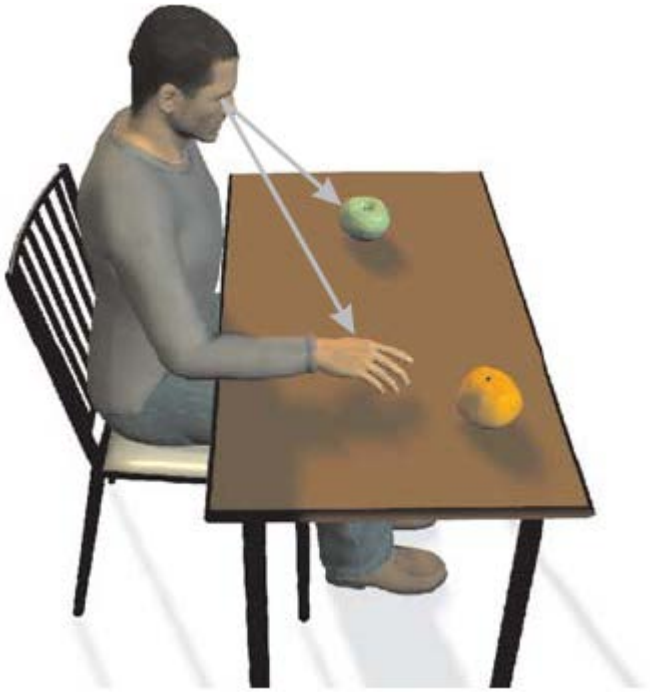
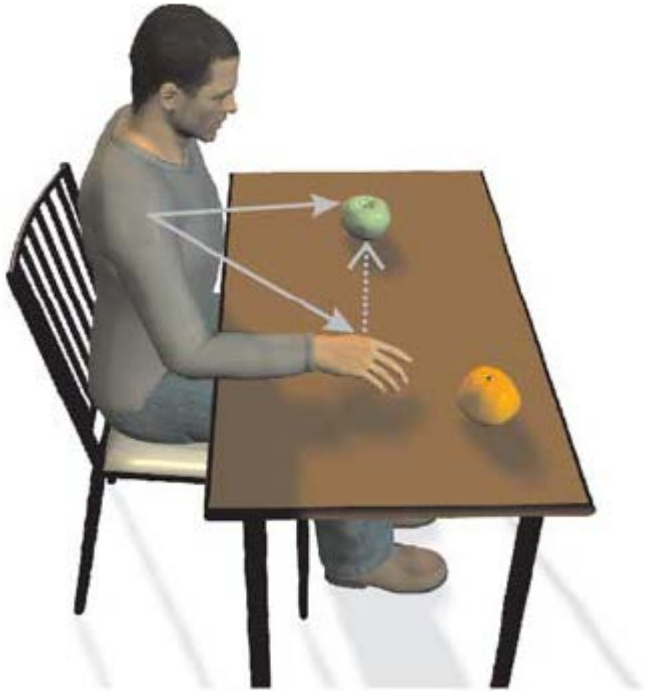
Sensory-motor control intro
Day 1

CoSMo 2017
Gunnar Blohm

Motor planning & execution

- Processes involved in the sensory guidance of action

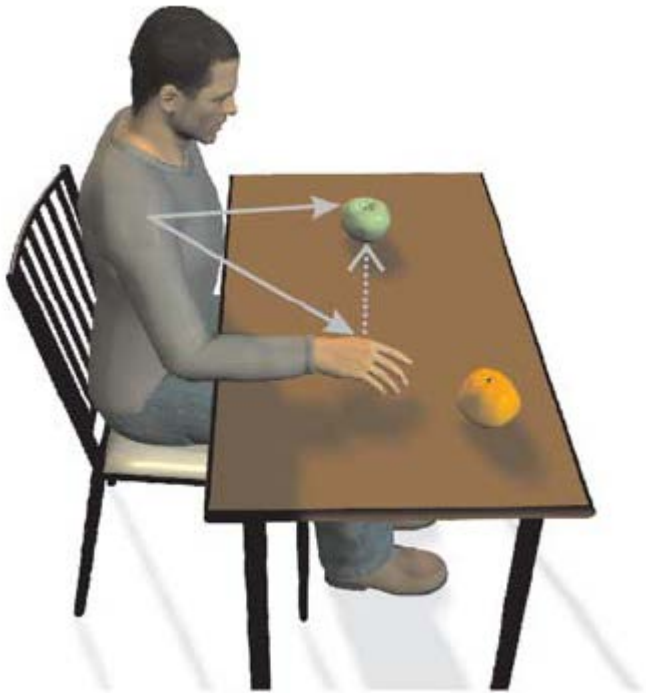




Blohm et al. 2009

Motor planning & execution

- Processes involved in the sensory guidance of action
  - Sensory processing
  - Multi-sensory integration
  - Reference frame transformations
  - Target selection
  - Decision making
    - Move or not
    - Which effector, which target
    - When to move (timing)
  - Motor planning
  - Motor control
  - Error corrections…



Blohm et al. 2009

Motor planning & execution

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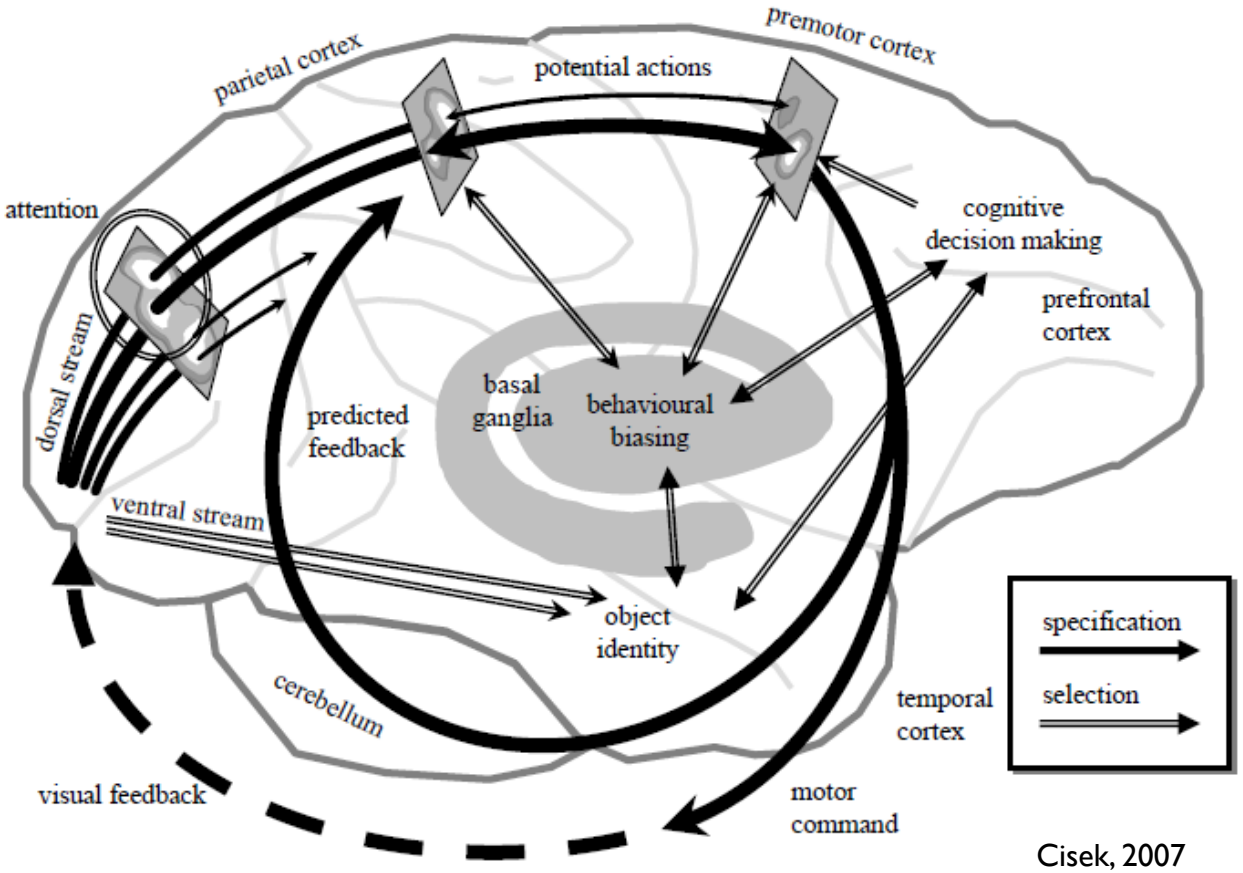
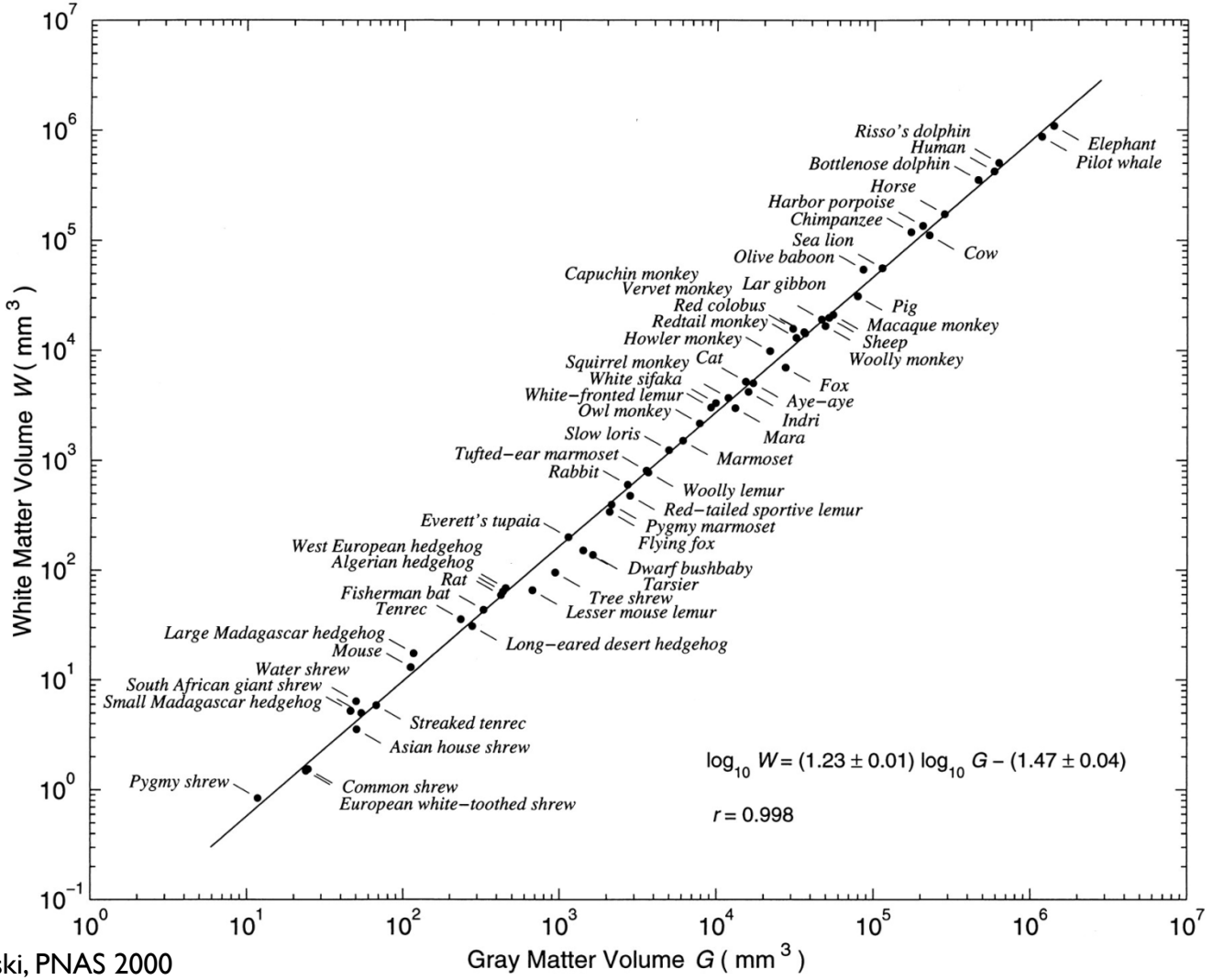


Cisek, 2007

The computational anatomy of sensory-motor control

Hierarchies

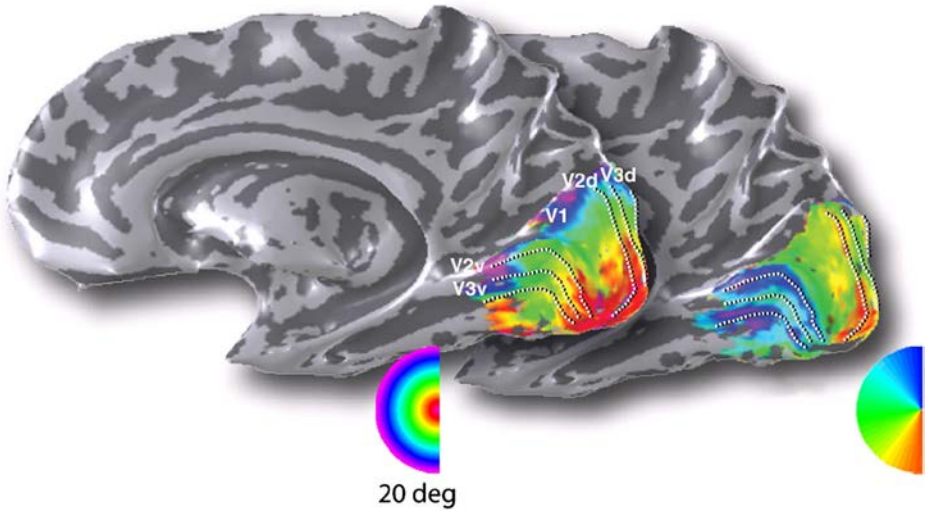
Computational anatomy of the brain



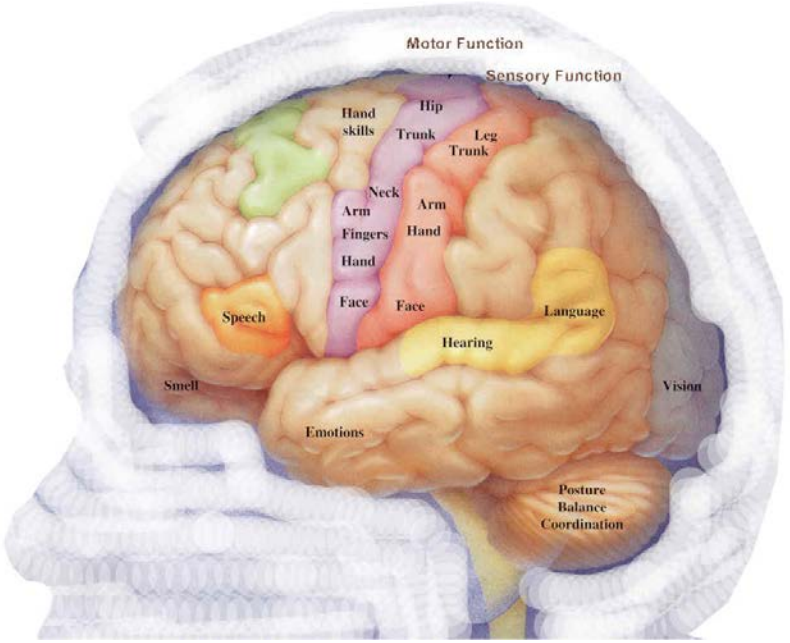
Zhang & Sejnowski, PNAS 2000

Computational hierarchy of the brain

- Brodmann's areas
- Functional areas
- Maps



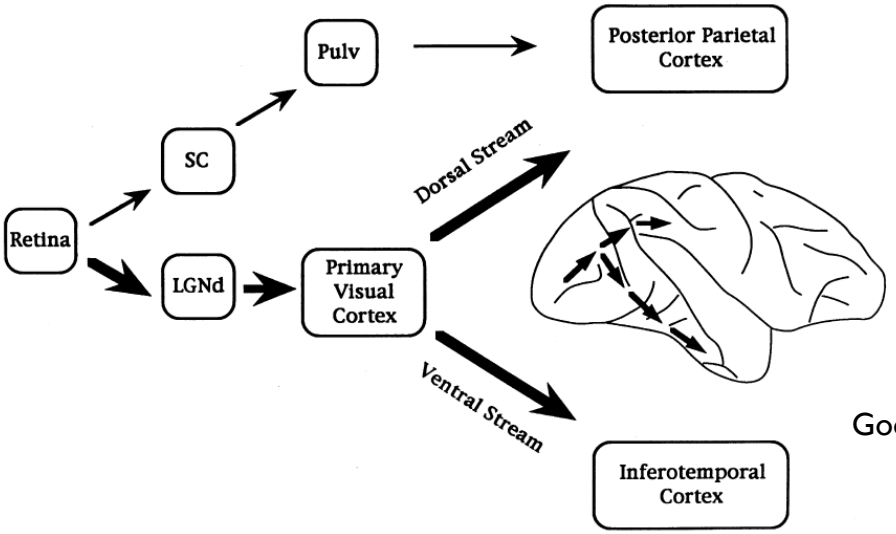
Wandell, et al., Neuron (2007)



Computational hierarchy of the brain

- Brodmann's areas
- Functional areas
- Maps
- Connectivity
- Functional pathways

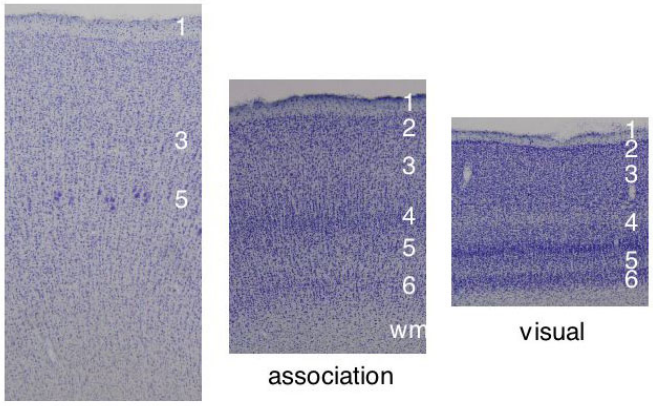
Courtesy of Kat Reinhart

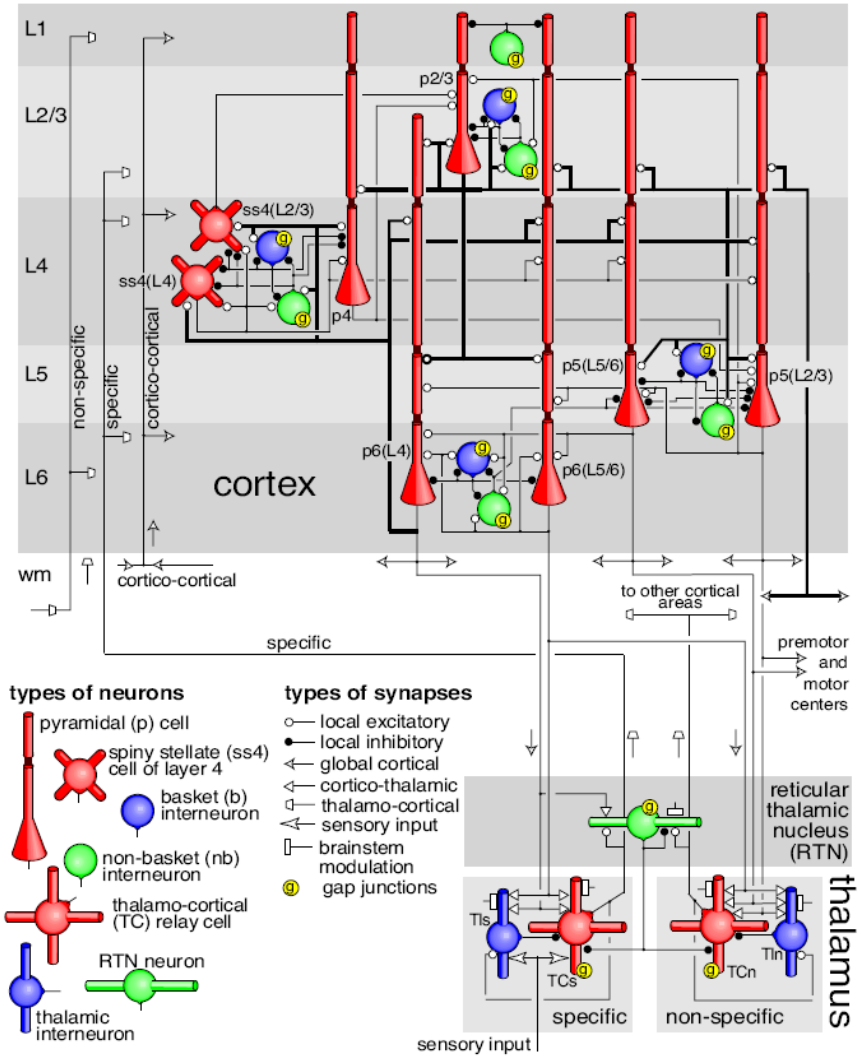


Goodale & Humphrey, 1998

Computational hierarchy of the brain

- Brodmann's areas
- Functional areas
- Maps
- Connectivity
- Functional pathways
- Detailed structure

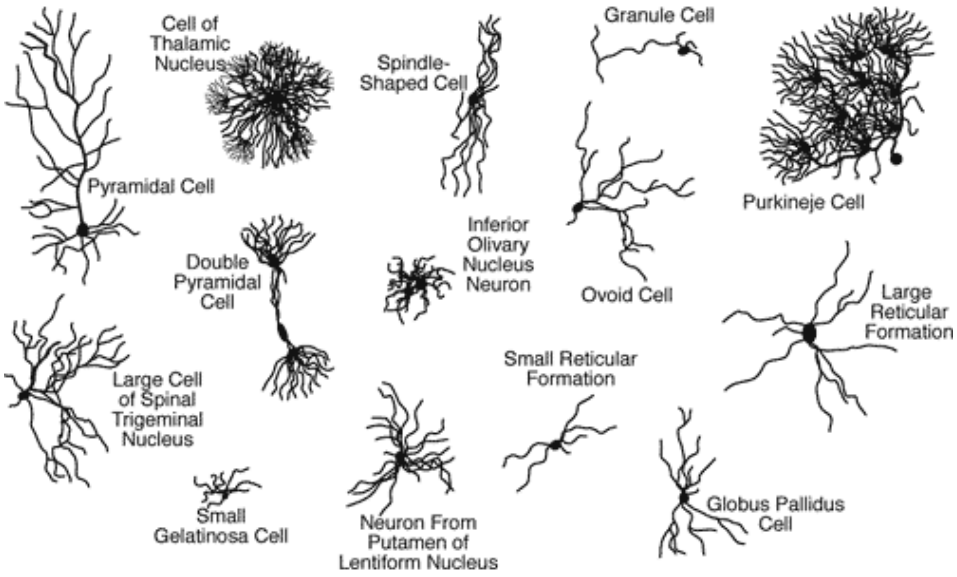


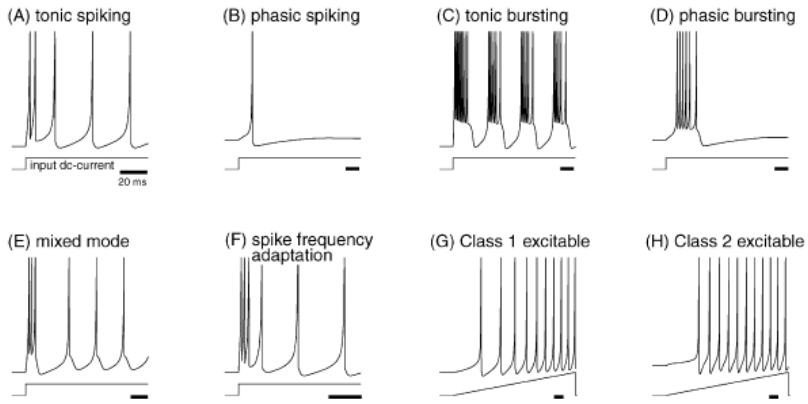


Izhikevich & Edelman PNAS (2008)

Computational hierarchy of the brain

- Brodmann's areas
- Functional areas
- Maps
- Connectivity
- Functional pathways
- Detailed structure
- Varied anatomy
- Heterogeneous behavior
- Chemical & molecular complexity
- …





Izhikevich, IEEE Transactions on Neural Networks (2004)

Motor planning & execution

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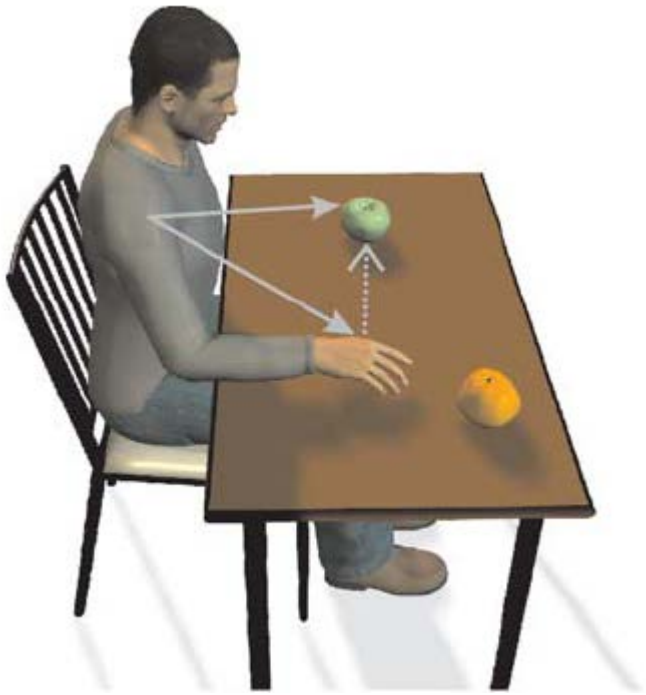


Blohm et al. 2009

Sensory-motor transformations

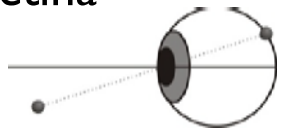
Blohm

Sensory-motor transformations

- Justin: DLR robot – ball catching
  - Sensory ref frames ~= motor ref frame…
  - Sensory code ~= motor code…
  - Movie…

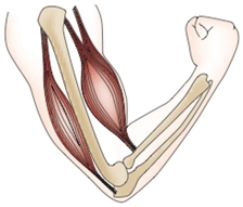
Sensory-motor transformations

- Reference frames
  - Determined by sensory and motor apparatus
    - Vision: attached to the retina

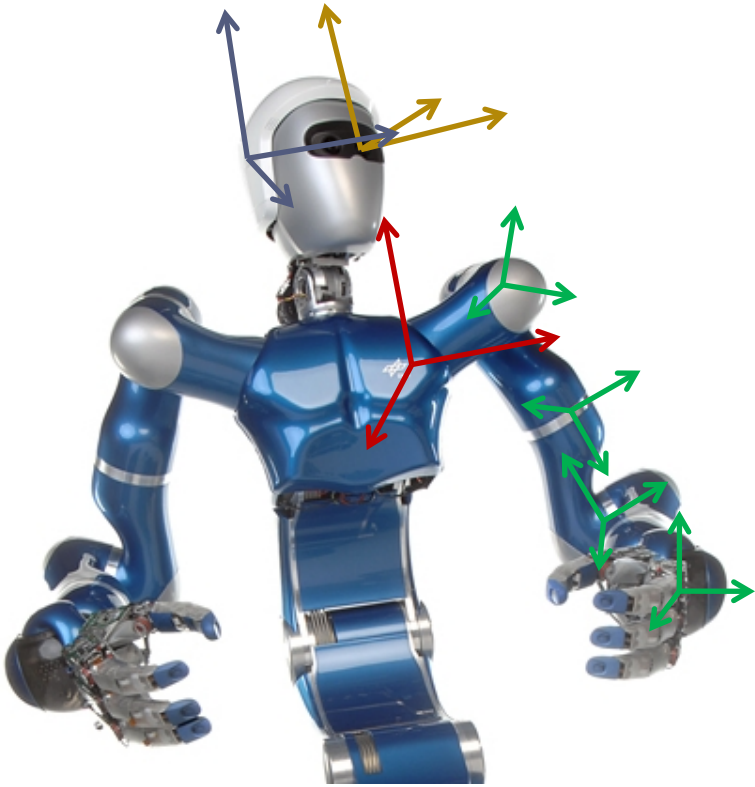


    - Audition: attached to the head

    - Proprioception: relative joint angles

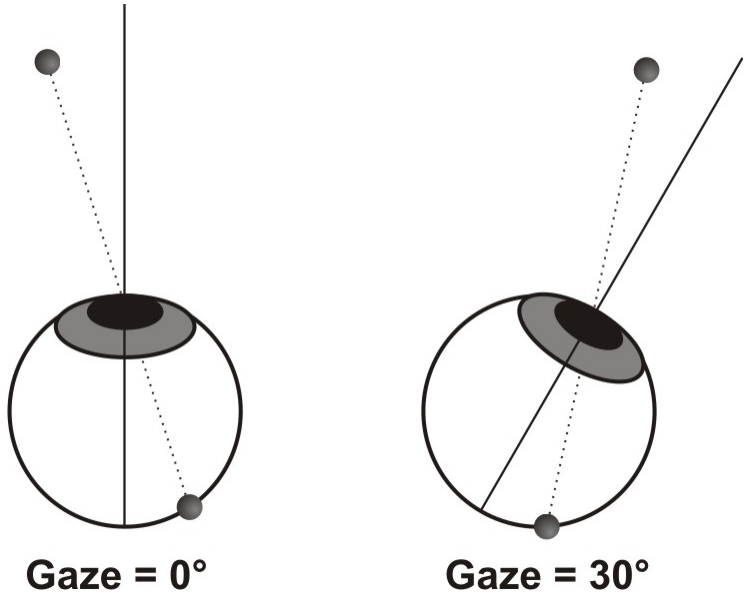


    - Arm movement: relative to attachment at shoulder



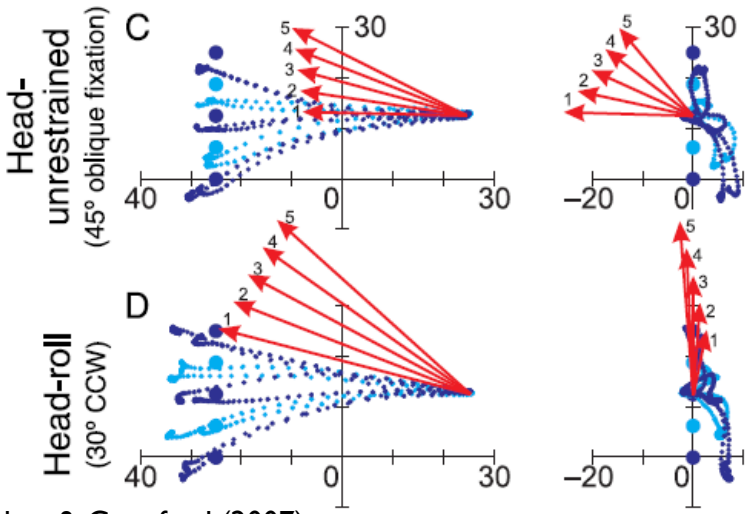
Sensory-motor transformations

- Reference frames
  - Knowledge about reference frames is required to localize sensory and motor events
    - Same retinal image – different spatial locations

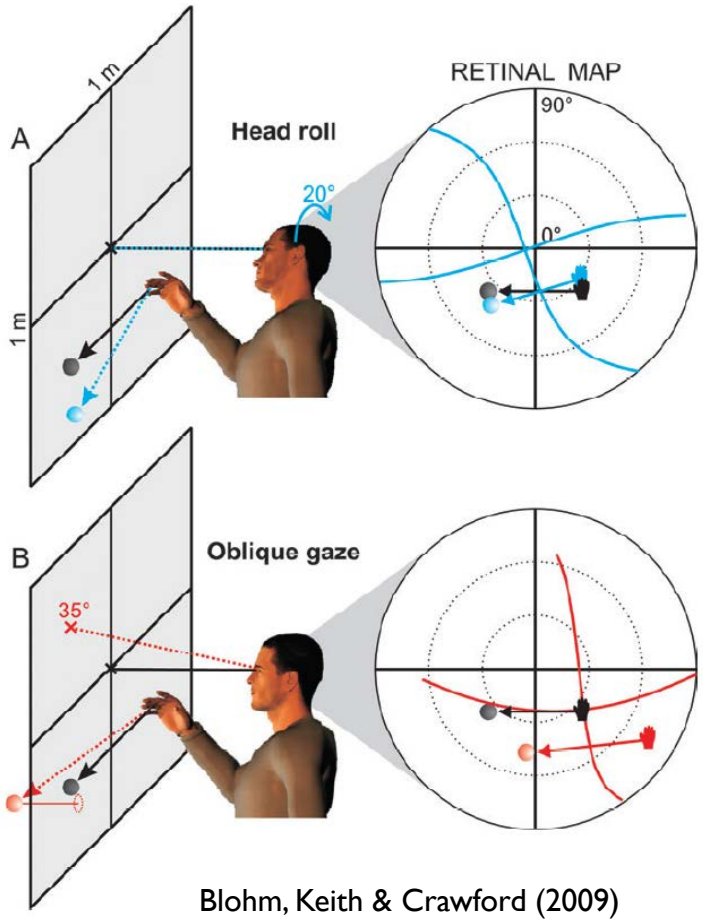


Examples: reference frame transformations

- Reaching / pointing



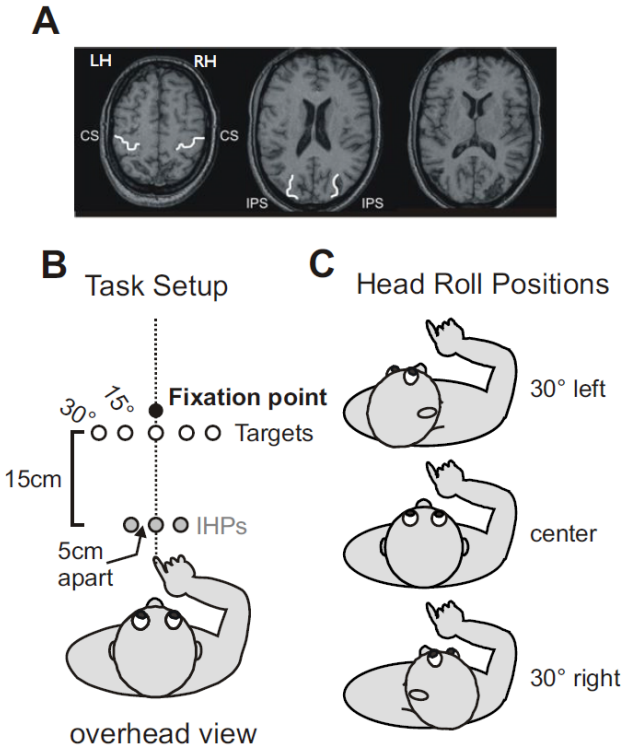
Blohm, & Crawford (2007)

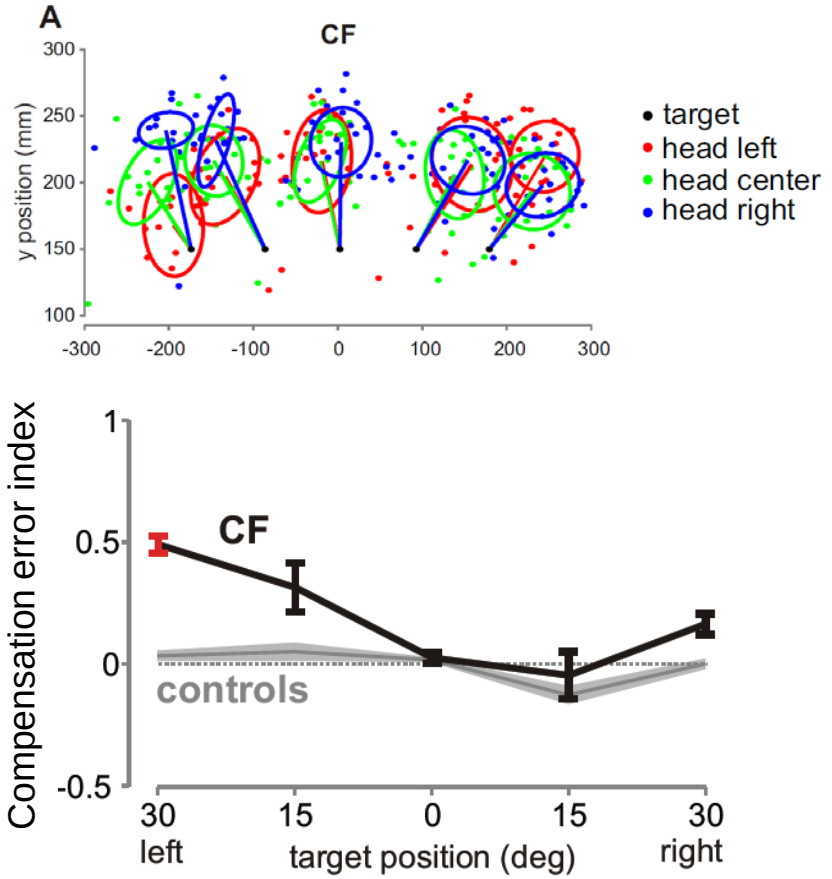


Blohm, Keith & Crawford (2009)

Examples: reference frame transformations

- Reference frame transformation deficits in optic ataxia

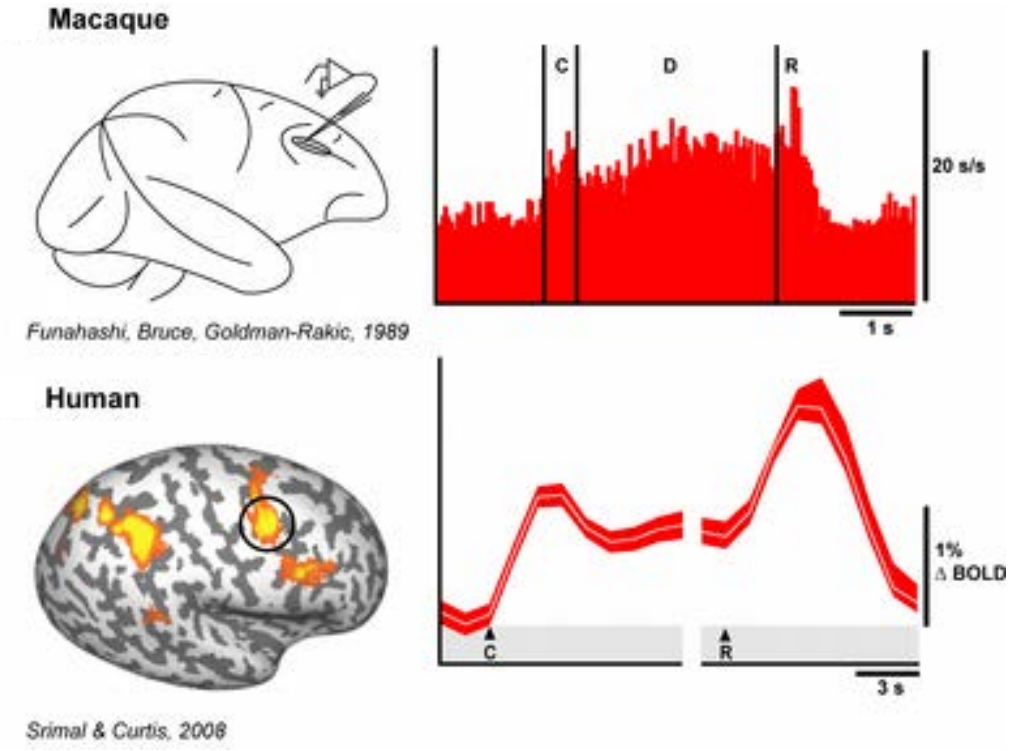


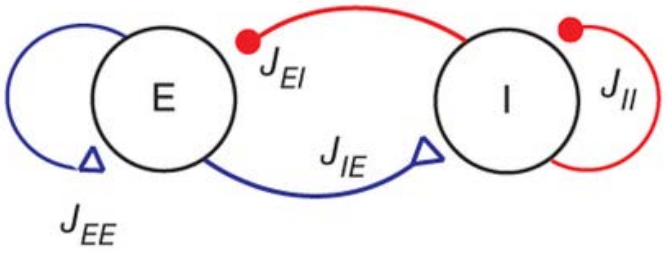


Khan, Pisella, Blohm (2013)

Working memory

- Retain important information for immediate action
  - Relies on persistent mnemonic activity through a balance of local excitation and global inhibition

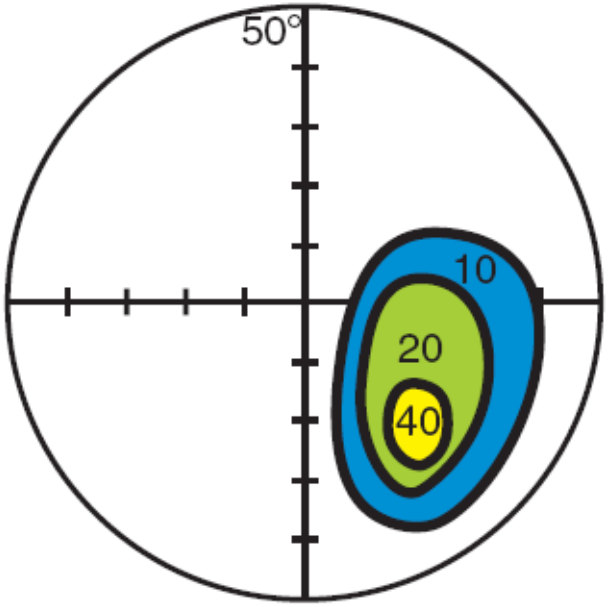




Lim & Goldman (2013)

Coding information in the brain

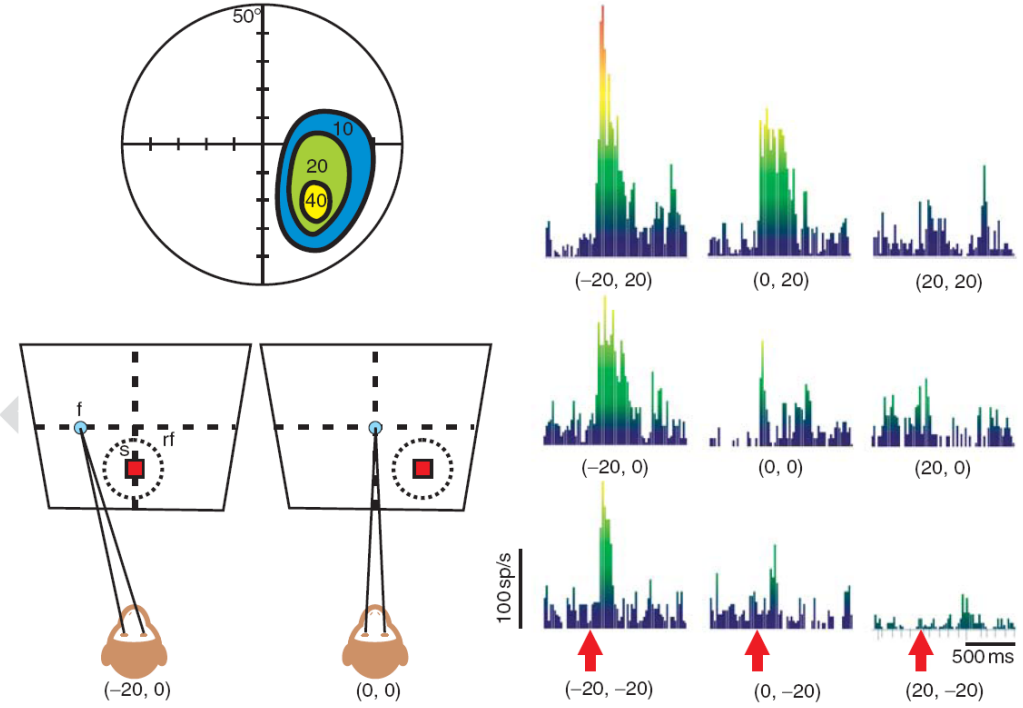
- Receptive fields
  - = activation pattern of a neuron for targets across space
    - We assume that the brain explicitly "codes" certain information
    - AND that we can decode it!



Blohm, Khan, Crawford, 2009 (adapted from Andersen, et al., 1985)

Gain modulation

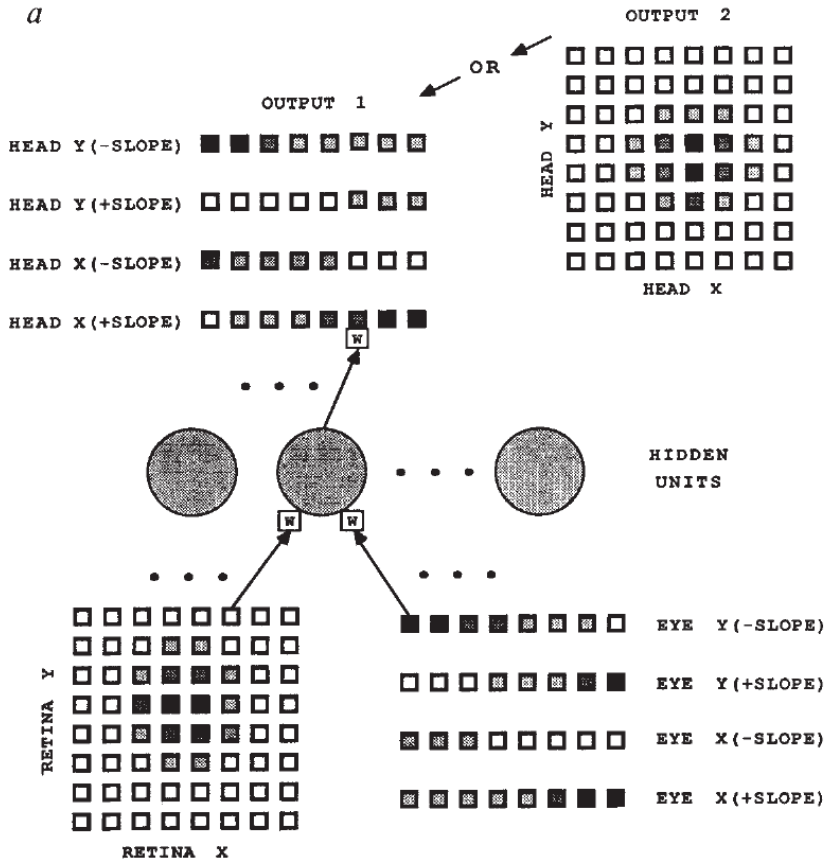
- = change of receptive field strength with secondary input
  - E.g. eye position gain modulation of visual receptive fields in posterior parietal cortex



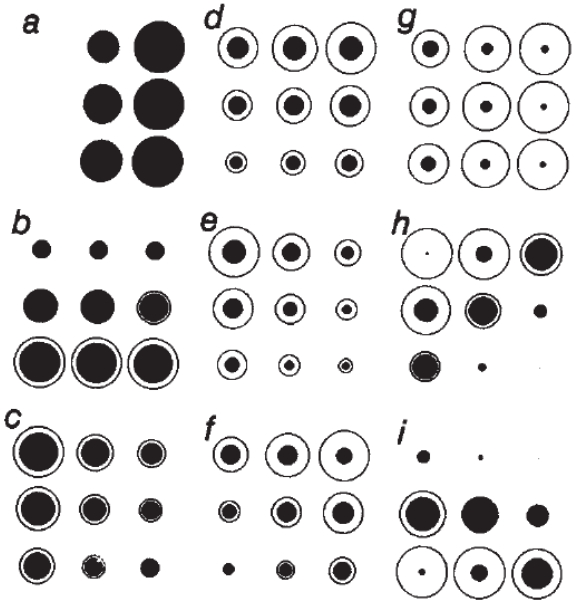
Blohm, Khan, Crawford, 2009 (adapted from Andersen, et al., 1985)

Gain modulation

- Reference frame transformations
  - Zipser & Andersen, Nature 1988

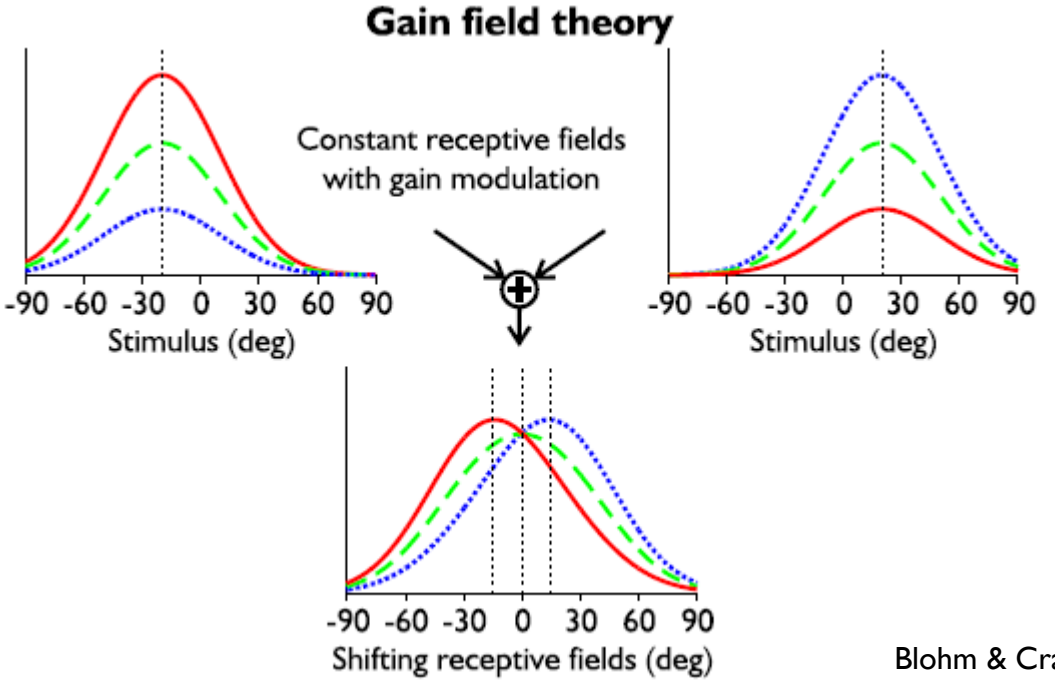


Eye position gain modulation of hidden layer units



Gain modulation

- Powerful computational means for
  - Cue combination
  - Reference frame transformations
  - Multi-sensory integration...



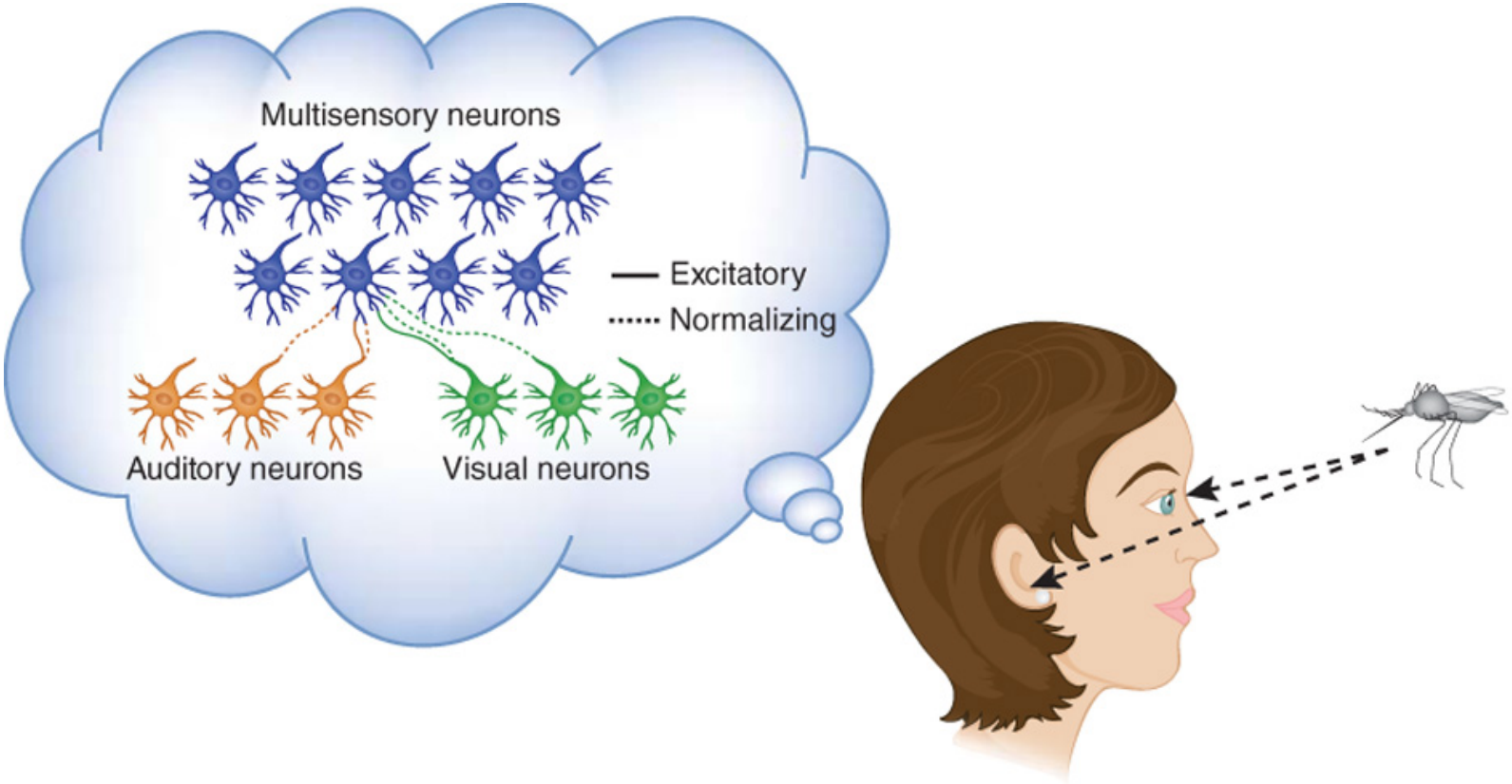
Blohm & Crawford, 2009

Multi-sensory integration

Kording & Schrater

Drugowitsch

Multi-sensory integration



Churchland (2011)

Mathematical framework for Bayesian integration

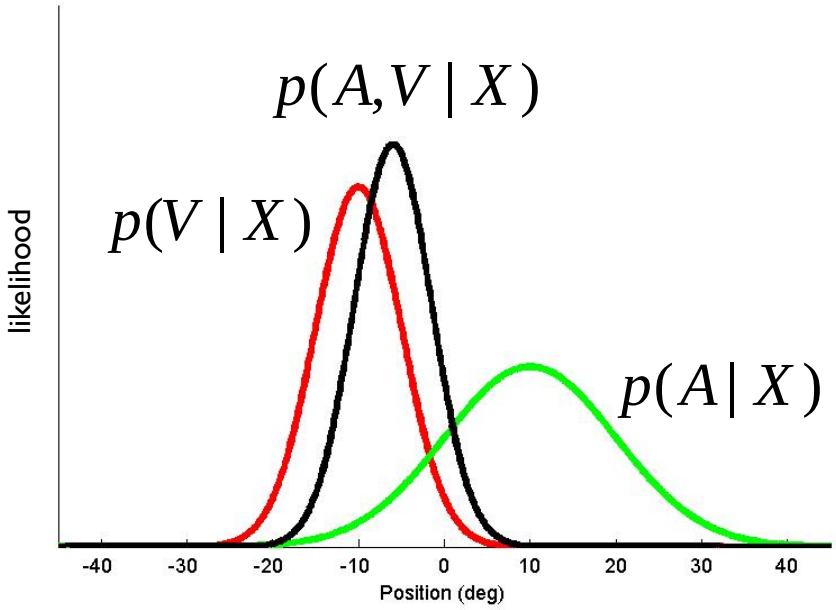
- Cue combination
  - Optimal Bayesian observer $p(X \mid A,V) = \dfrac{p(A,V \mid X) \cdot p(X)}{p(A,V)}$
  - Independent observations A,V

$$p(A,V \mid X) = p(V \mid X) \cdot p(A \mid X)$$

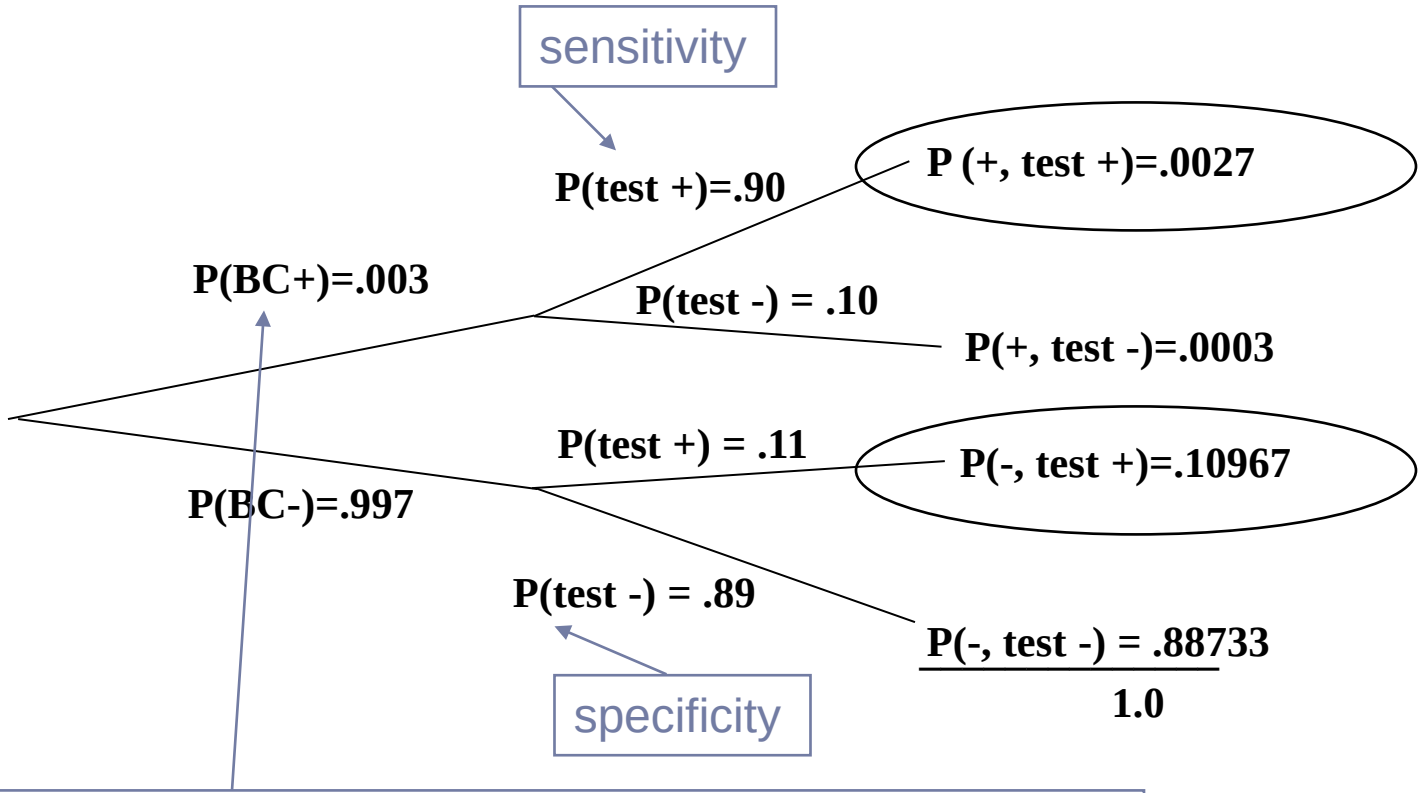
  - If uniform priors, then

$$p(X \mid A,V) \propto p(V \mid X) \cdot p(A \mid X)$$

  - The brain always uses all available useful information.
  - Information from different sources is combined in a statistically optimal fashion



Example: breast cancer

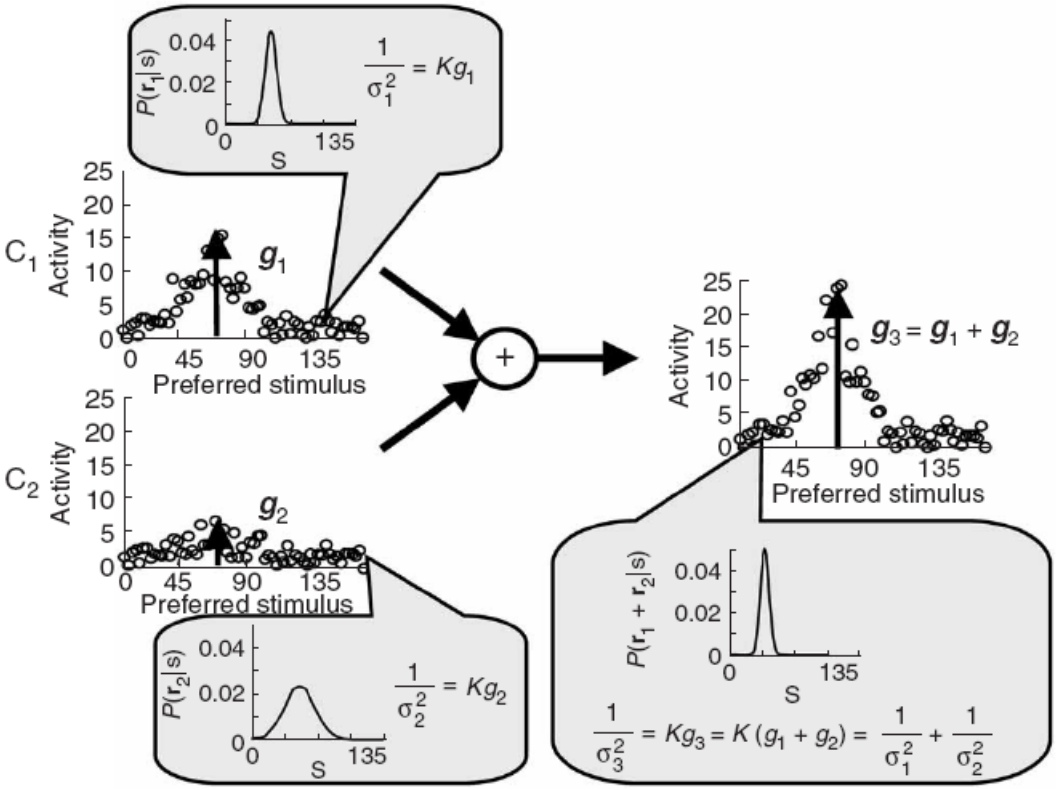


Marginal probabilities of breast cancer….(prevalence among all 54-year olds)

P(BC/test+)=.0027/(.0027+.10967)=2.4%

Bayesian computations in population codes

- Representing uncertainty with population codes
  - Probabilistic population codes
    - Poisson-like neural noise
    - Variance inversely related to gains of population code



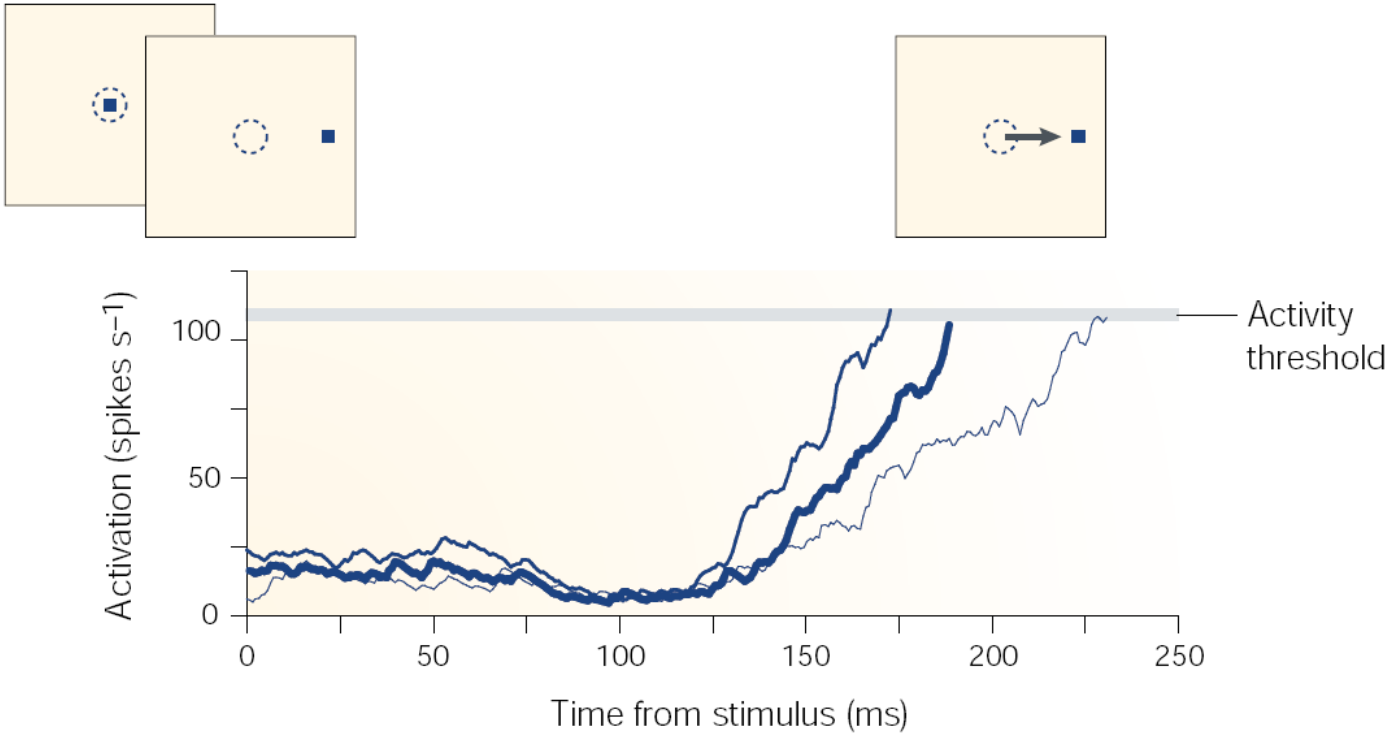
Ma et al. (2006)

Target selection & decision making

Drugowitsch, Schrater

Choice & decisions

- Competition of alternatives
- Example: areas LIP / FEF

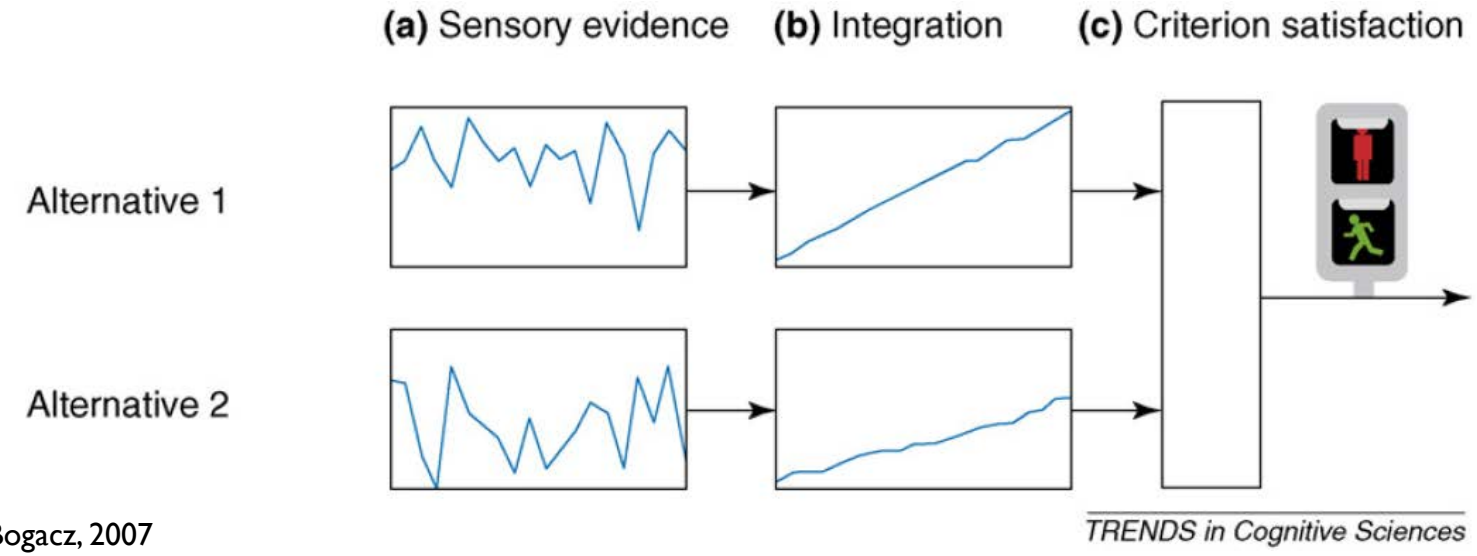


Schall, 2001

Current theories

- Target selection
  - Through the interaction of bottom-up and top-down attention

- Decision making
  - Different versions of rise-to-threshold models



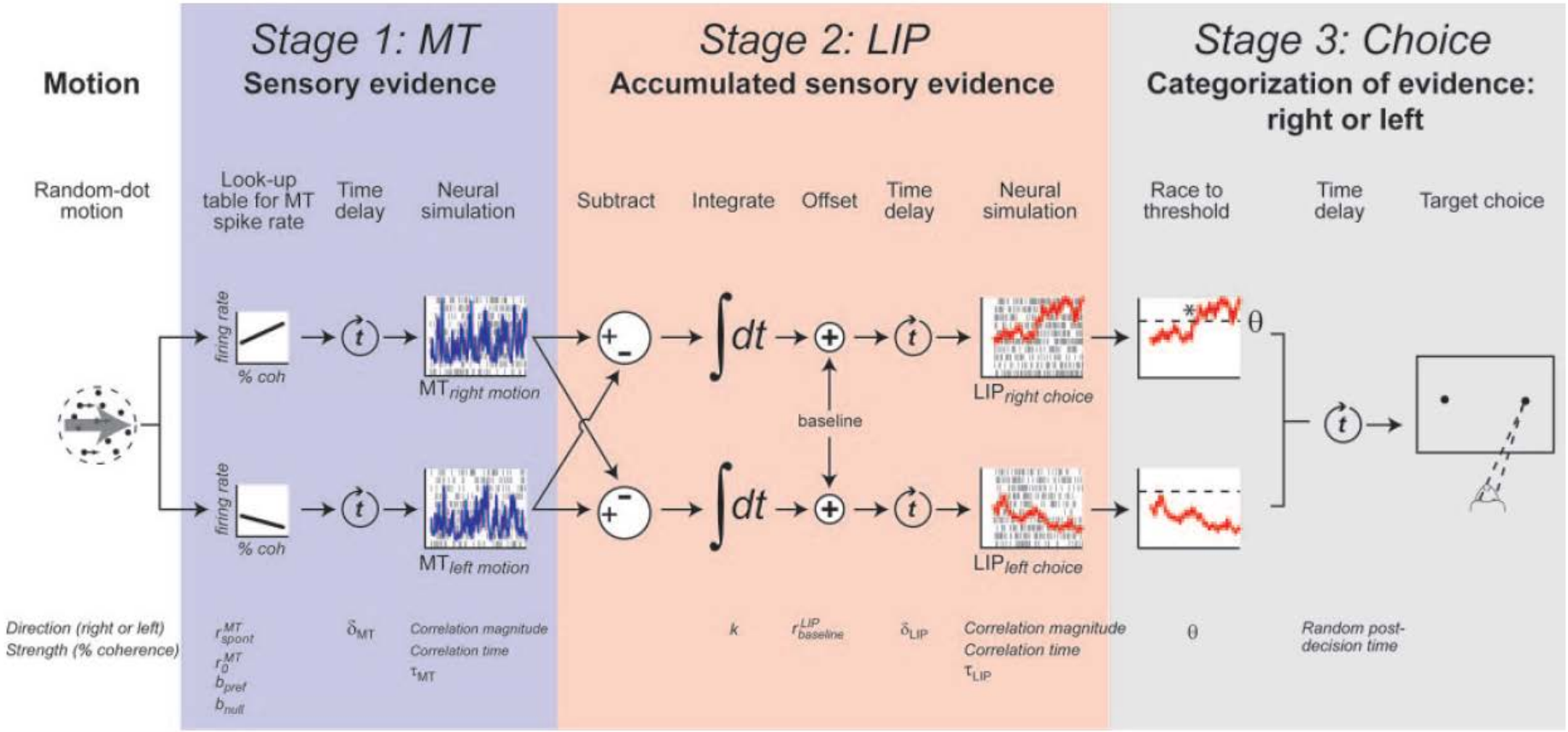
Bogacz, 2007

Current theories

- Target selection
  - Through the interaction of bottom-up and top-down attention
- Decision making
  - Different versions of rise-to-threshold models
- Computational principles at work?
  - Competitive processing
  - Divisive normalization
  - Gain modulation

Diffusion models

- Example: left-right decisions
  - Integrated decision model (Mazurek, et al. 2003)



Motor planning, motor control & error corrections

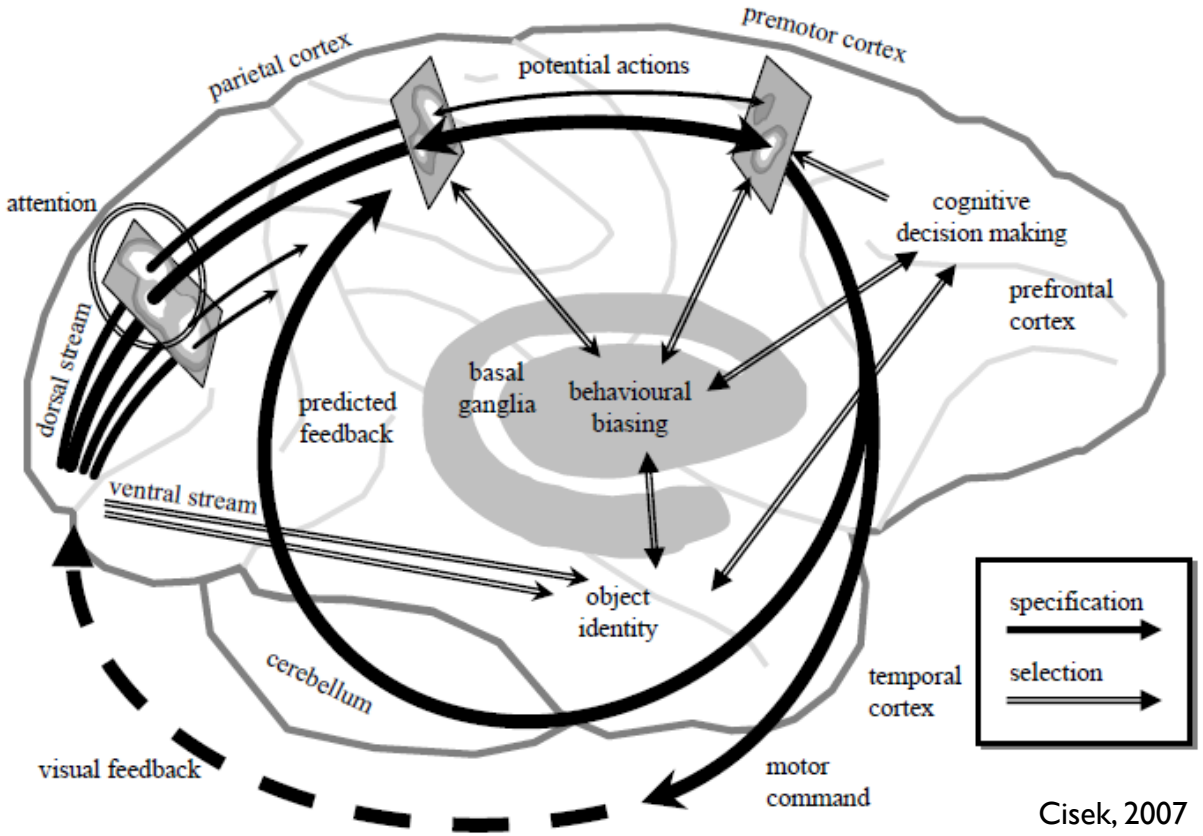
Kording, Schrater, Blohm

Shadmehr & Ahmed

Sternad

Motor planning & execution

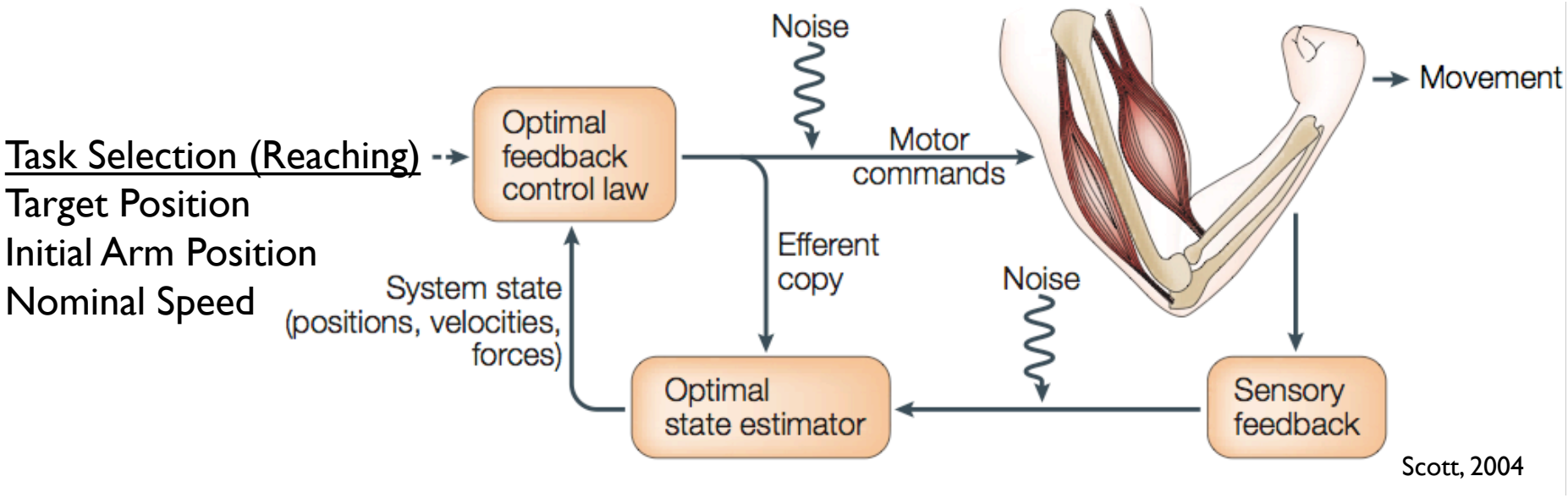
- Planning, execution and error correction are all part of the same system



Cisek, 2007

Motor planning & control

- Motor planning is the result of all previous steps…
  - Sensory processing
  - Transformations & multi-sensory integration
  - Target selection & decision making
- Motor control
  - Execution of the motor plan…



Scott, 2004

Eye/head plants

- Eye and neck muscles properties
  - Damped spring-mass system equivalent

Equation of motion of eye ball:

$$J \cdot \frac{d^2\theta}{dt^2} + F_p = F_m$$

Muscle force applied:

$$F_m = F_0 - R_m \cdot \frac{d\theta}{dt} - \frac{R_m}{K_{se}} \cdot \frac{dF_m}{dt}$$

Passive muscle/tissue force:

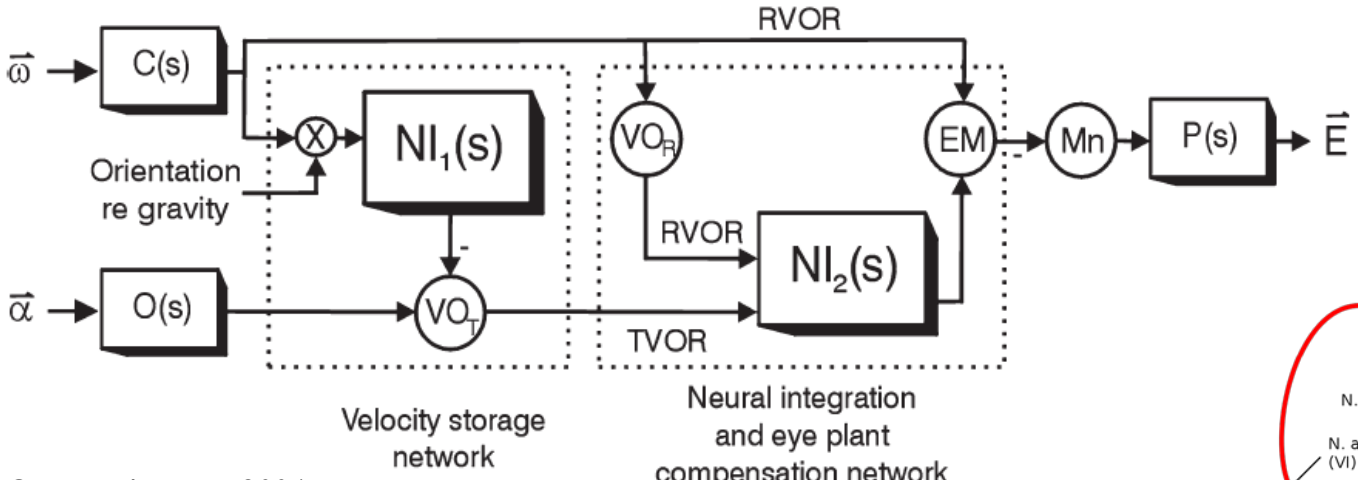
$$F_p = \frac{R_1 R_2 \cdot \frac{d^2\theta}{dt^2} + (R_1 K_2 + R_2 K_1) \cdot \frac{d\theta}{dt} + K_1 K_2 \cdot \theta - (R_1 + R_2) \cdot \frac{dF_p}{dt}}{(K_1 + K_2)}$$

Robinson (1964), Scudder (2009)

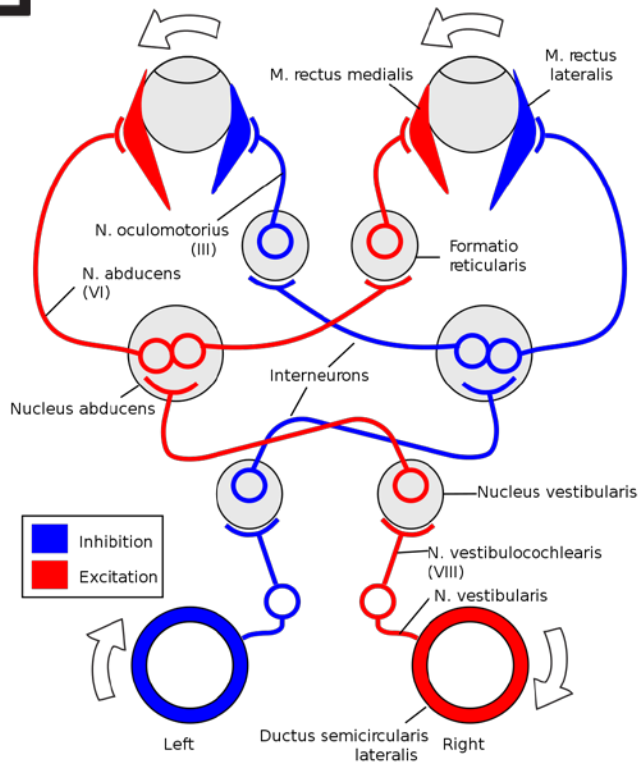
J: moment of inertia
F_p: passive force (muscle tissue)
F_m: active muscle force

Classical control

- Vestibulo-ocular reflex



Green & Angelaki 2004



- Angular velocity from semi-circular canals: ω
- Linear acceleration senses by otolith organs: α
- VO: vestibular-only neurons
- EM: eye movement sensitive neurons

Optimal feedback control

Sensory state of our body and the world we interact with

motor command

$$\mathbf{x}^{(k+1)} = A\mathbf{x}^{(k)} + C\mathbf{u}^{(k)} + \boldsymbol{\varepsilon}_u^{(k)}$$

motor noise

What we can observe about the state

$$\mathbf{y}^{(k)} = B\mathbf{x}^{(k)} + \boldsymbol{\varepsilon}_y^{(k)}$$

sensory noise

Cost to minimize

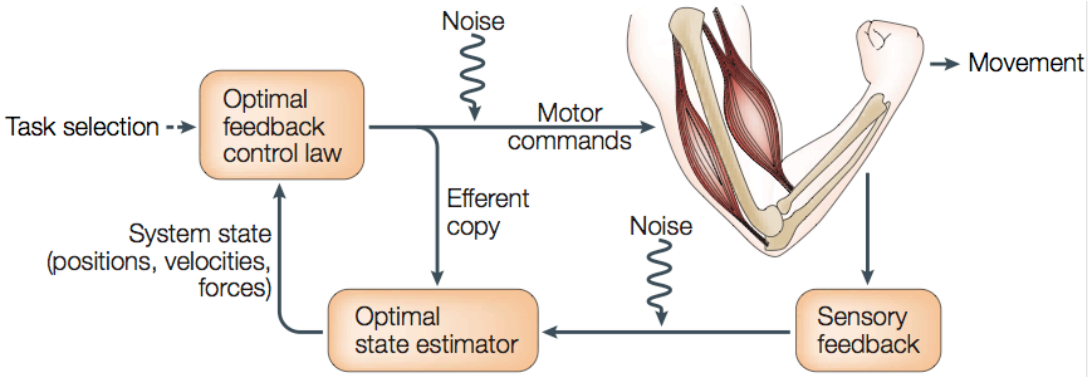
$$J = \sum_{k=0}^{p-1} \mathbf{u}^{(k)T} L^{(k)} \mathbf{u}^{(k)} + \mathbf{y}^{(k+1)T} T^{(k+1)} \mathbf{y}^{(k+1)}$$

Feedback control policy

$$\mathbf{u}^{(k)} = G^{(k)} \hat{\mathbf{x}}^{(k)}$$

Belief about state

$$\hat{\mathbf{x}}^{(k+1)} = \hat{A}\hat{\mathbf{x}}^{(k)} + \hat{A}K^{(k)}\left(\mathbf{y}^{(k)} - \hat{\mathbf{y}}^{(k)}\right) + \hat{C}\mathbf{u}^{(k)}$$

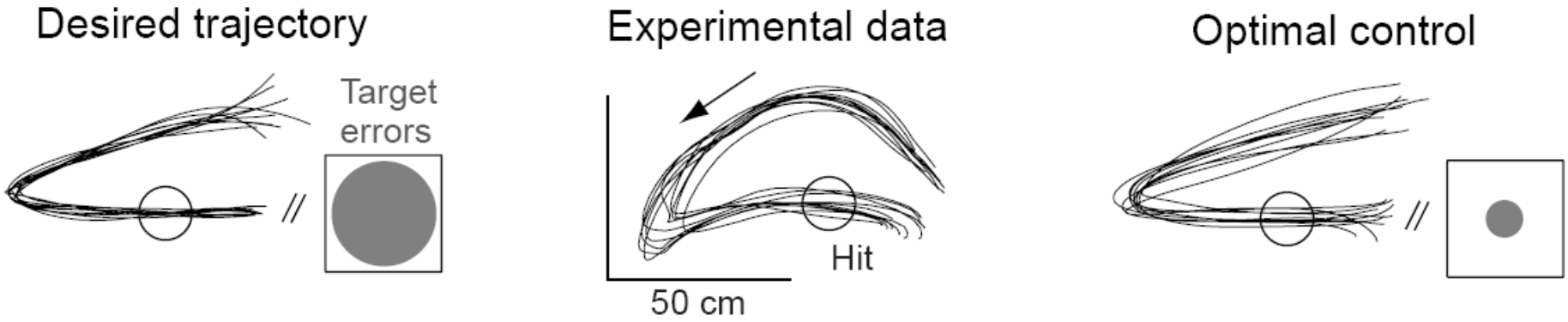


Predicted sensory consequences

Measured sensory consequences

Optimal feedback control

- Example: tennis

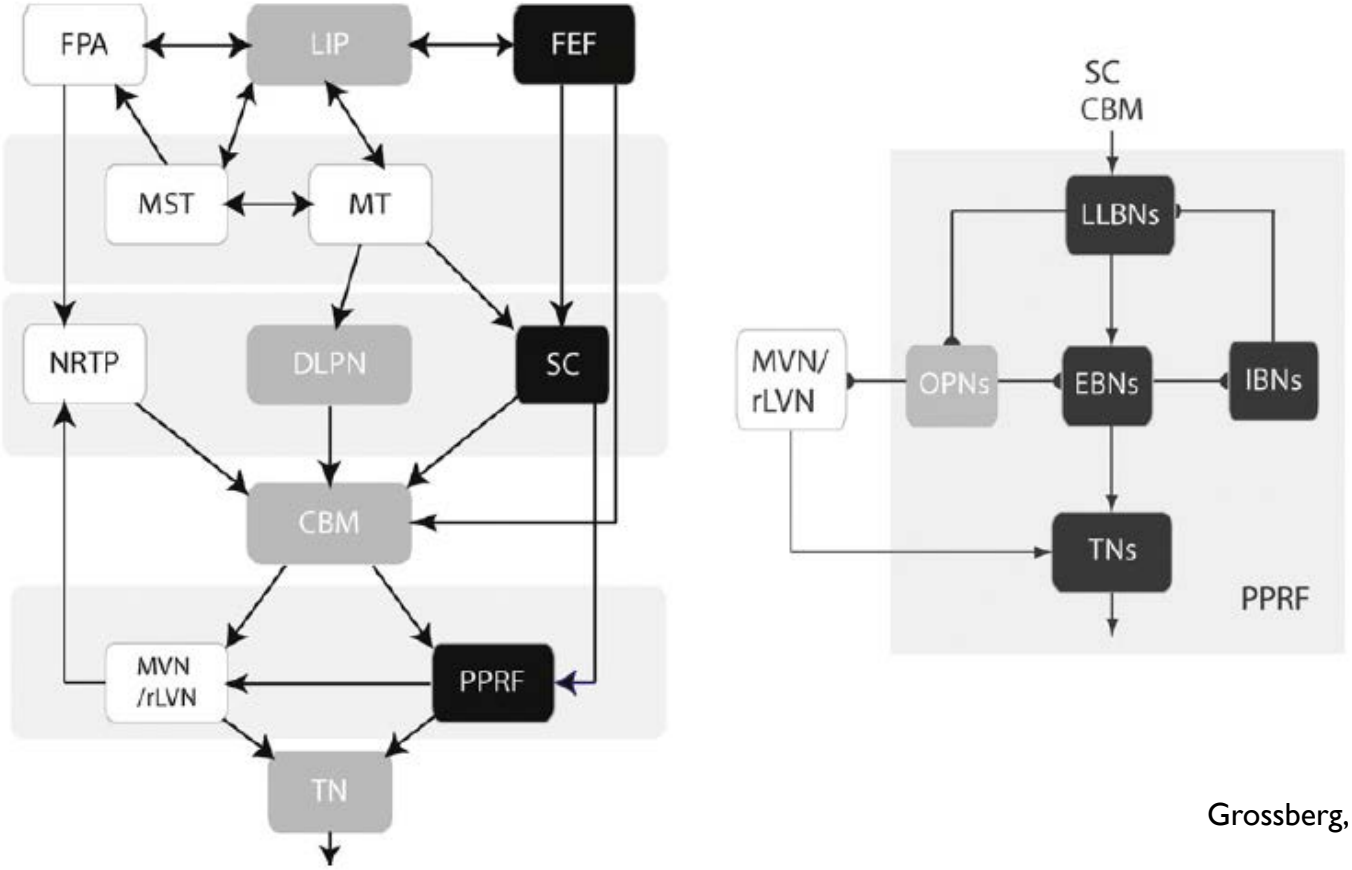


Torodov & Jordan, 2002

- Optimal control reproduces backward swing

Neural Networks

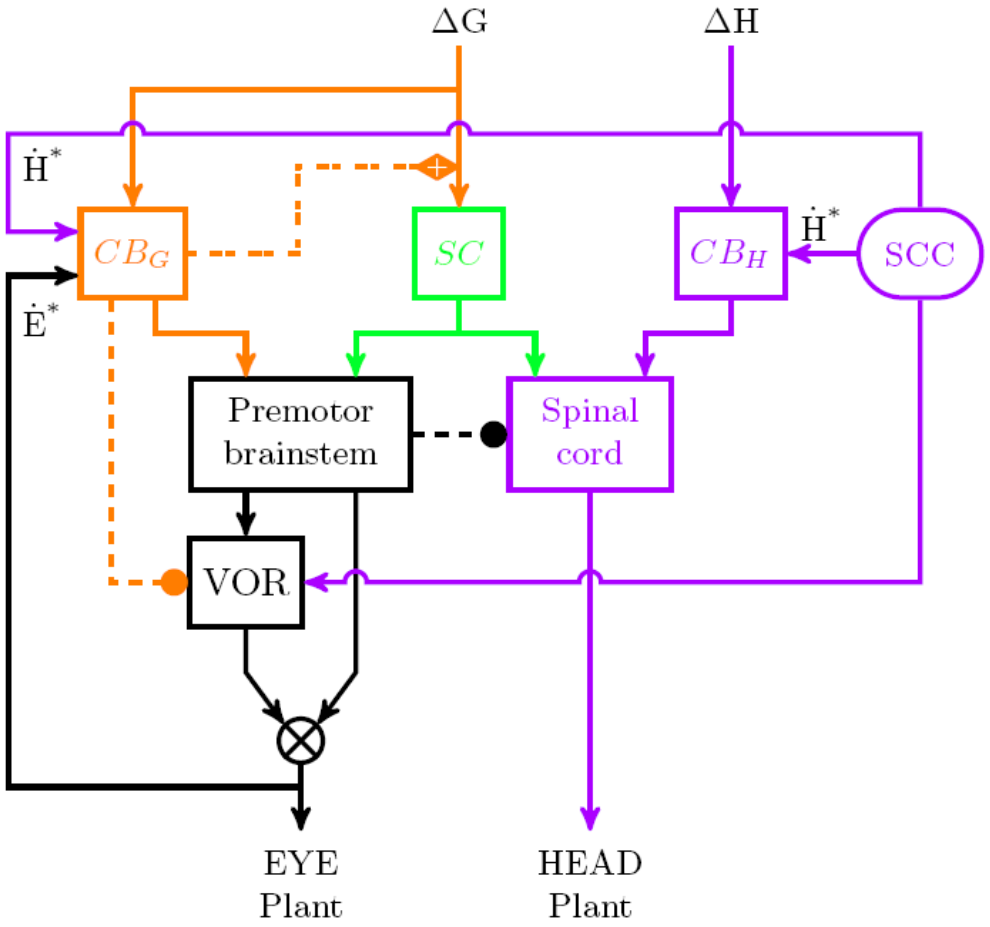
- Smooth pursuit – saccades coordination



Grossberg, et al. (2012)

Hierarchical control

- Eye-head Saccades
  - Endpoint control
    - Vs. trajectory control
  - Head motion = perturbation to gaze goal



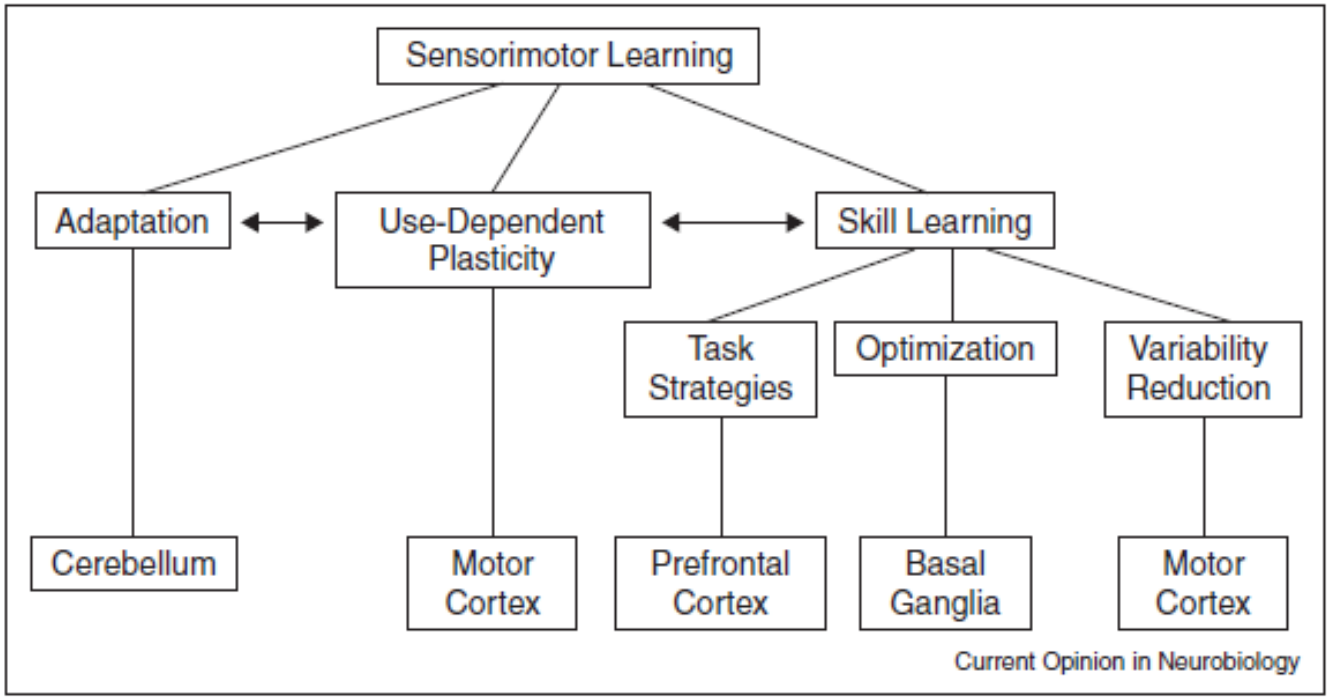
Daye, Optican, Blohm, Lefèvre (2014)

Adaptation & learning

Shadmehr & Ahmed

Learning theories

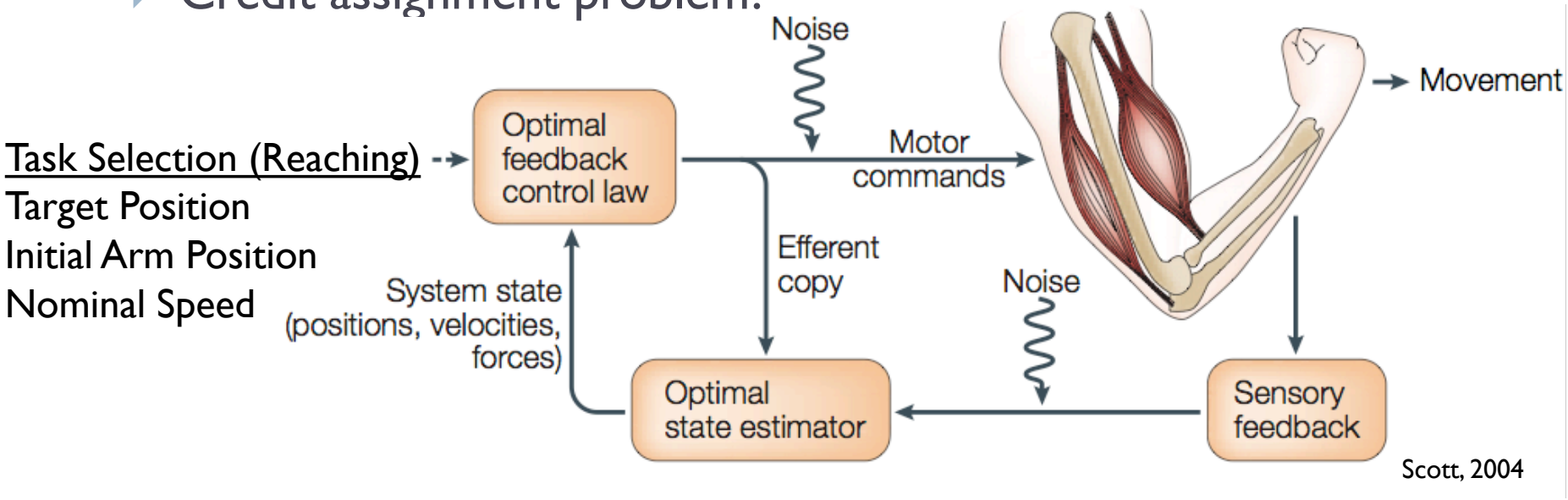
- Learning results in behavioral changes
  - Definition: "Any relatively permanent change in behavior that occurs as a result of experience."



Krakauer & Mazzoni 2011

Learning theories

- Learning results in behavioral changes
  - Error-based learning: what went wrong?
    - Initial state?
    - OFC – inverse model?
    - State estimation – forward model? …
  - Credit assignment problem!



Scott, 2004


That's all Folks!