Décision et fonction exécutive préfrontale

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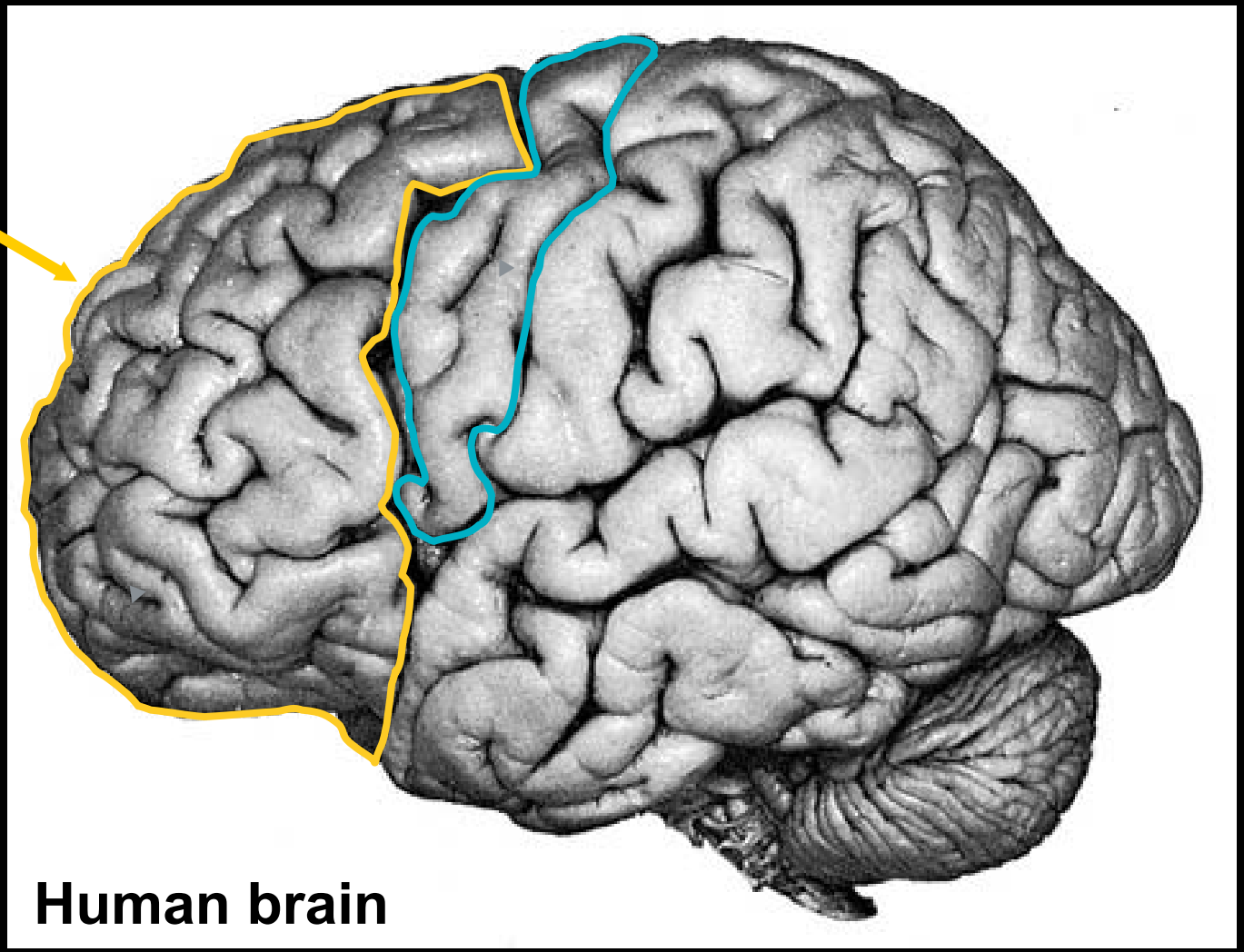
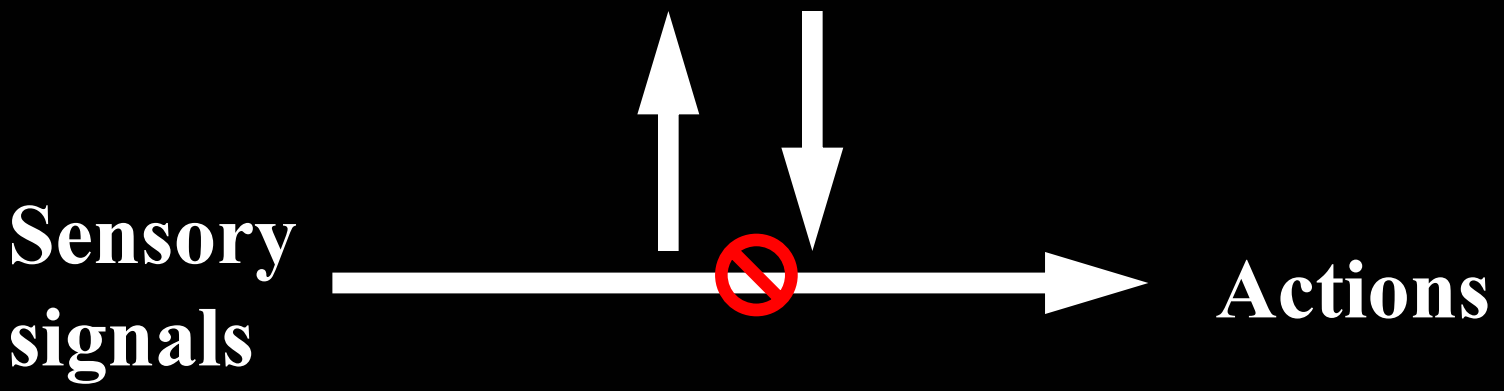
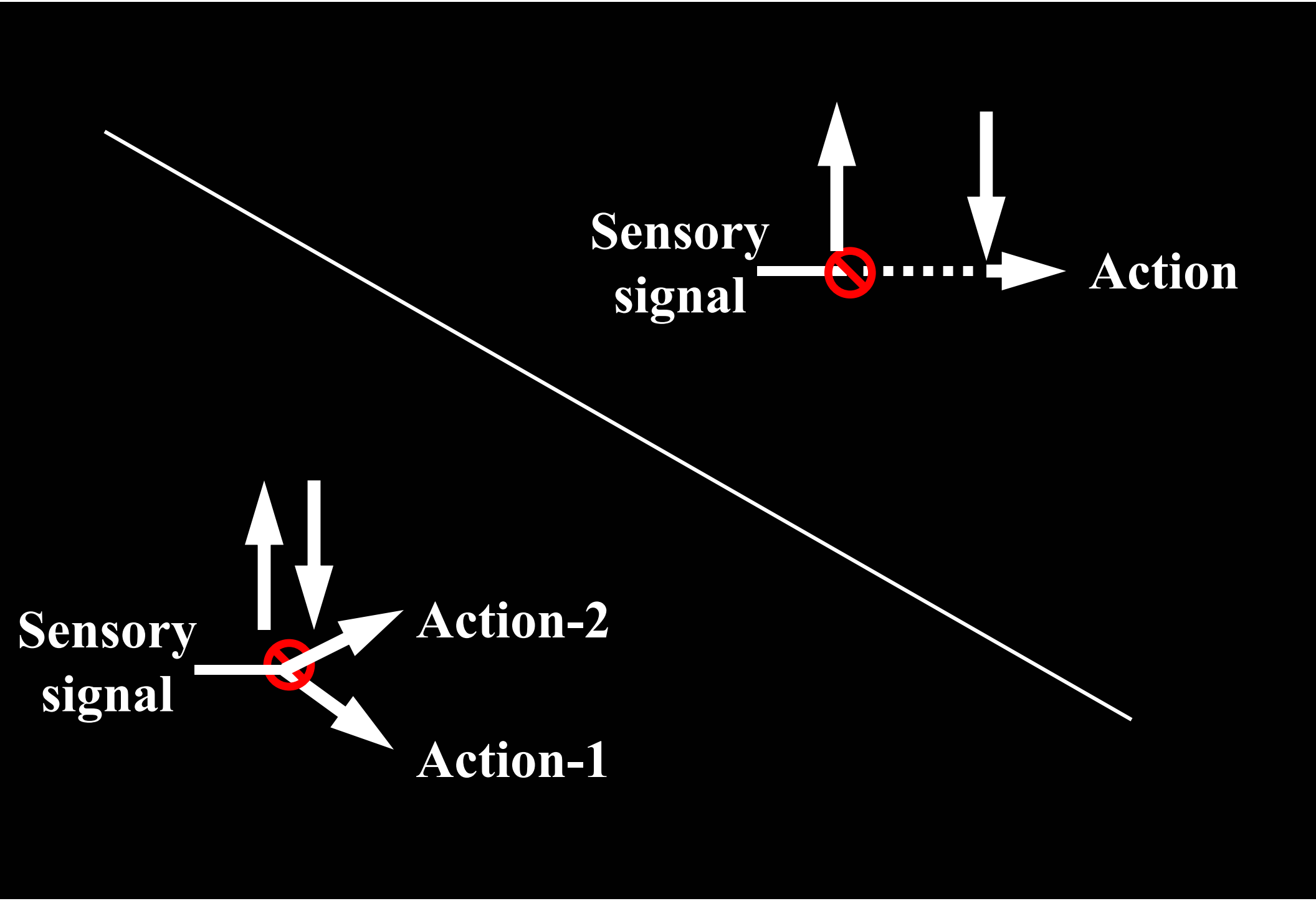
The prefrontal cortex

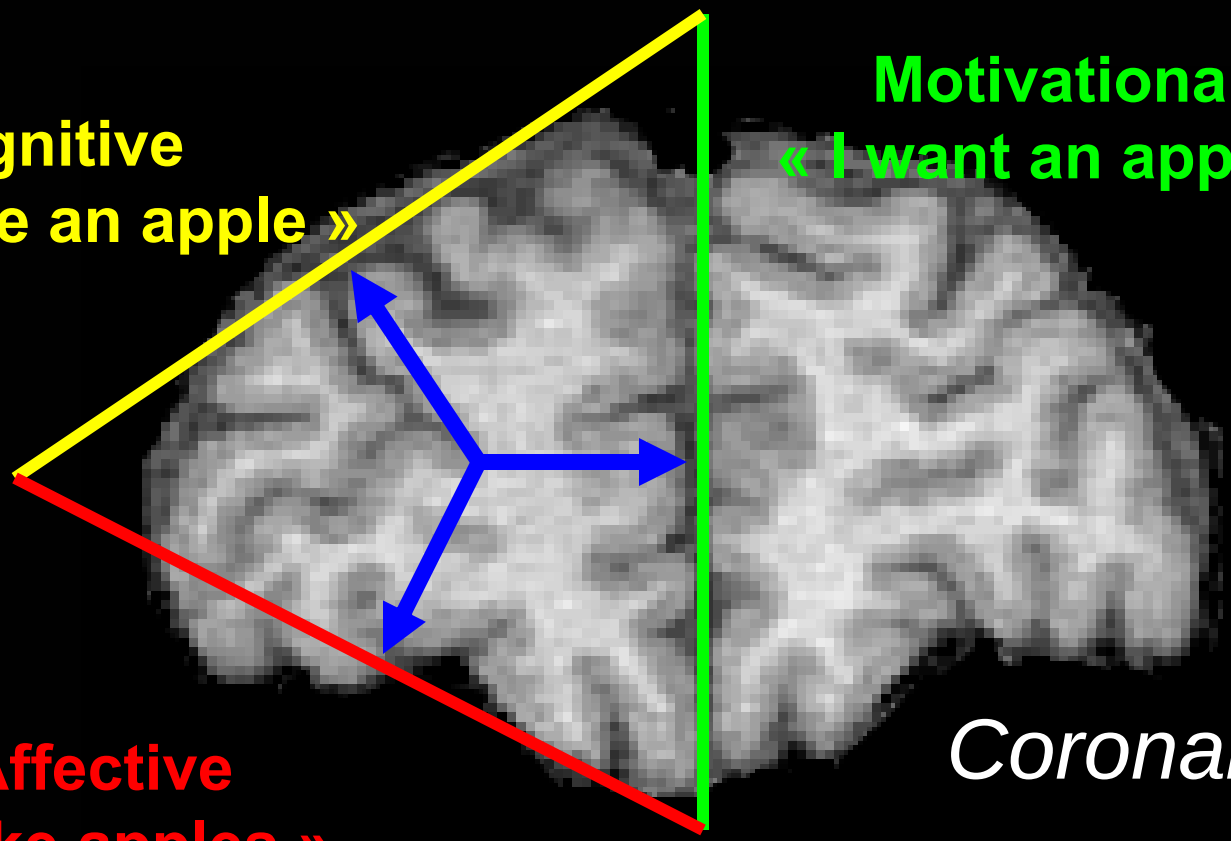


Prefrontal Executive Function




Sensory
signal
Action
Sensory
signal
Action-2
Action-1

Executive Control in the Human Prefrontal cortex



Summerfield & Koechlin, in press

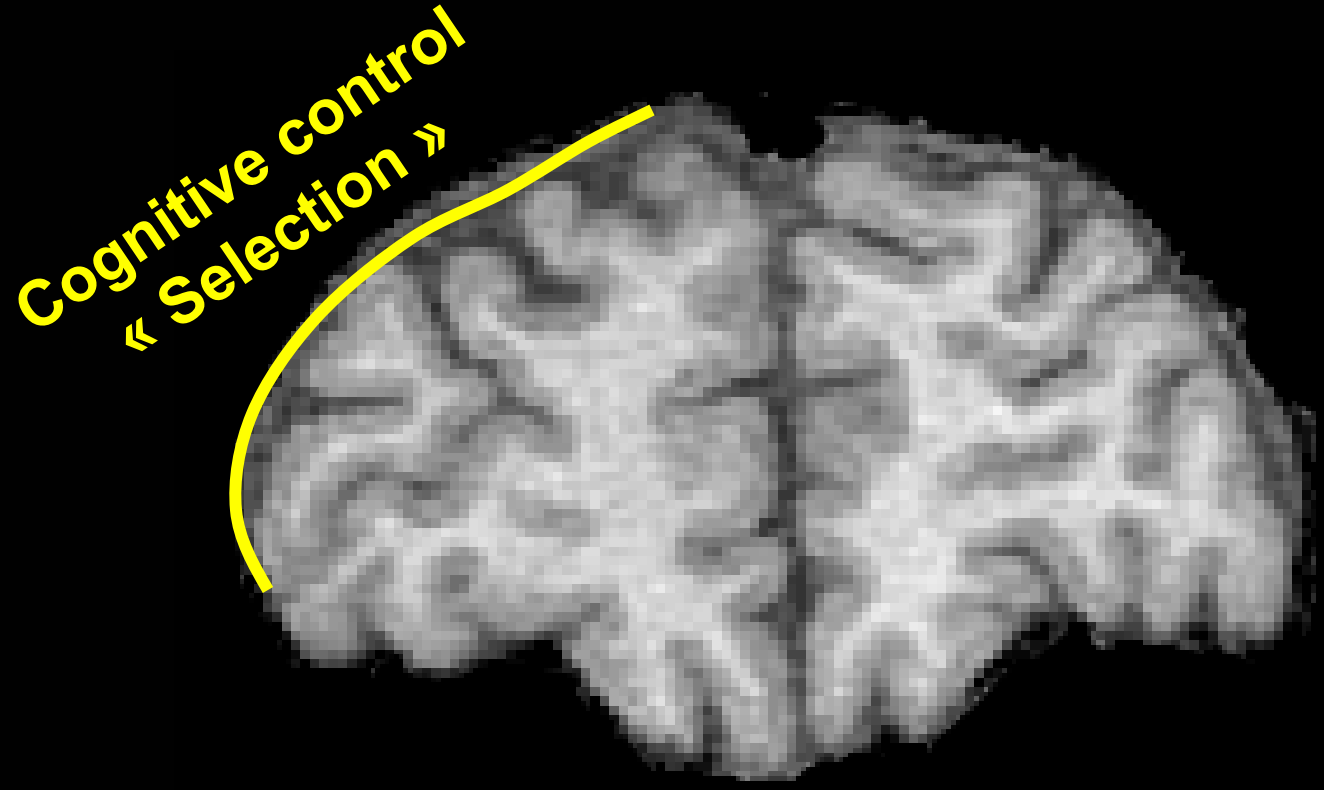
How the PFC function achieves action selection?

« Cognitive control »

How the engagement of the PFC function is driven?

« Motivation »

Hypothesis:
the LPFC subserves cognitive control



PFC coronal section

Cognitive Control and Information Theory

Total Information for selecting action A | **Mutual Information between Signal S & action A** | **Remaining Information for selecting action A unrelated to signal S**

$$Q(A) = I(S,A) + Q(A|S)$$

$$= \log_2 \frac{P(S,A)}{P(S)P(A)} + [-\log_2 P(A|S)]$$

Measures Cognitive Control …

Predictions

Reaction Times

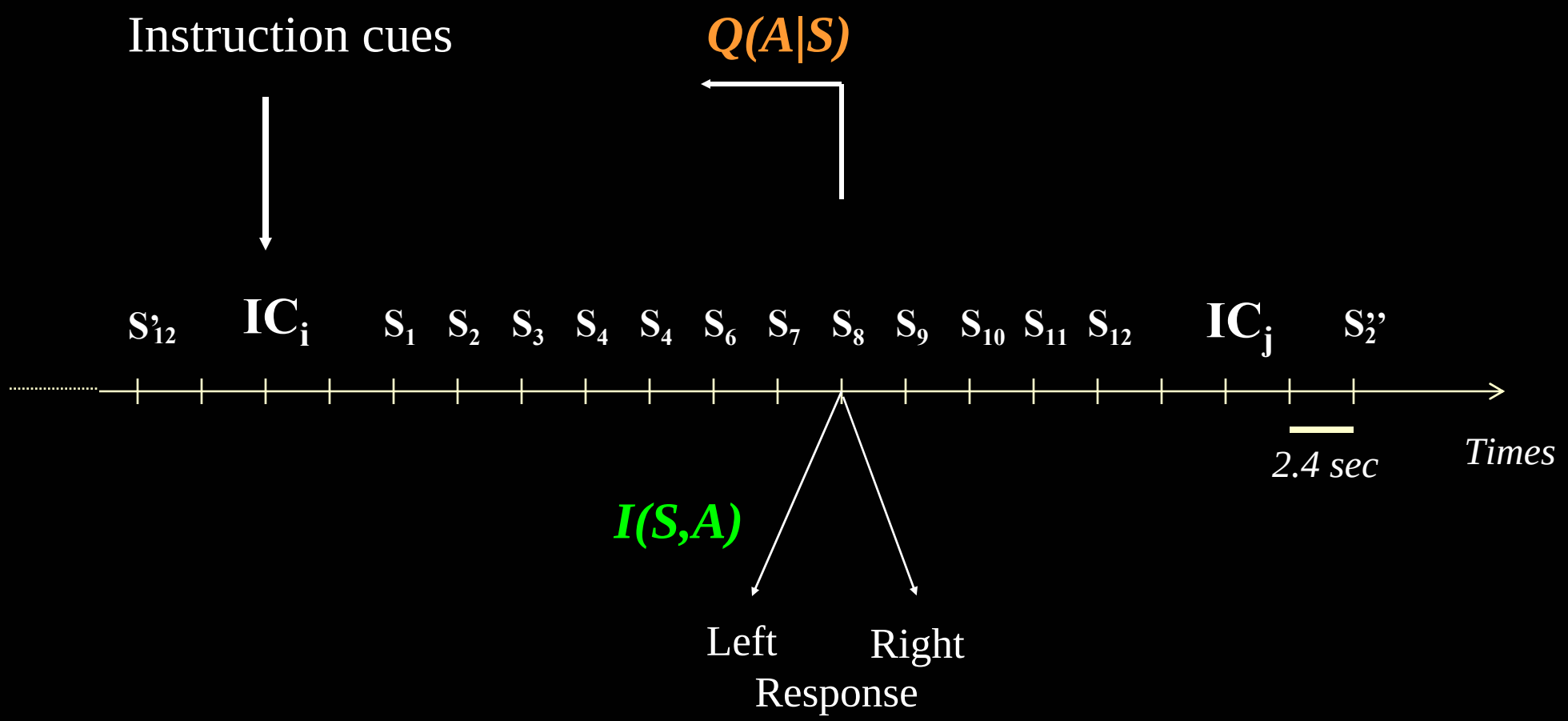
- RTs ~ $Q(A) = I(S,A) + Q(A|S)$

fMRI Activations

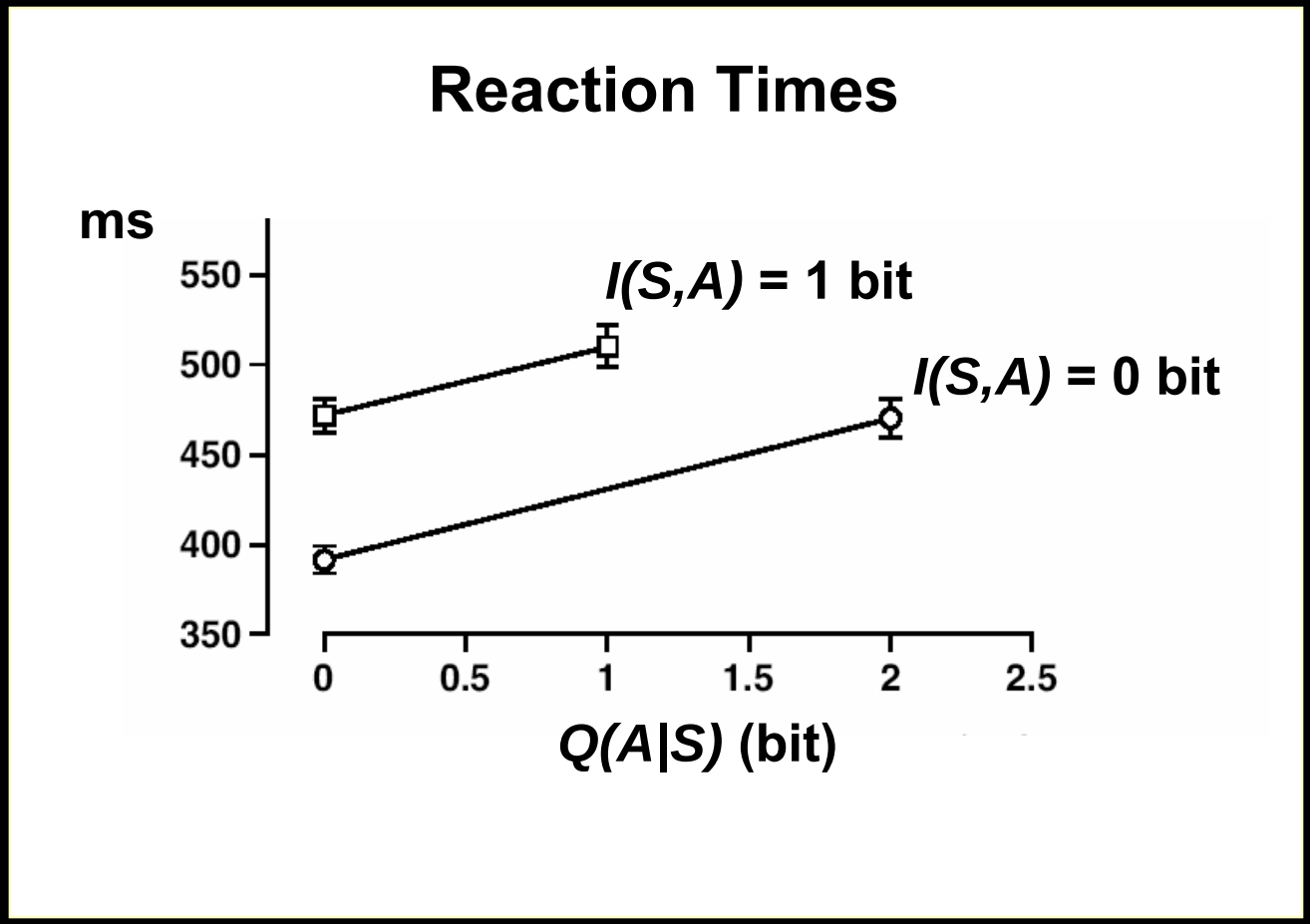
- LPFC ~ $Q(A|S)$

- PM ~ $Q(A) = I(S,A) + Q(A|S)$

Experimental Protocol

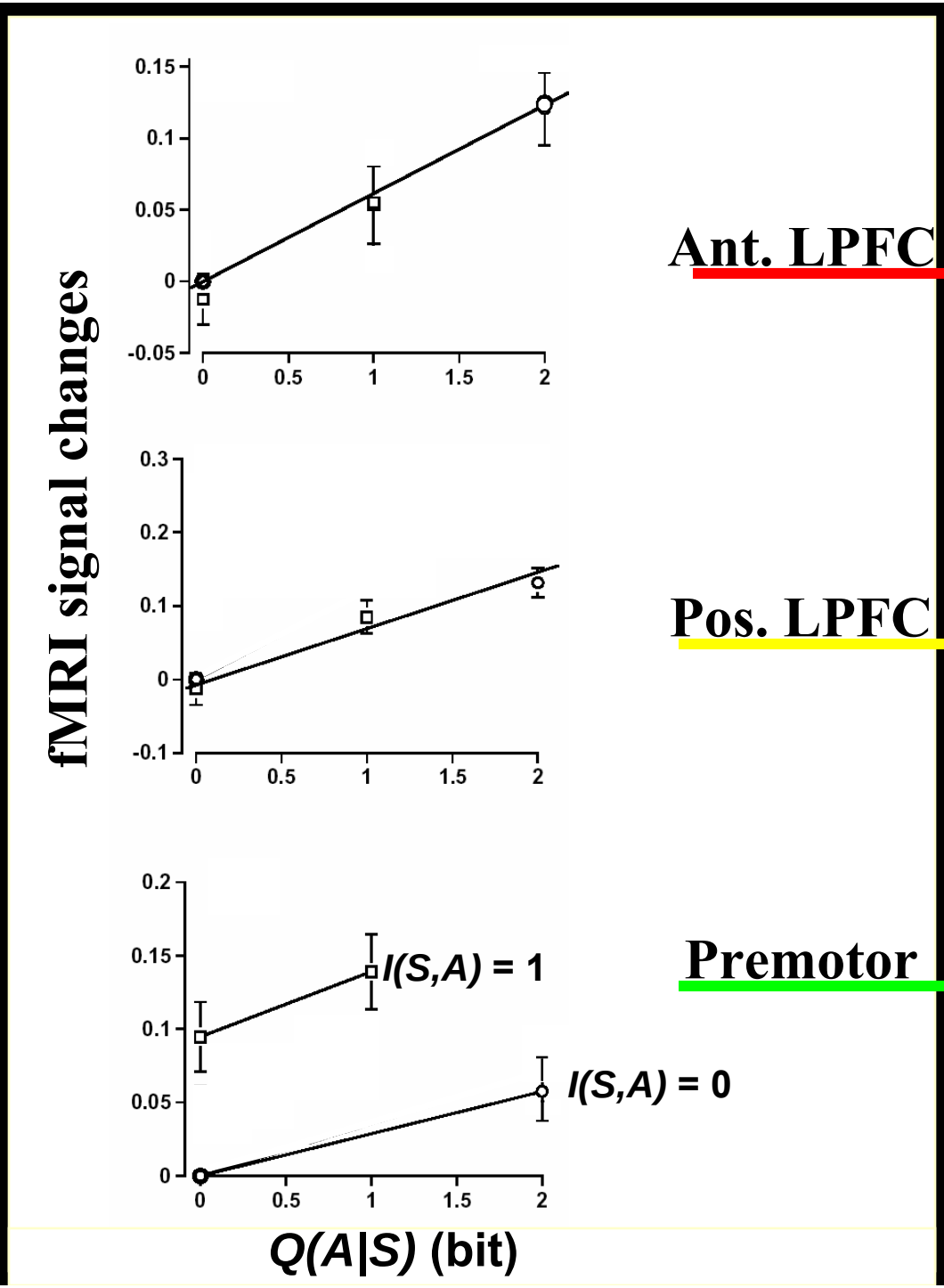


Behavioral results

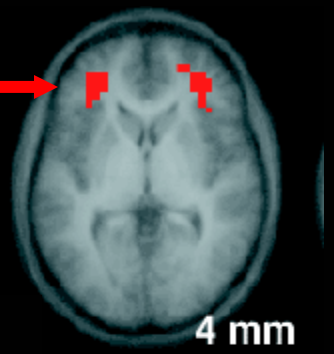


Koechlin, Ody, Kouneiher, *Science*, *2003*

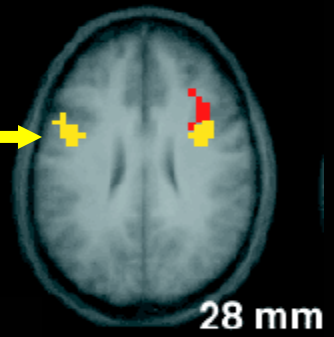
fMRI data



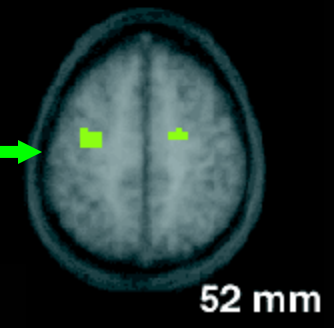
Ant. LPFC



Pos. LPFC

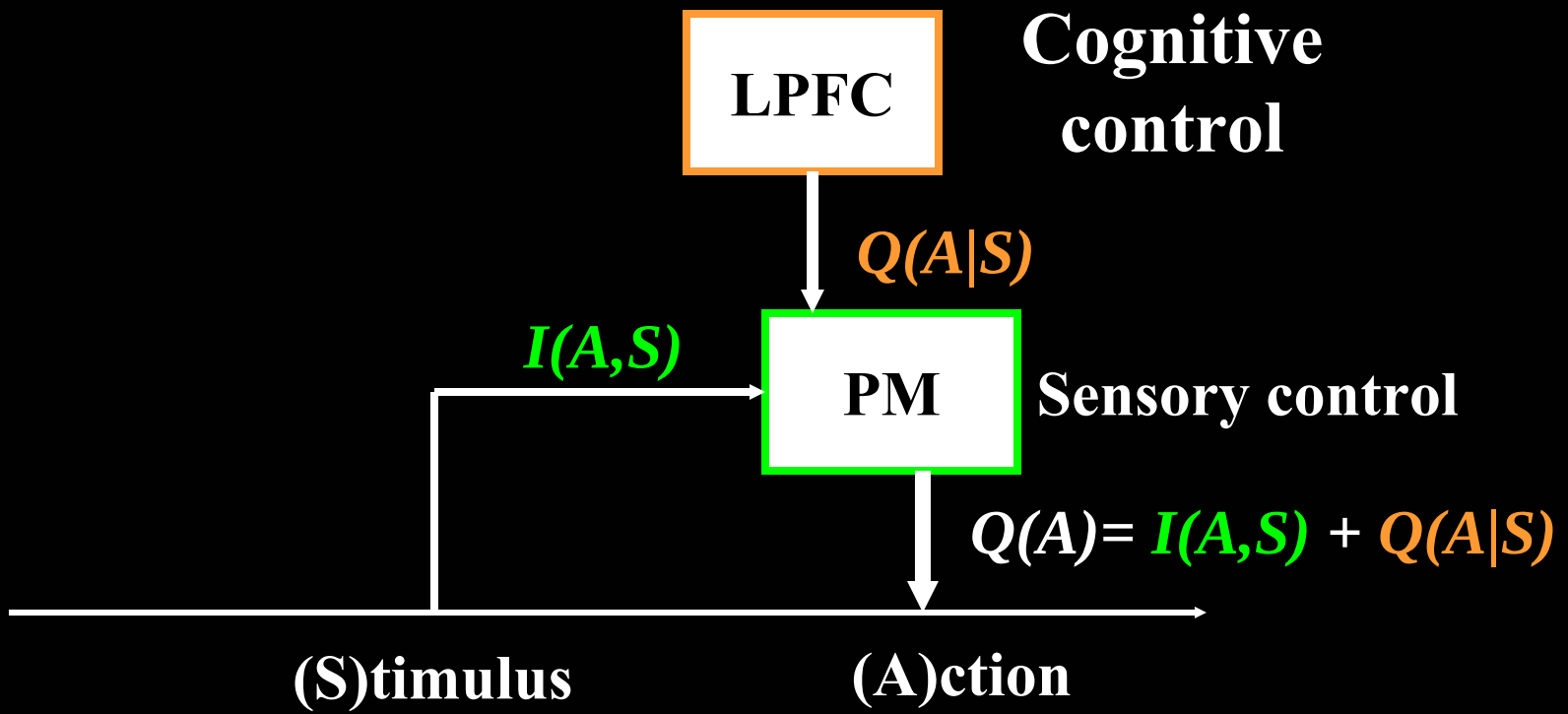


Premotor



Koechlin et al., *Science, 2003*

The model


LPFC
Cognitive control
Q(A|S)
I(A,S)
PM
Sensory control
Q(A)= I(A,S) + Q(A|S)
(S)timulus
(A)ction

Is Cognitive Control fractionable?

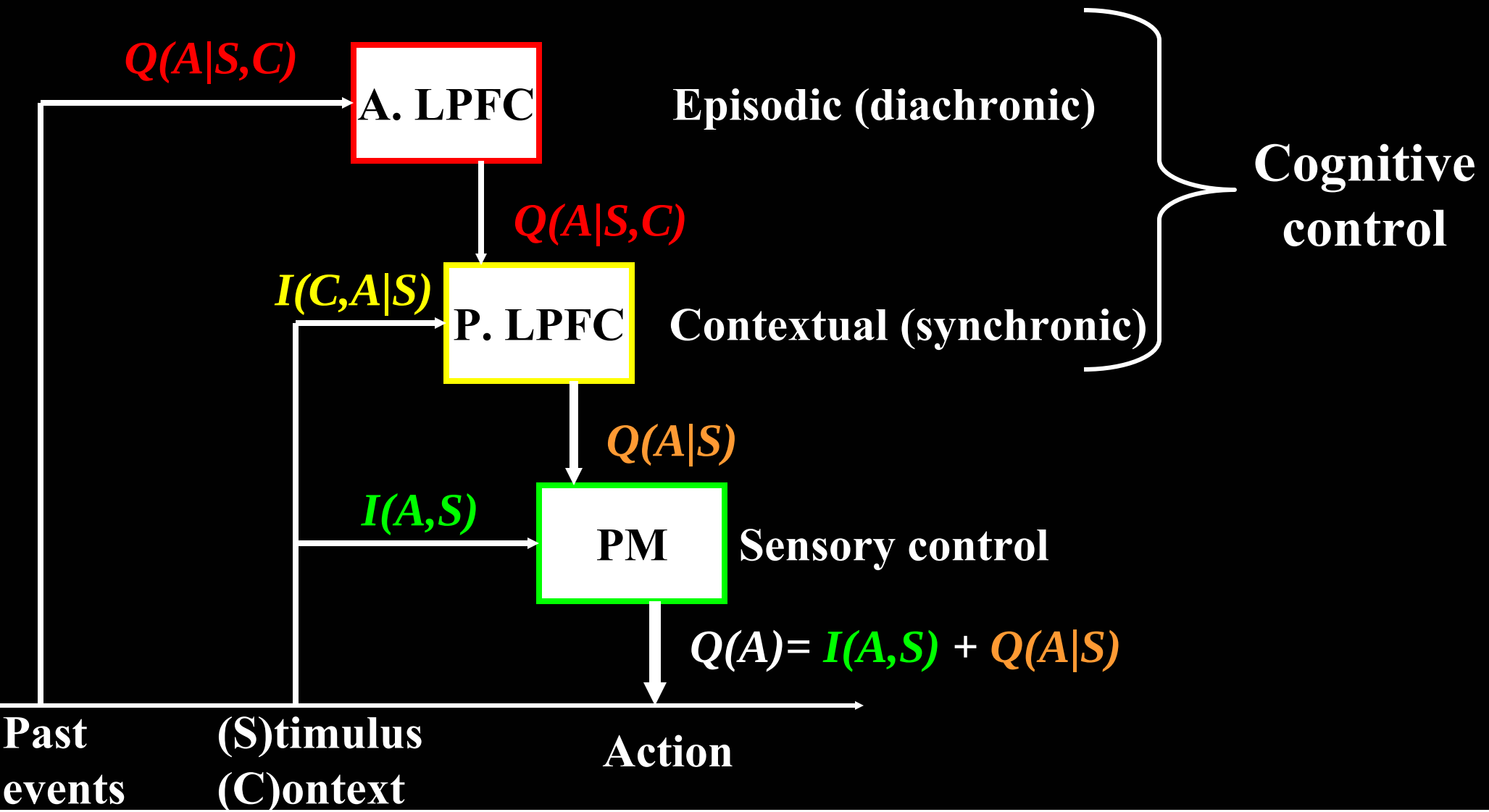
Back to Information Theory

Cognitive control | **Contextual control** | **Episodic control**

$$Q(A|S) = I(C,A|S) + Q(A|S,C)$$

$$Q(A) = I(S,A) + Q(A|S)$$

The cascade architecture



Predictions

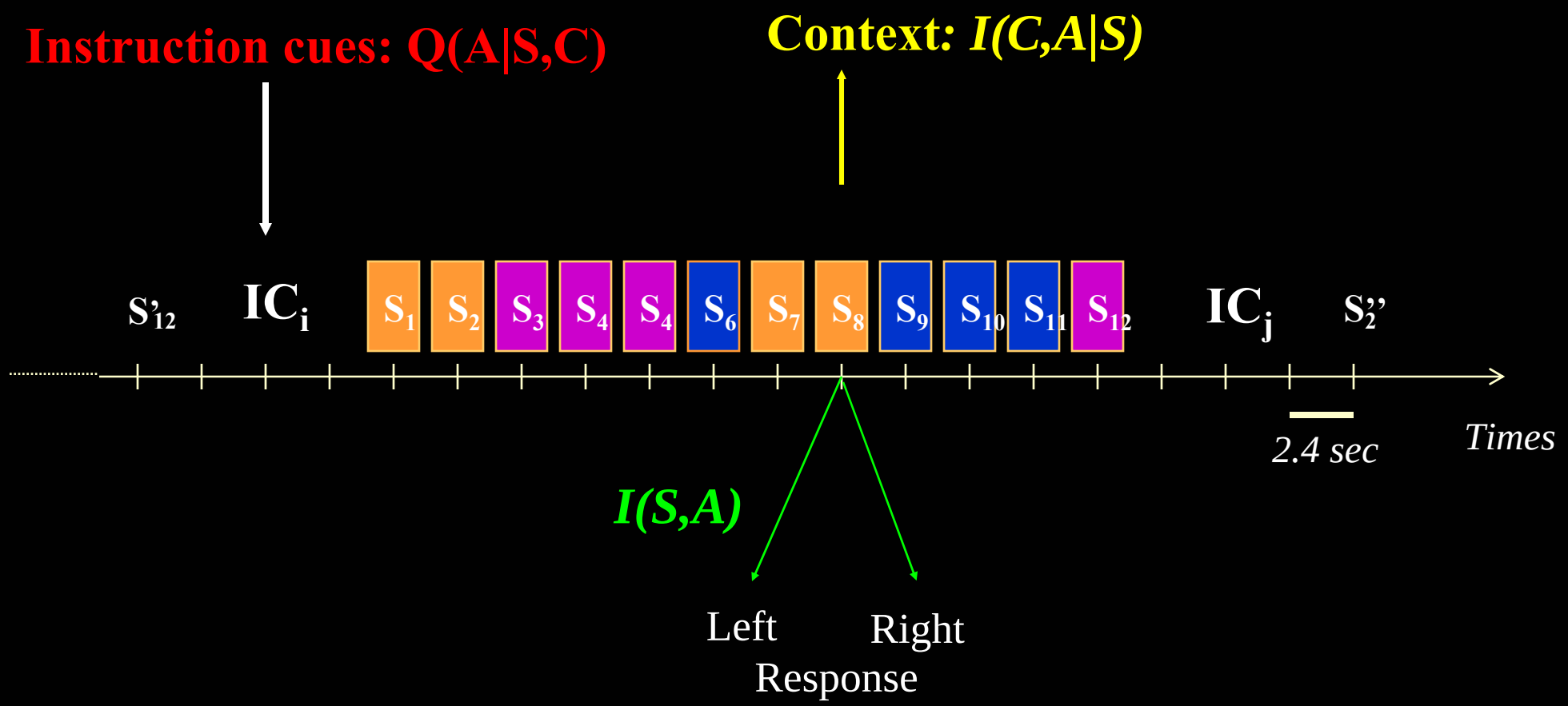
Reaction Times

- RTs ~ $I(S,A) + I(C,A|S) + Q(A|S,C)$

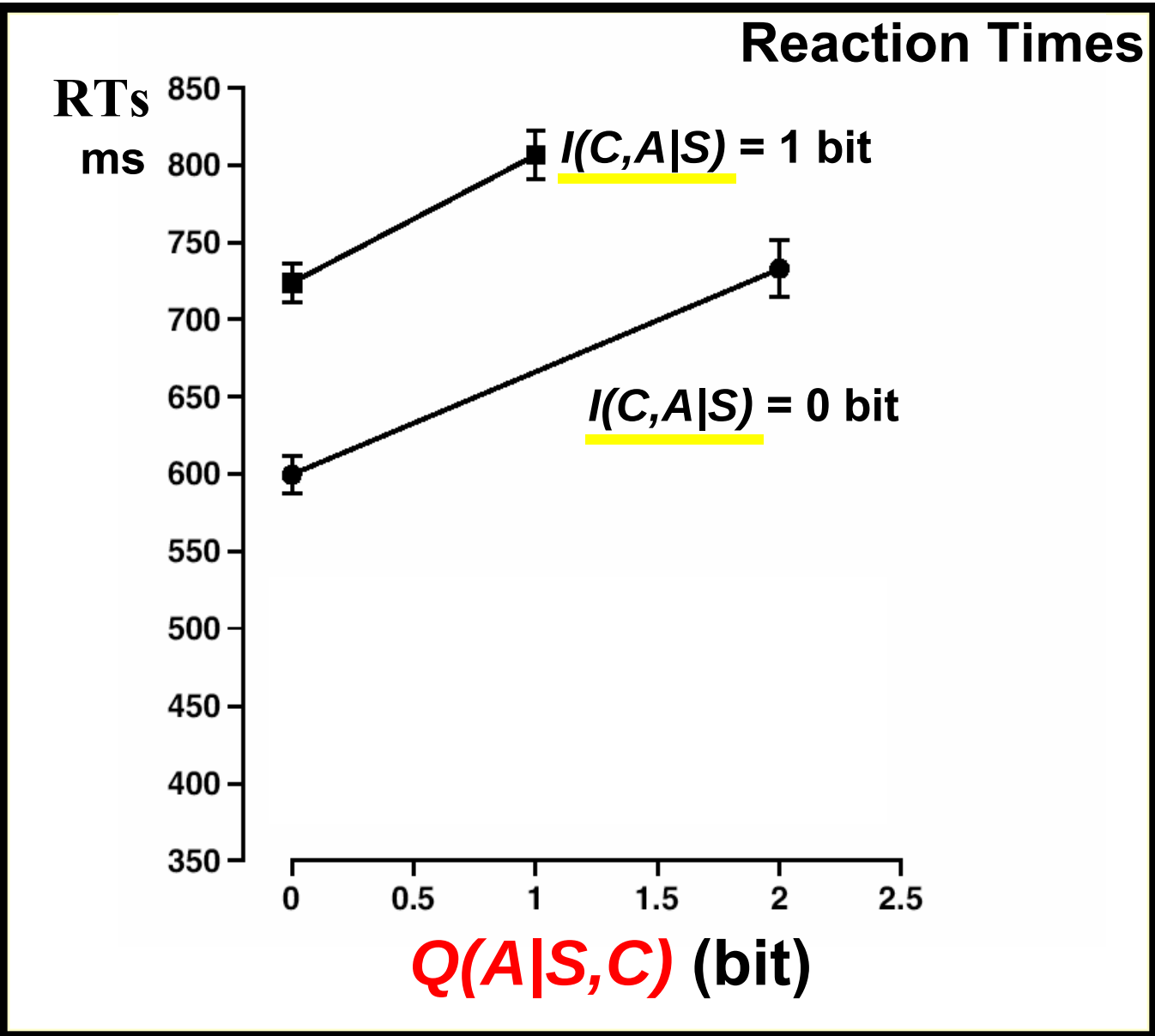
fMRI Activations

- A. LPFC ~ $Q(A|S,C)$
- P. LPFC ~ $I(C,A|S) + Q(A|S,C)$
- PM ~ $I(S,A) + I(C,A|S) + Q(A|S,C)$

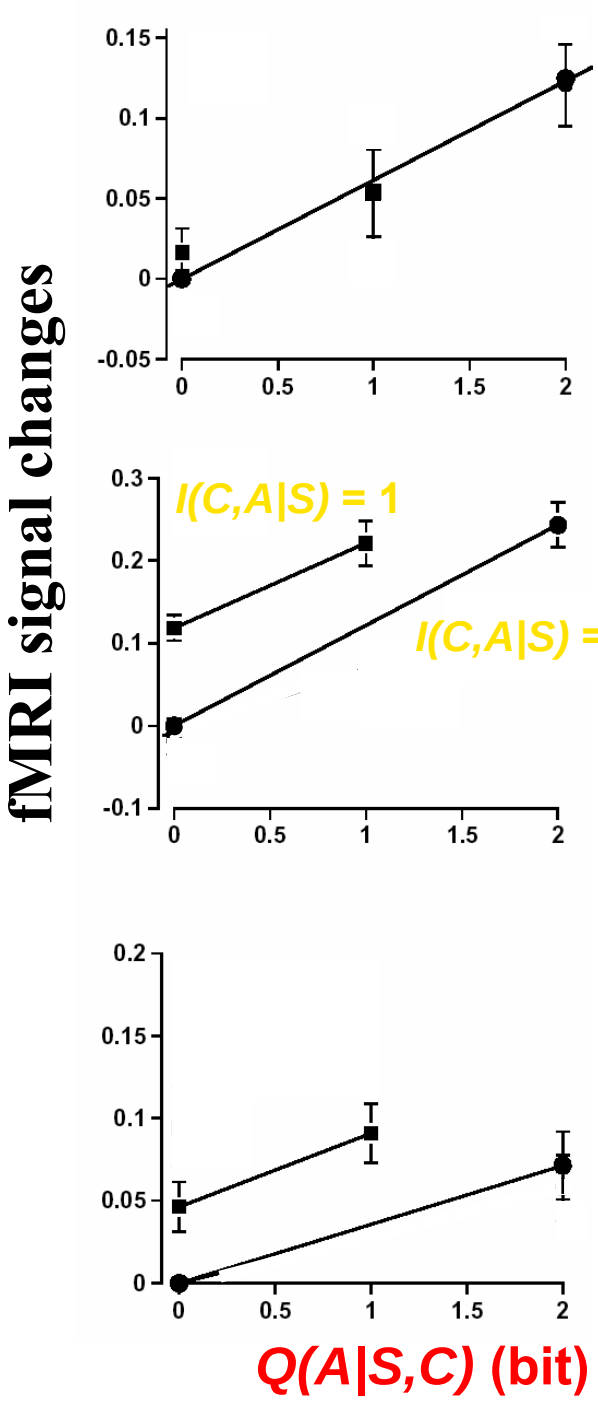
Experimental Protocol

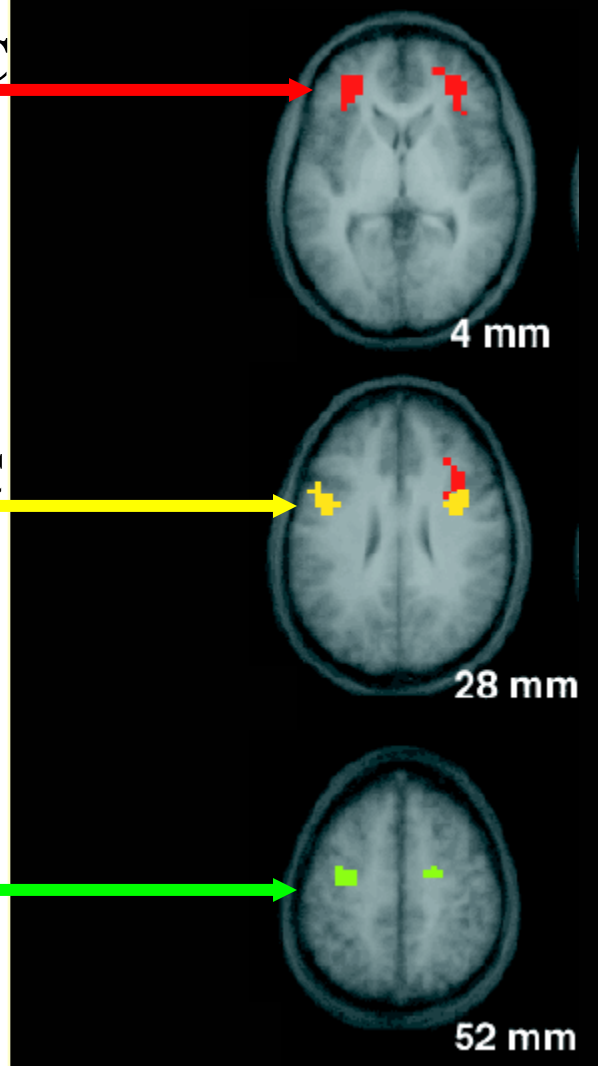


Behavioral results



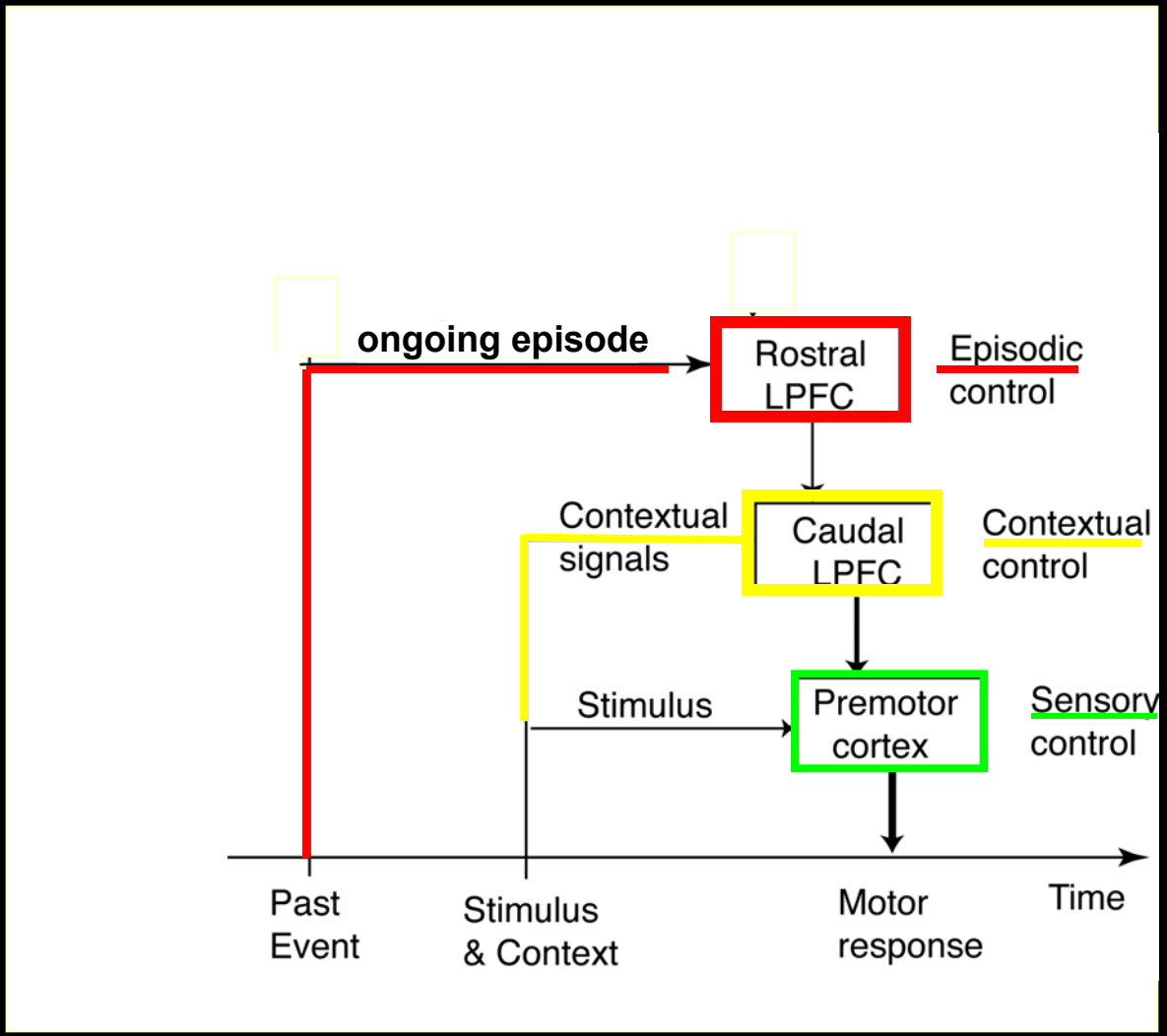
Koechlin, Ody, Kouneiher, *Science*, *2003*

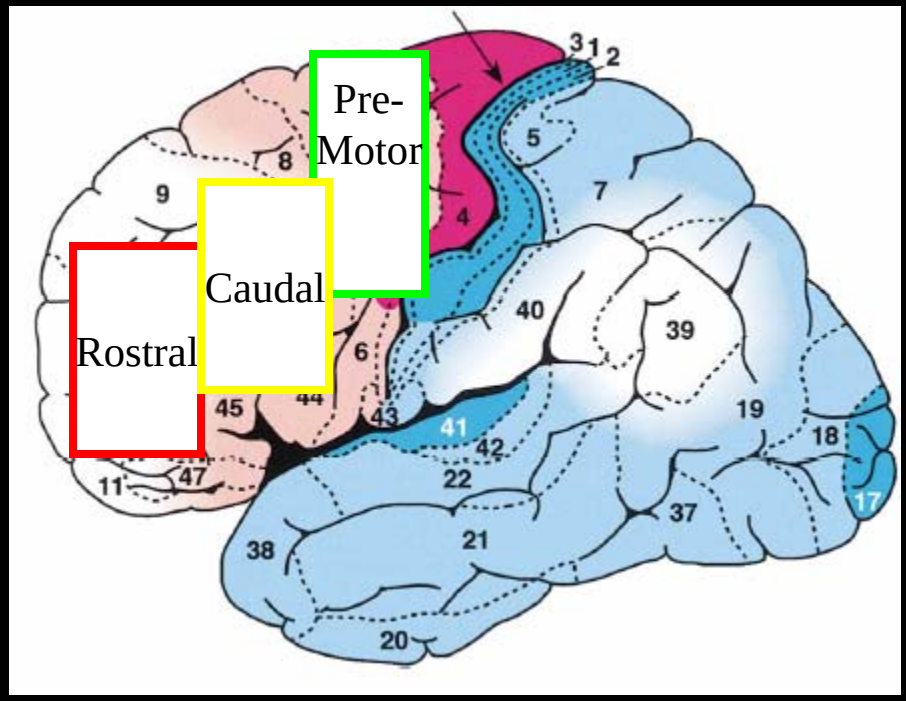




Koechlin et al., Science, 2003

Contextual vs. episodic control in the LPFC



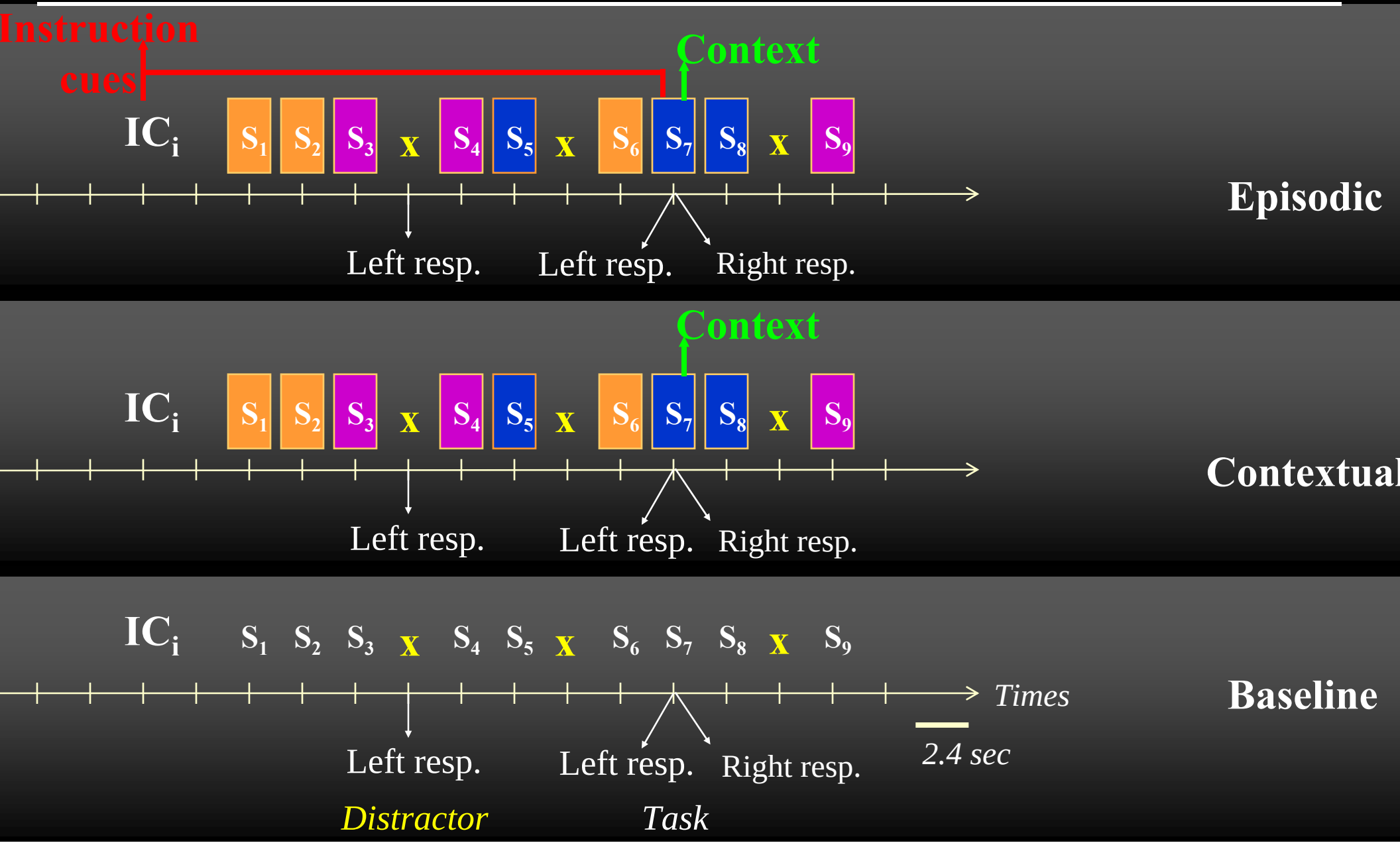


Temporal dimensions of cognitive control

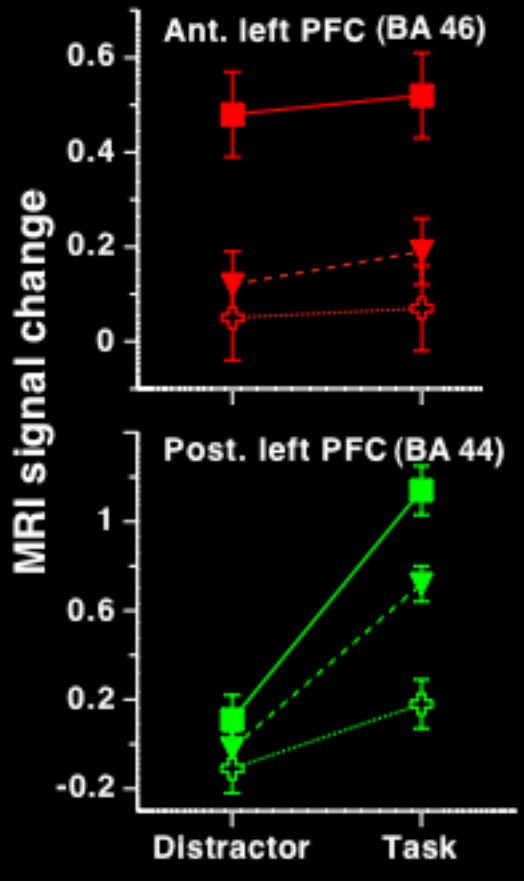
Synchronic

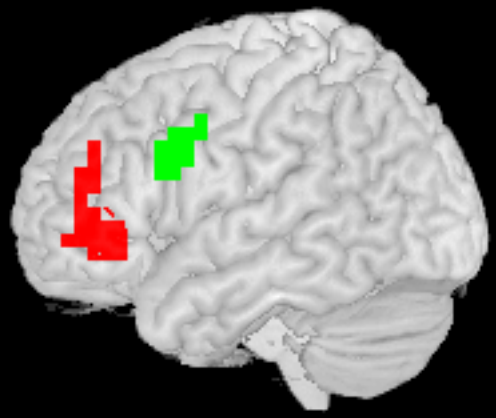
Diachronic

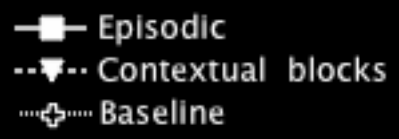
Experimental Protocol: cognitive factors

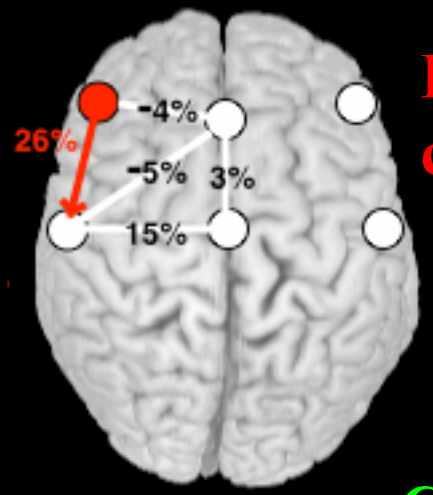


Contextual vs. Episodic control



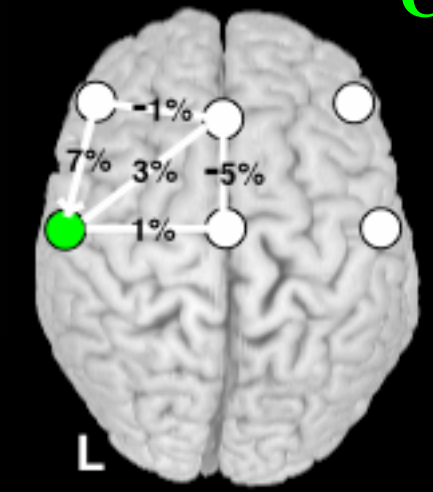


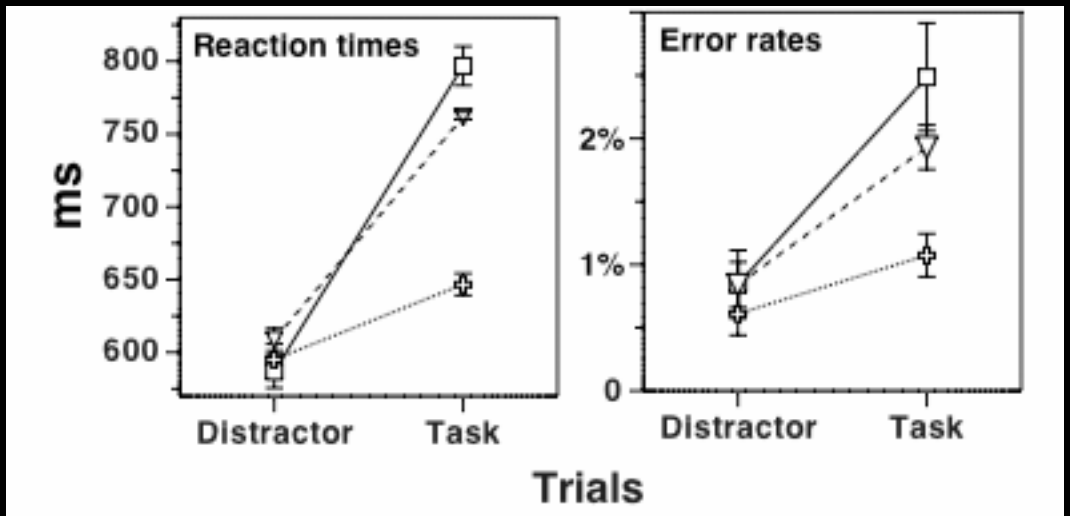




Episodic control

Contextual control



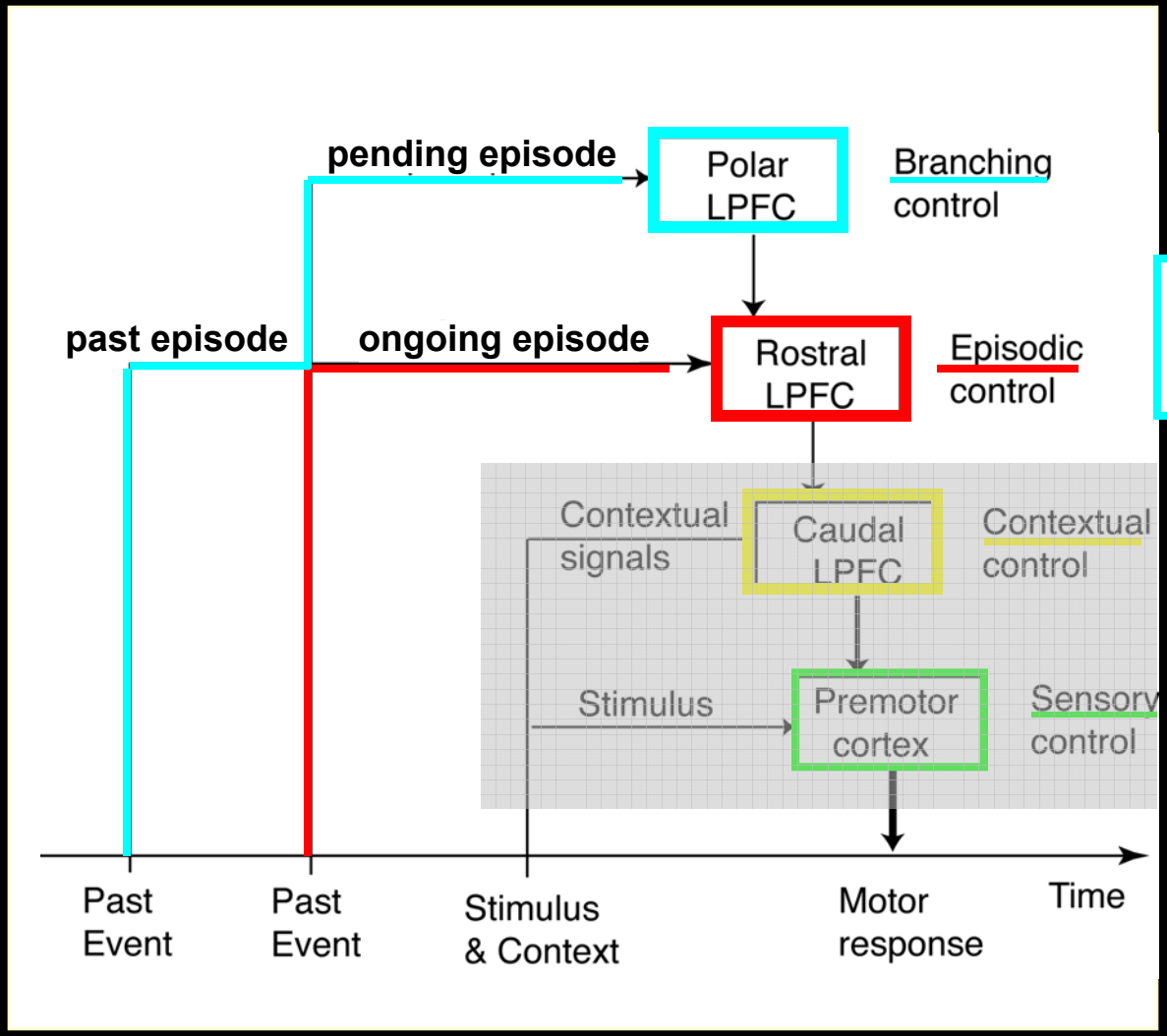


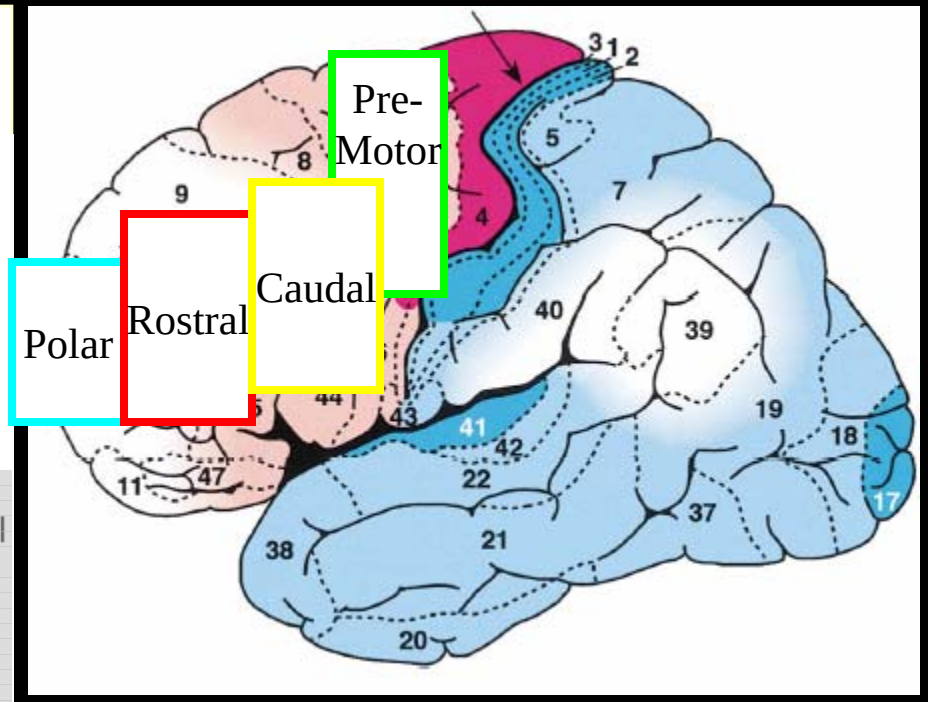
Kouneiher, Charron, Koechlin, *Nature Neurosci.*, *2009*

Is cognitive control further fractionable ?

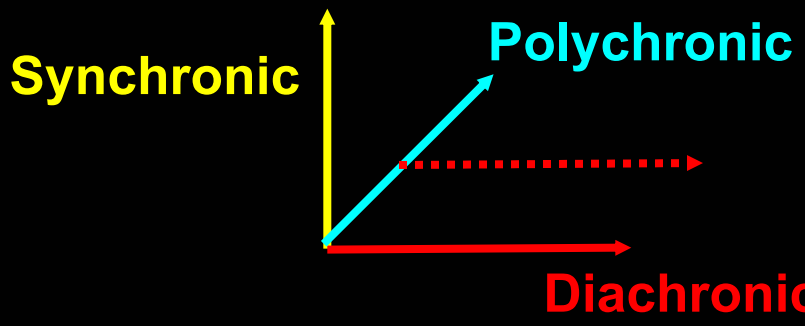
Yes …

Episodic vs. branching control



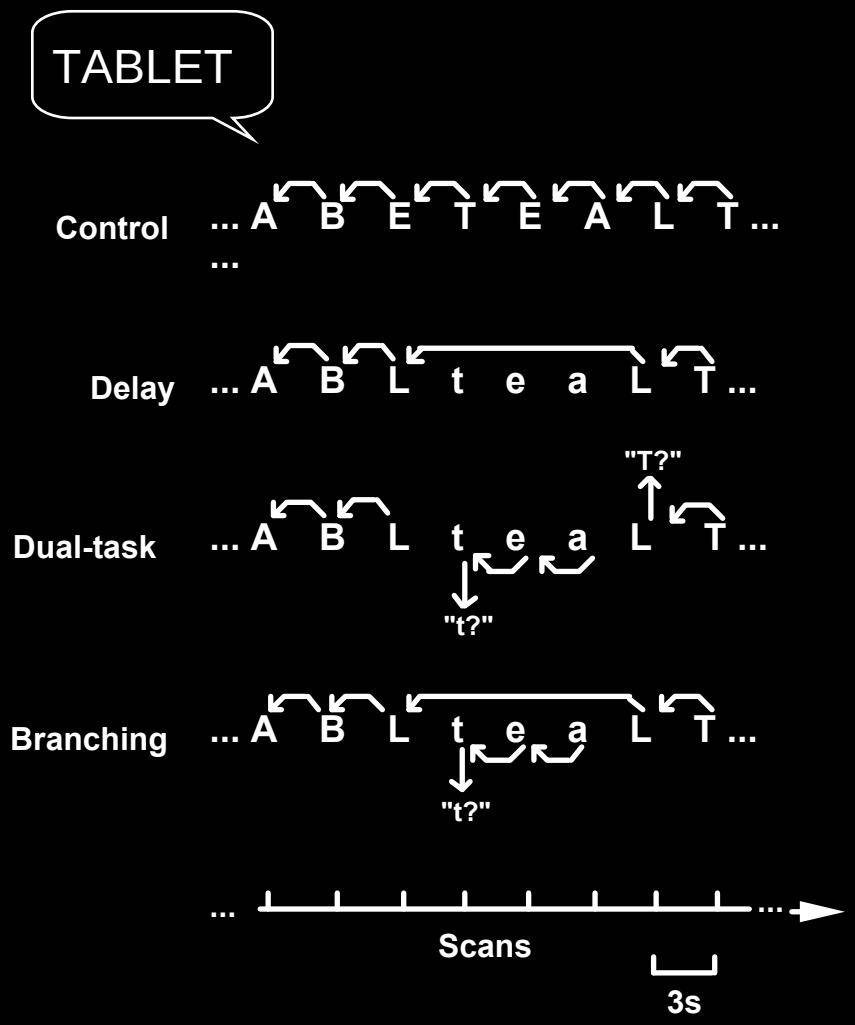


Temporal dimensions of cognitive control



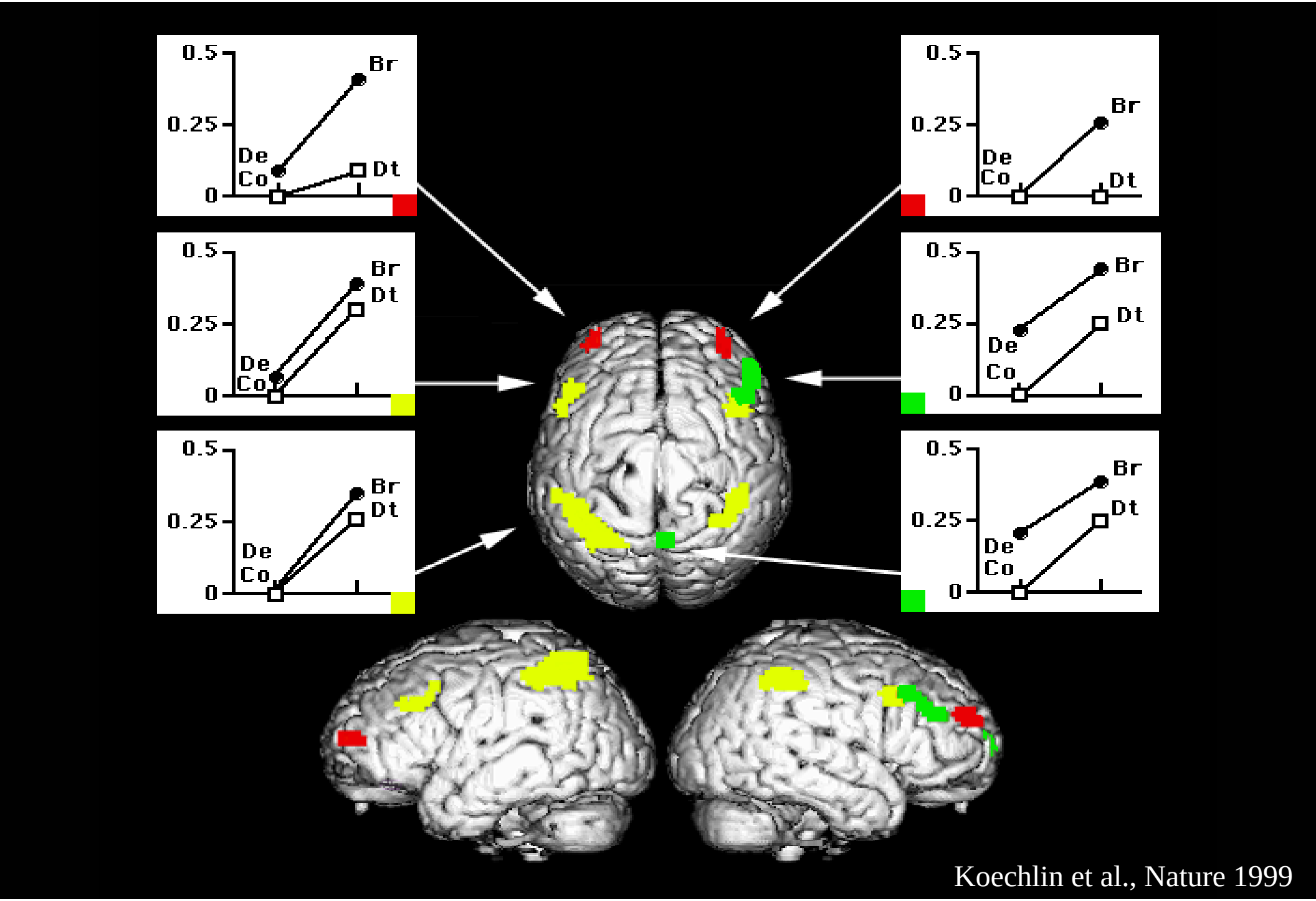
Koechlin et al., 1999: Nature; 2000: PNAS.
Koechlin & Hyafil, 2007, Science.

Experimental paradigm



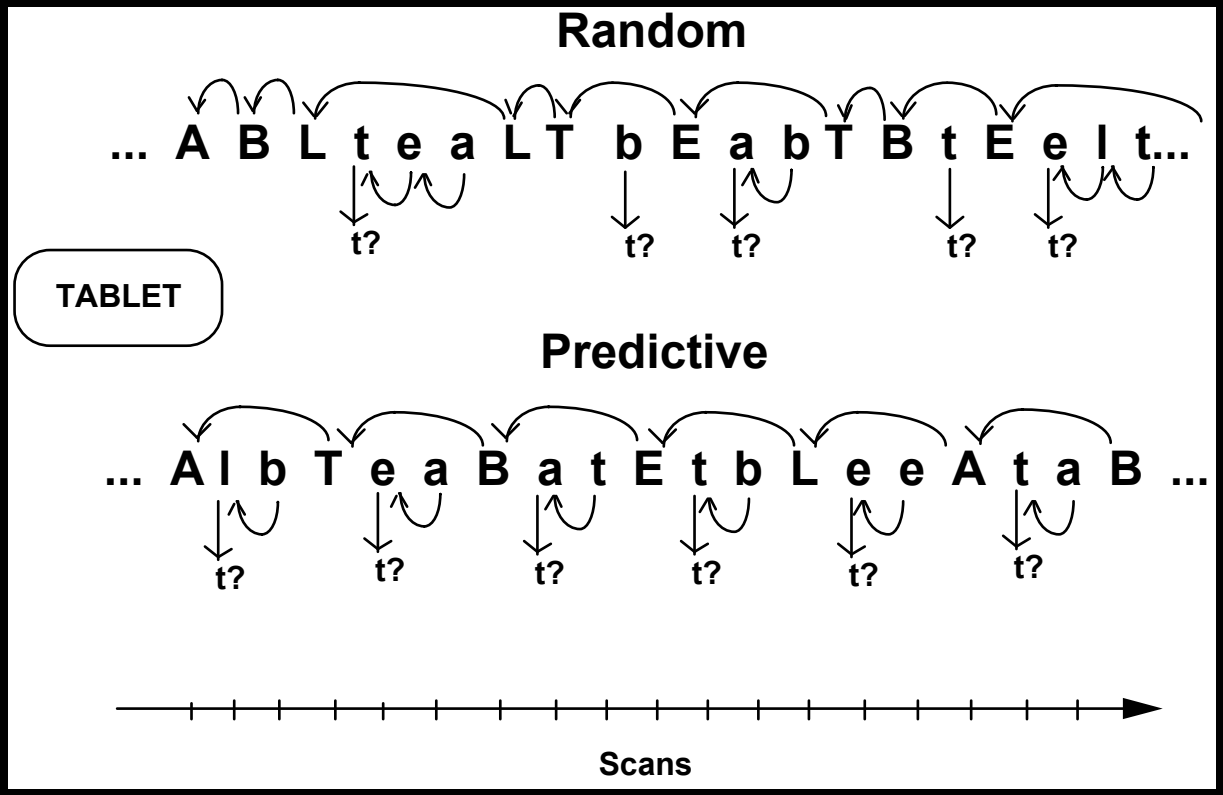
Delayed performance	Contextual control	Episodic control	Branching control
		√	
	√	√	
√	√	√	√

—	Caudal LPFC	Rostral LPFC	Polar LPFC



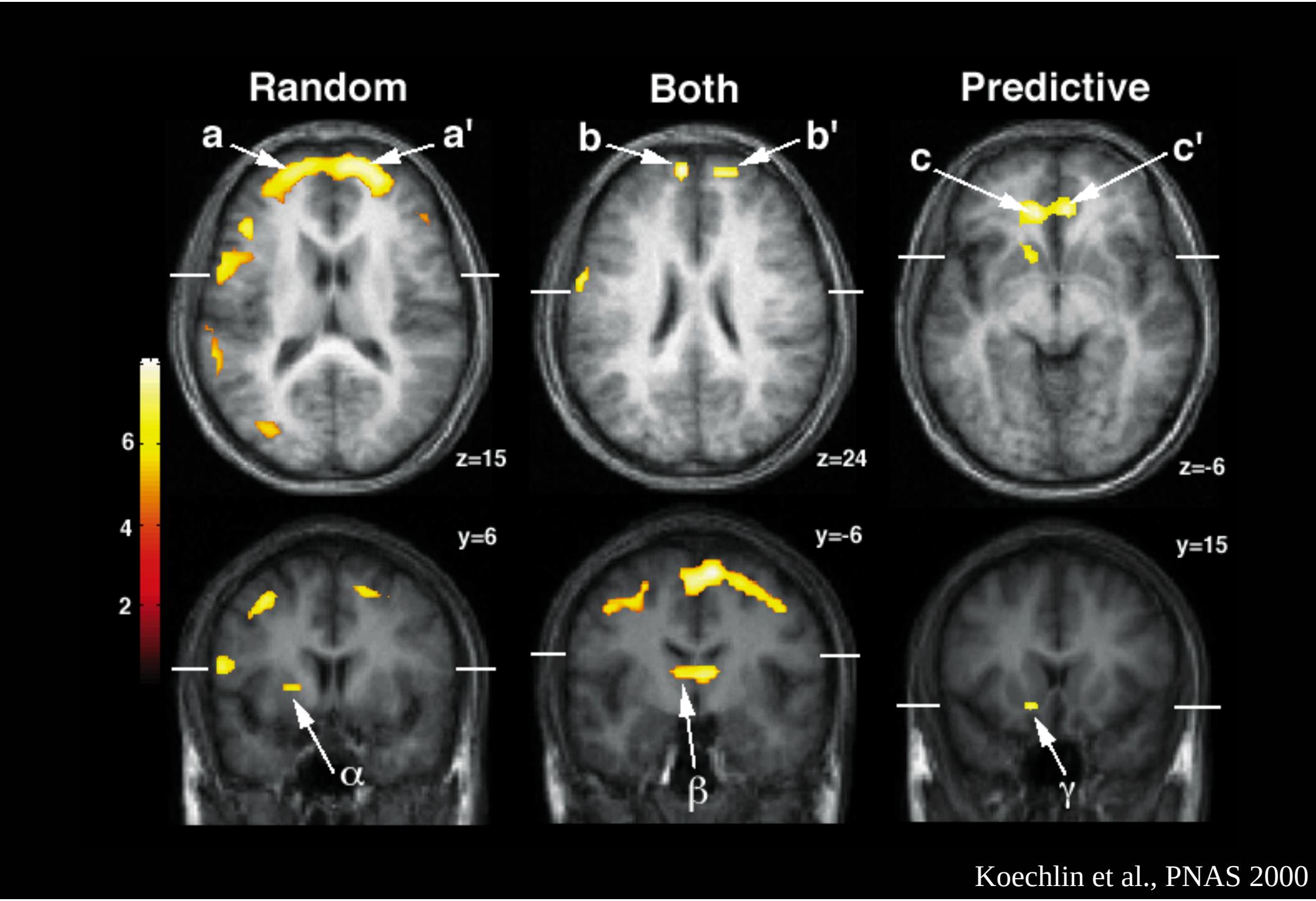
Koechlin et al., Nature 1999

Experimental Paradigm



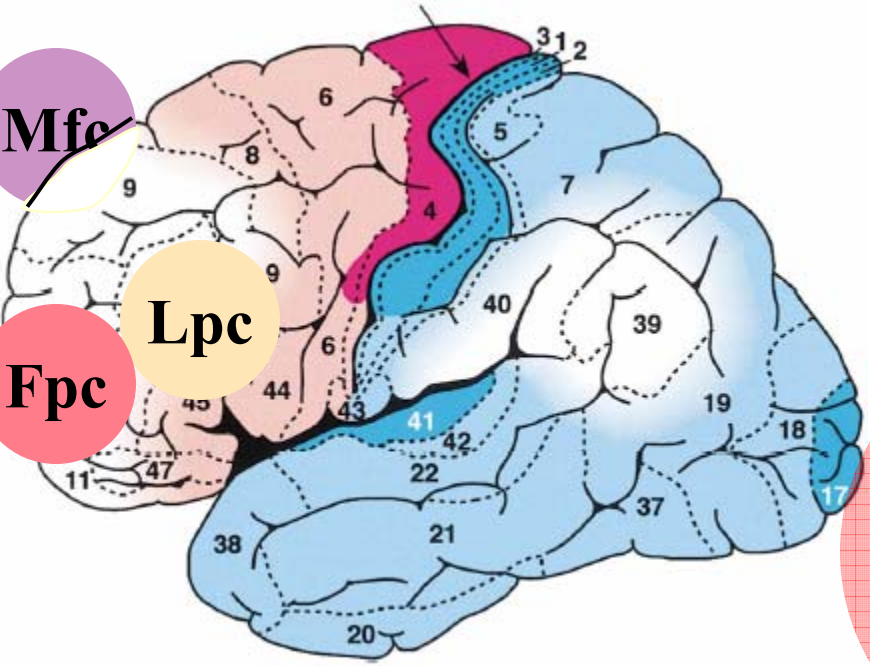
Baseline

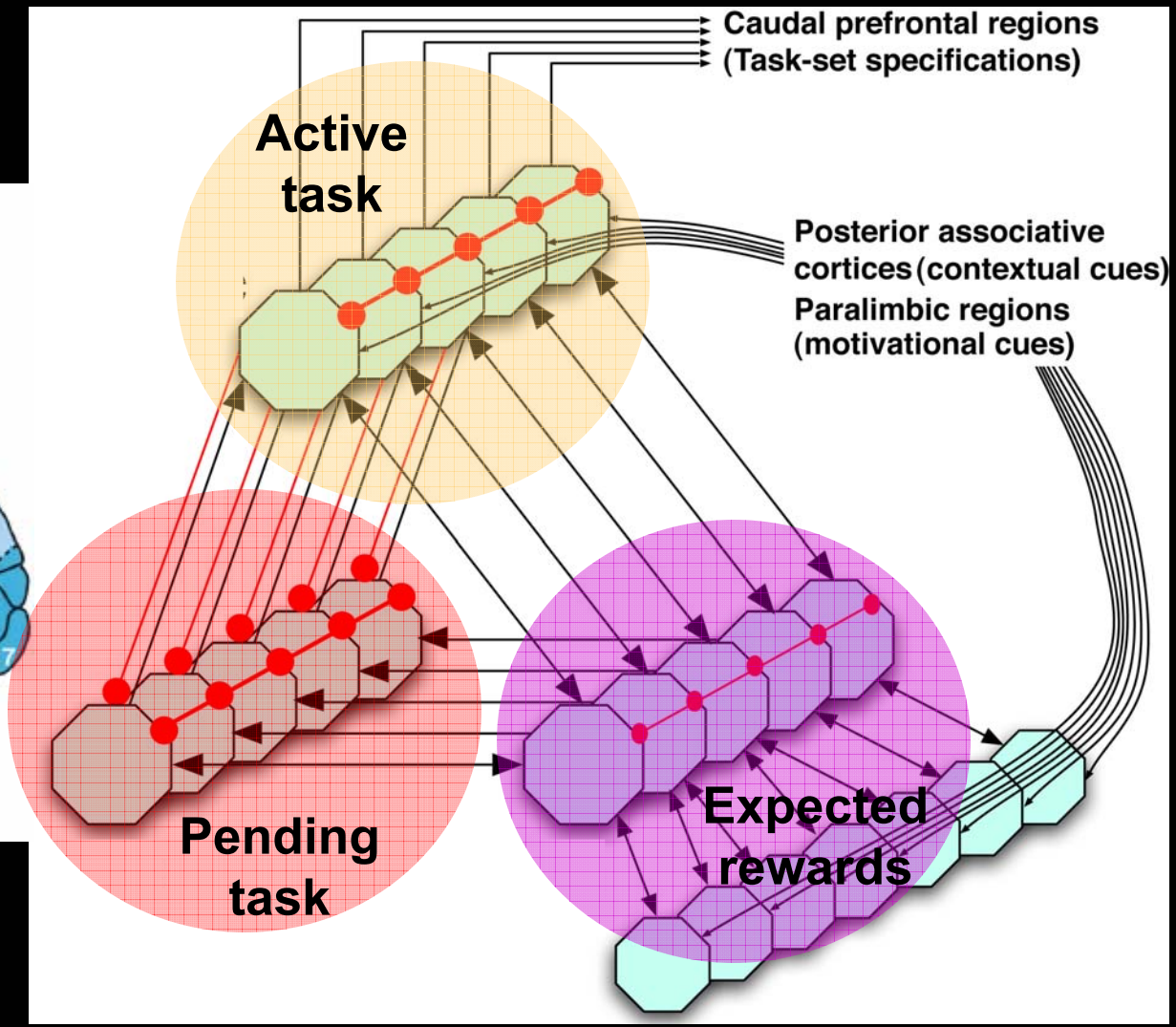
Repetitive Stimulus-Response associations



Koechlin et al., PNAS 2000

Neurocomputational model

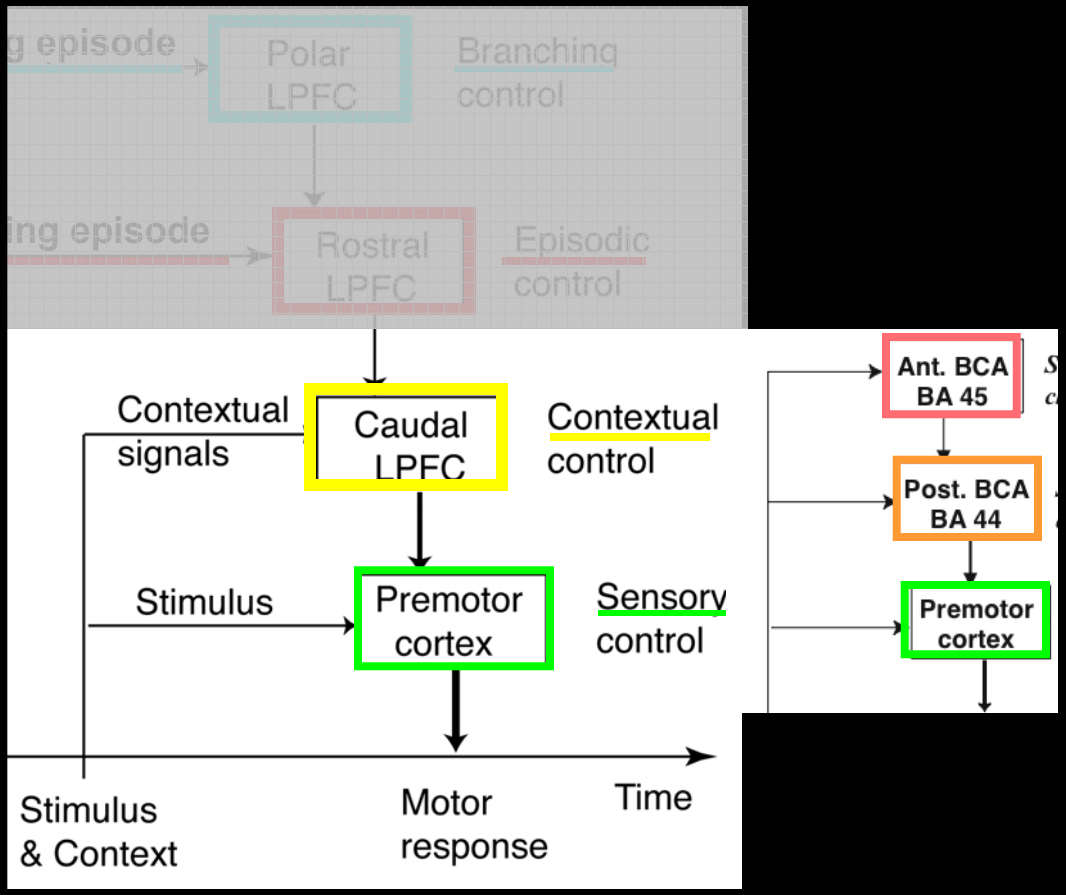


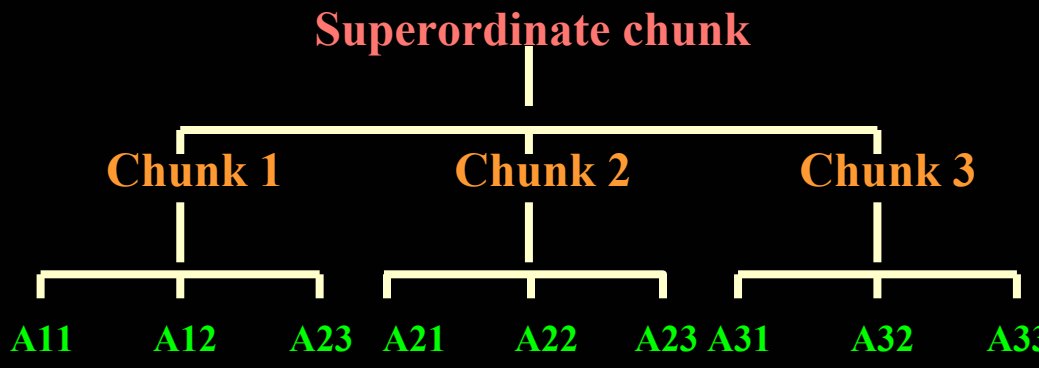


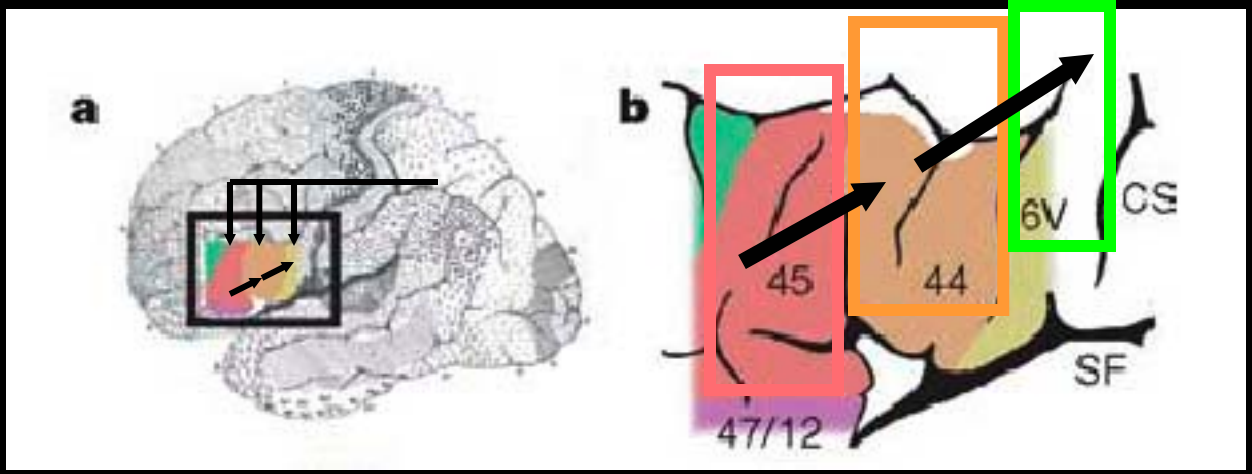
$$X_j(t+dt) = X_j(t) + dt\left((1 - X_j(t))\, E_{X_j}(t) - (.5 + X_j(t))\, I_{X_j}(t) + \eta_X\sqrt{dt}\right)$$

Koechlin, Hyafil 2007, Science

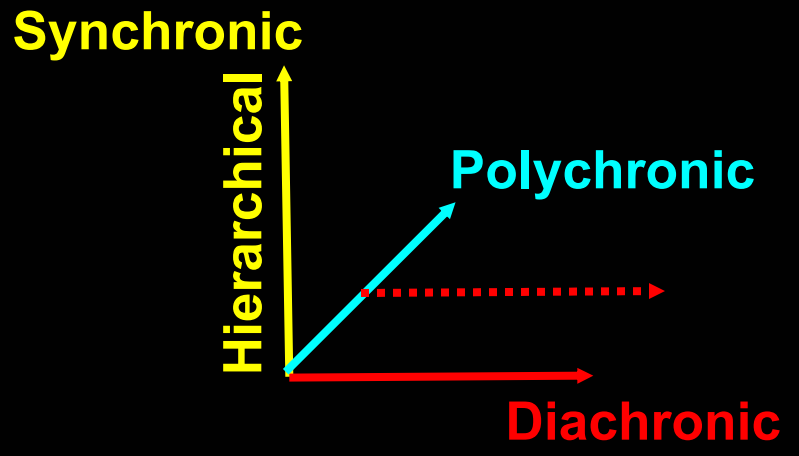
Contextual control: Hierarchical levels

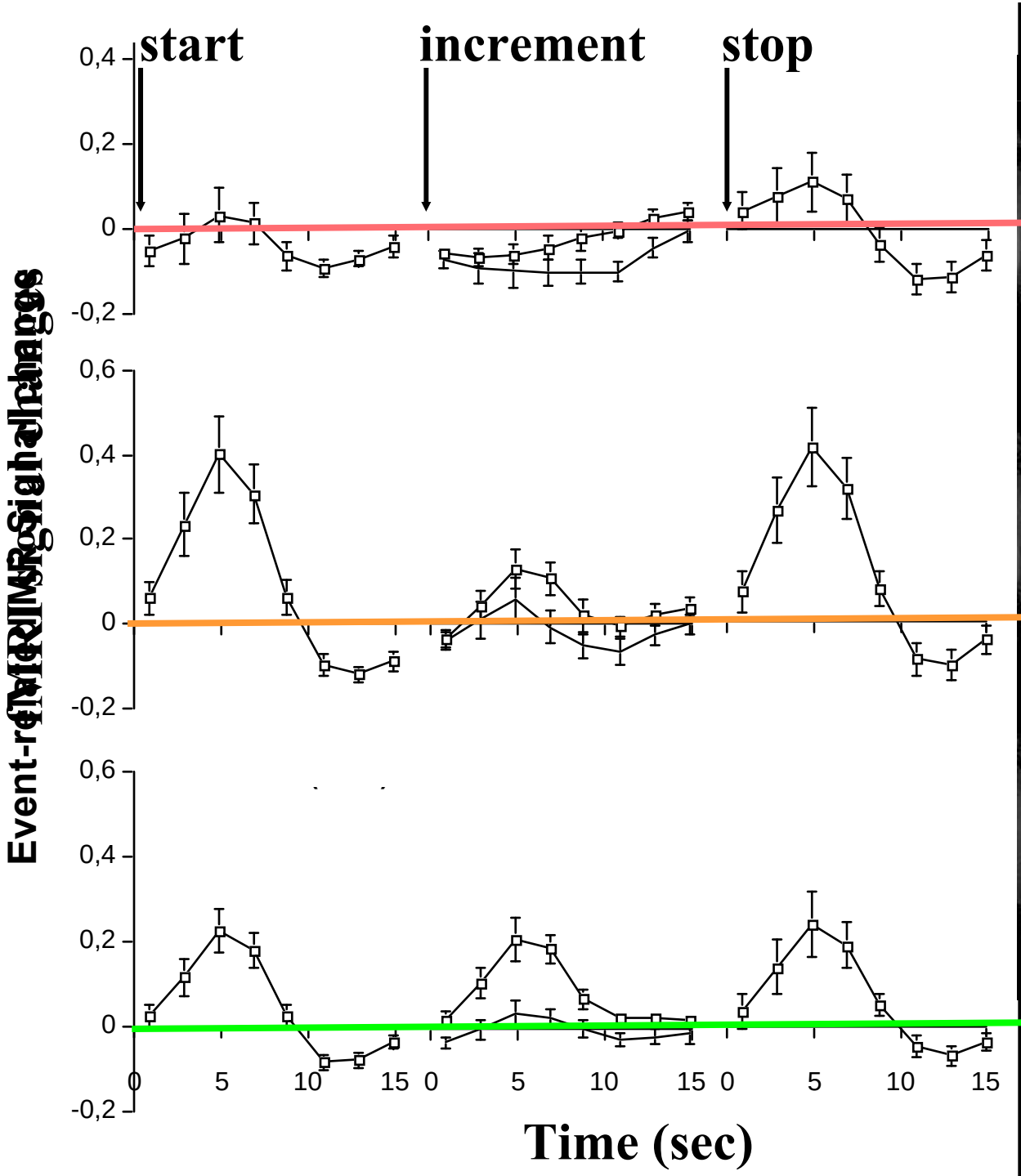


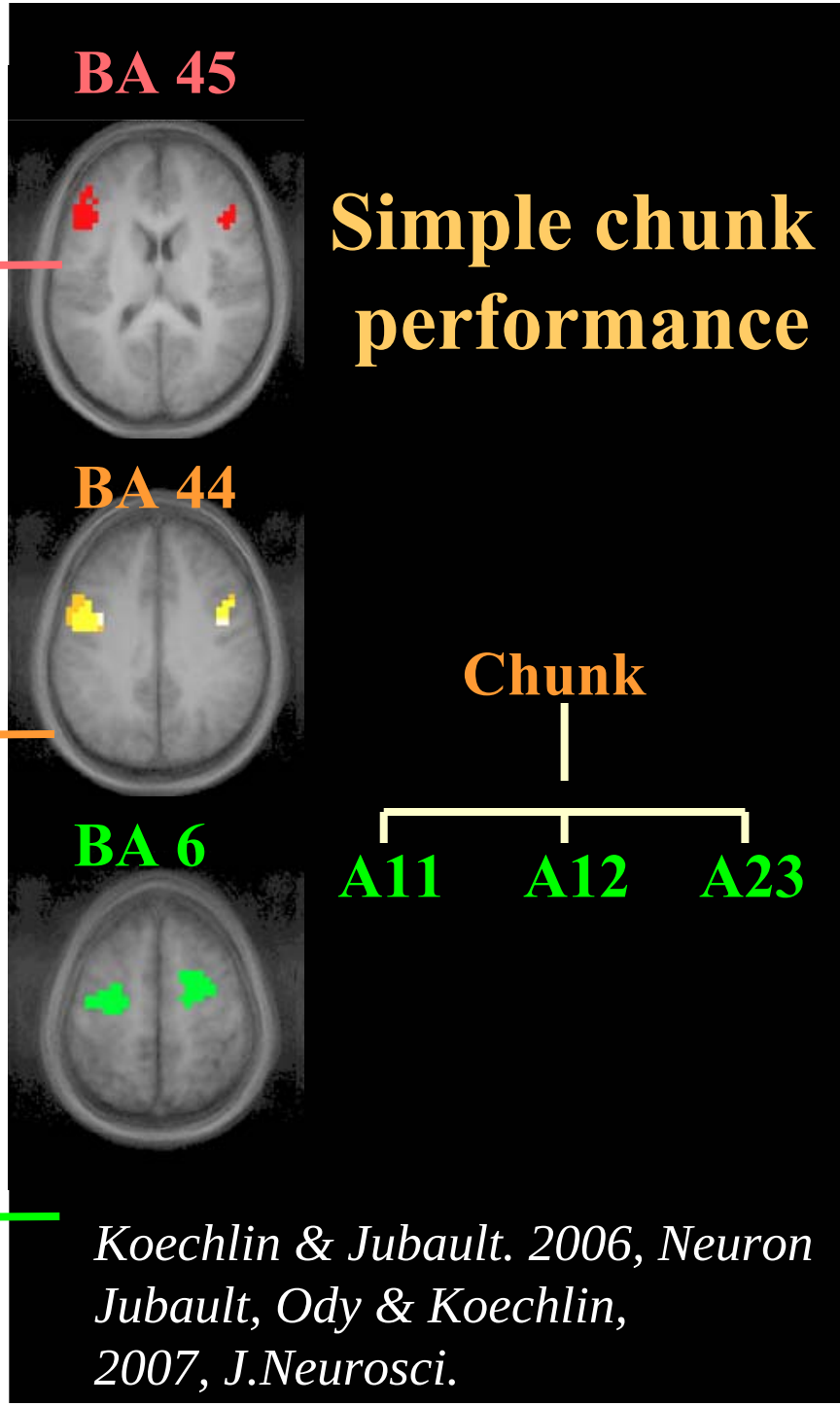


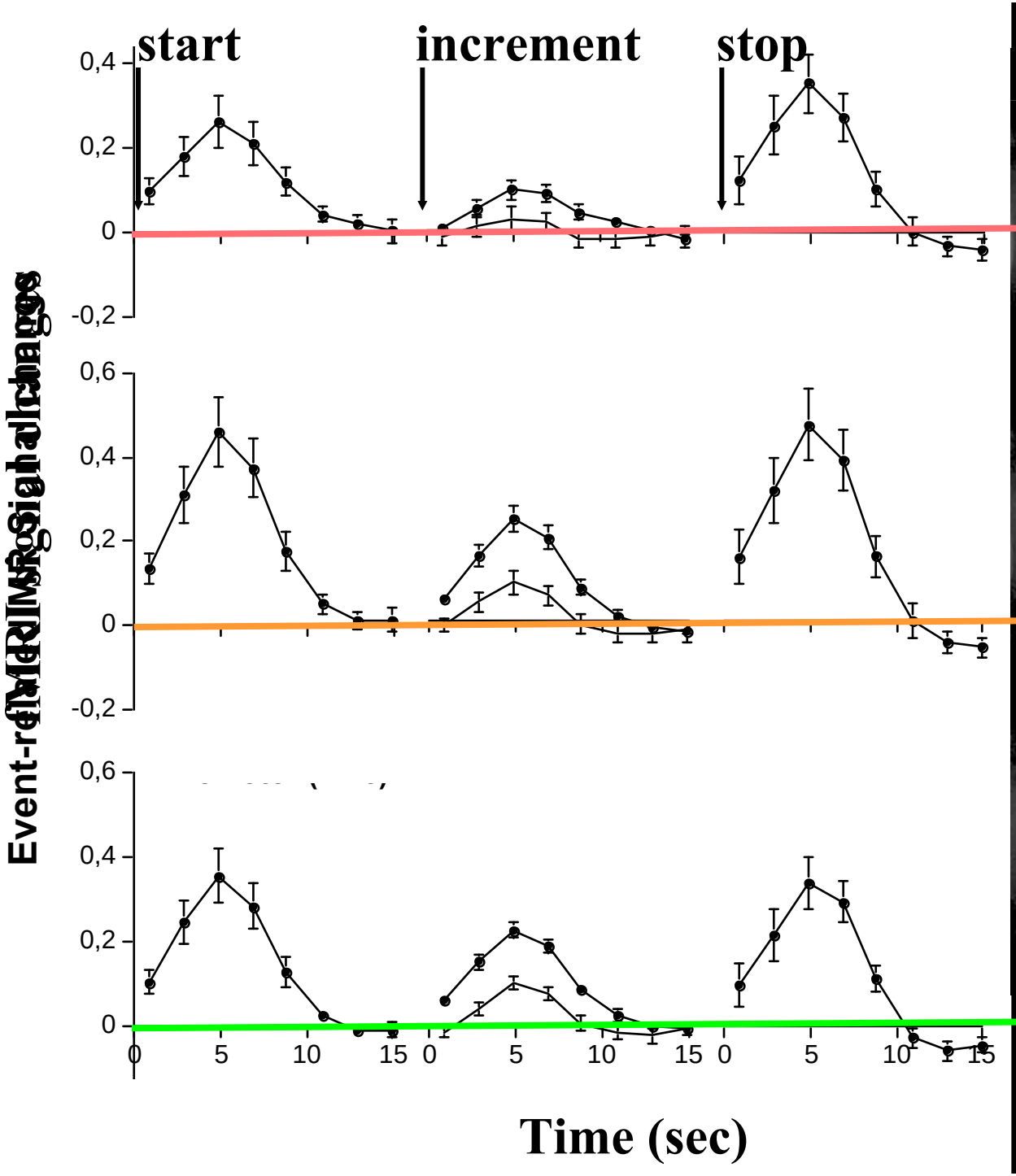


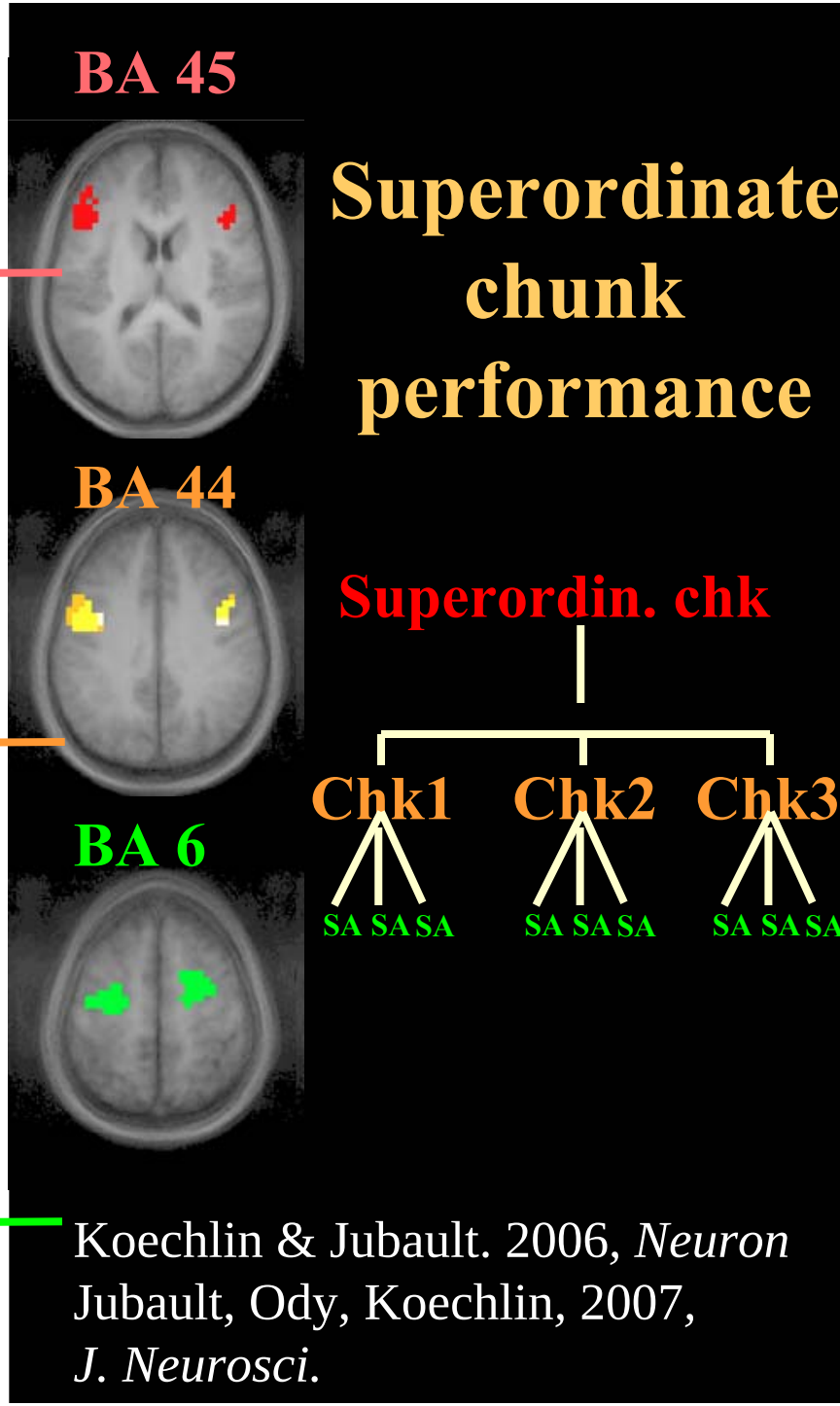
Hierarchical dimensions of cognitive control




start
increment
stop
0,4
0,2
0
-0,2
0,6
0,4
0,2
0
-0,2
0,6
0,4
0,2
0
-0,2
0
5
10
15
Time (sec)


BA 45
BA 44
BA 6
Simple chunk performance
Chunk
A11
A12
A23
Koechlin & Jubault. 2006, Neuron
Jubault, Ody & Koechlin, 2007, J.Neurosci.





Koechlin & Jubault. 2006, *Neuron*
Jubault, Ody, Koechlin, 2007, *J. Neurosci.*

Summary: cognitive control

- Cognitive control is organized as a cascade of top-down selection processes from posterior to anterior LPFC regions.
- Contextual control is implemented in posterior LPFC
- Episodic control is implemented in anterior PFC
- Both contextual and episodic control are further fractionable into two control levels.
- Conditional entropy **Q(A/lower level signals)** measures selection demands at each control level.

What drives the engagement of cognitive control in the LPFC ?

Motivation …?

Psychological theory of motivation (Hull, 1943)

Excitatory potential of action *i*

$$E_i = P_i \times D$$

P_i: Frequency of action *i*

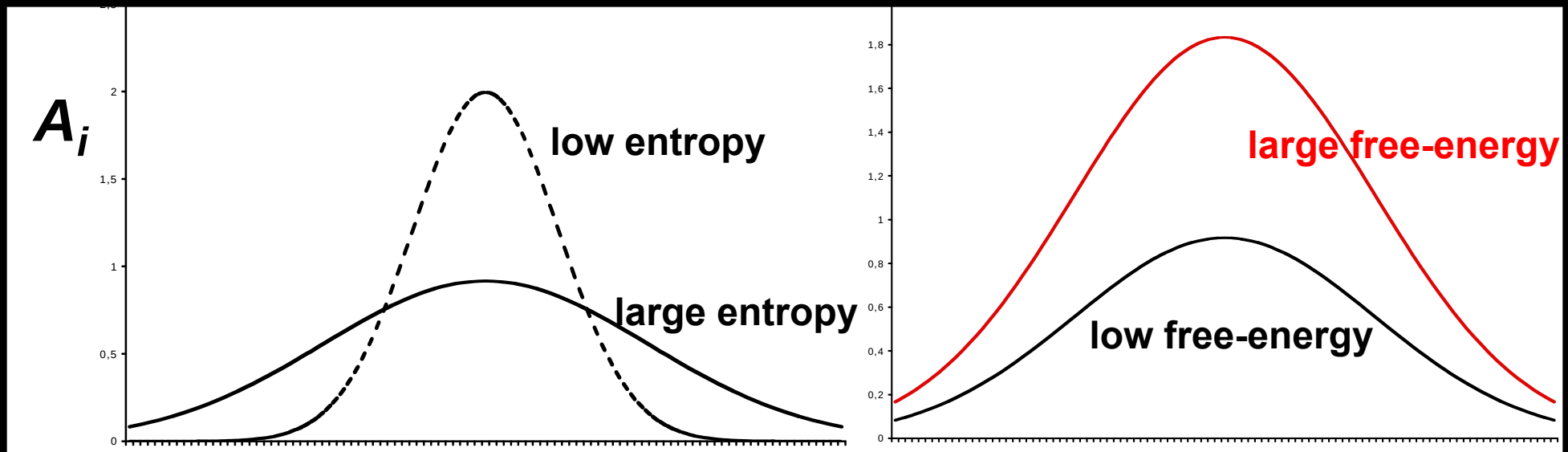
D: Global incentive factor

Motivation has ambiguous effects on action selection: beneficial or detrimental

Cognitive vs. Motivational

Selective information
Conditional entropy
(Koechlin et al., 2003)

Incentive values
Free-energy
(Friston et al., 2007)



Distribution of neuronal activity over alternative options

$$\text{Entropy} = -\sum \frac{A_i}{\sum A_j} \log \frac{A_i}{\sum A_j}$$

$$\text{Free-energy} = \log \sum A_j$$

Statistical Physics of executive function

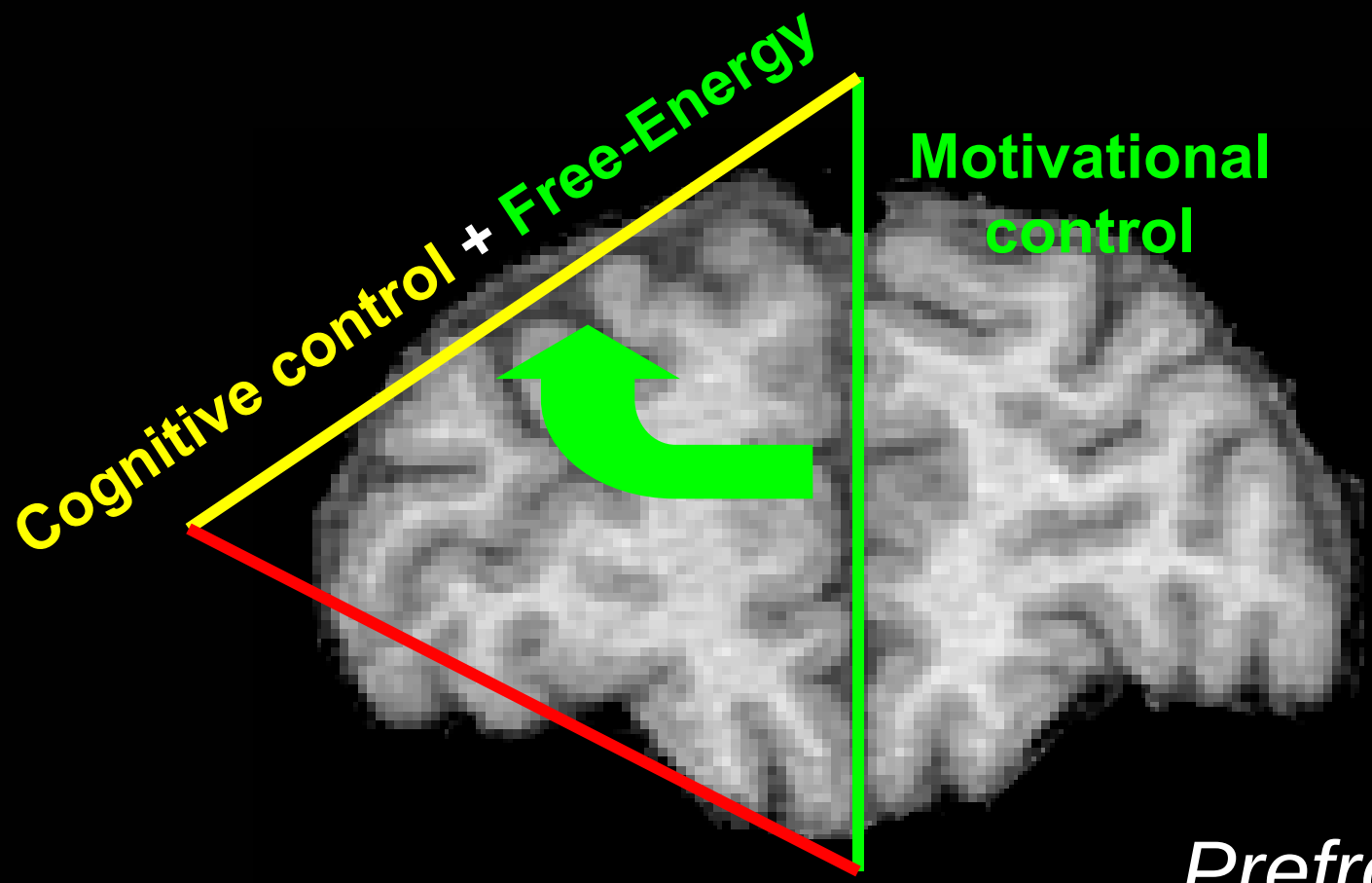
$$\textit{Total Energy} = \textit{Entropy} + \textit{Free-Energy}$$

Lateral prefrontal activations

Cognitive control demands

Motivational control

Hypothesis:
The medial PFC subserves motivational control



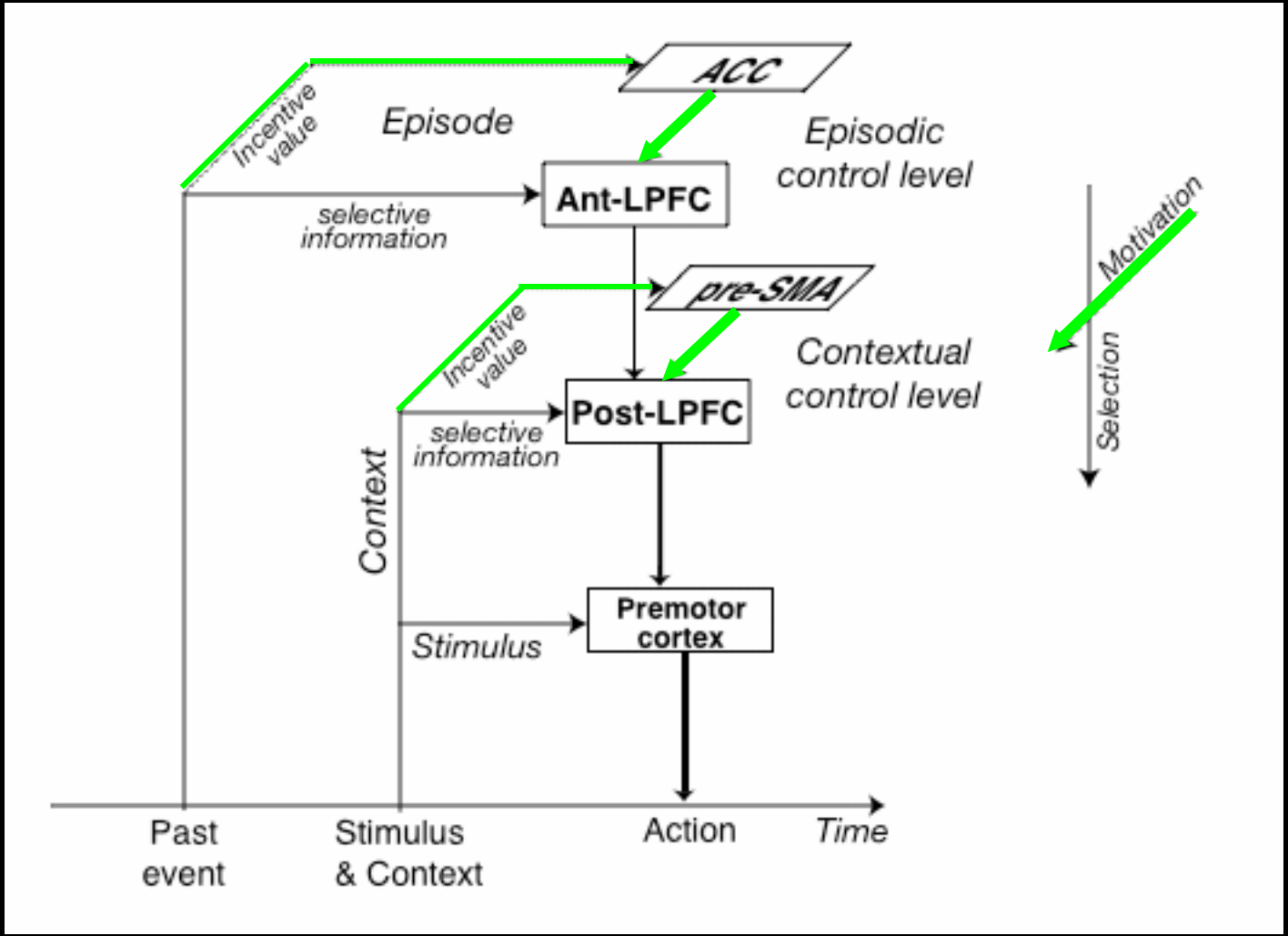
Prefrontal cortex
Coronal section

Hypotheses

- Medial PFC regulate the engagement (i.e. free-energy) of lateral PFC regions in cognitive control *according to rewards/penalty at stake in action*, *independently of control demands* (i.e. conditional entropy).

- The organization of motivation in the medial PFC parallels the architecture of cognitive control in the lateral PFC: To each cognitive control level corresponds a medial region modulating its free-energy

The dual model

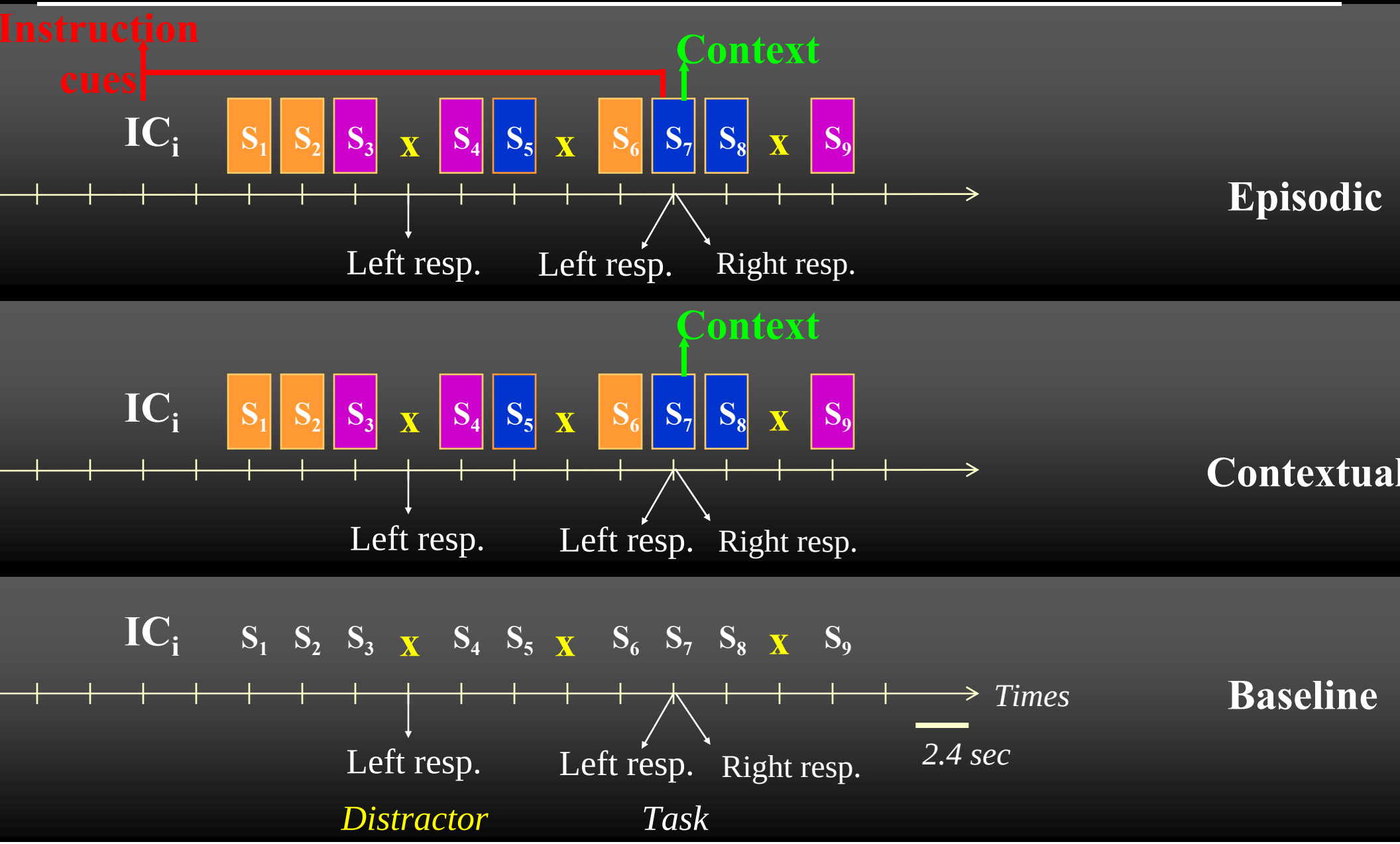


Kouneiher, Charron, Koechlin, *2009*, *Nature Neurosci.*

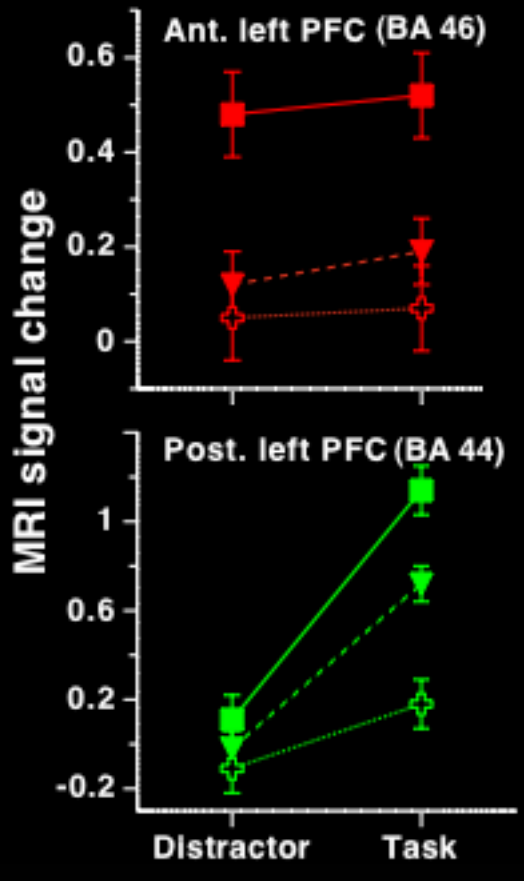
Predictions

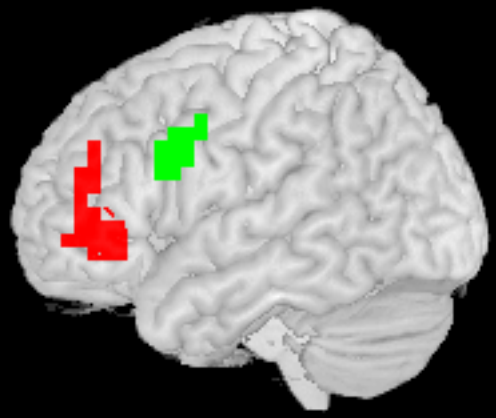
- Pre-SMA exhibits transient activations varying as the reward/penalty at stake in immediate action (contextual motivation).
- dACC exhibits sustained activations representing the reward/penalty at stake in subsequent action (episodic motivation).
- Interactions from medial to lateral PFC regions convey contextual and episodic motivation values.
- Post-LPFC activations show additive effects of contextual motivation and control, whereas anterior LPFC activations show additive effects of episodic motivation and control.
- top-down interactions from anterior to posterior LPFC reflect episodic control and motivation

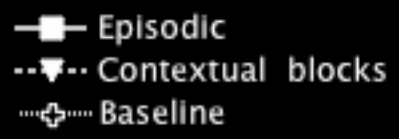
Experimental Protocol: cognitive factors

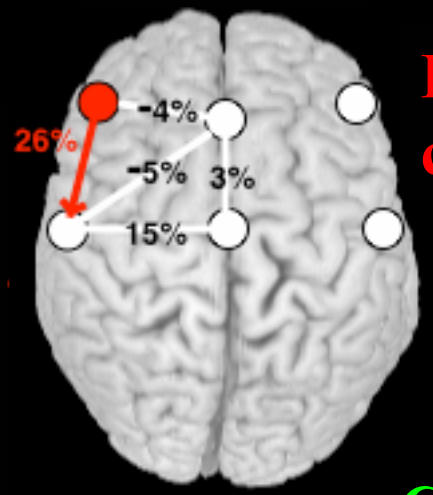


Contextual vs. Episodic control



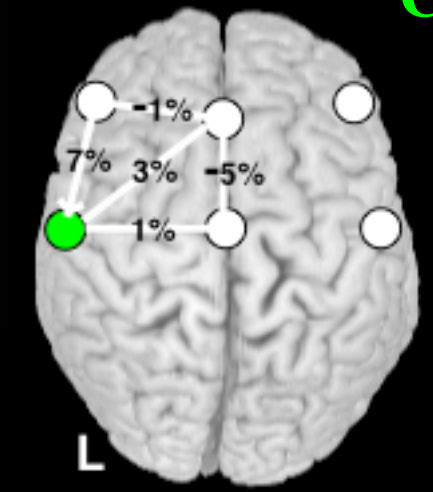


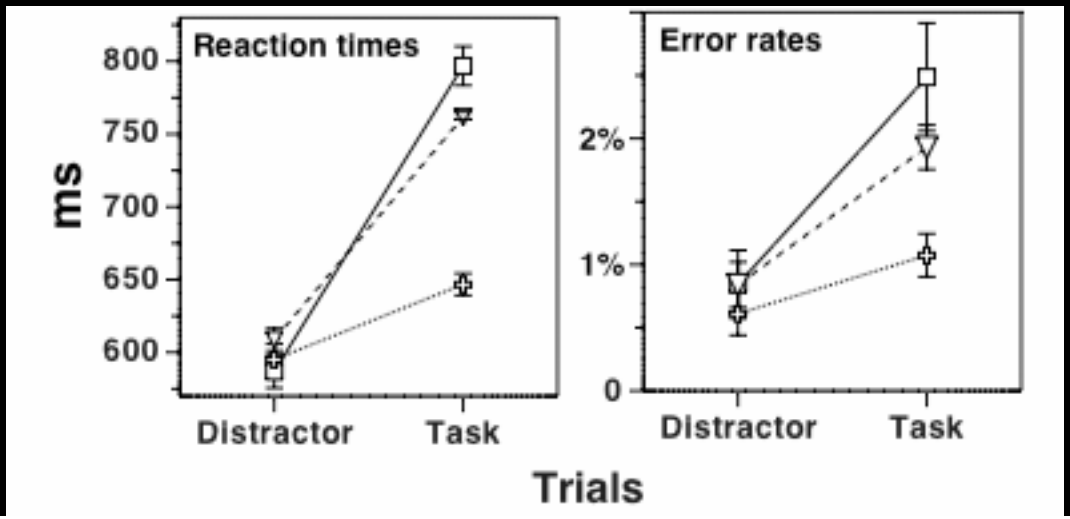




Episodic control

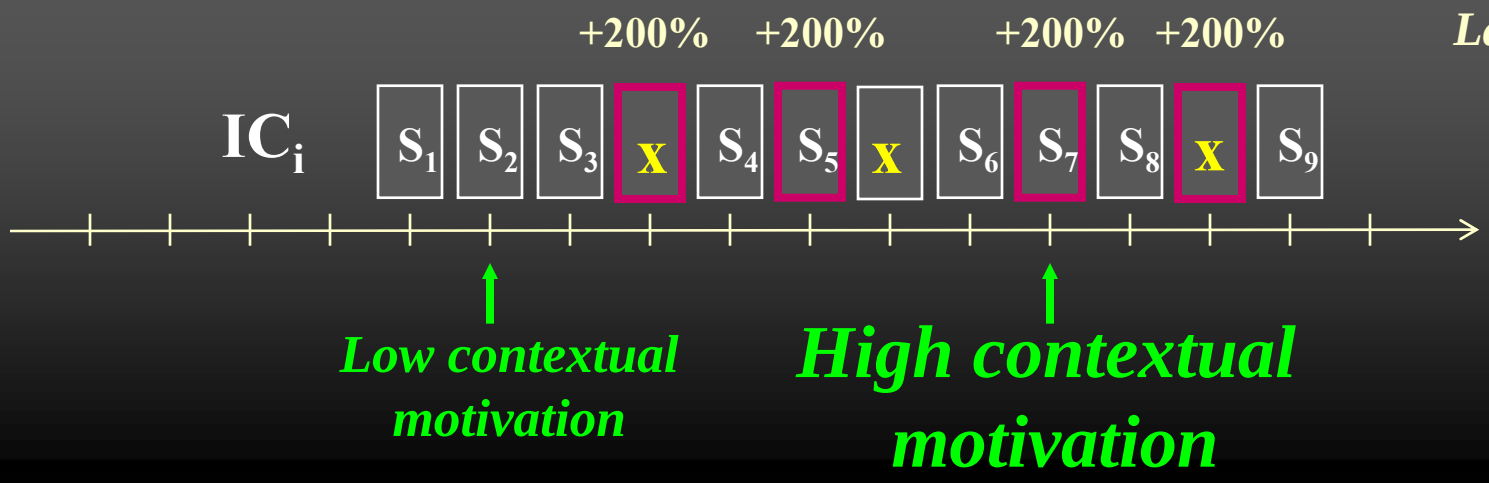
Contextual control

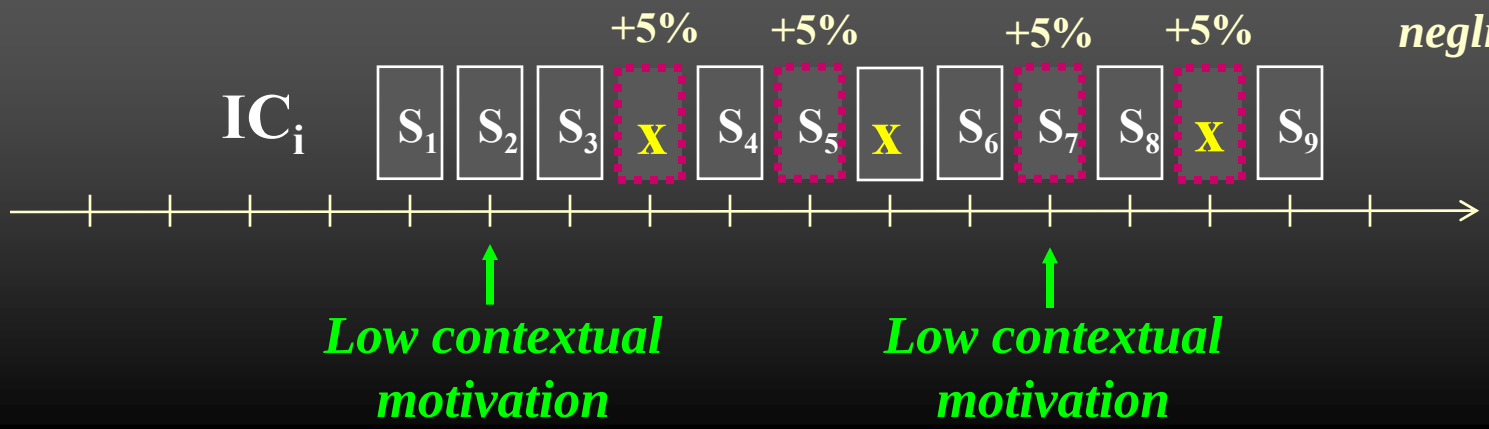




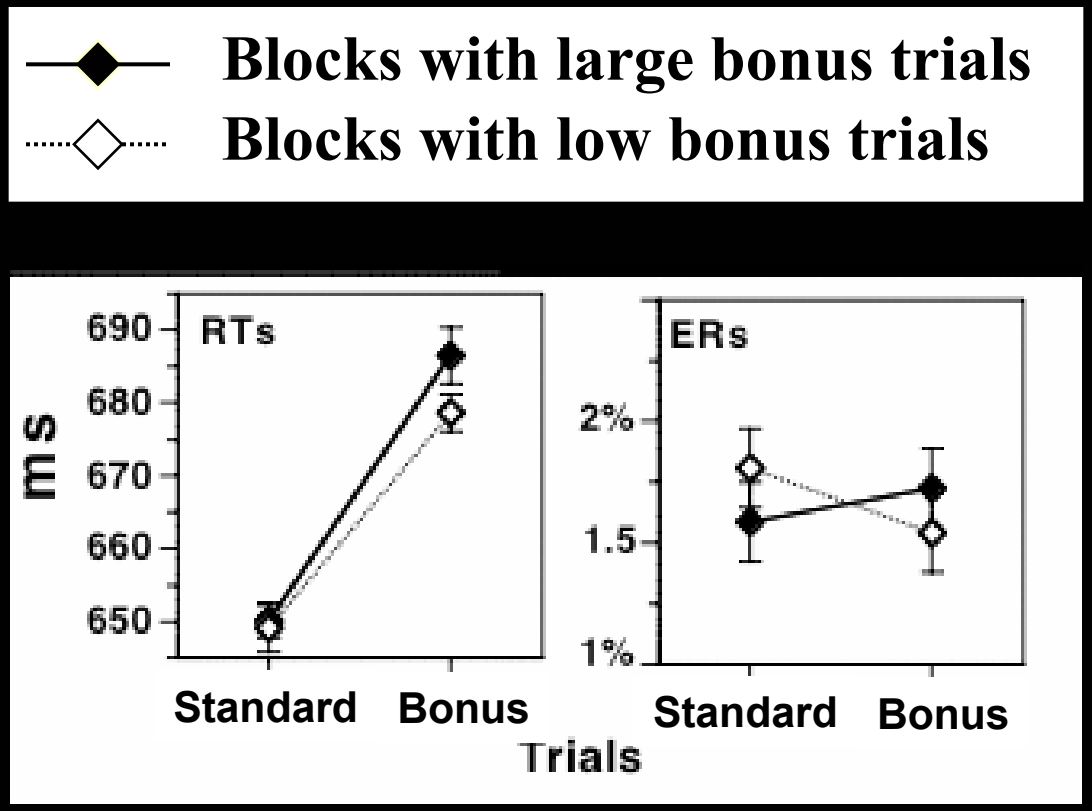
Kouneiher, Charron, Koechlin, *Nature Neurosci.*, *2009*

Experimental Protocol: contextual motivation





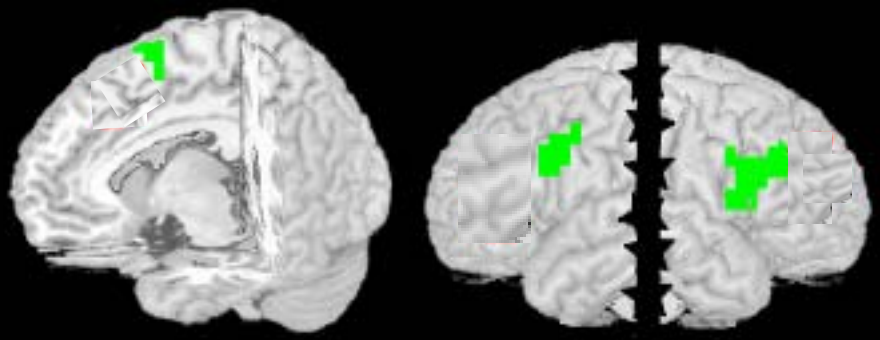
Behavioral performances

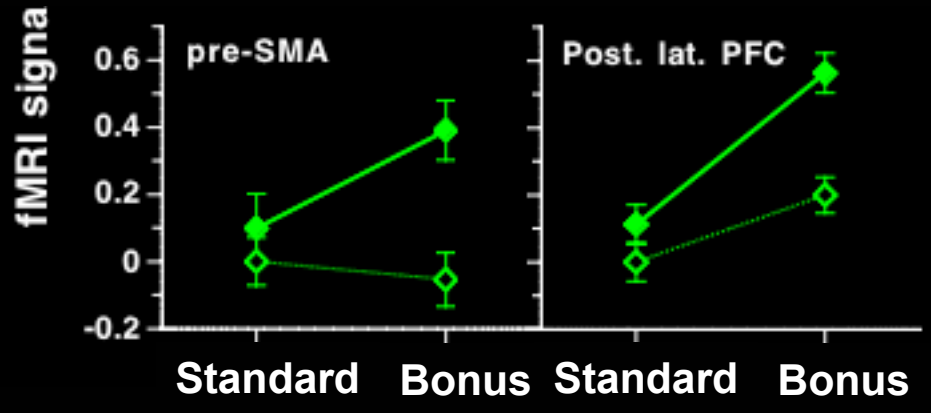


Kouneiher, Charron, Koechlin, *Nature Neurosci., 2009*

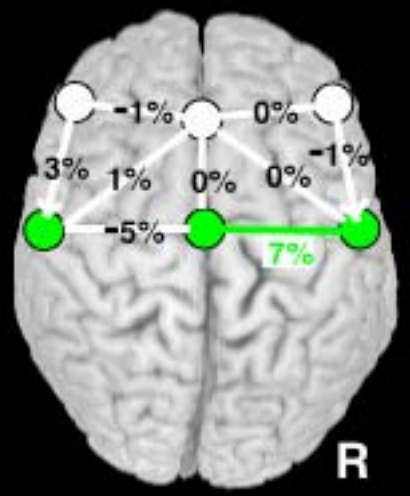
Contextual motivation: fMRI data

Medial **Lateral**





Effective connectivity

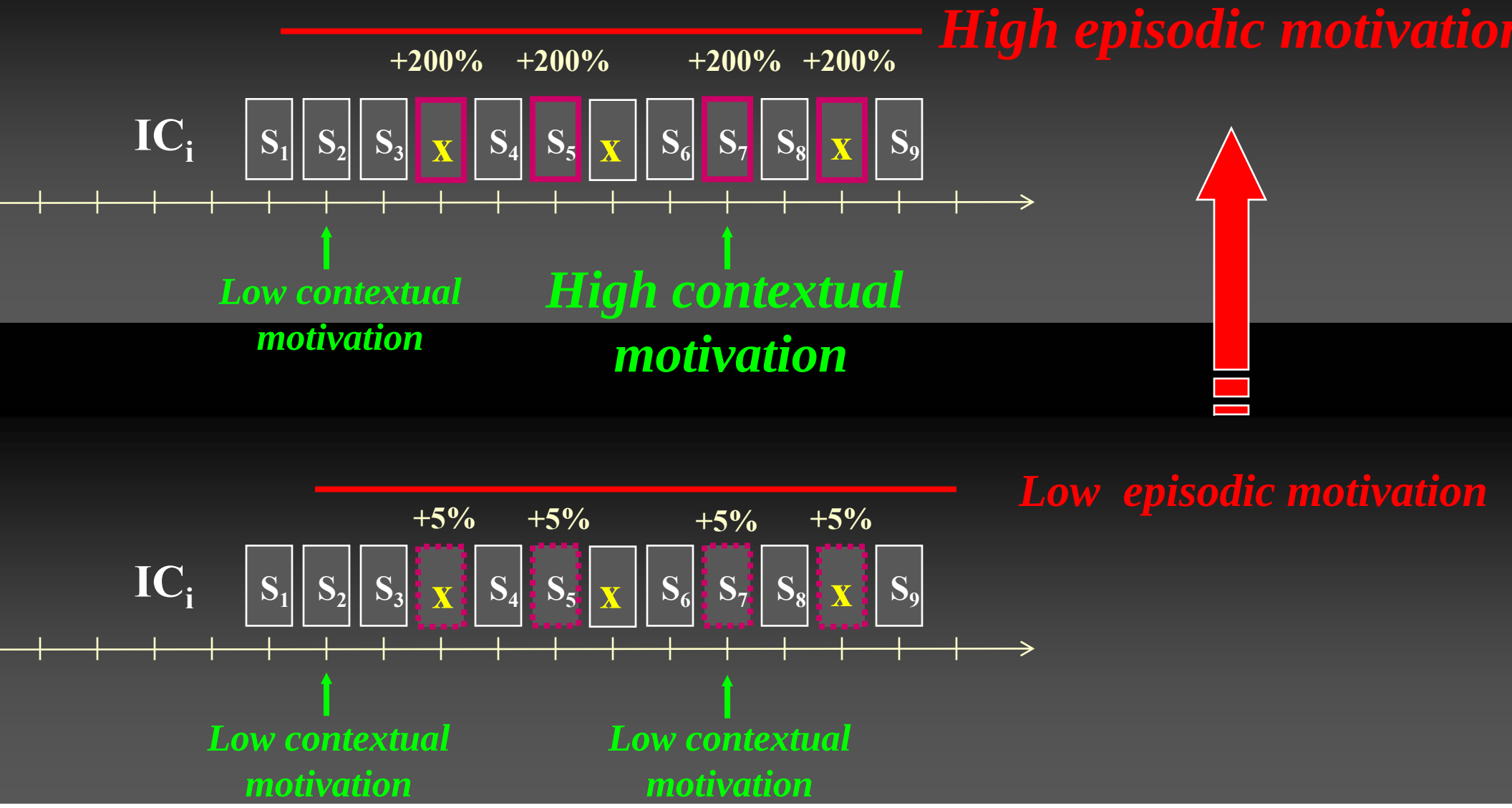


Blocks with large bonus trials

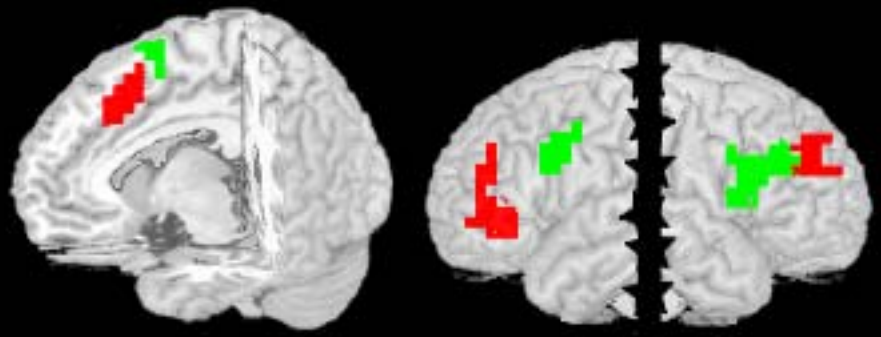
Blocks with low bonus trials

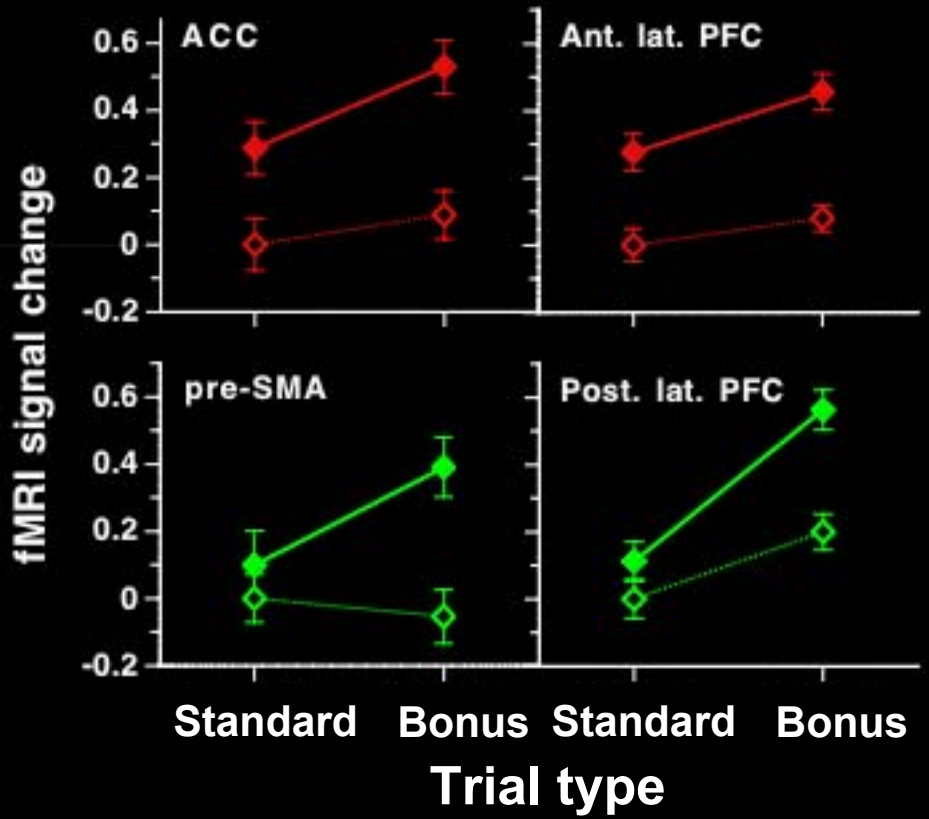
Kouneiher, Charron & Koechlin, *Naturre Neurosci. 2009*

Experimental Protocol: episodic motivation



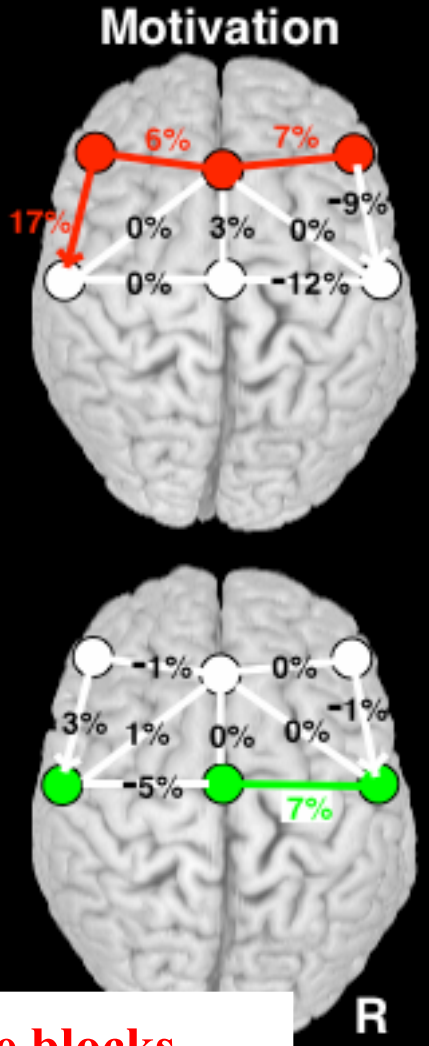
fMRI data: Episodic motivation





Episodic motivation

Contextual motivation

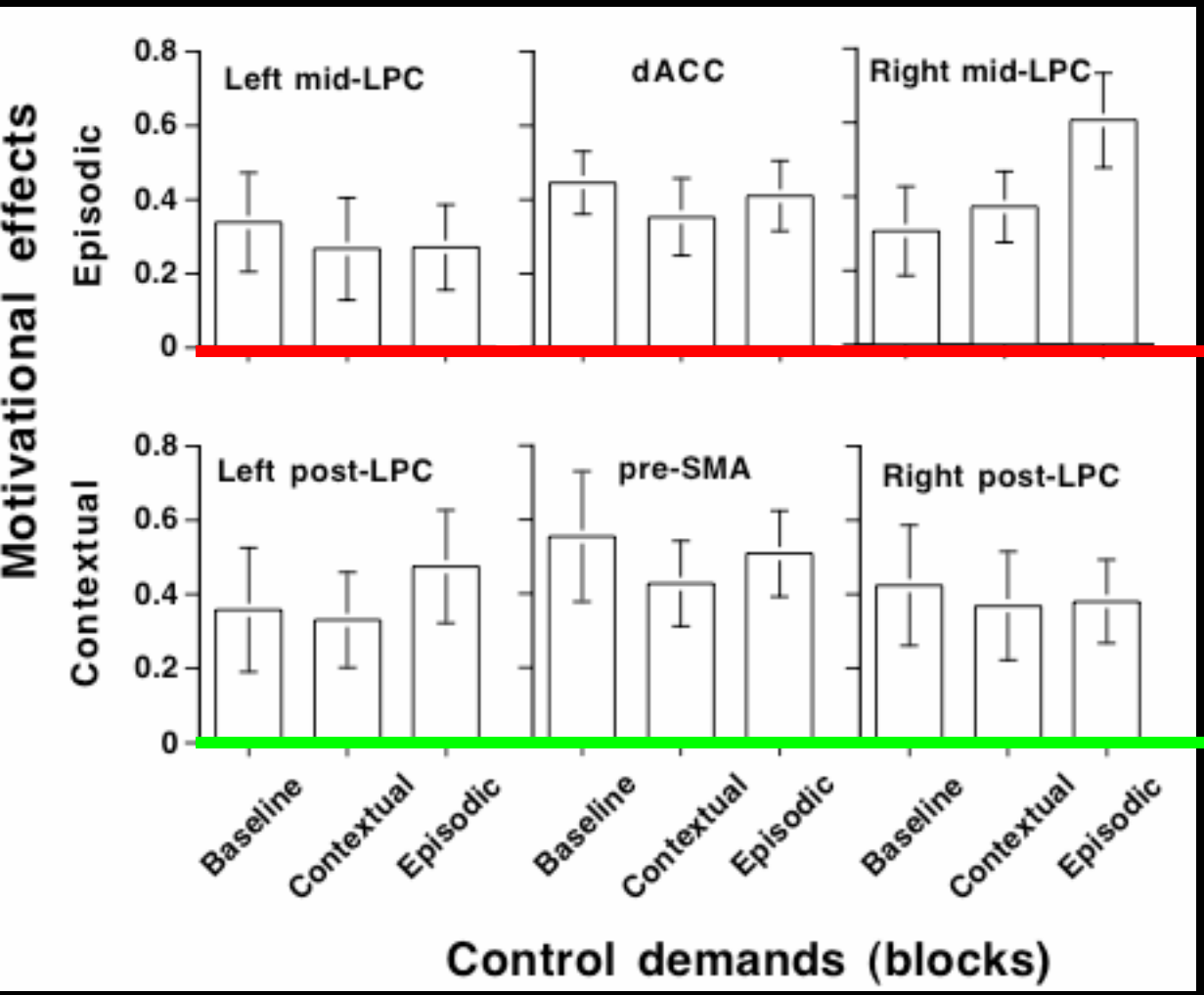


High incentive blocks

Low incentive blocks

Kouneiher, Charron, Koechlin, *Nature Neurosci.*, *2009*

Control + Motivation

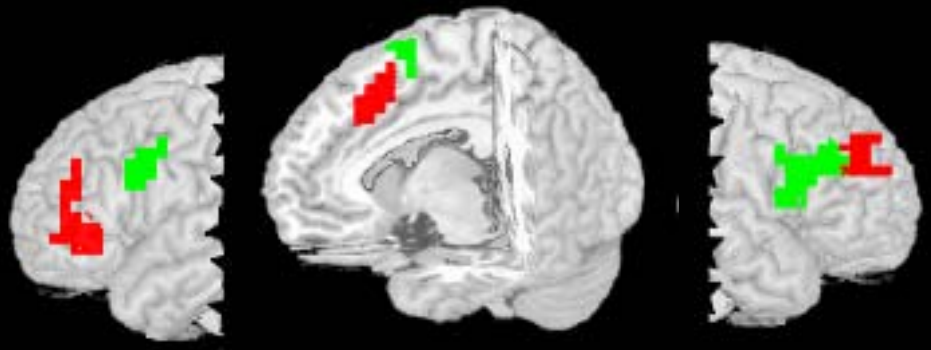


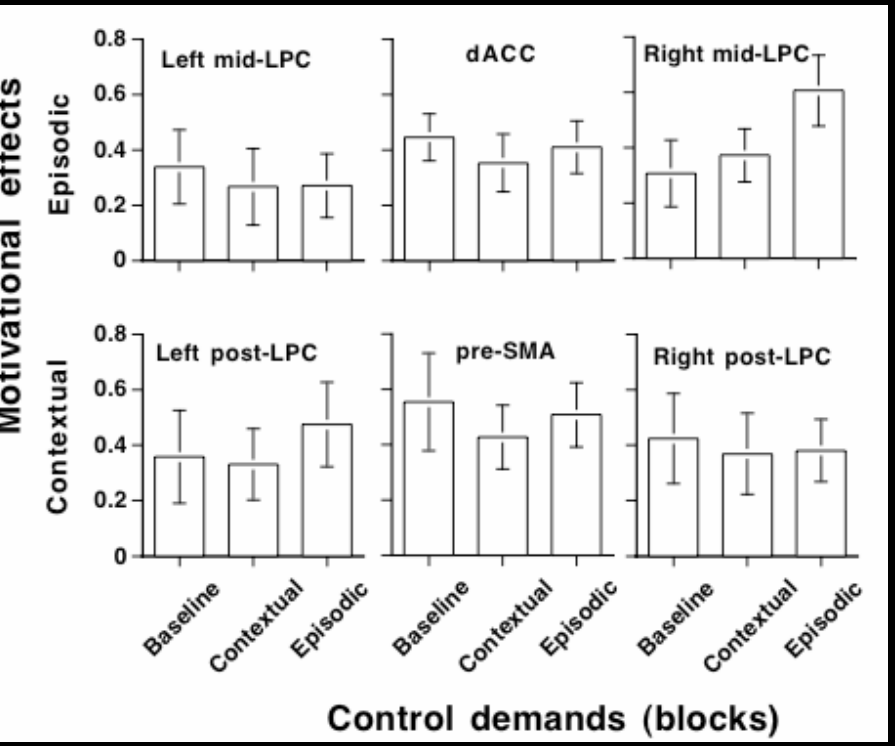
Episodic motivation (sustained effect)

Contextual motivation (transient effect)

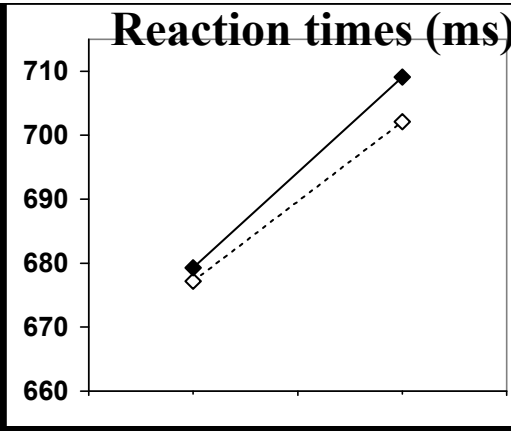
Kouneiher, Charron, Koechlin, *Nature Neuro 2009*

Control + Motivation

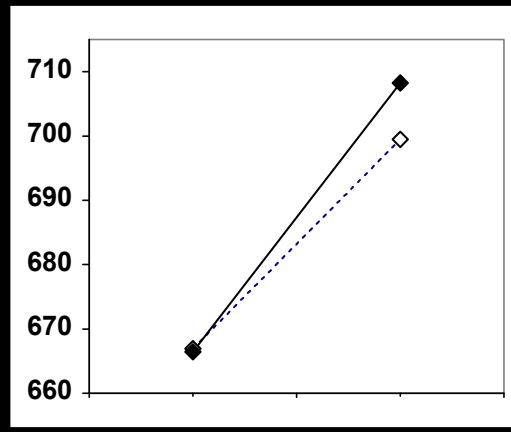




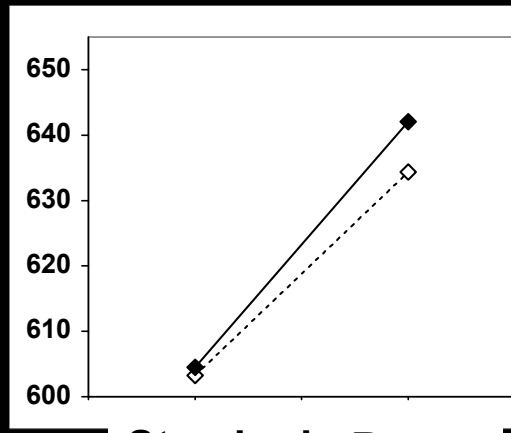
Episodic blocks



Contextual blocks



Baseline blocks



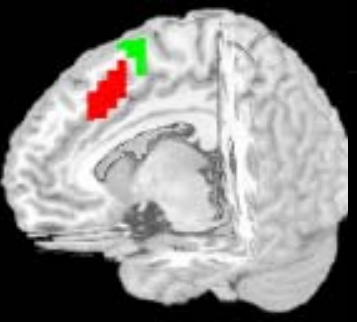
Blocks with large bonus trials

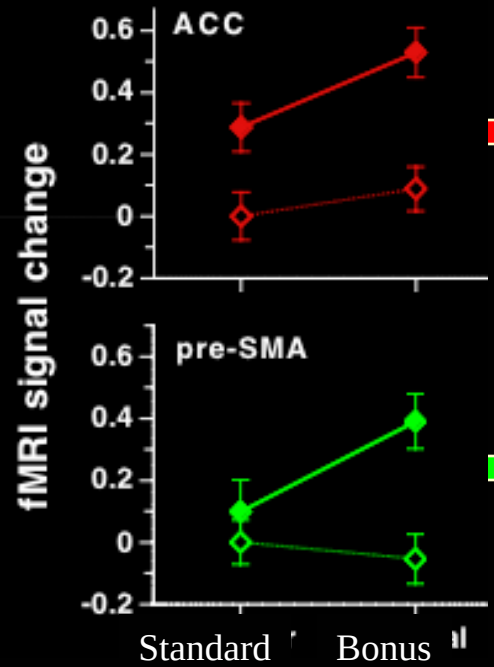
Blocks with low bonus trials

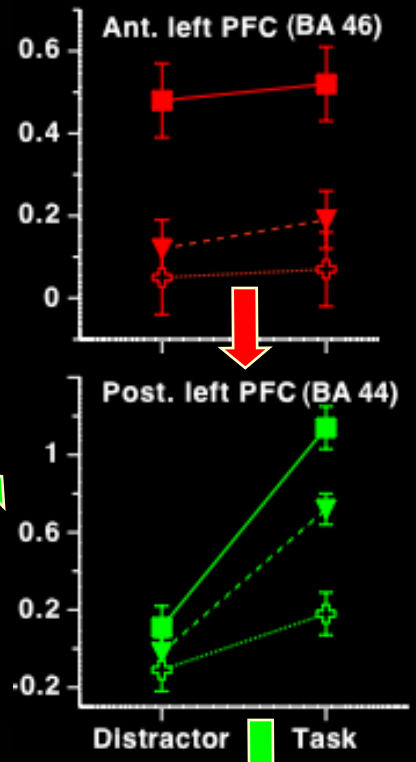
Standard Bonus

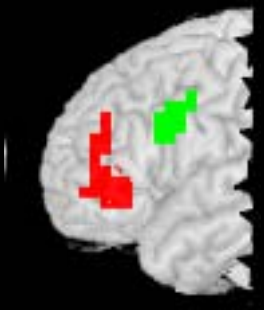
Trials

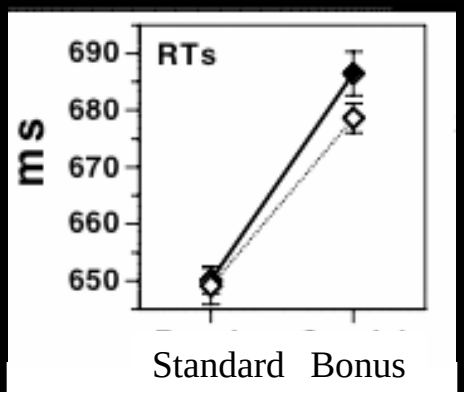
Motivation and control in the PFC

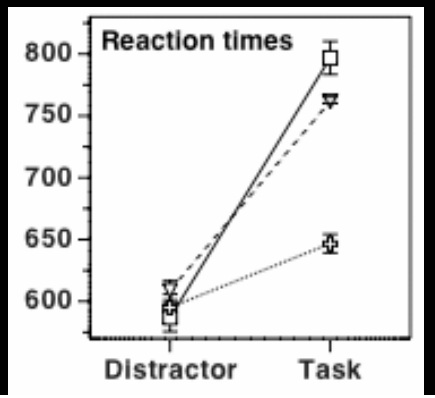












To conclude…

- The prefrontal executive function is organized as two parallel, hierarchical systems from posterior to anterior regions in the medial and lateral PFC .

- Post- and mid- lateral PFC select action sets according to immediate contextual signals (contextual control) and temporally remote events (episodic control) respectively, operating through a cascade of top-down interactions towards premotor cortex.

- Post- and mid-. medial PFC evaluate immediate contextual incentives and temporally remote incentives for weighting through medial-to-lateral interactions the involvment of contextual and episodic control, respectively.

- The dichotomy between control and motivation in prefrontal executive function is captured by the basic distinction between the concept of entropy and free-energy in population of neurons.

- Motivation enhances prefrontal control rather than improving selection!