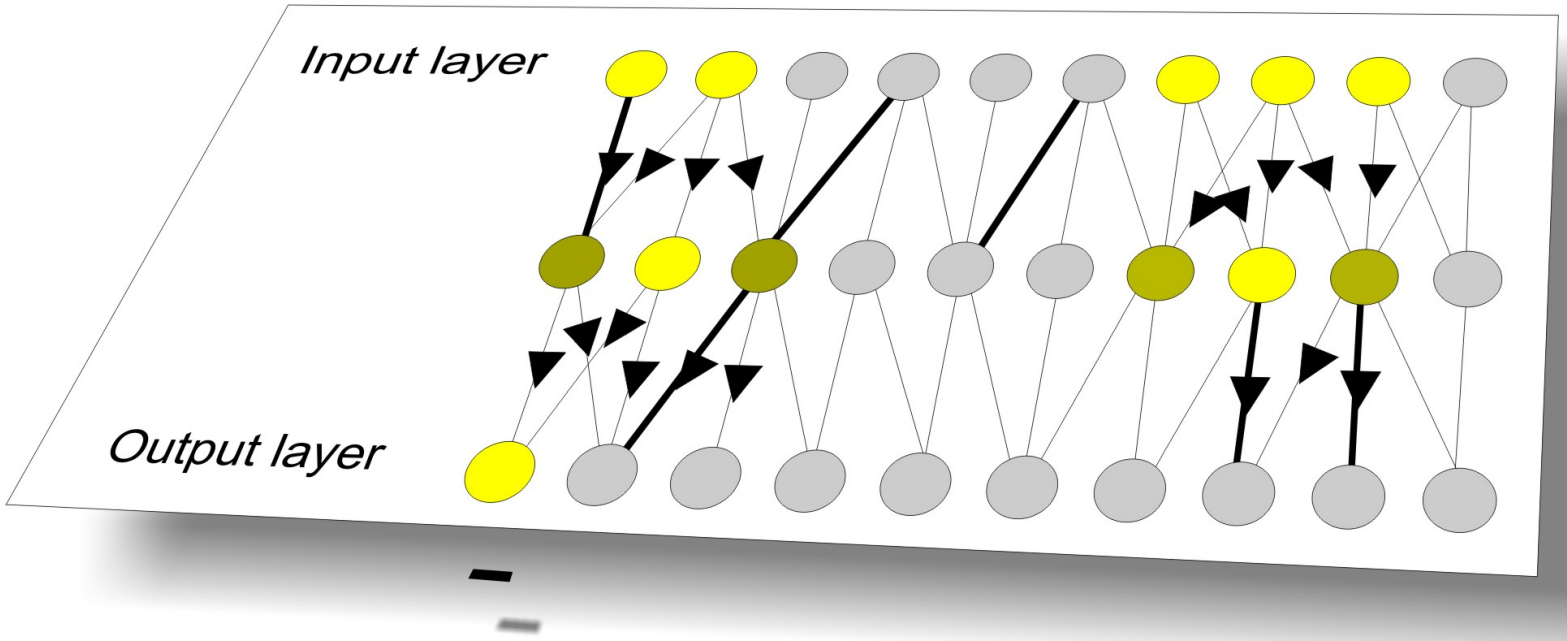
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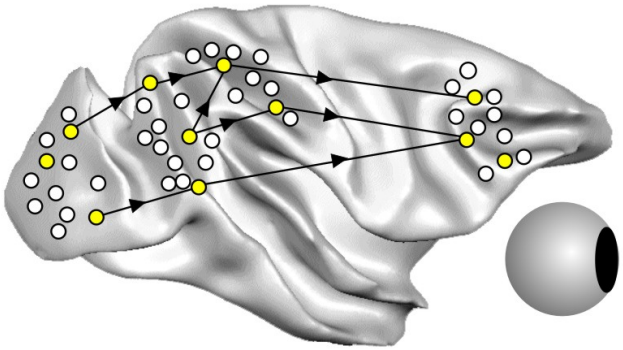
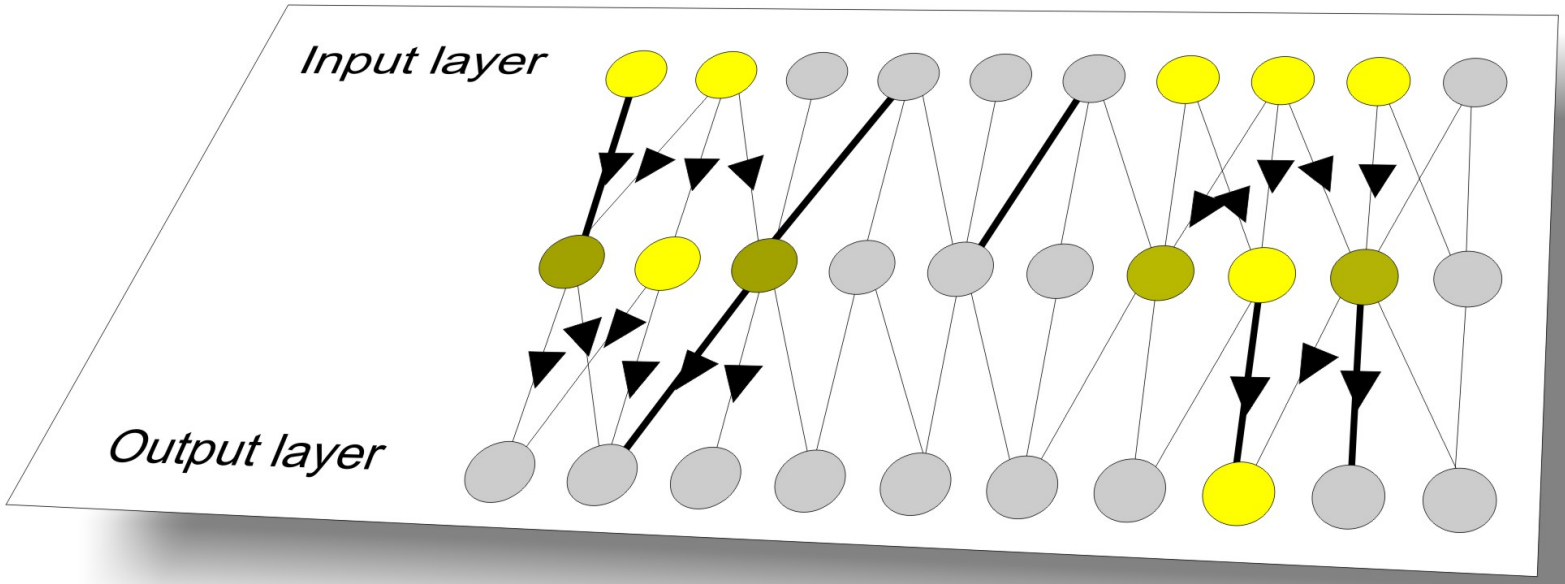
Output layer

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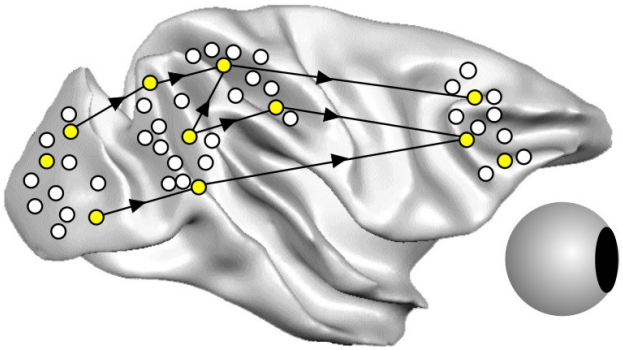
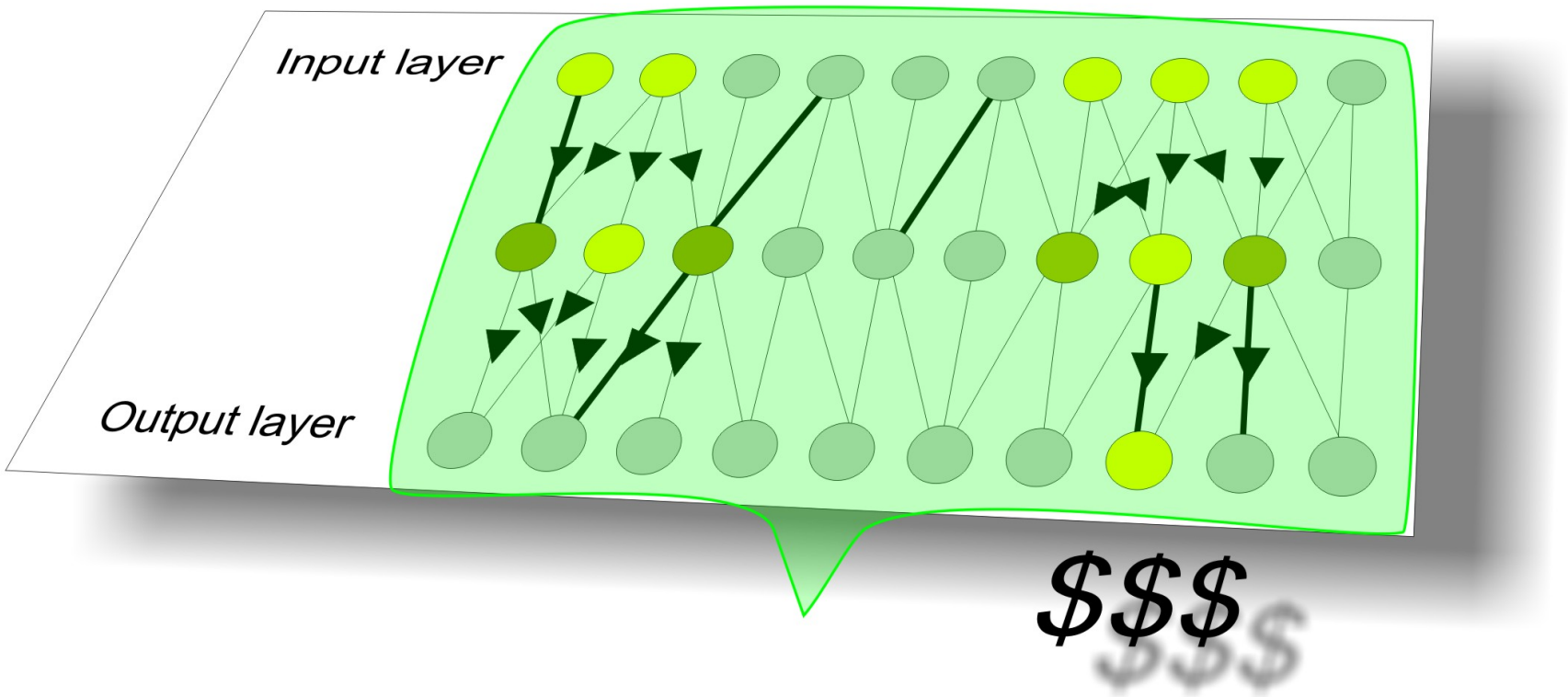
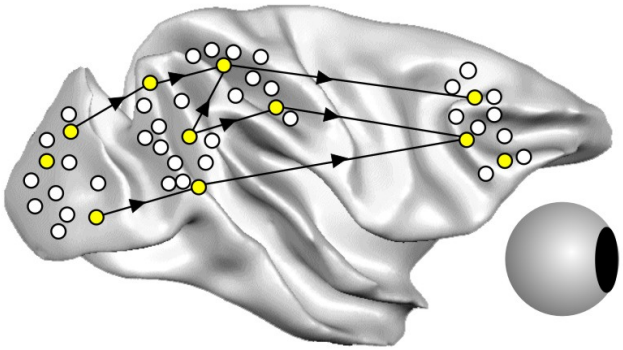


Neuromodulator, e.g. DA
(Schultz, 2002 Neuron)





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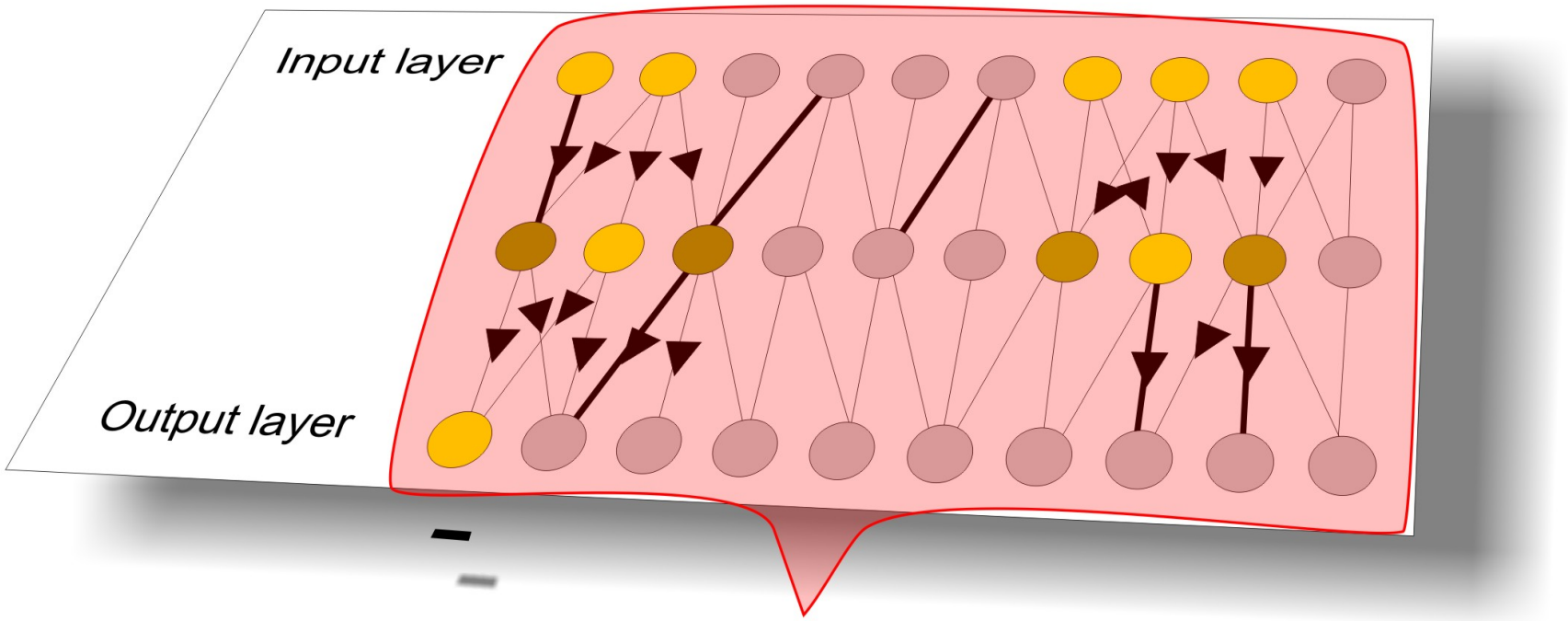
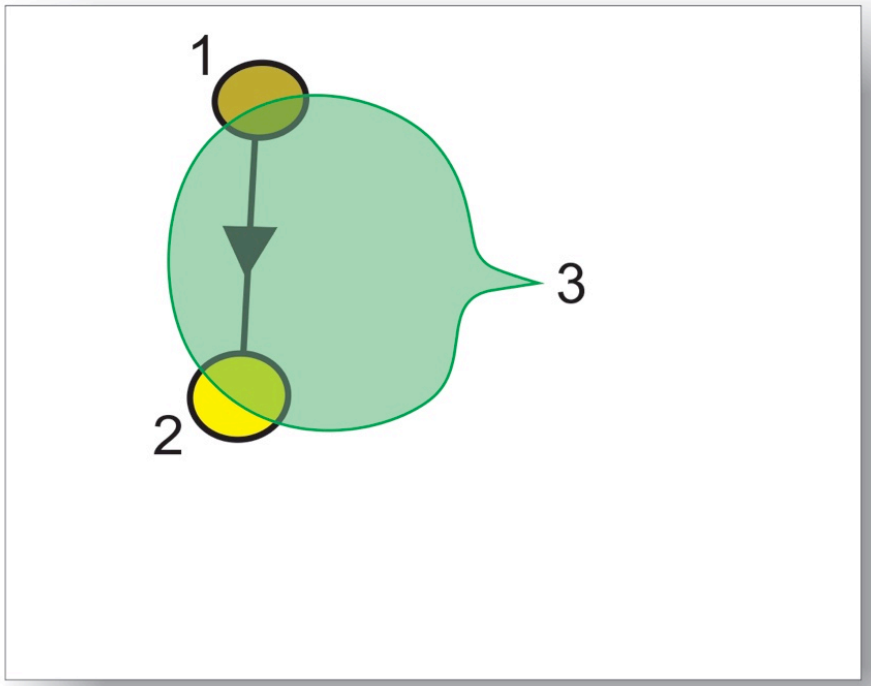
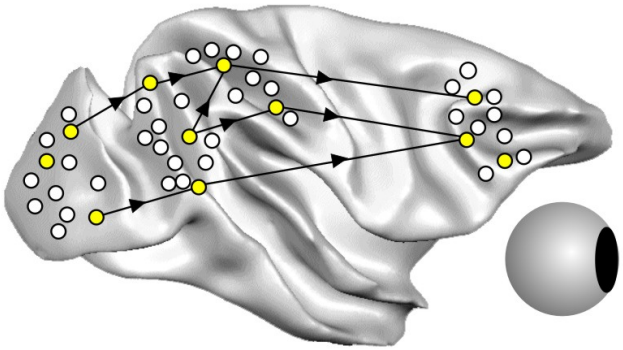
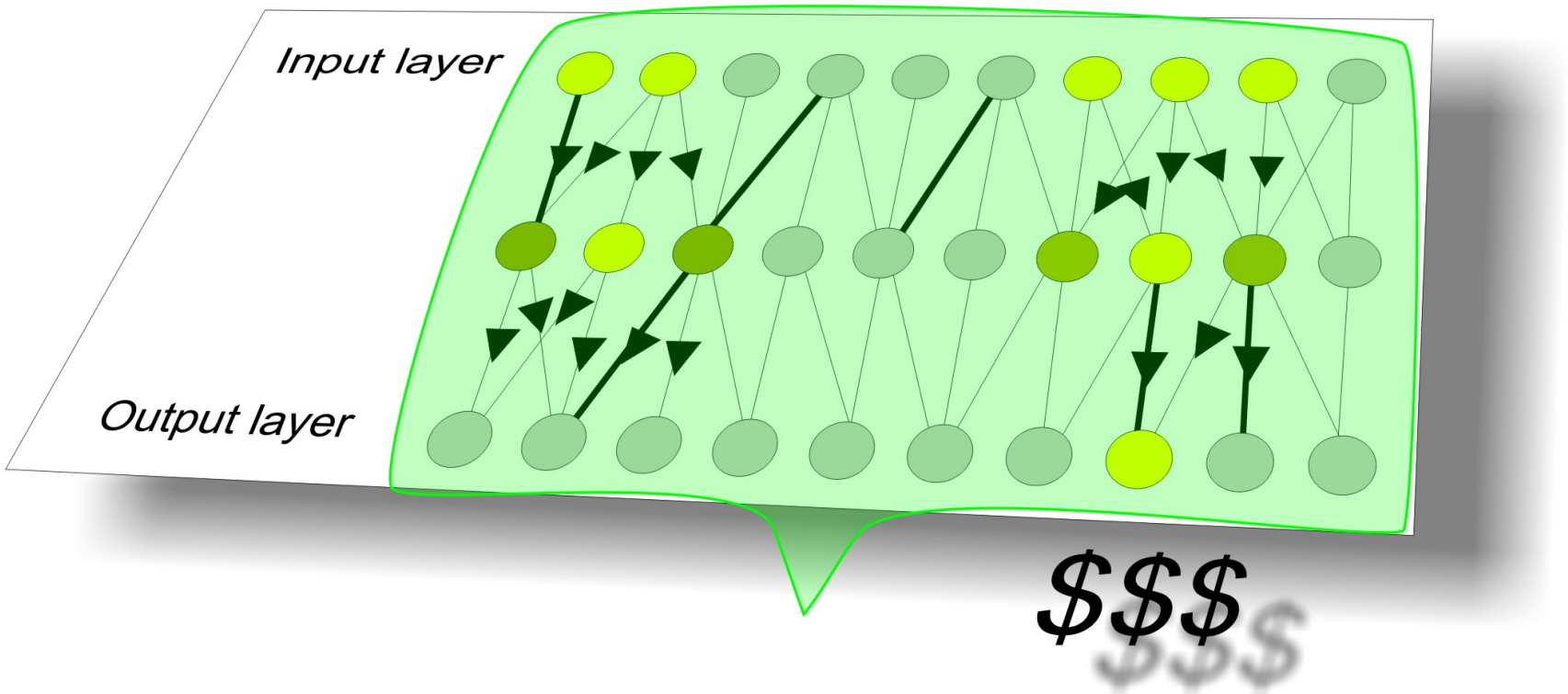




Factor 3: Global neuromodulator - better or worse than expected




Input layer
Output layer
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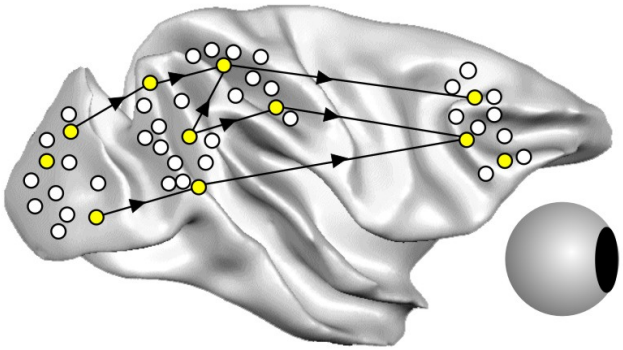
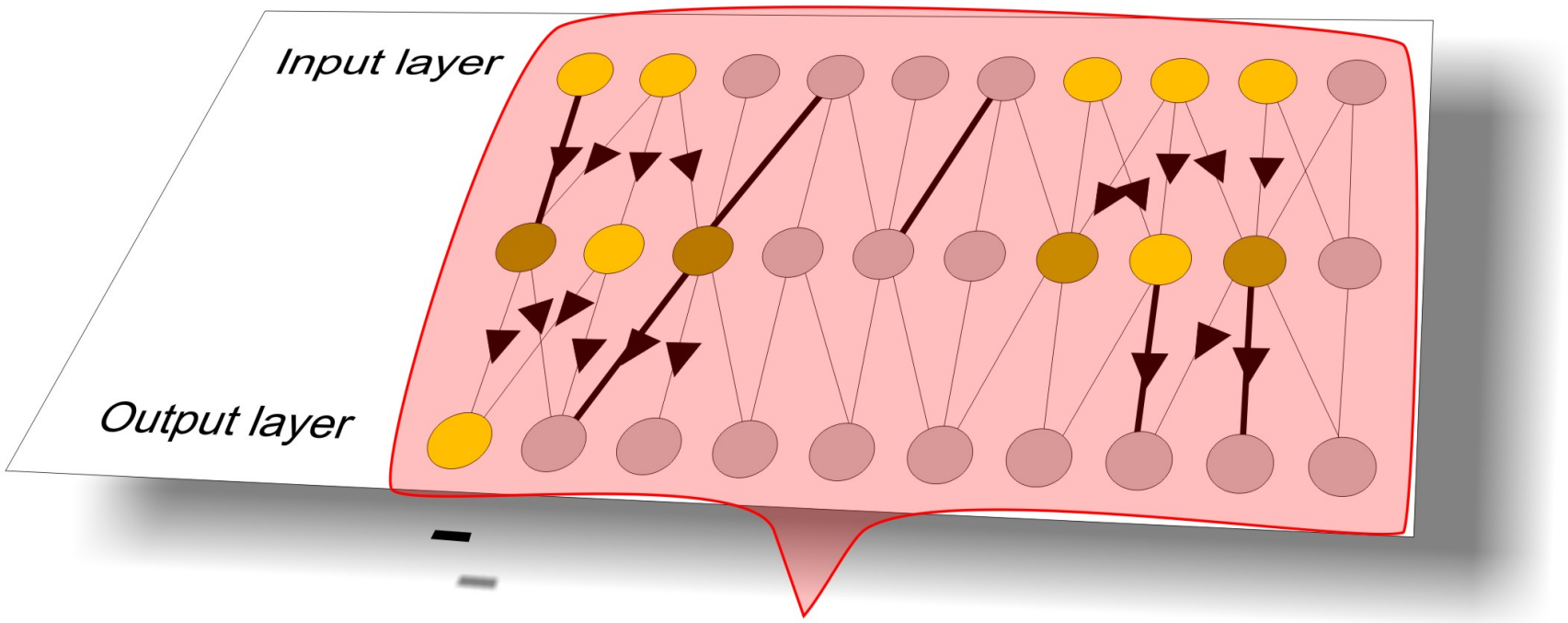


Something is missing..



Introduction: feedforward and feedback processing

Contour grouping: layers and higher areas

Training the primate Turing machine– role of feedback connections in learning

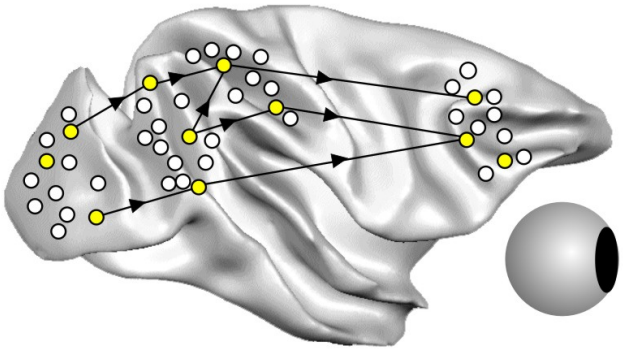
The neurobiology of guiding synaptic plasticity

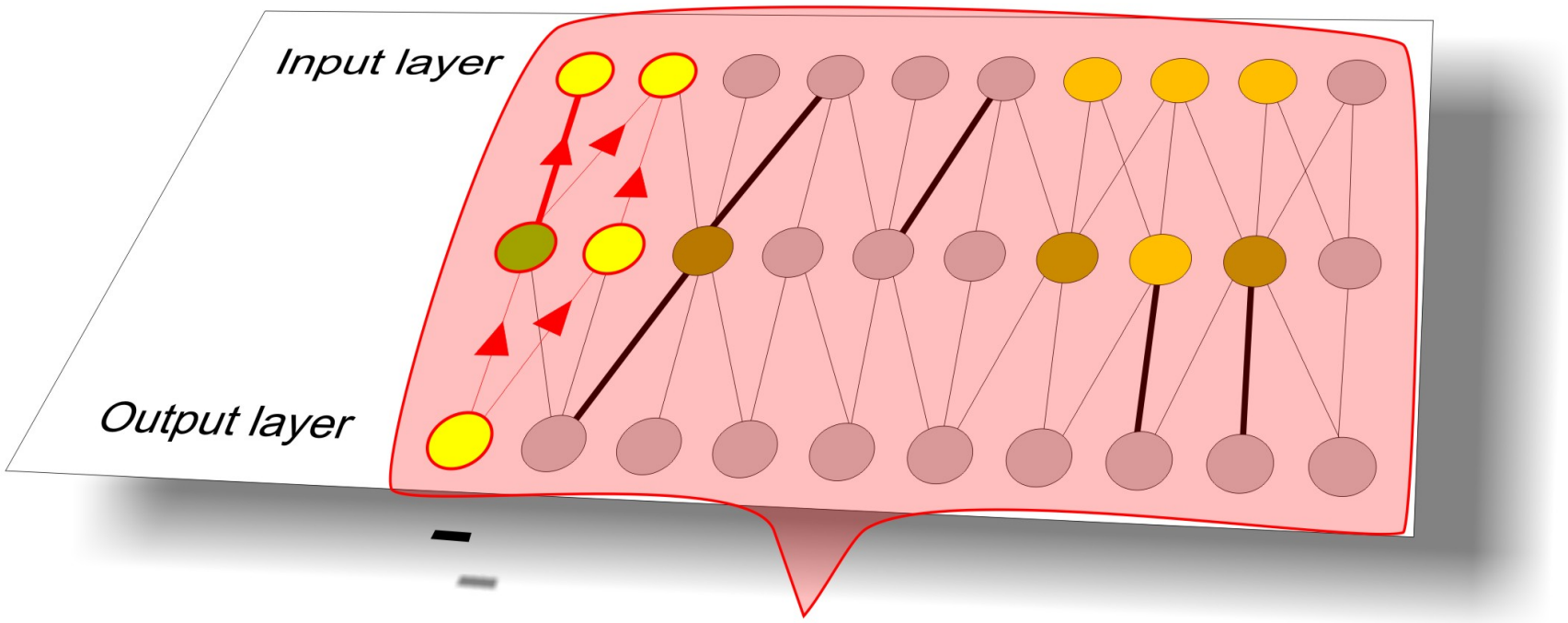
Introduction: feedforward and feedback processing

Contour grouping: layers and higher areas

Training the primate Turing machine– **role of feedback connections** in learning

The neurobiology of guiding synaptic plasticity

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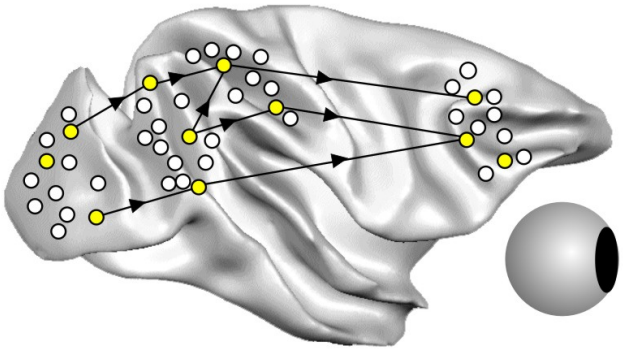

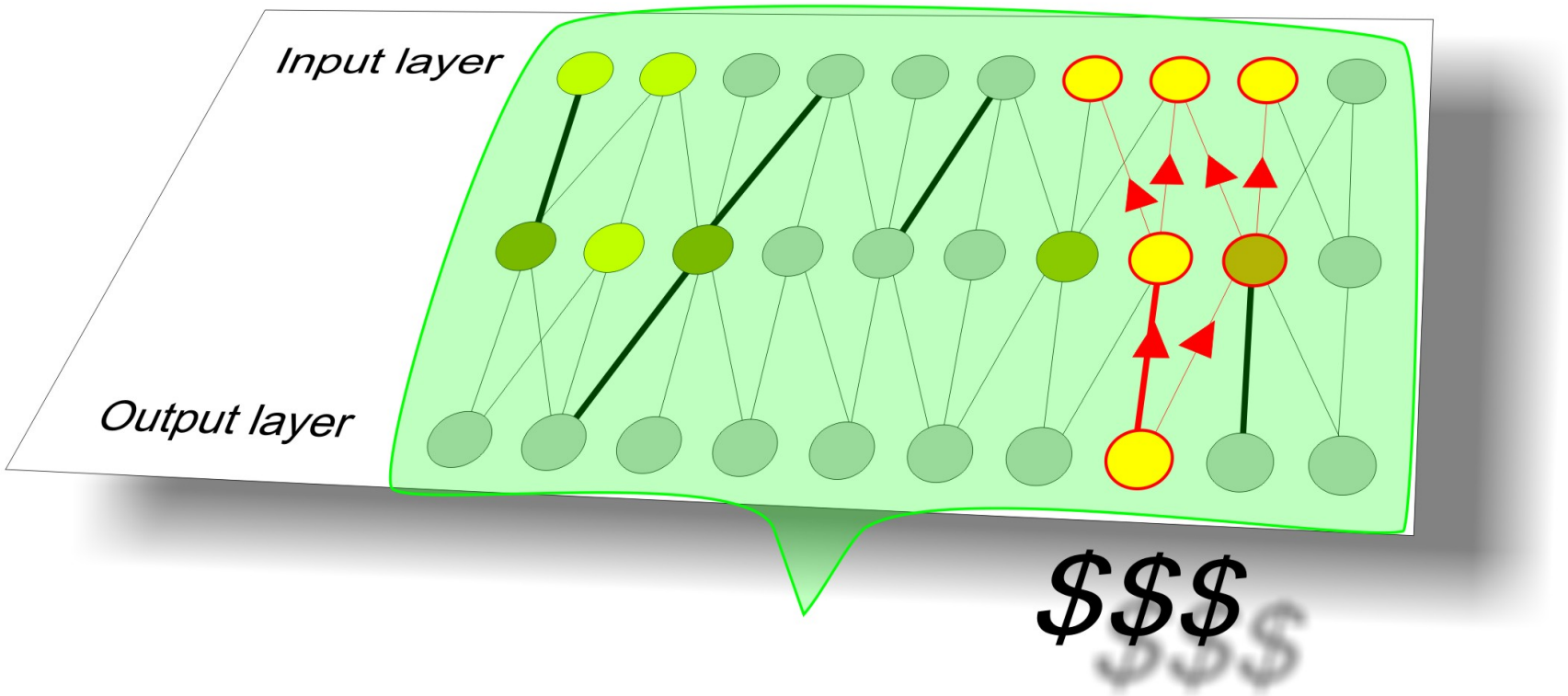
Input layer
Output layer
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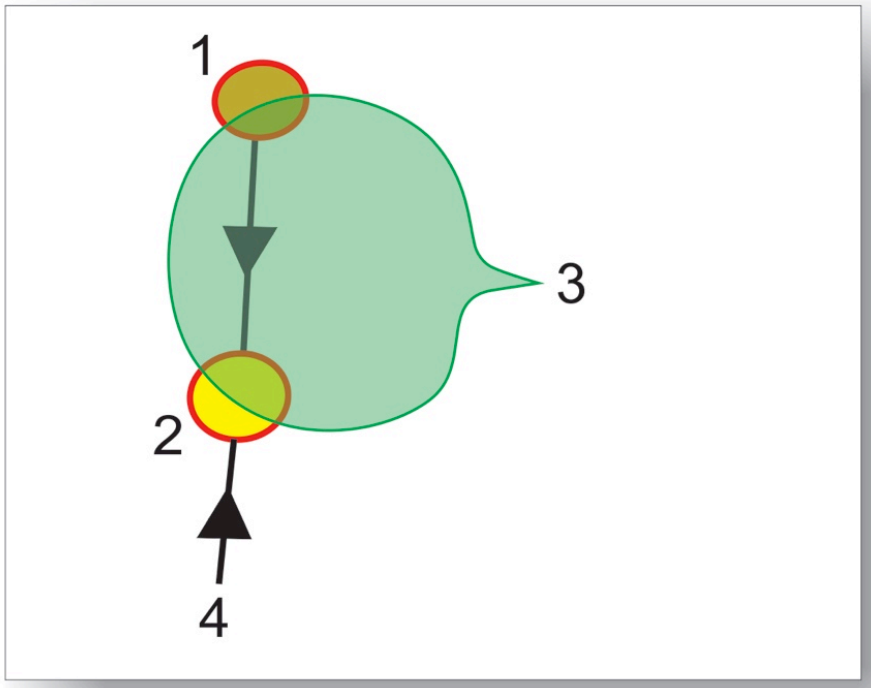
AGREL = attention-gated reinforcement learning

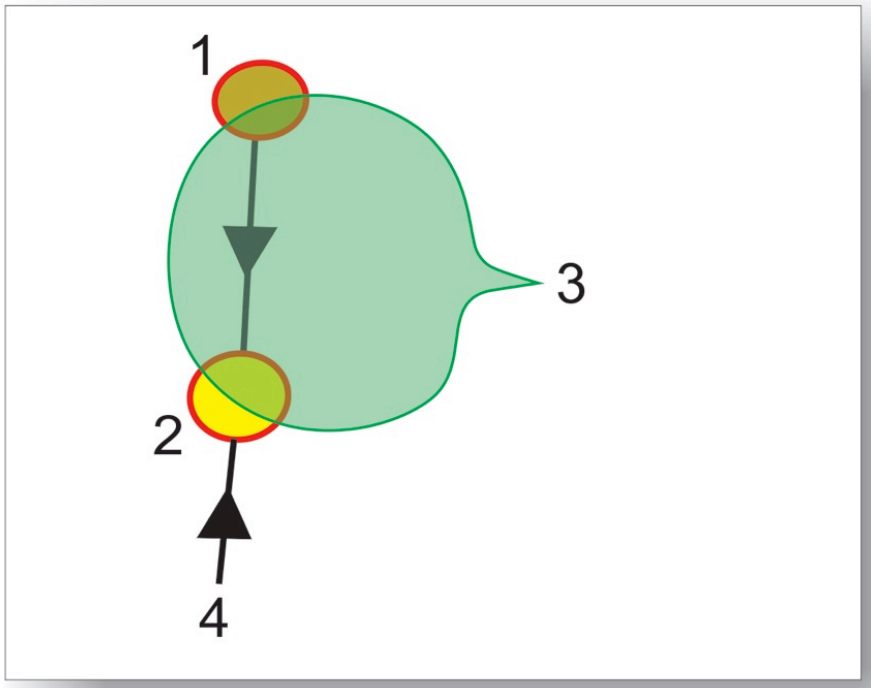


Factor 3: Global neuromodulator - better or worse than expected

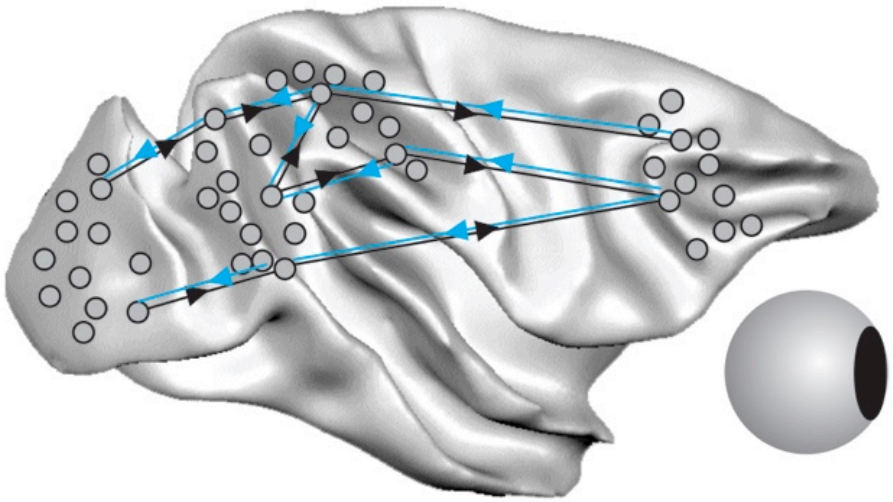
Factor 4: Feedback – “attentional” signal from response selection stage

These effects depend on NMDA receptors (Self et al., PNAS, 2012)

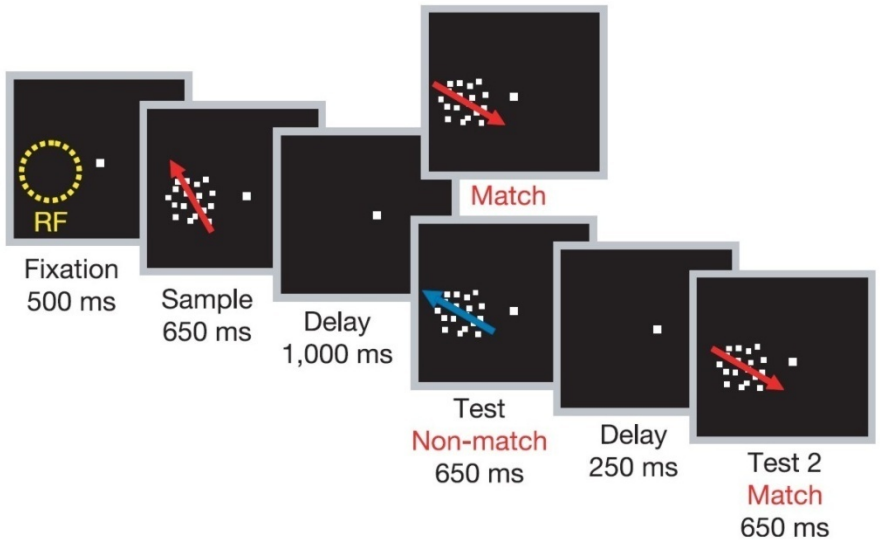
AGREL = attention-gated reinforcement learning

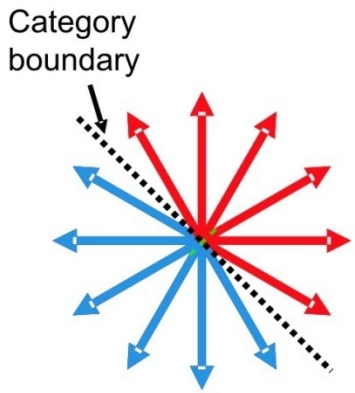


On average the same synaptic modifications as BP (Roelfsema & van Ooyen, 2005, *Neural Comp.;* review by Roelfsema, van Ooyen and Watanabe, 2010, *TiCS*)

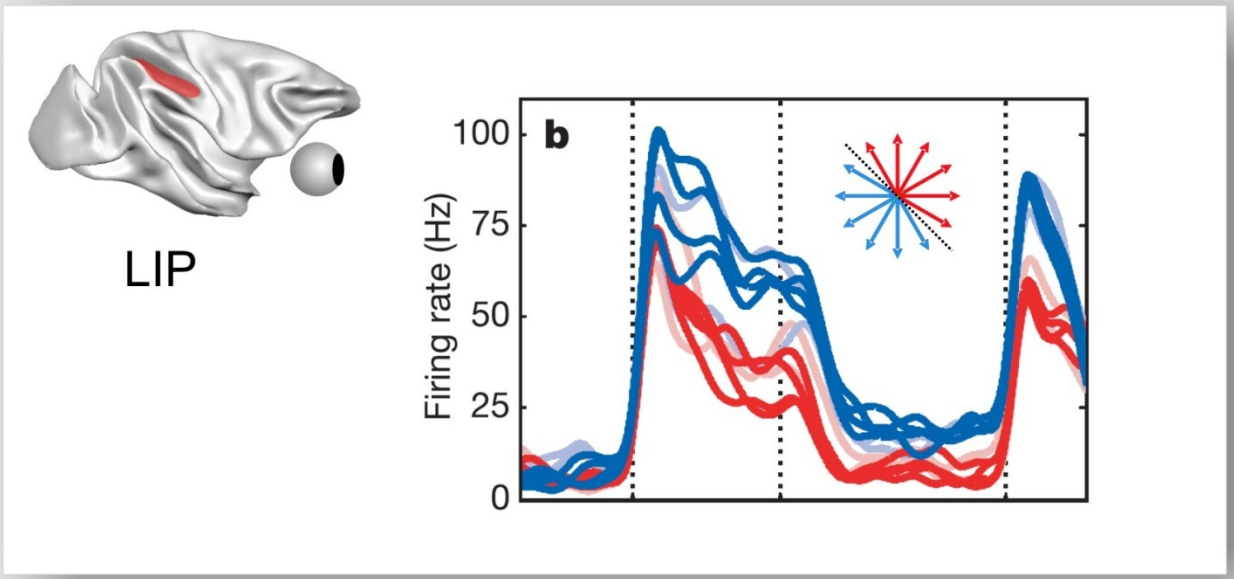


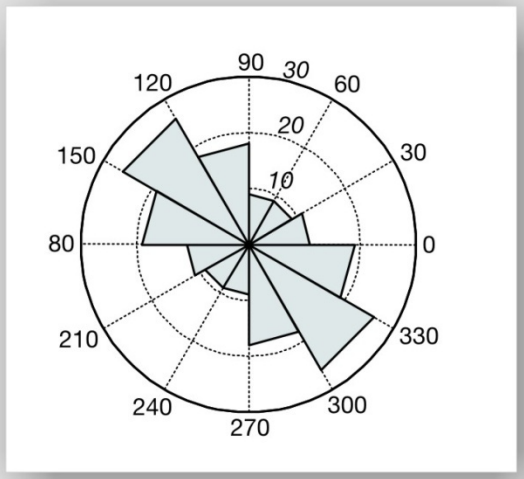
Gate plasticity



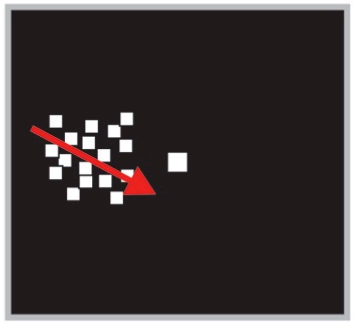


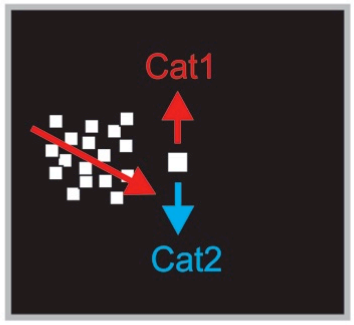
Freedman & Assad, 2006, *Nature*

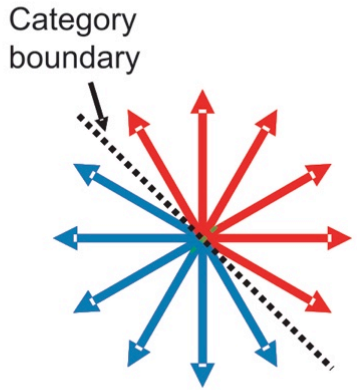


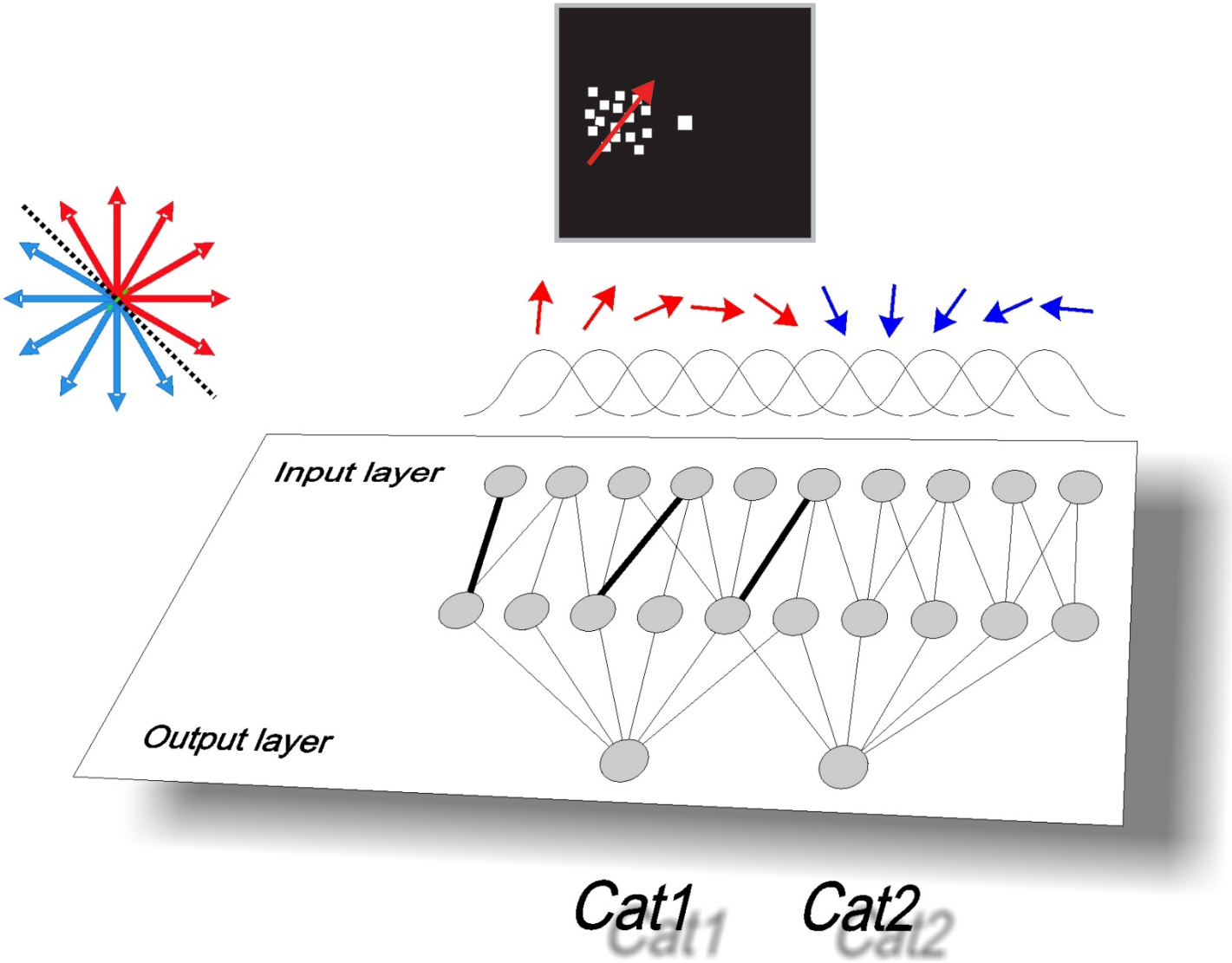


Freedman & Assad, 2006, *Nature*

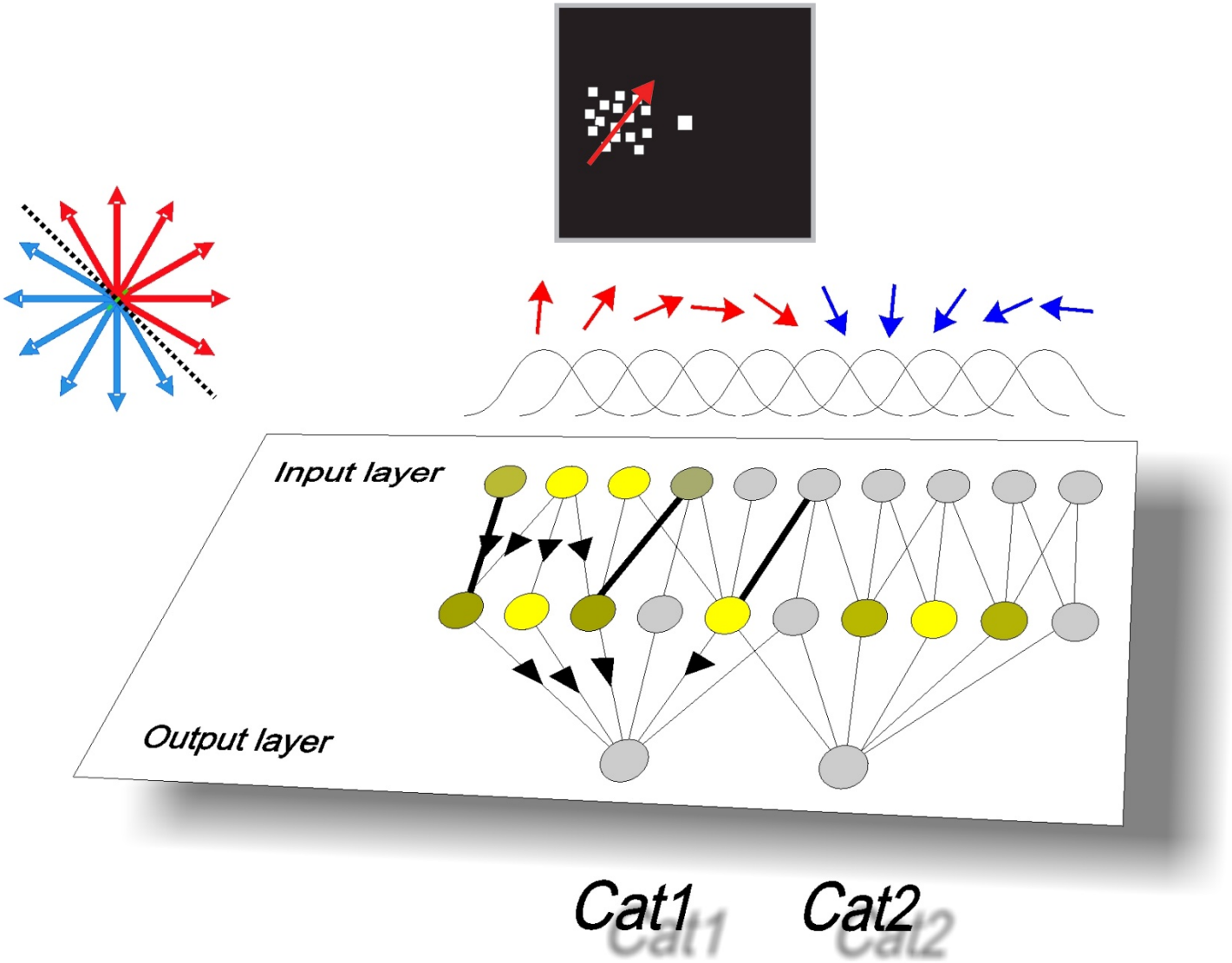



Cat1
Cat2

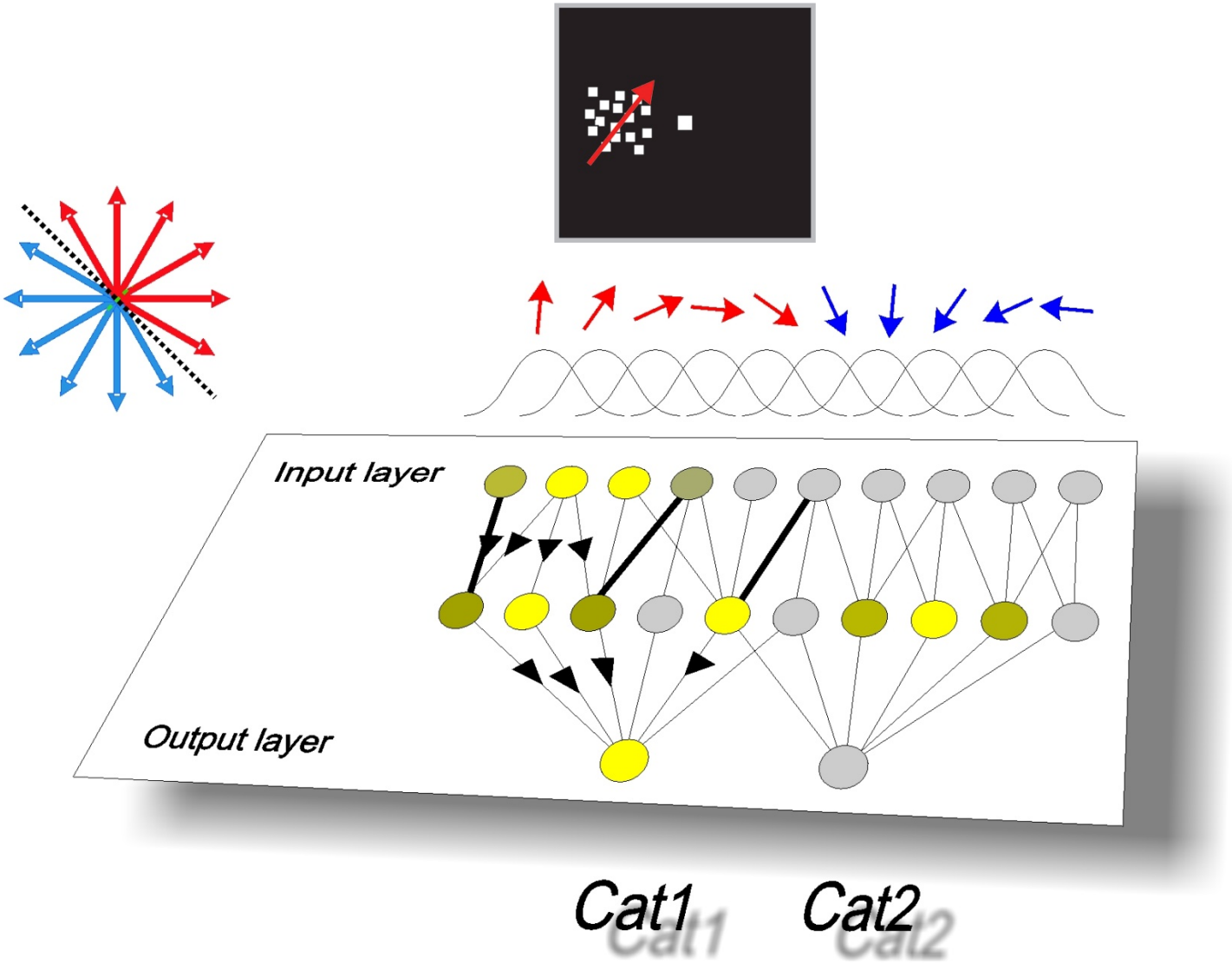

Category
boundary



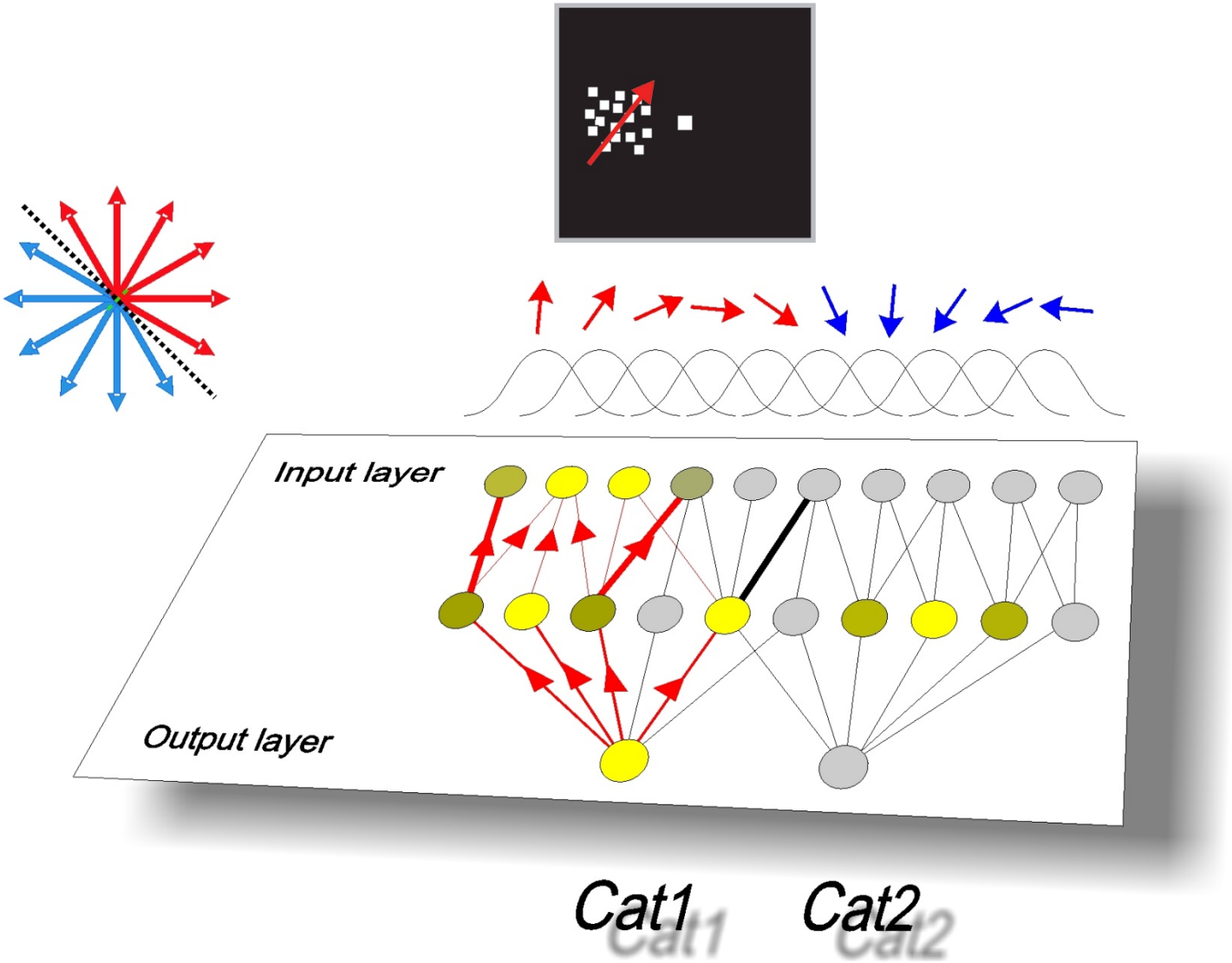
Lawrence Watling, Arjen van Ooyen



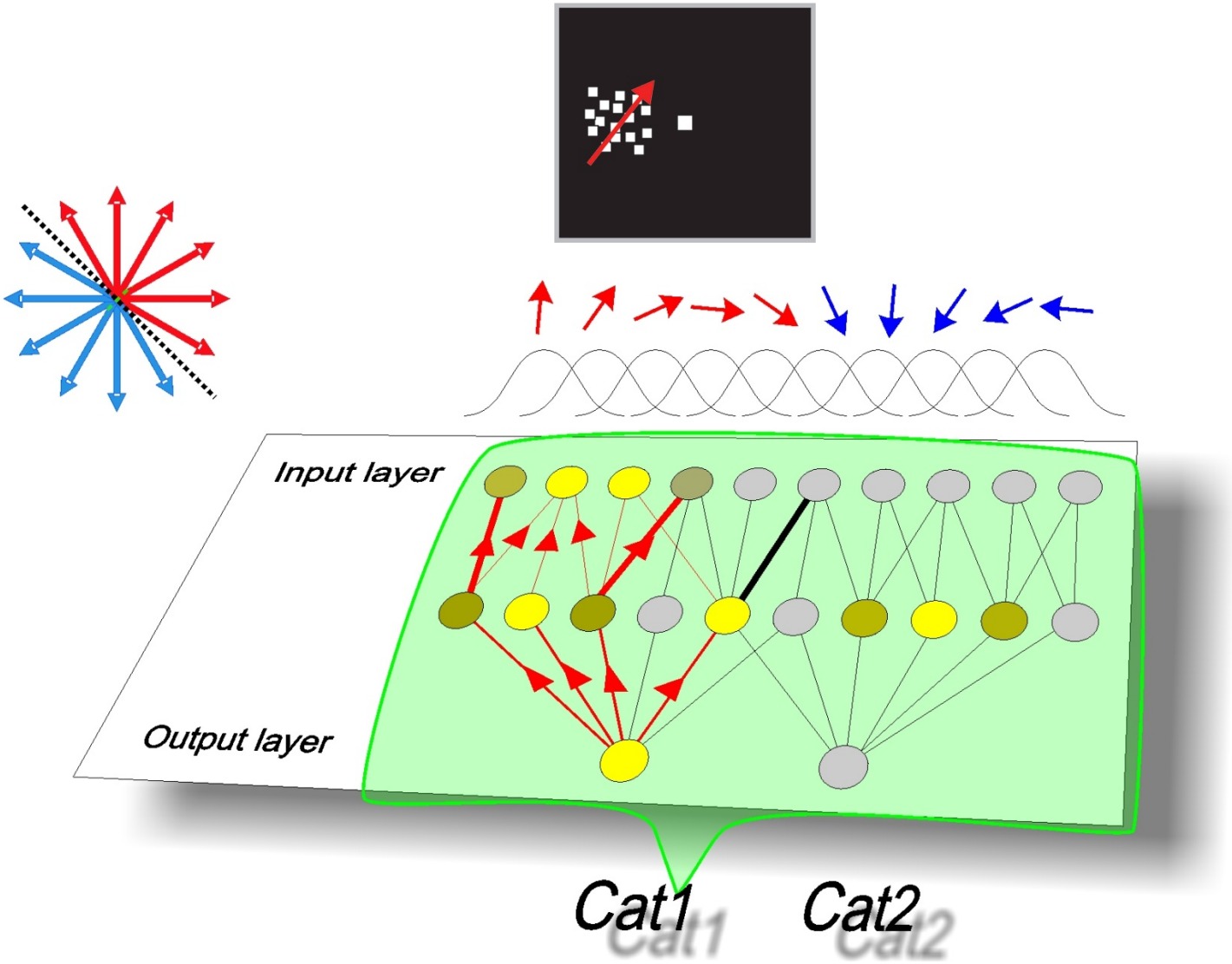
Lawrence Watling, Arjen van Ooyen

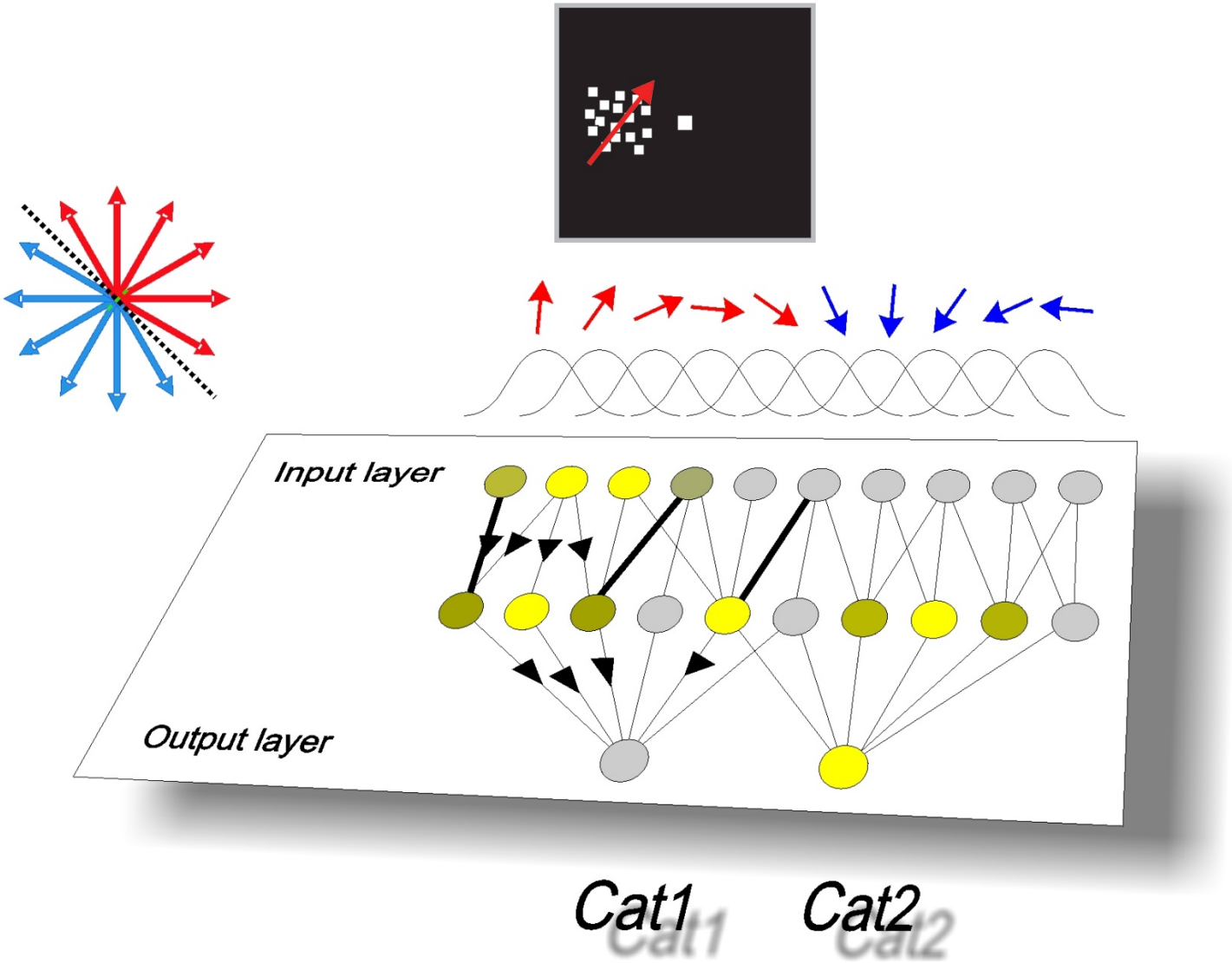


Lawrence Watling, Arjen van Ooyen

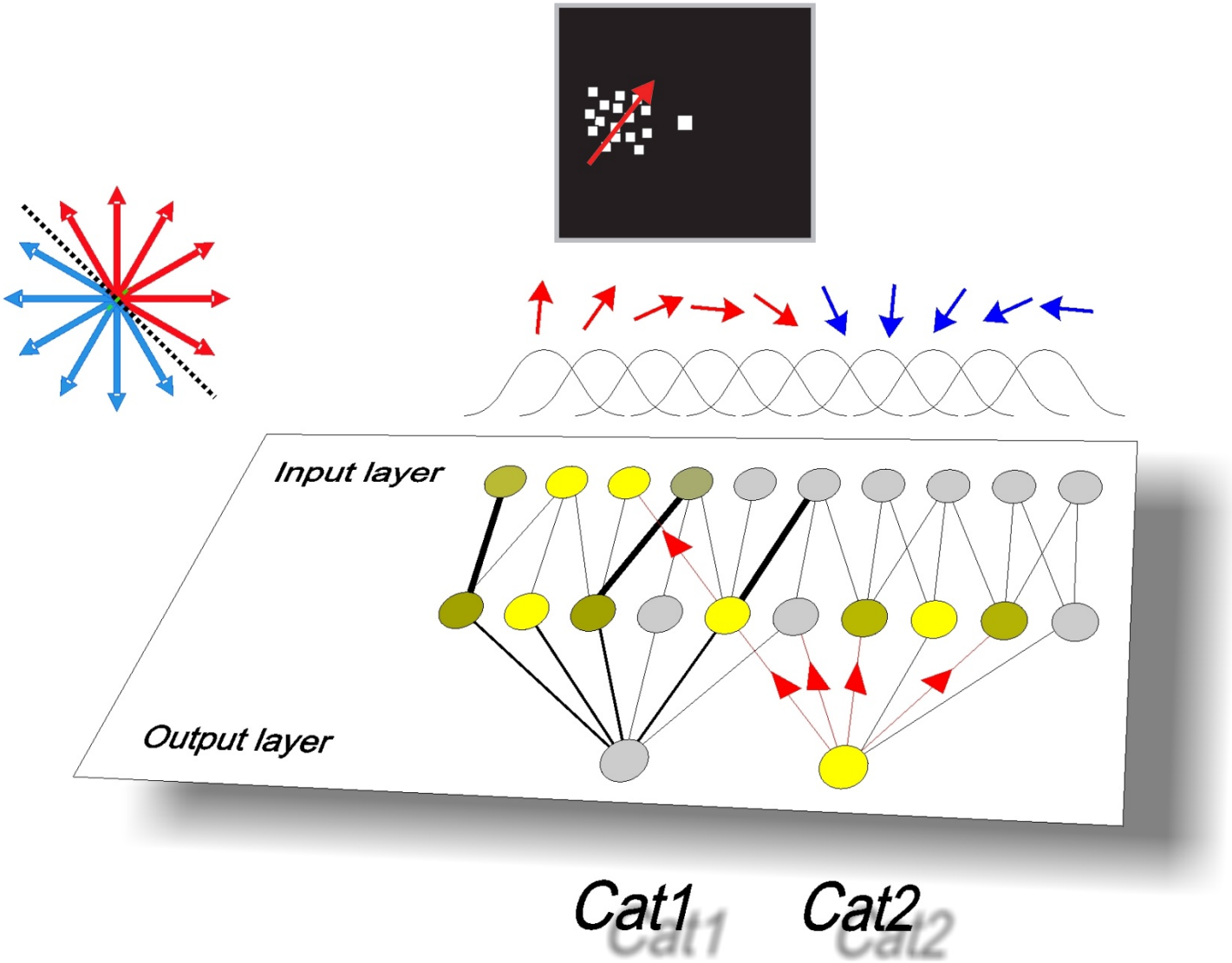


Lawrence Watling, Arjen van Ooyen

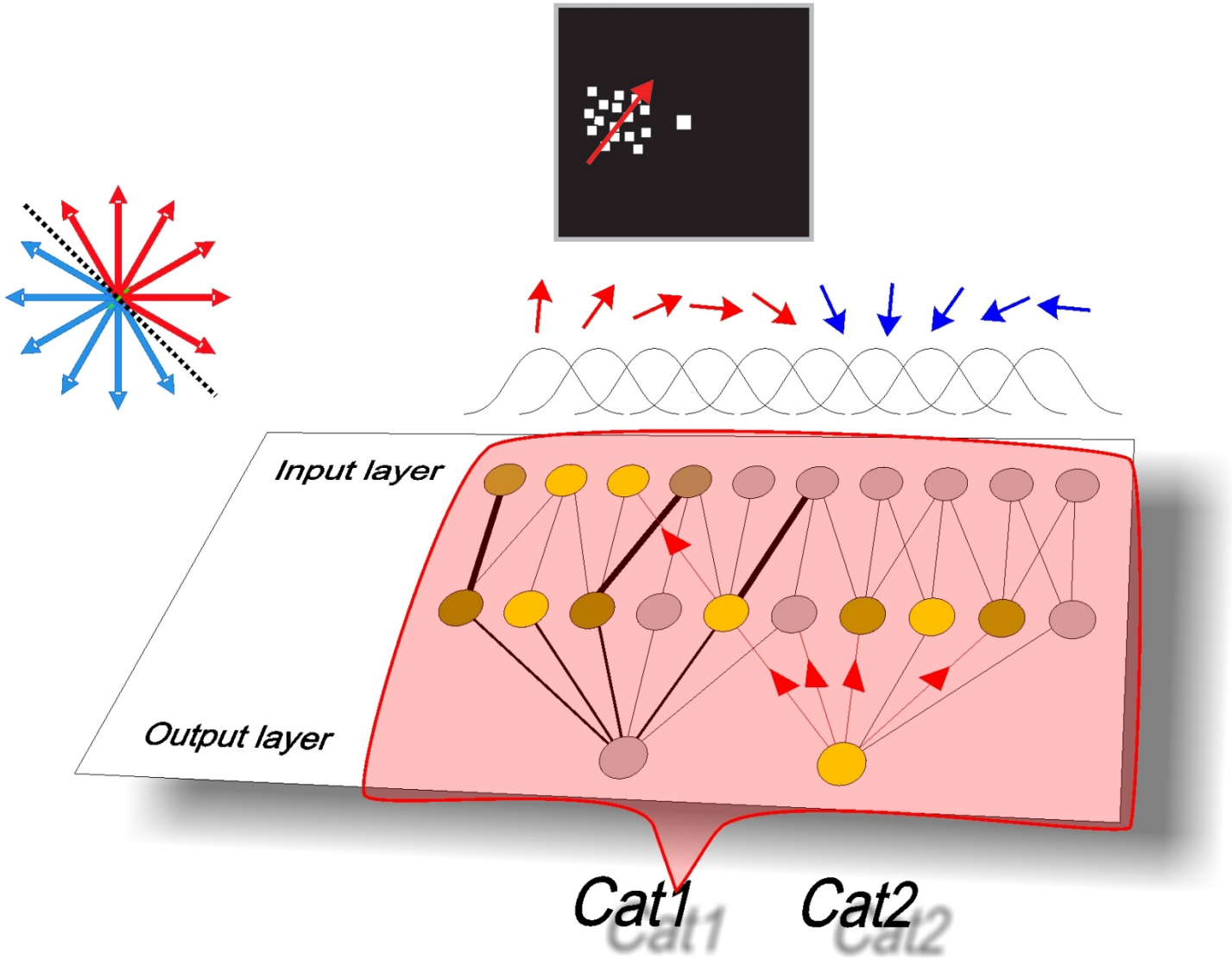

Input layer
Output layer
Cat1
Cat2



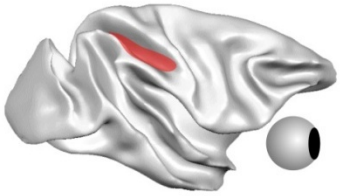
Lawrence Watling, Arjen van Ooyen



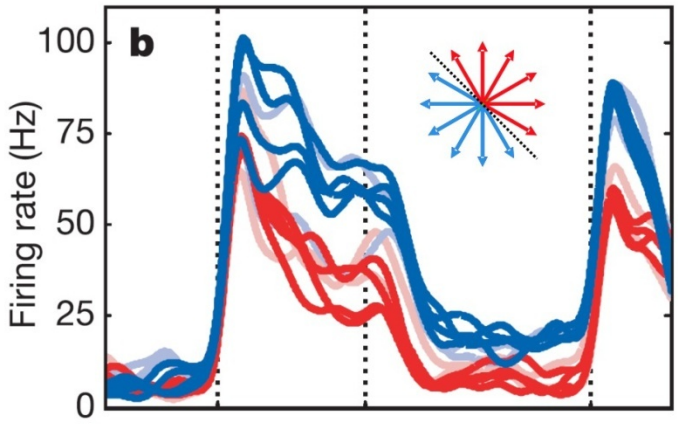
Lawrence Watling, Arjen van Ooyen



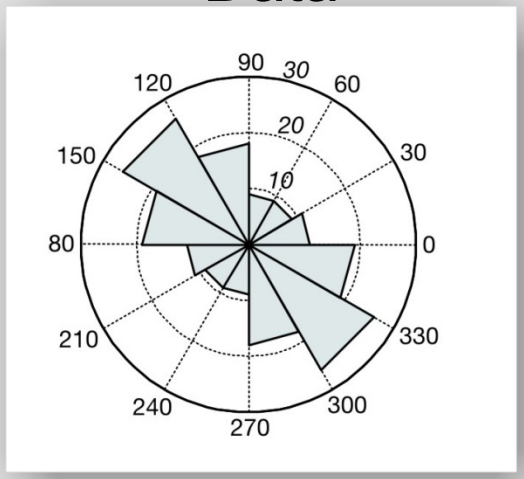
Lawrence Watling, Arjen van Ooyen



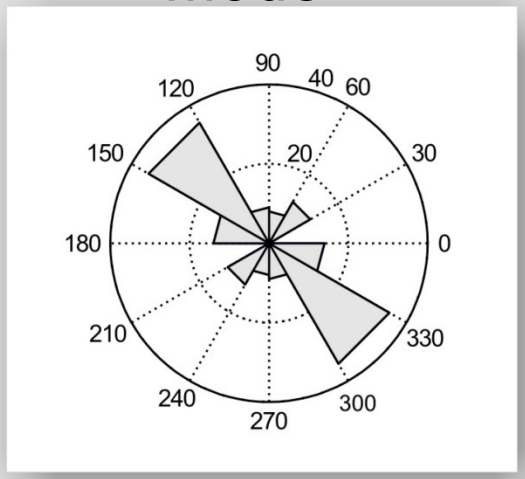
LIP



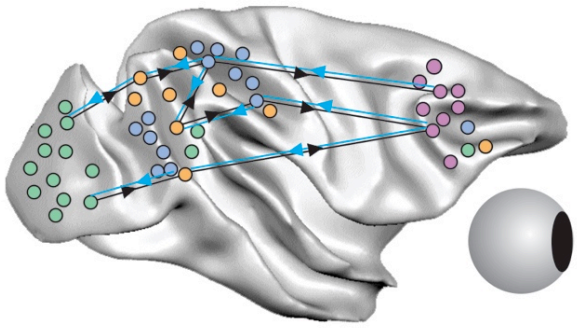
Data

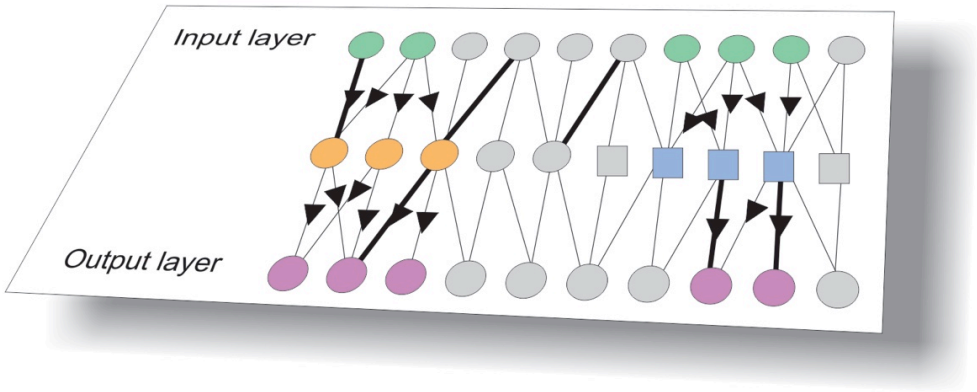


Model



Freedman & Assad, 2006, *Nature*



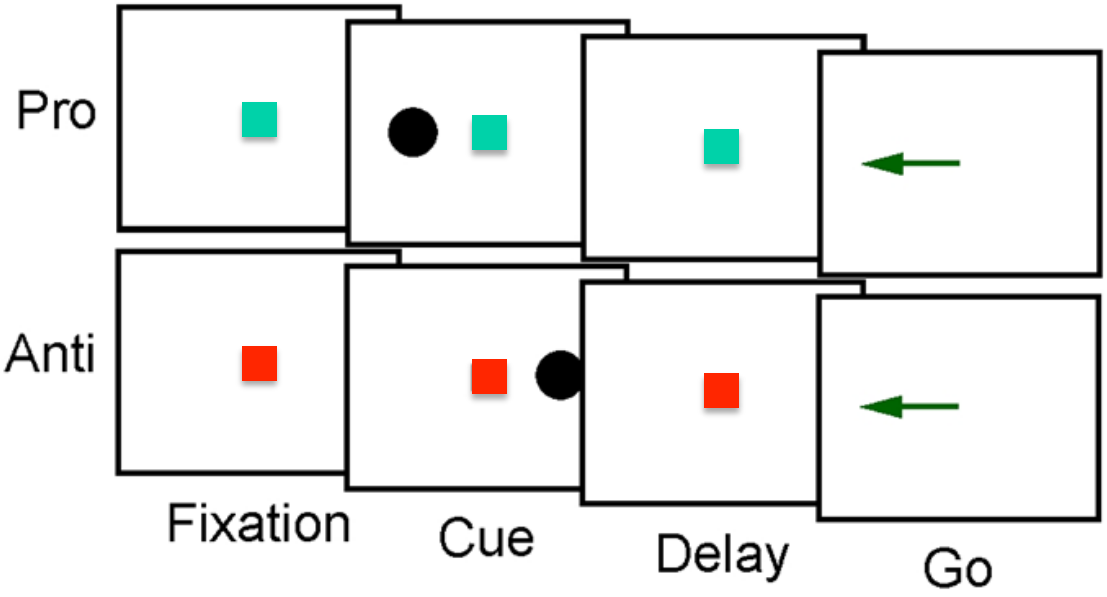


Neurons in the association layer become tuned to:

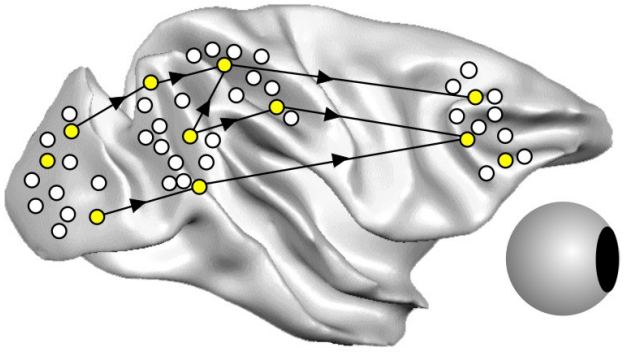
- The features that are important for the stimulus-response mapping
- The boundaries between categories

Roelfsema & van Ooyen, 2005, *Neural Comp.*; Roelfsema et al., 2010, *TiCS*

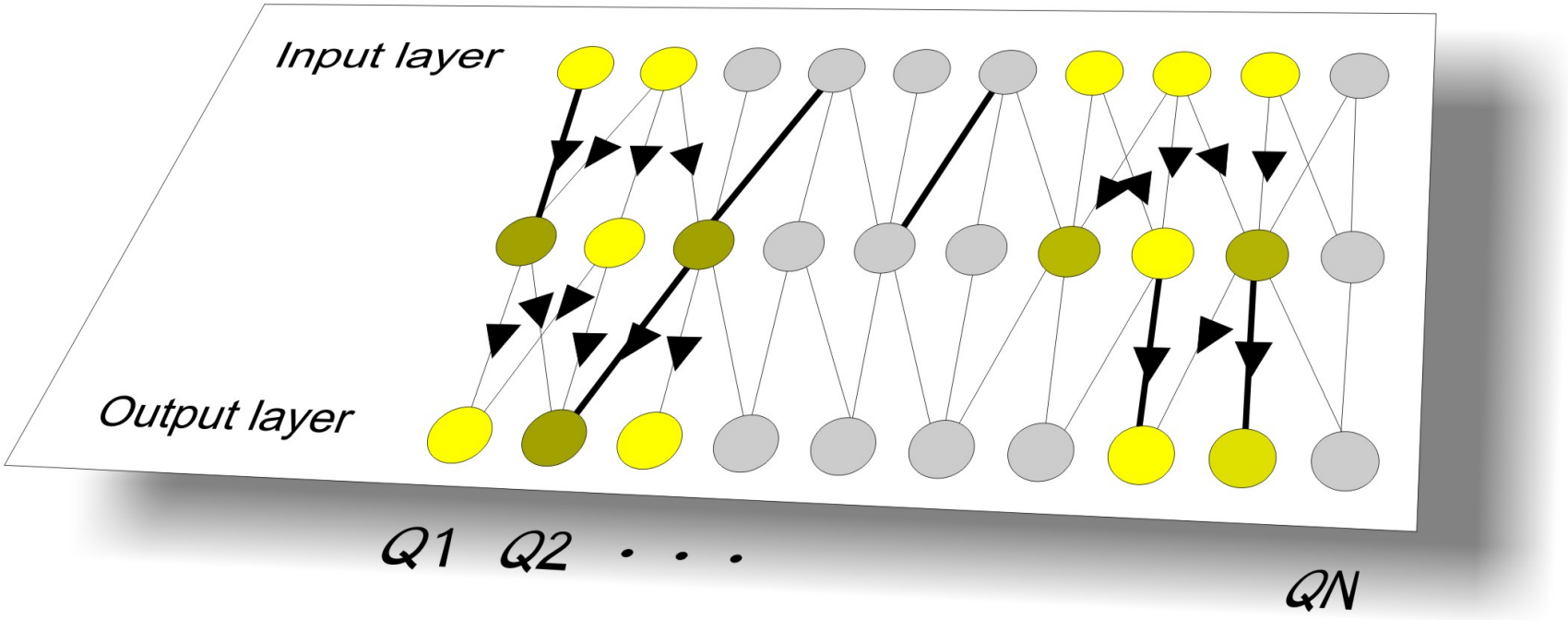
Delayed saccade-antisaccade task



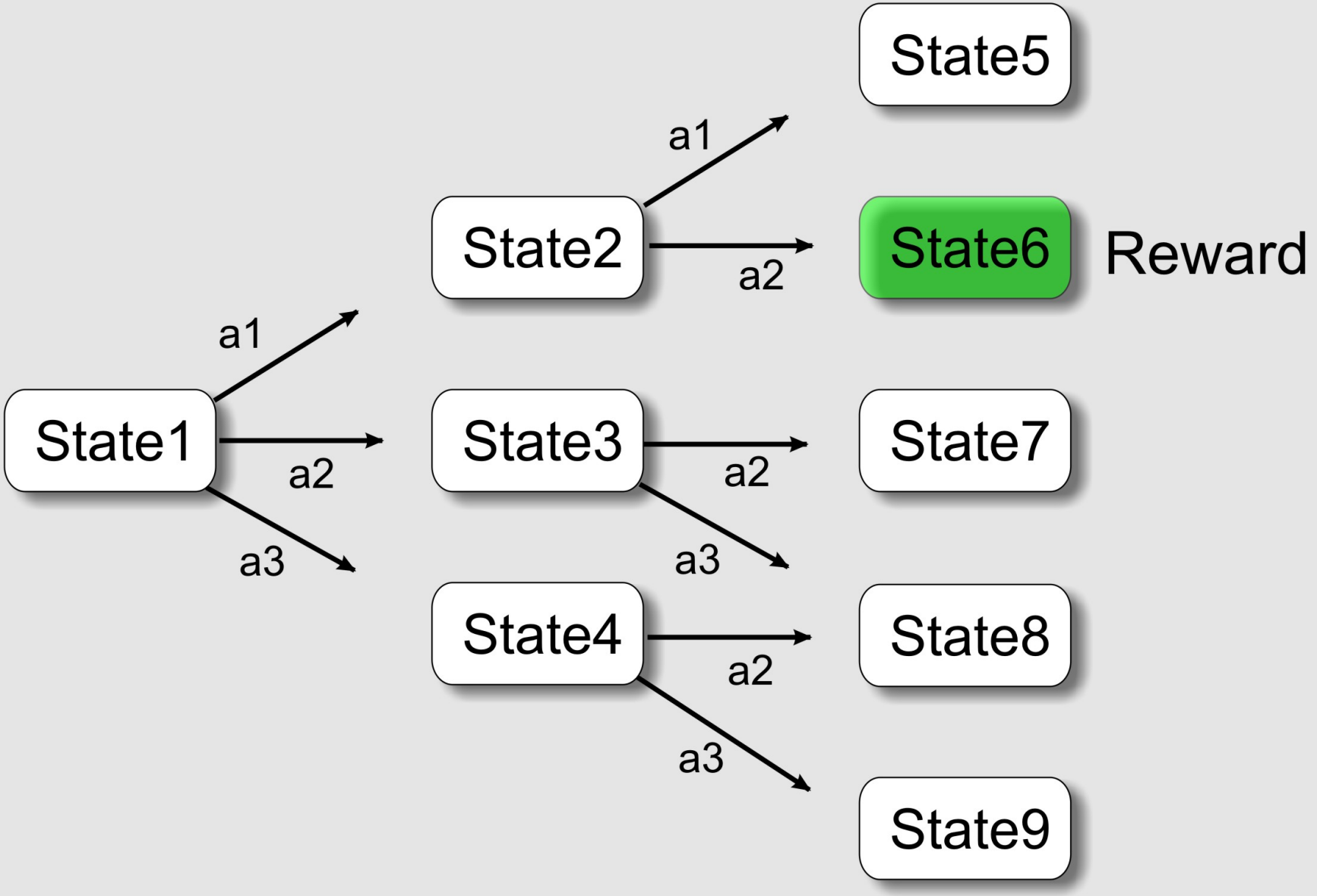
e.g. Gottlieb & Goldberg *Nature Neurosci* (1999)



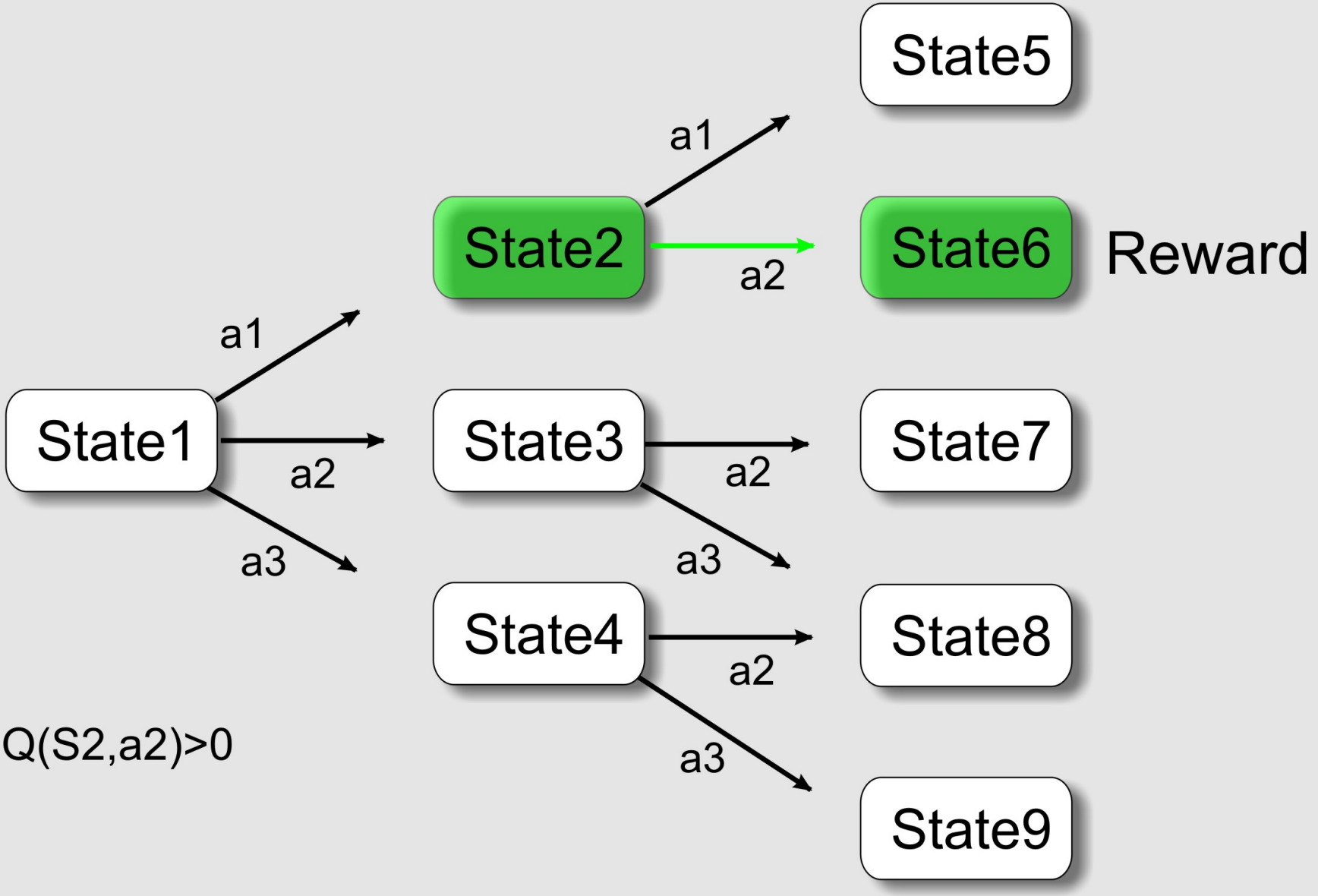
We will now use the network to compute all Qs (i.e. action values) for the current sensory stimulus



Rombouts, Bohte & Roelfsema, PLoS Comp Biol, 2015



Q-learning: Watkins & Dayan, Machine learning, 1992



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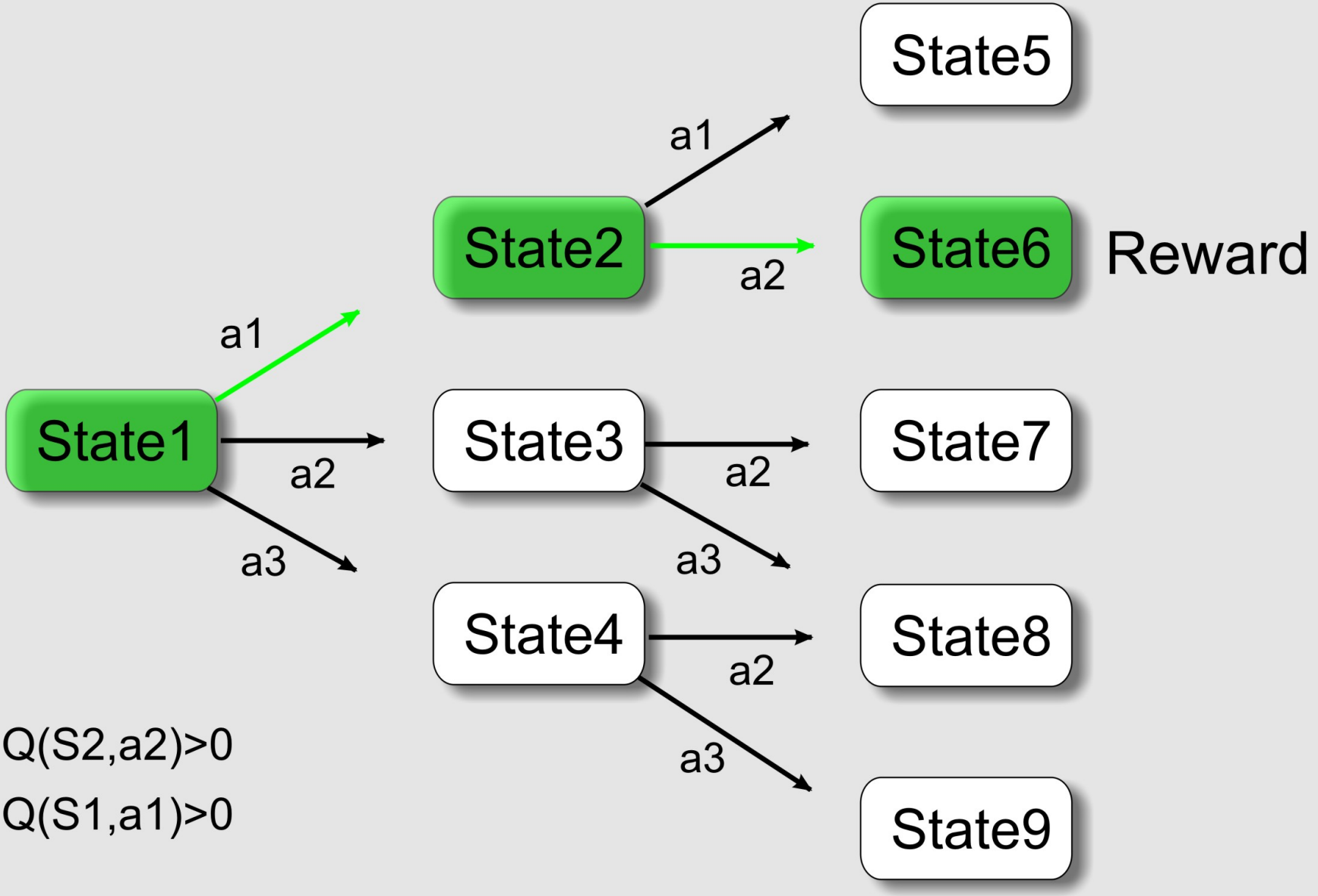

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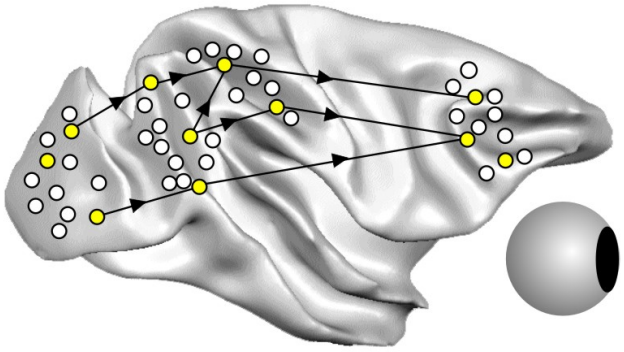

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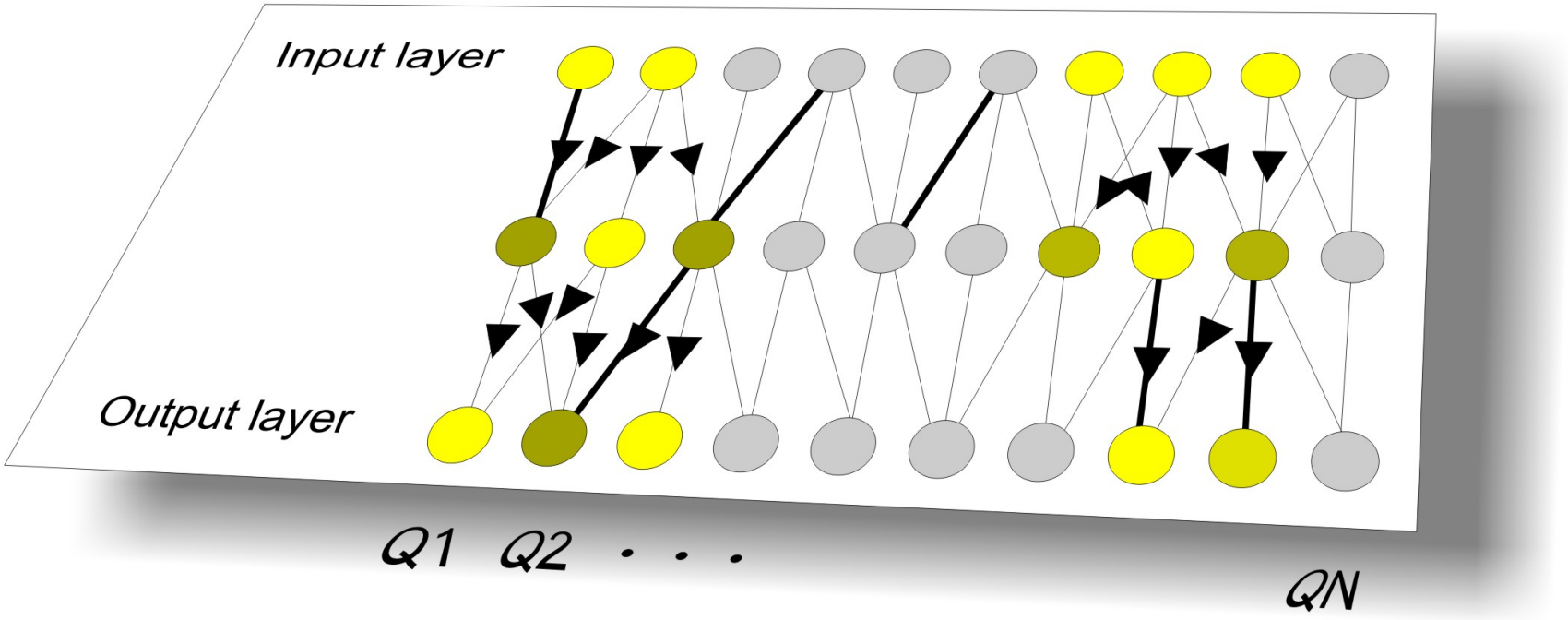
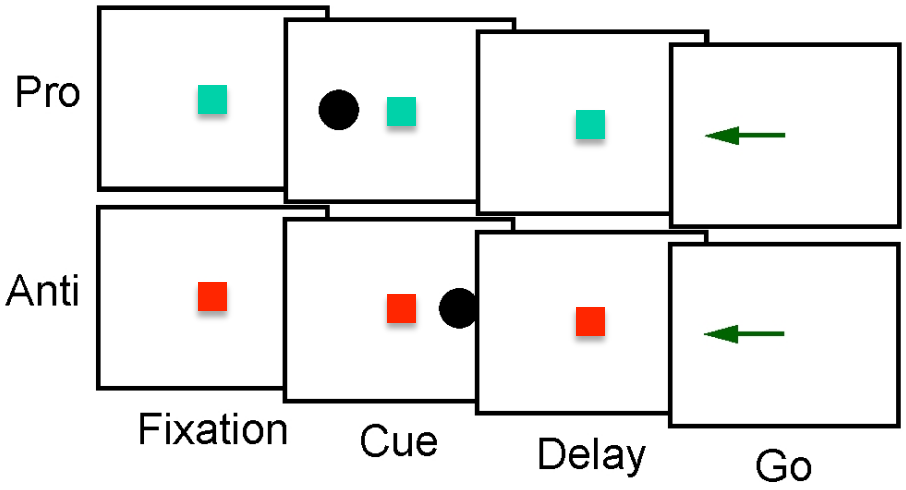
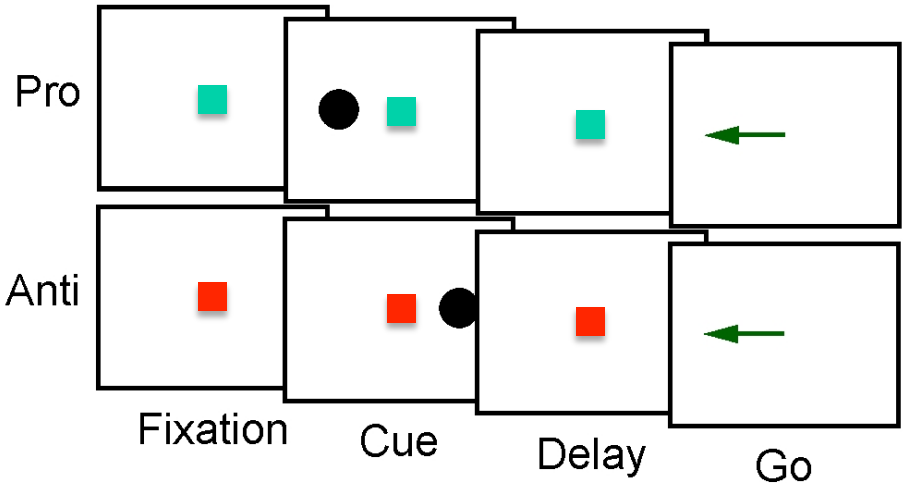


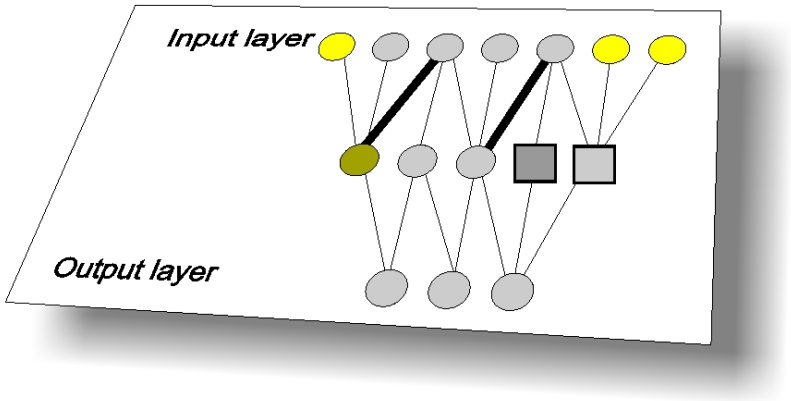
Rombouts, Bohte & Roelfsema, PLoS Comp Biol, 2015

Saccade/anti-saccade task

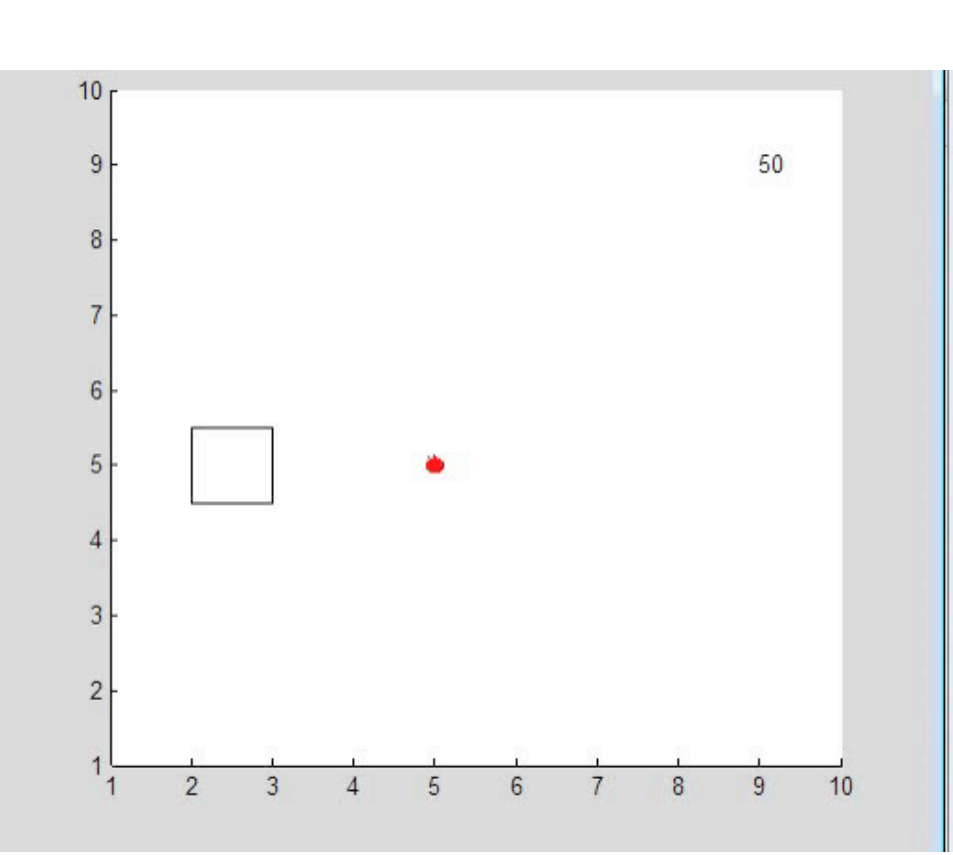


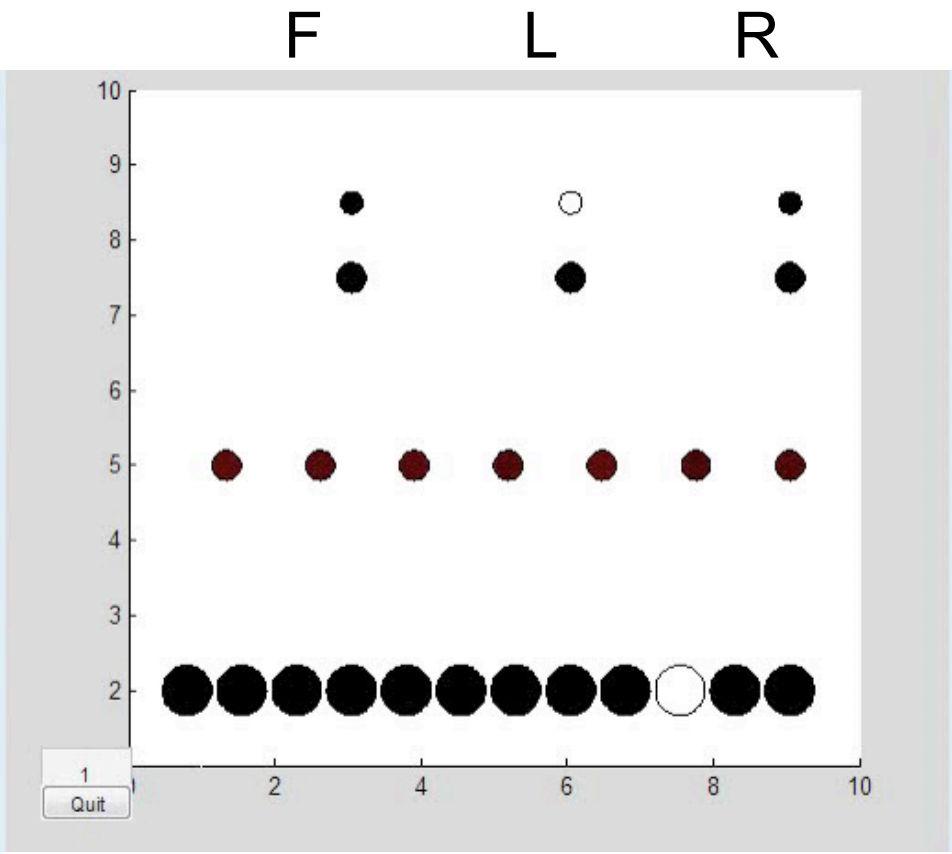
Saccade/anti-saccade task





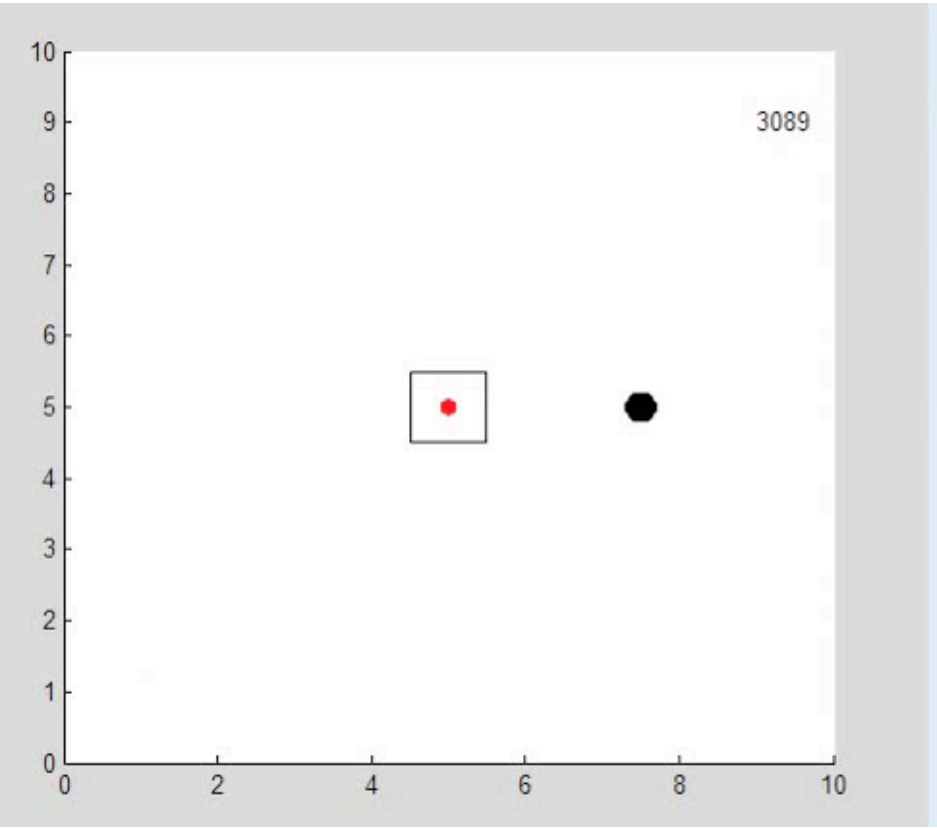
Trials 50-57

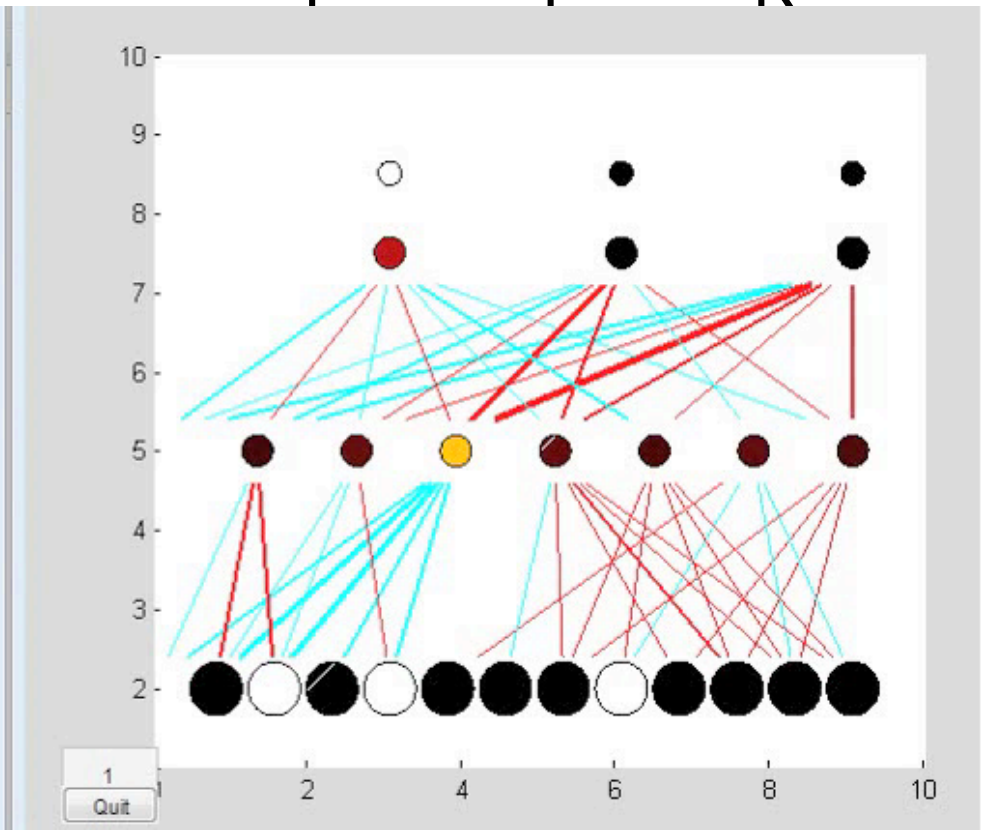




L R On Off

Trials 3089-3097

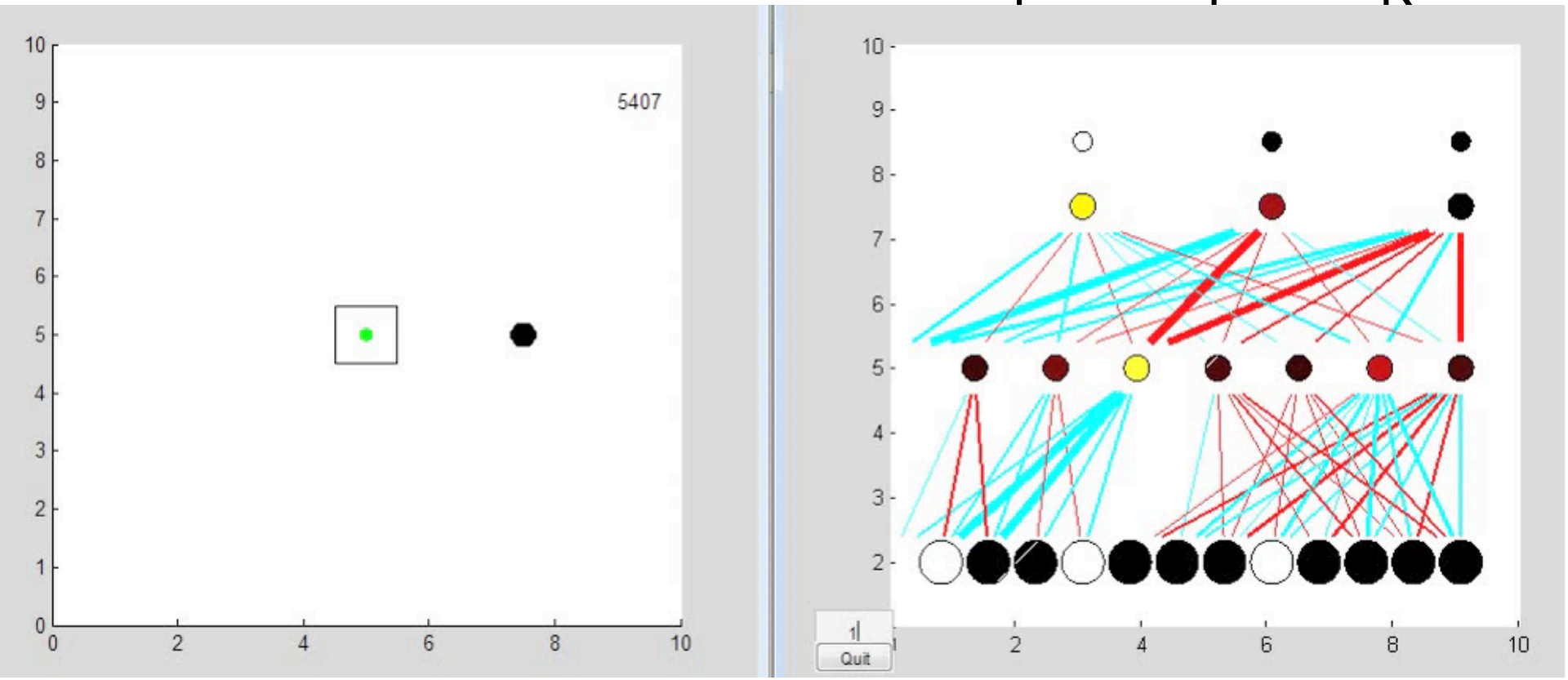




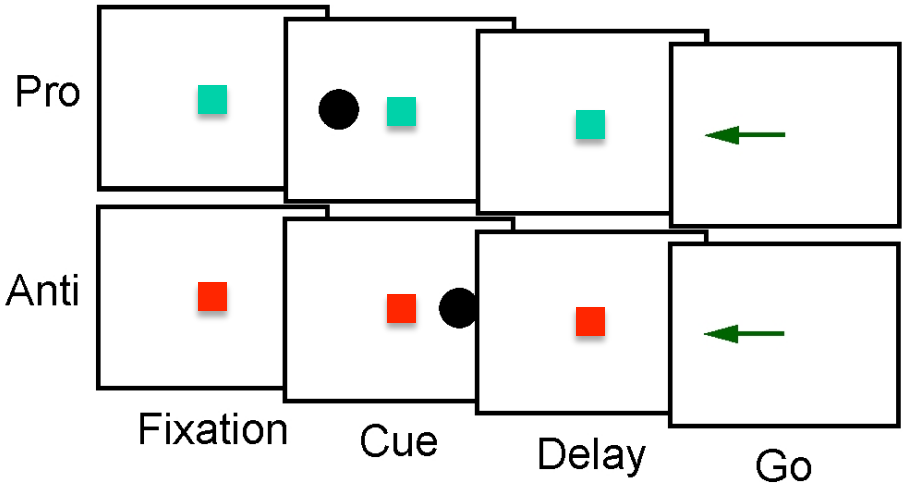
F I R

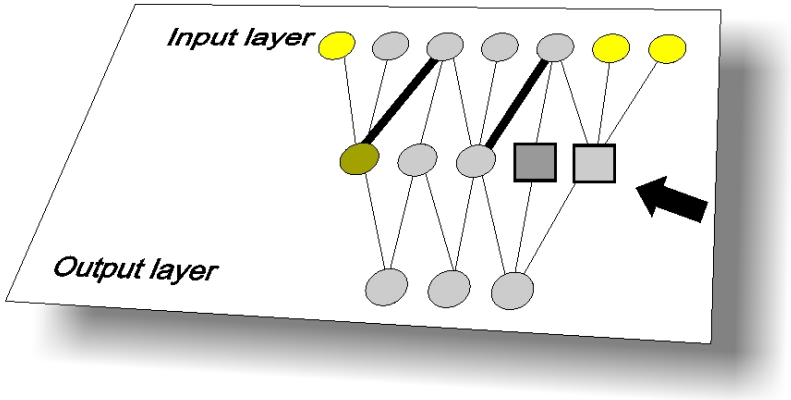
L R On Off

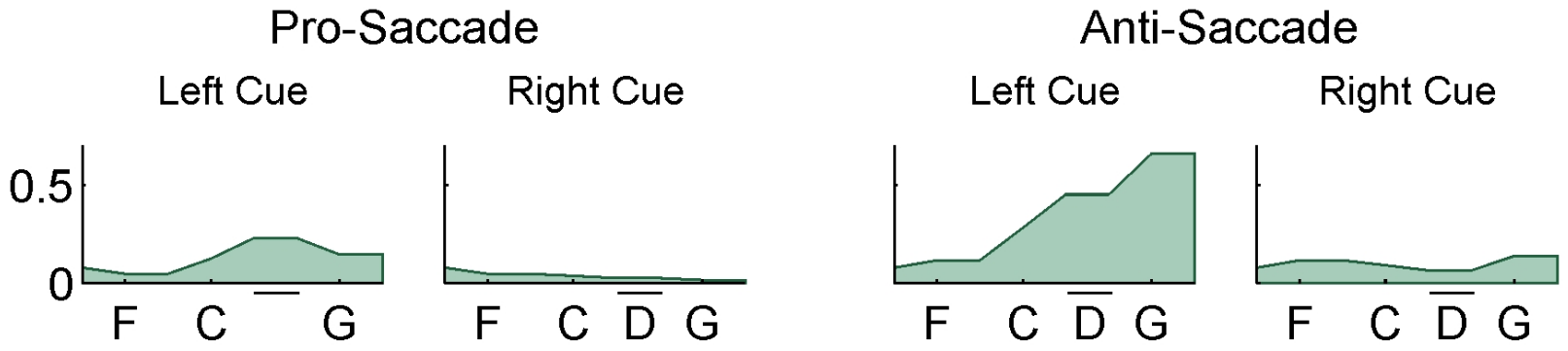
Trials 5407-5417



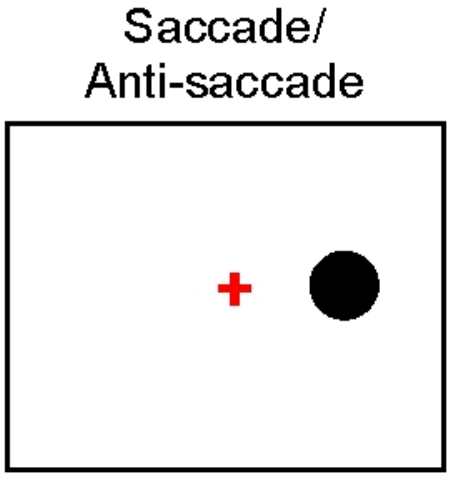
Saccade/anti-saccade task







Rombouts, Bohte & Roelfsema, PLoS Comp Biol, 2015



Pineda-Almeida algorithm - Brosch, Neumann & Roelfsema, PLoS Comp Biol, 2015

Introduction: feedforward and feedback processing

Contour grouping: layers and higher areas

Training the primate Turing machine– **role of feedback connections** in learning

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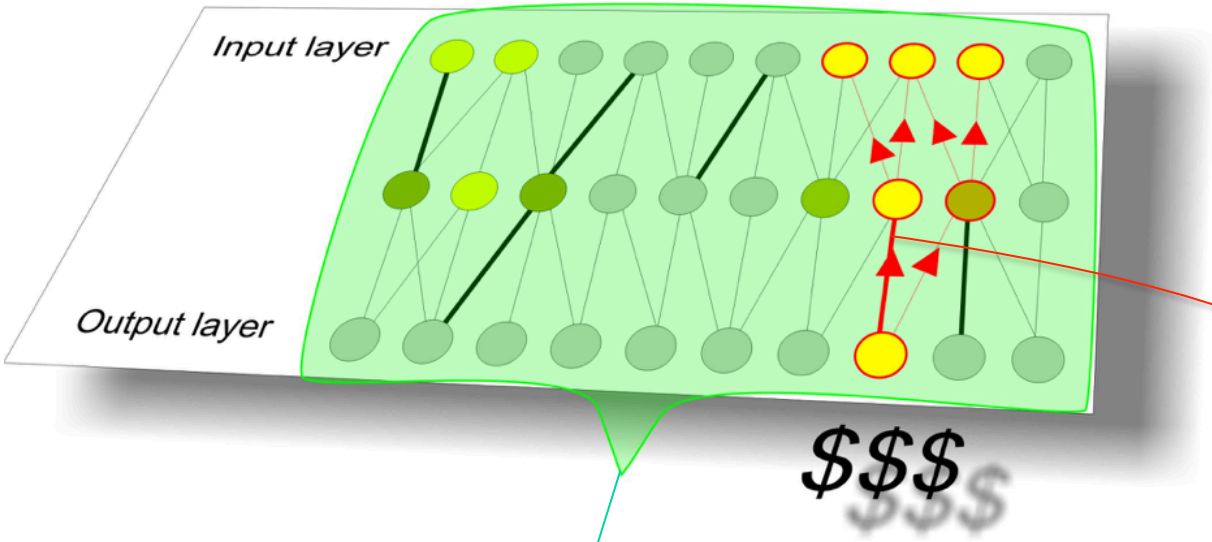

What is needed:

1) Gating of plasticity by neuromodulators that code for the reward prediction error, e.g. DA (Bao et al., 2001; Yagishita et al., 2014) or ACh (Kilgard & Merzenich, 1998)

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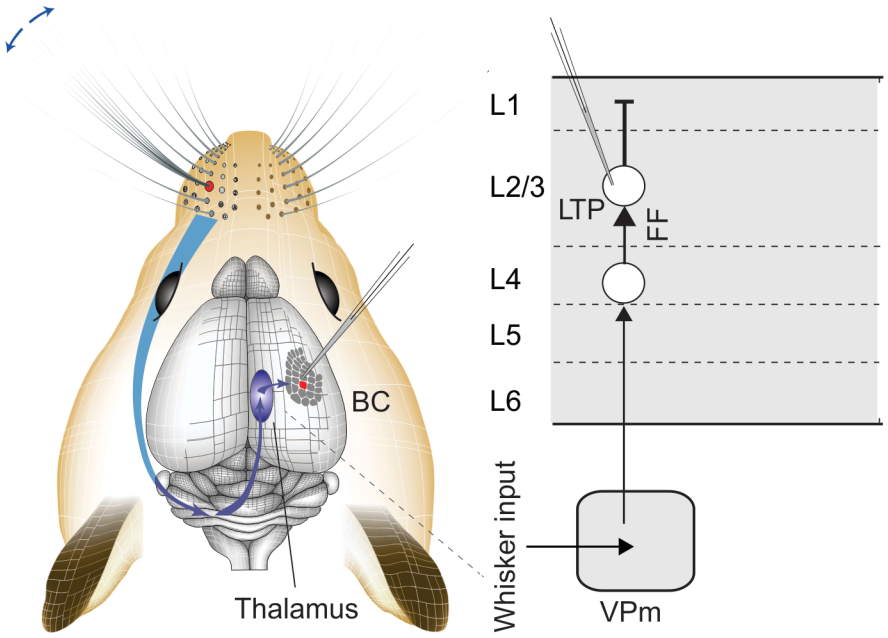
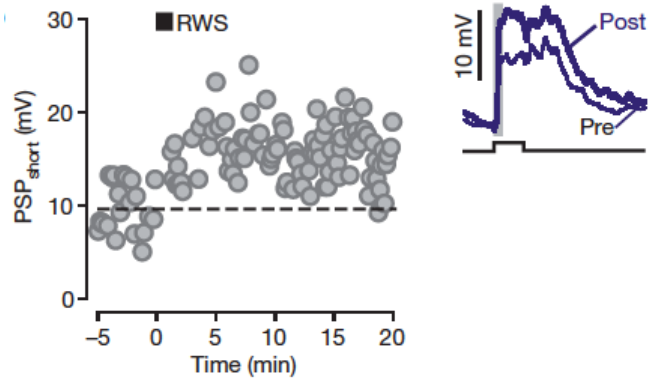
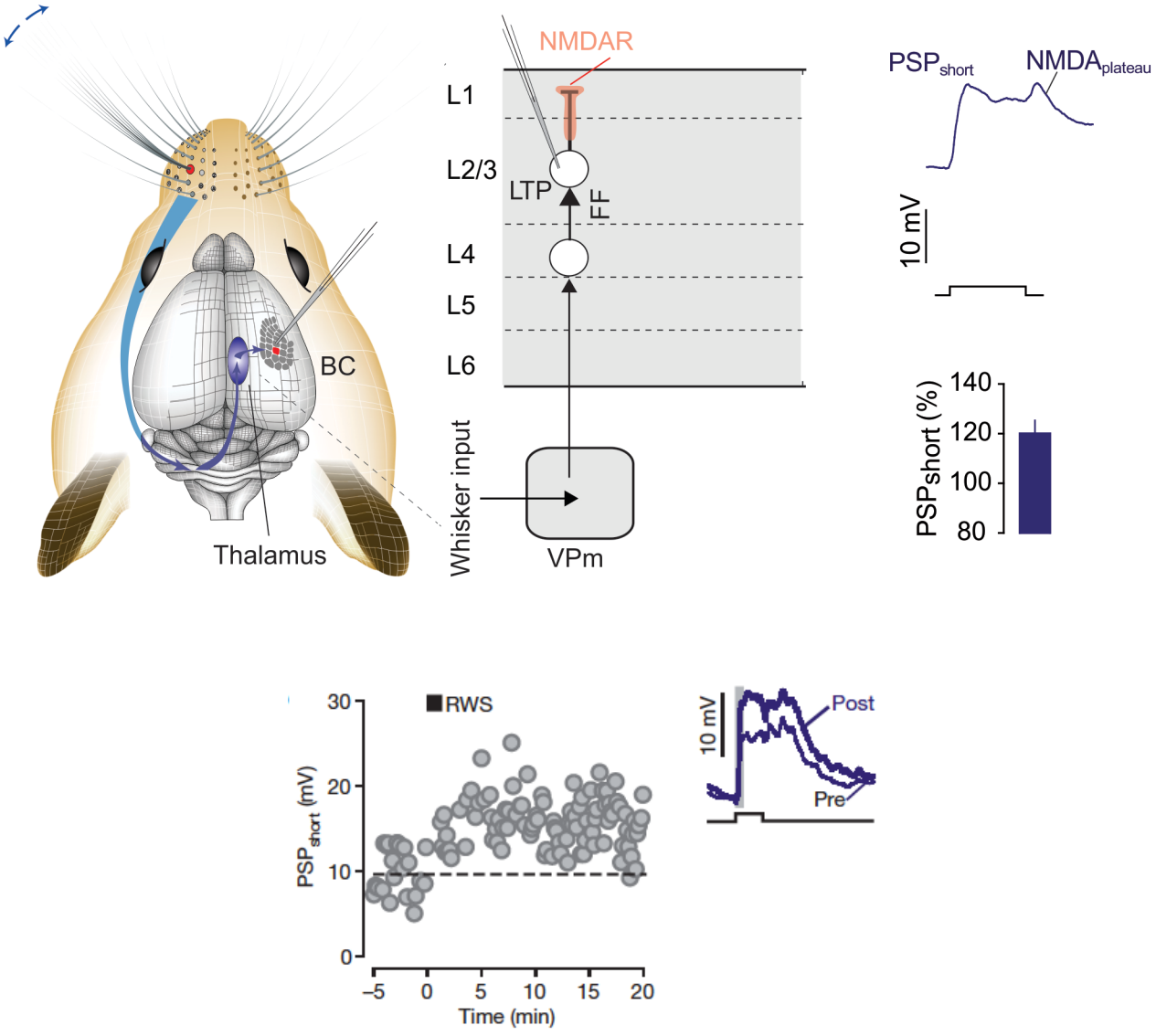




Gambino, Pages, Kehayas, Baptista,Tatti, Carleton & Holtmaat, Nature (2014)



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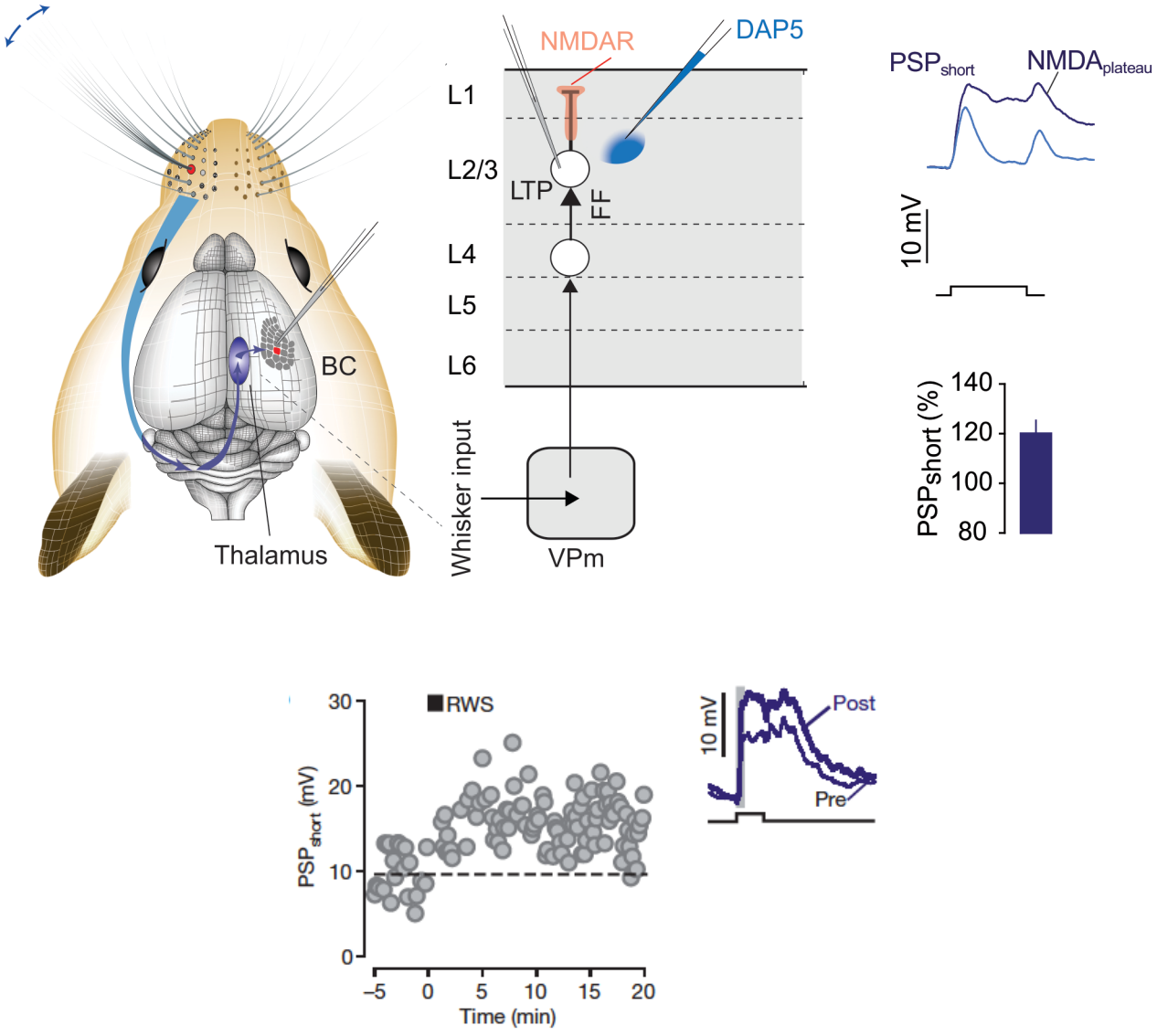

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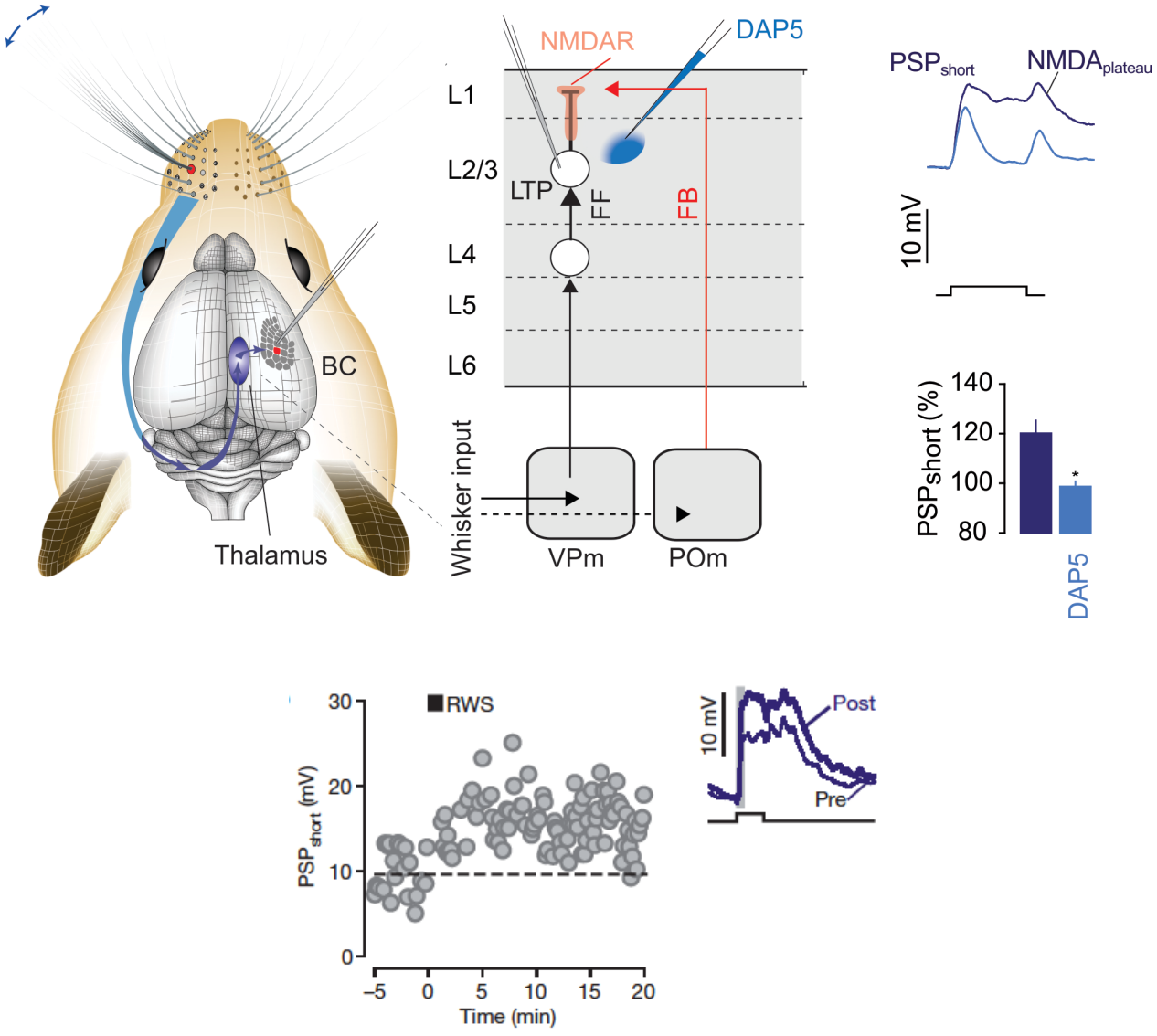

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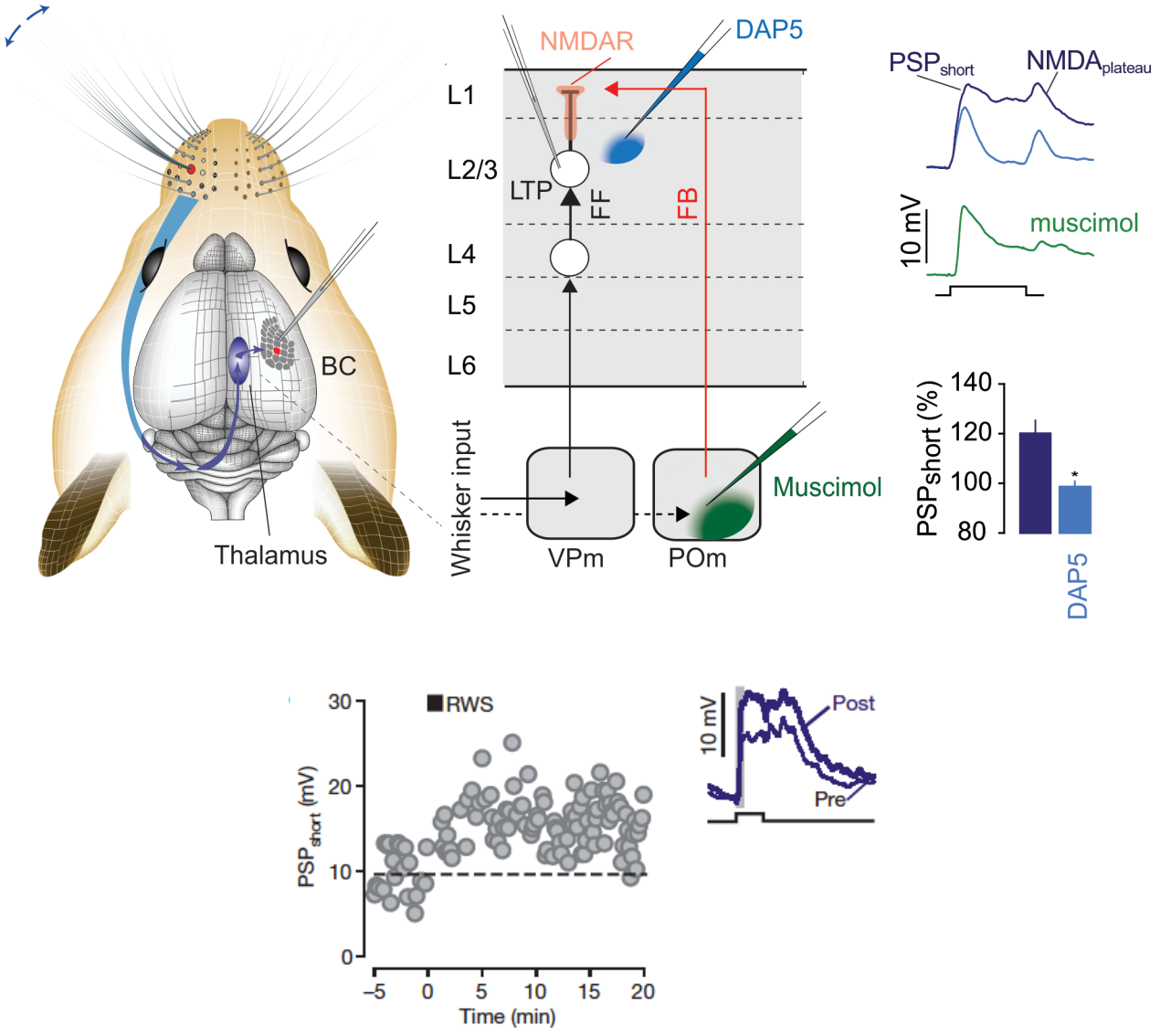

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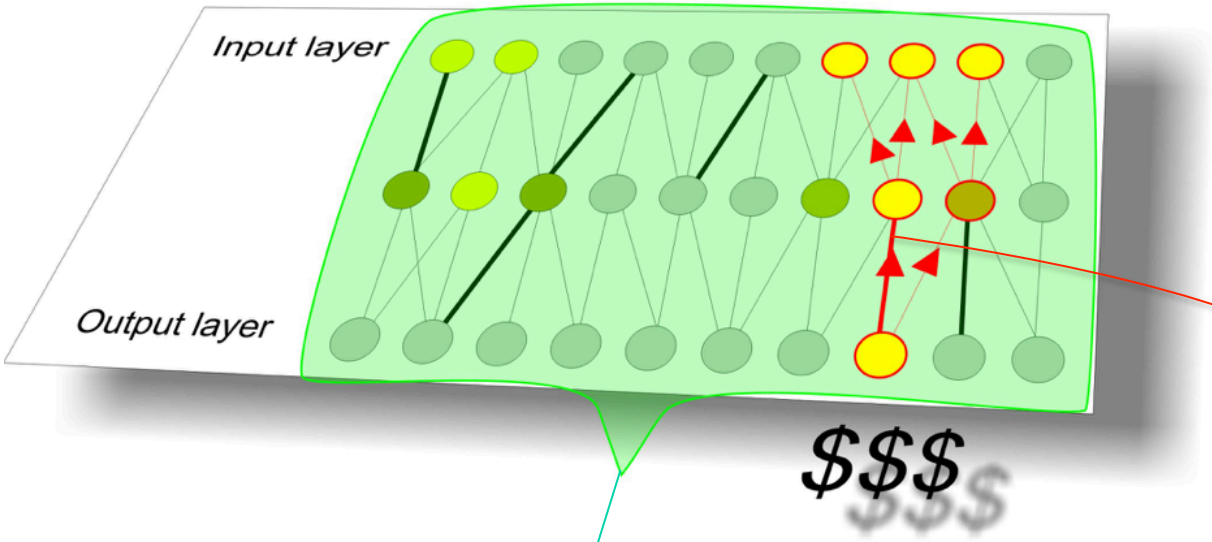

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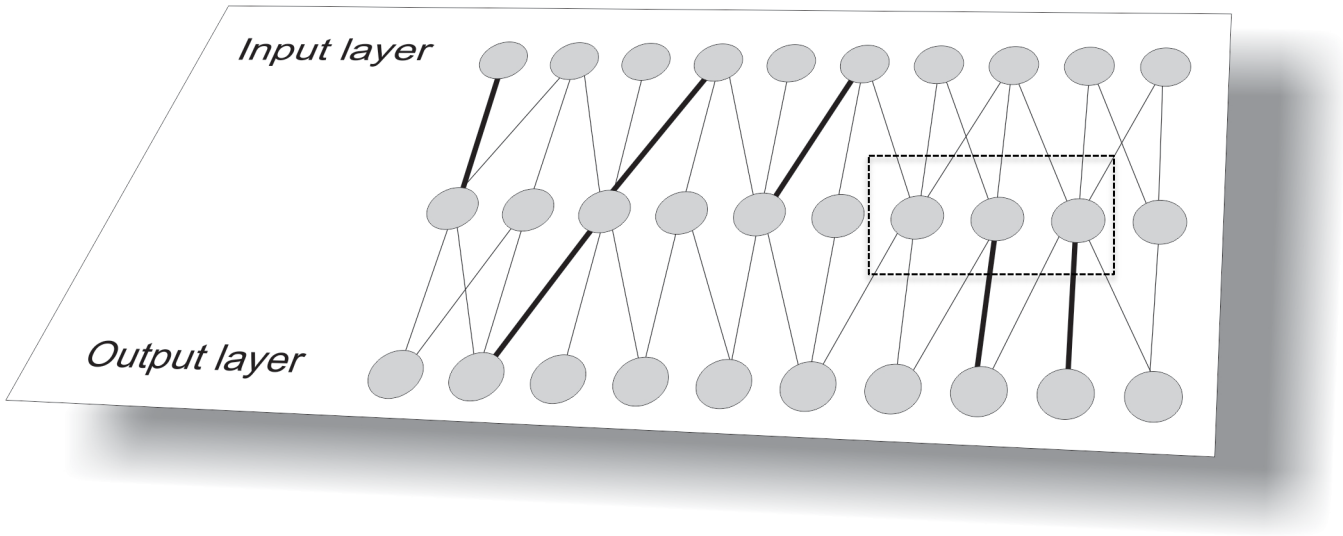
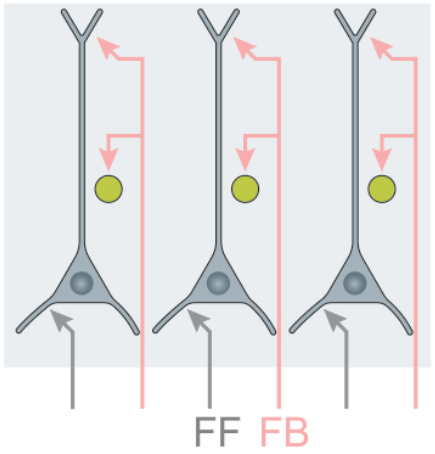
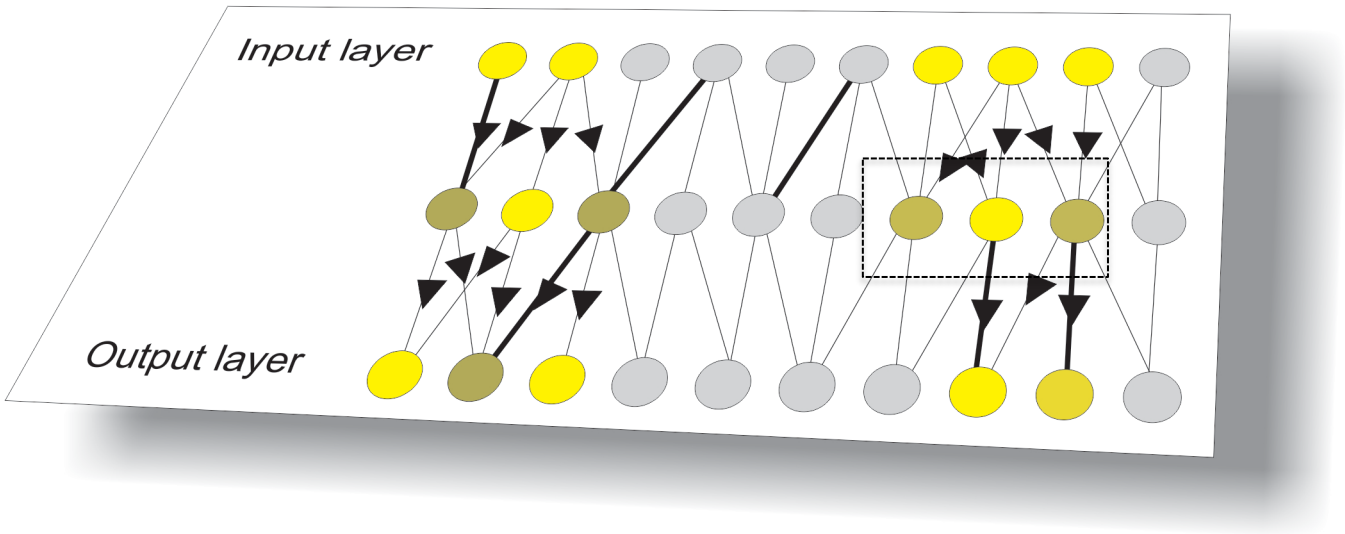
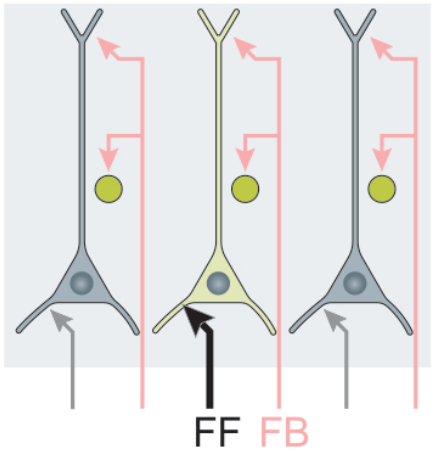
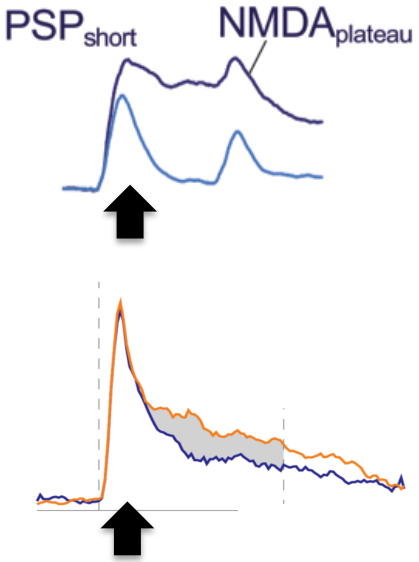




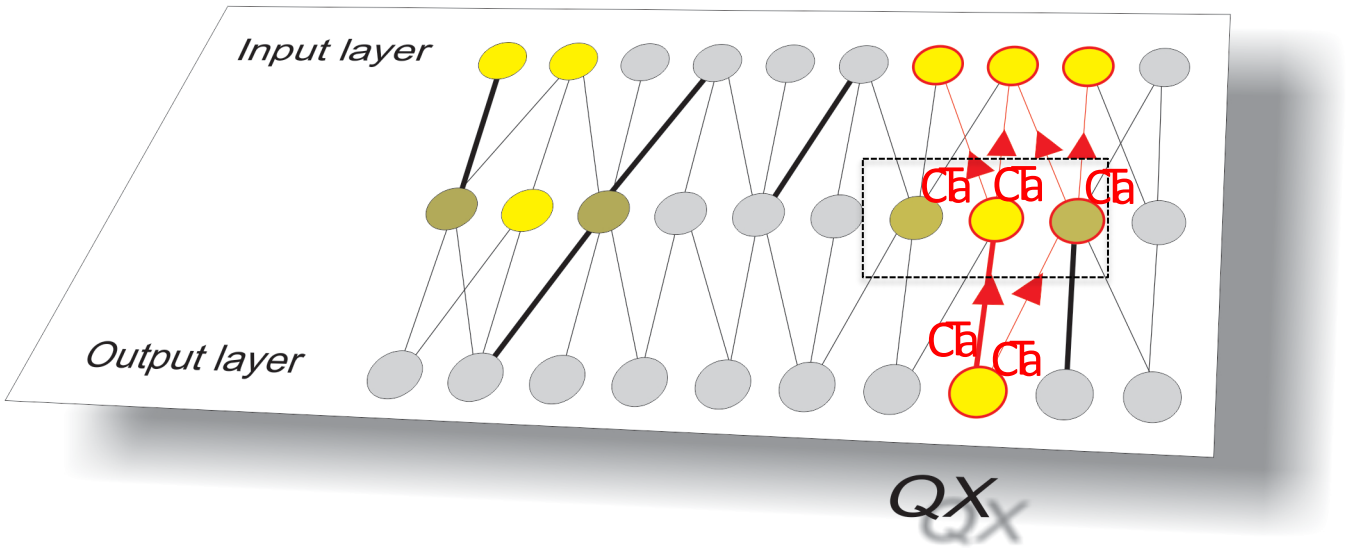
Roelfsema & Holtmaat Nature Reviews Neuroscience 2018

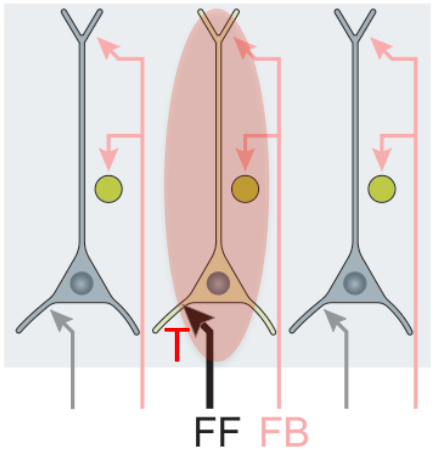


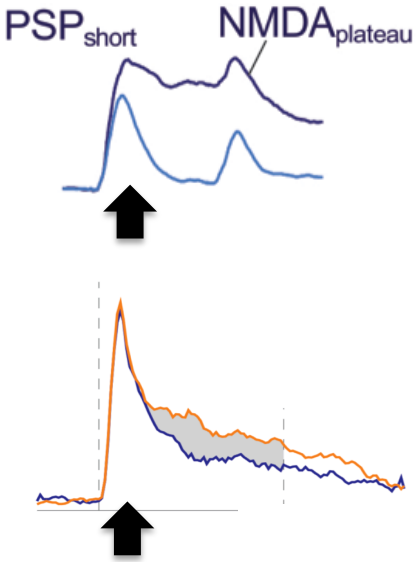




Roelfsema & Holtmaat Nature Reviews Neuroscience 2018







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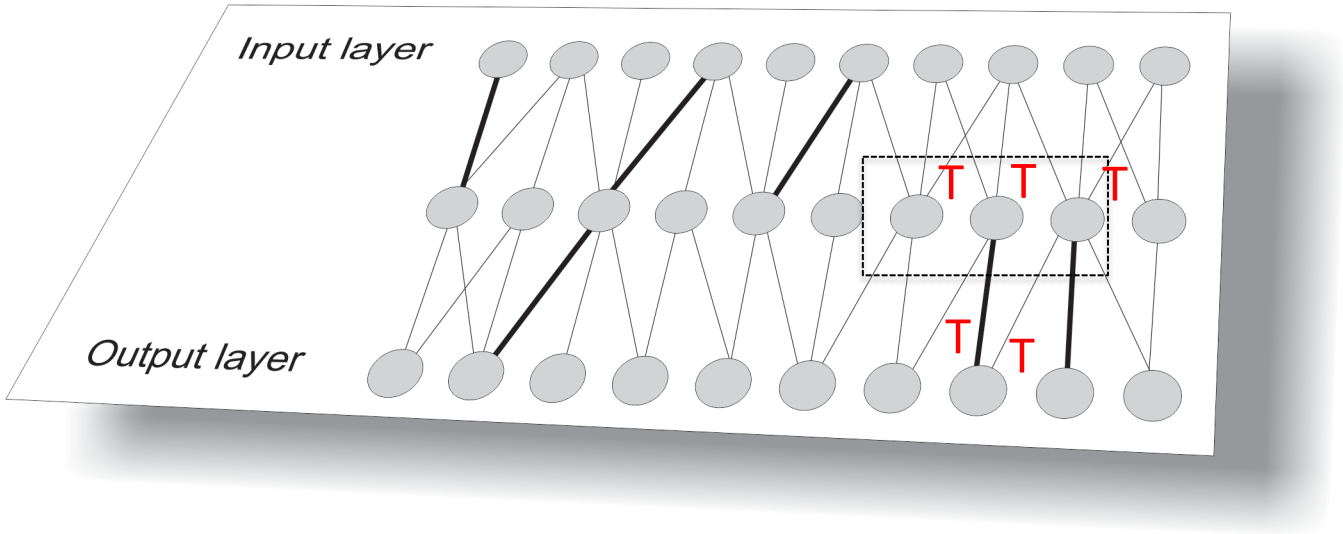

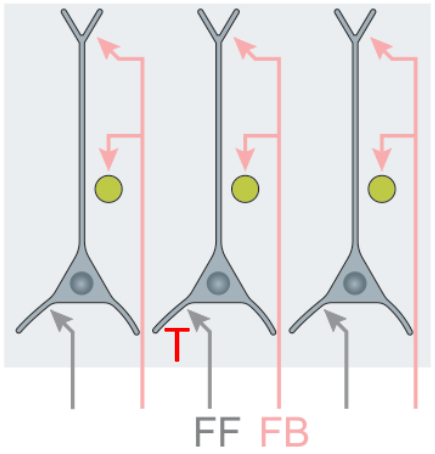

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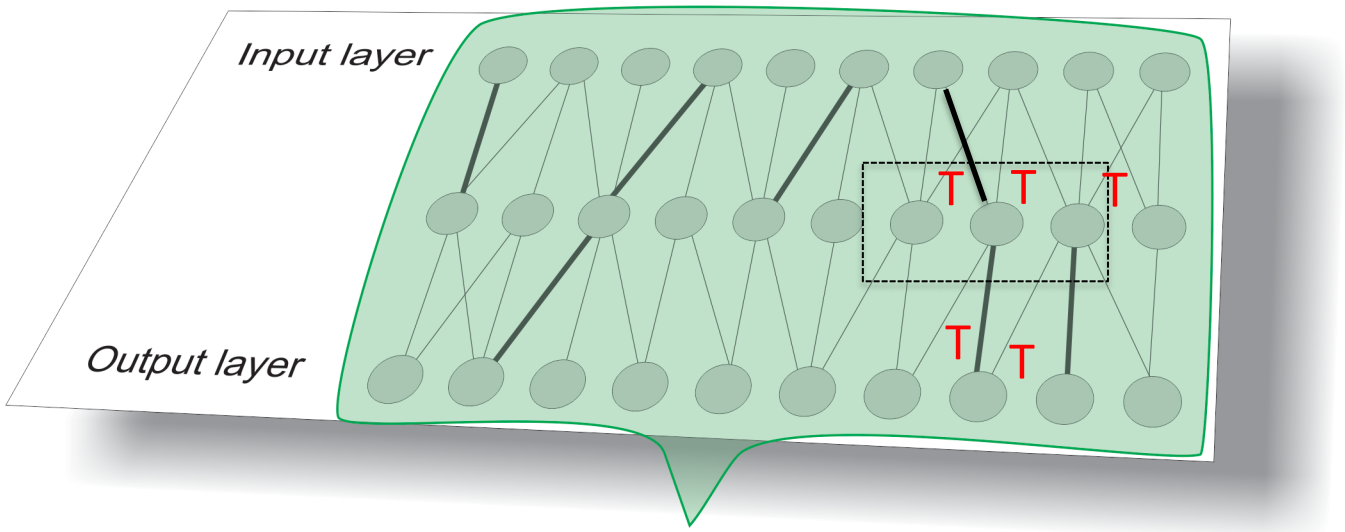

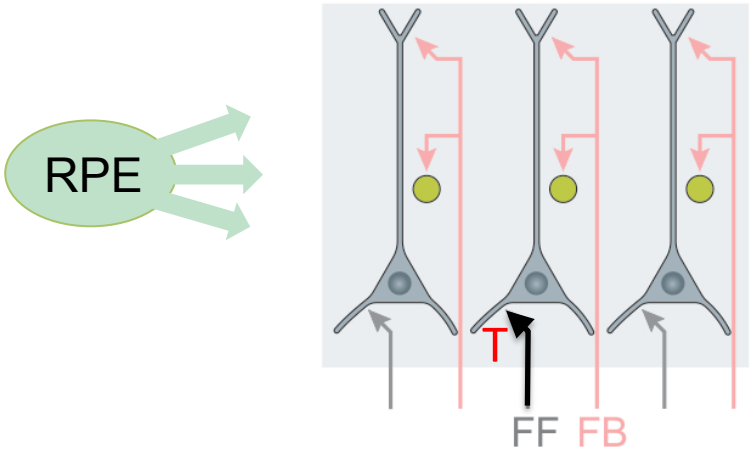

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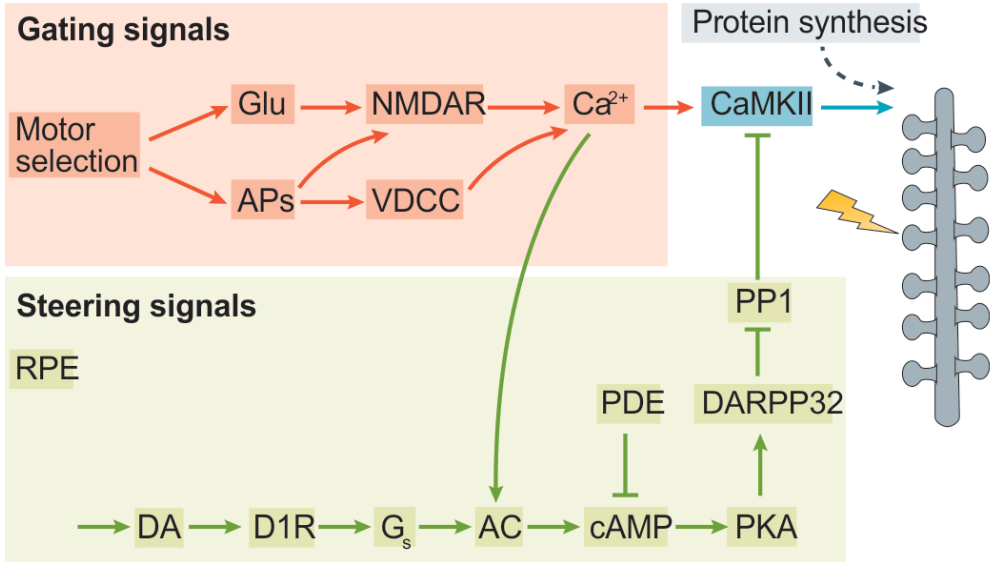
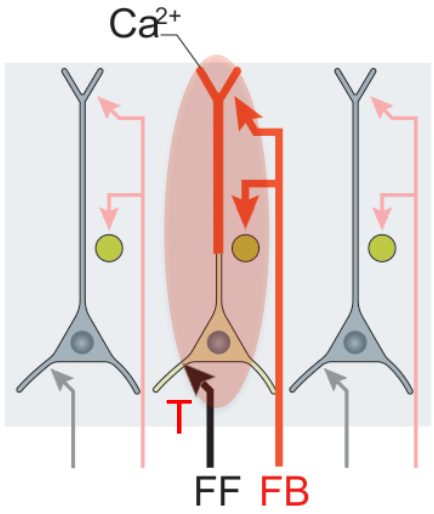
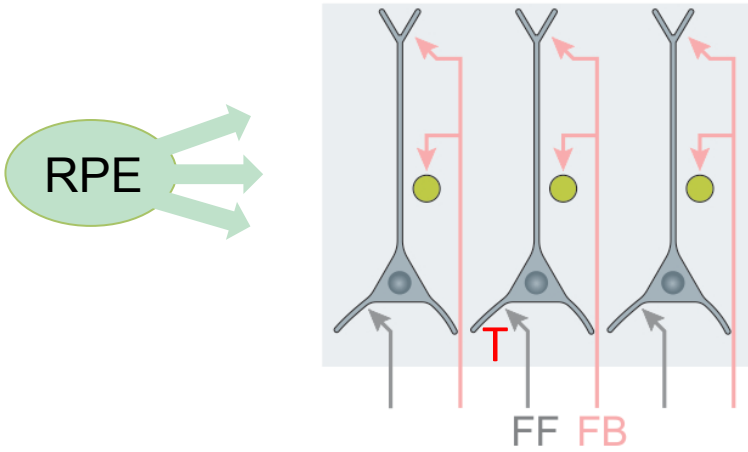


1. Eligibility

2. RPE





Yagishita et al, *Science* 2014

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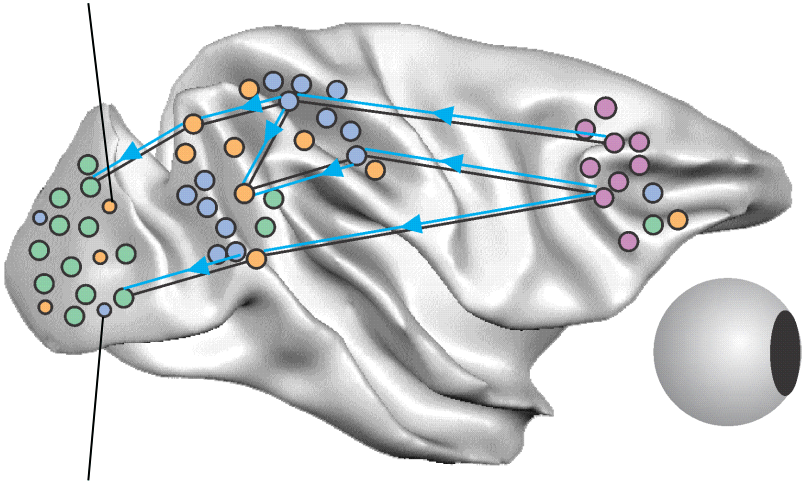
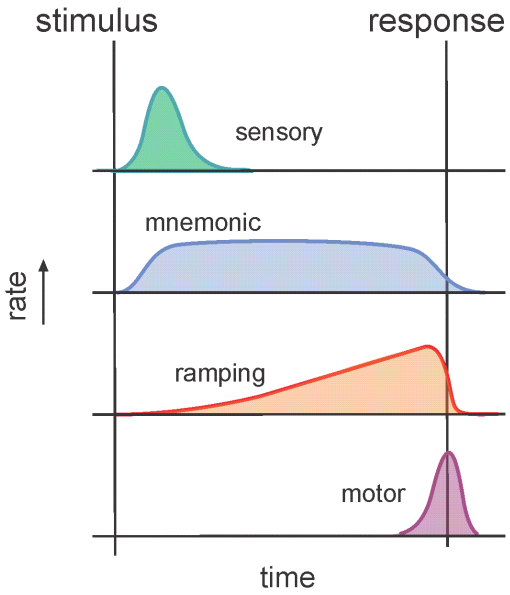
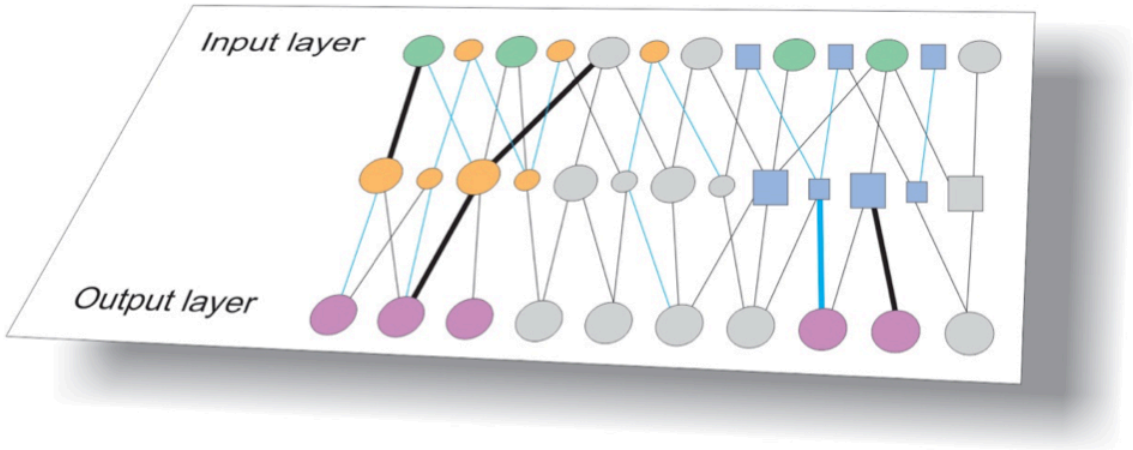
Selection signals (attention)



Working memory





Recurrent activity network

Plasticity network (credit assignment)

Conclusions

1) Contour grouping is associated with the labeling of contour elements with enhanced neuronal activity

2) This labeling signal (selective attention) enables plasticity – making some connections sensitive to the reward prediction error

3) The conjoint influence of attention and reward on plasticity allows the implementation of error backpropagation in a biologically plausible manner

4) These considerations make deep learning (even more) relevant for understanding of learning in the brain

Victor Lamme
Henk Spekreijse


Paul Khayat
Arezoo Pooresmaeili
Jasper Poort



Jaldert Rombouts
Sander Bohte
Florian Raudies
Heiko Neumann (Ulm)
Lawrence Watling
Arjen van Ooyen






Anthony Holtmaat

Thank you