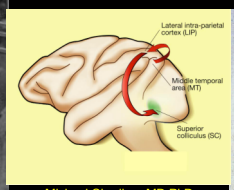
A Neural Mechanism for Decision Making

K C Y W D K D O P E D B A I Q S D F M K C N F A E Q I E N C V N S
E N C H P D N C O E N A S H Q E N D N C K R N D N Q I O M Z C P Q



Michael Shadlen, MD PhD

Computational Neuroscience
CSE/NB 528
April 19, 2007

www.shadlen.org

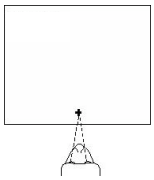
Outline

- The neural mechanism of a simple perceptual decision
- Combining probabilistic information: reasoning

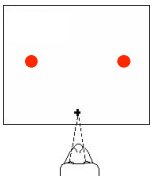
What is a decision?

- A commitment to a proposition or plan of action/behavior
  - Based on evidence, prior knowledge, payoff, urgency

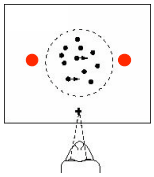
Direction-Discrimination Task
Reaction-time version

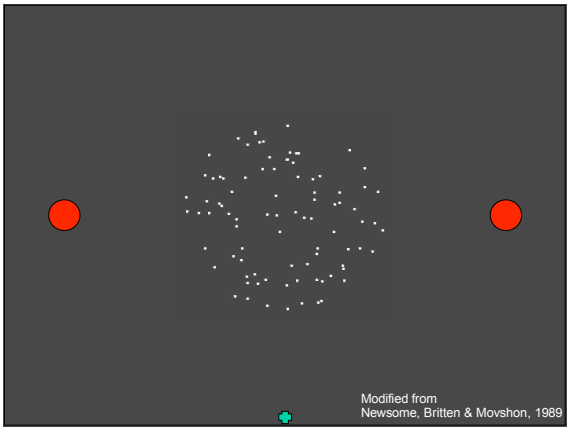


Direction-Discrimination Task
Reaction-time version

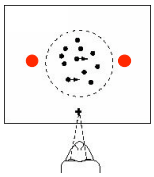


Direction-Discrimination Task
Reaction-time version



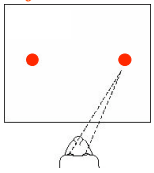


Direction-Discrimination Task
Reaction-time version

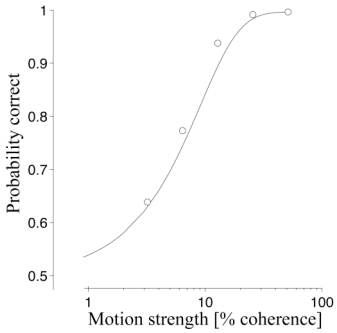


Direction-Discrimination Task
Reaction-time version

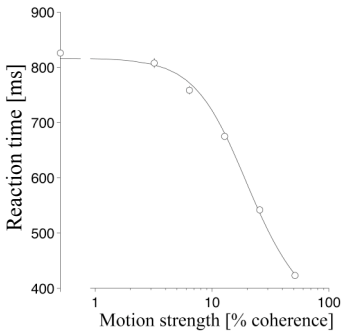
Reward for correct choice

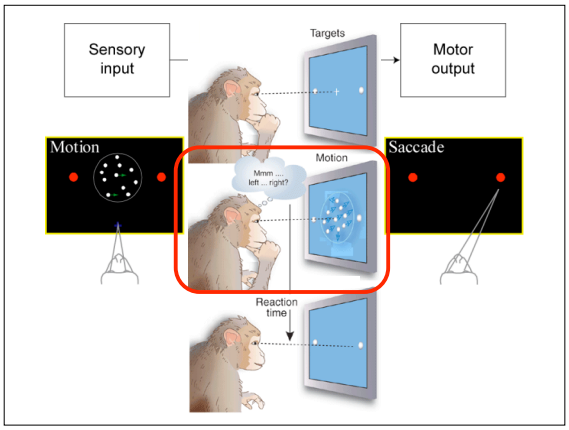


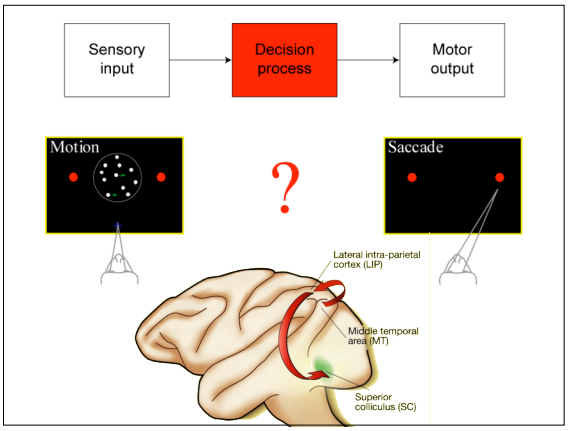
Psychometric function: Accuracy

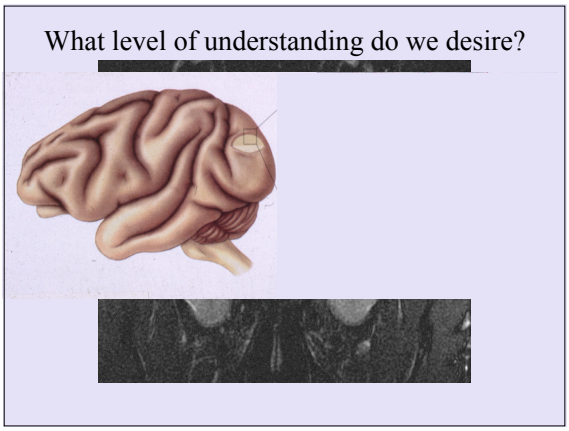


Chronometric function: Speed

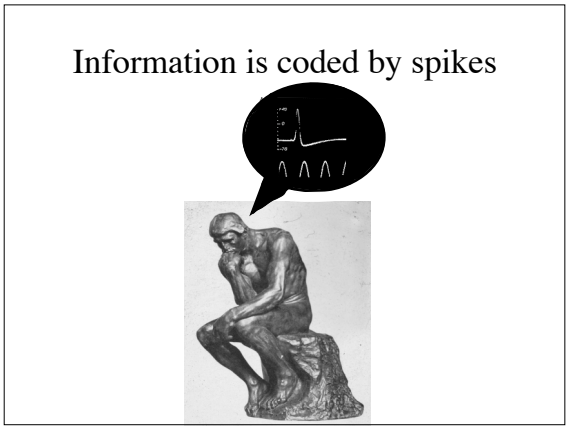


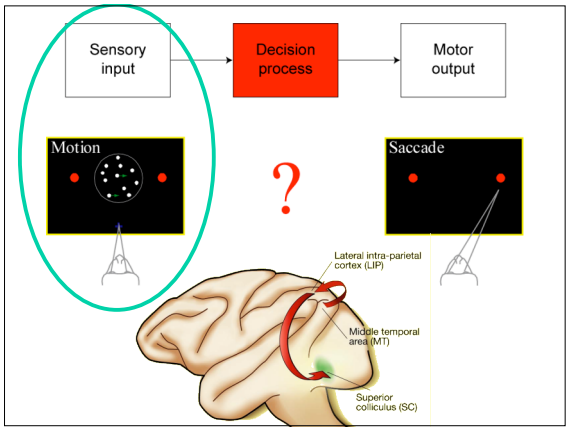

Sensory input
Targets
Motor output
Motion
Saccade
Motion
Mmm ... left ... right?
Reaction time


Sensory input
Decision process
Motor output
Motion
?
Saccade
Lateral intra-parietal cortex (LIP)
Middle temporal area (MT)
Superior colliculus (SC)


What level of understanding do we desire?

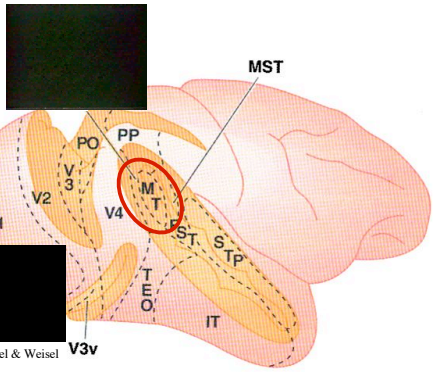

What level of understanding do we desire?
Hubel, 1988 "Eye, brain and vision"


Information is coded by spikes


Sensory input
Decision process
Motor output
Motion
?
Saccade
Lateral intra-parietal cortex (LIP)
Middle temporal area (MT)
Superior colliculus (SC)

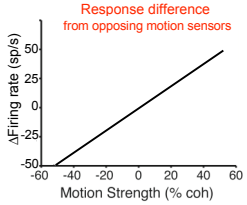
Sensory "Evidence"

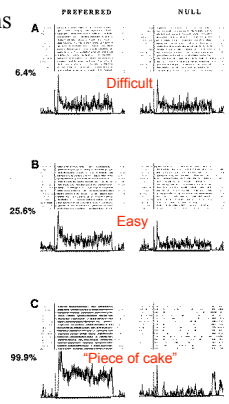
Celebrini & Newsome



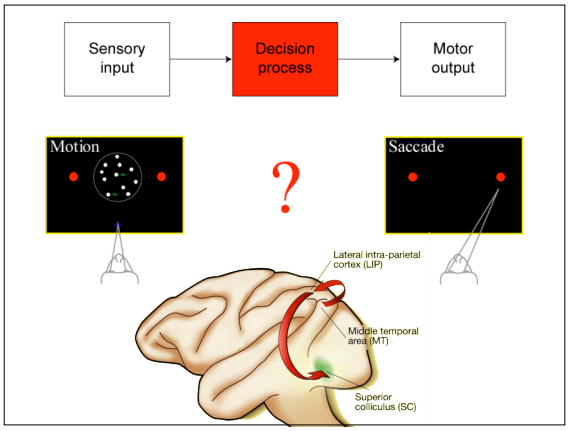
Courtesy Hubel & Weisel

Response of MT neurons to random dot motion

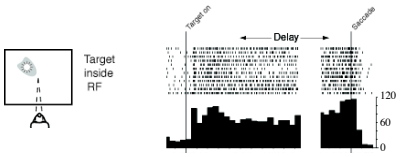




(Britten et al., 1993)

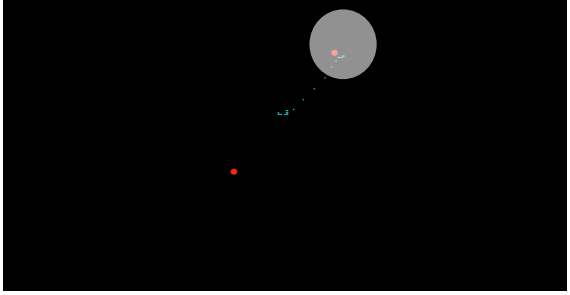


Spatially-selective, eye movement-related, persistent activity in area LIP



100 ms

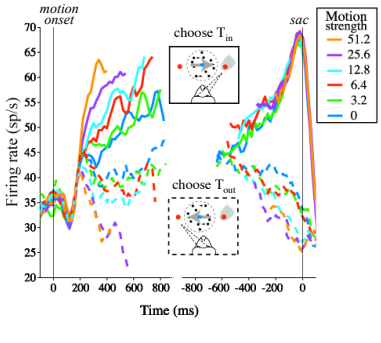
LIP activity during direction discrimination task



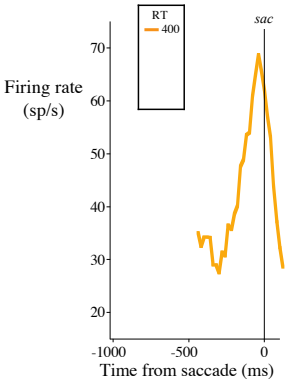
LIP activity during direction discrimination task

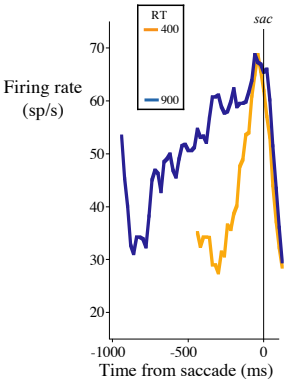
LIP activity during direction discrimination task

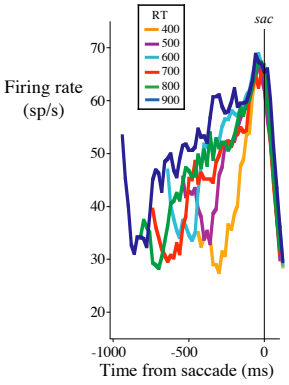
Average LIP activity in RT motion task



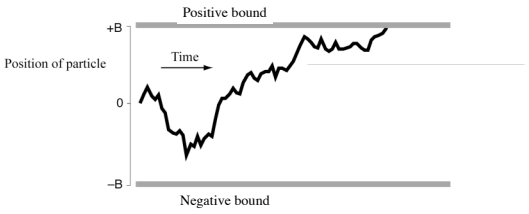
Roitman & Shadlen, 2002 J. Neurosci.



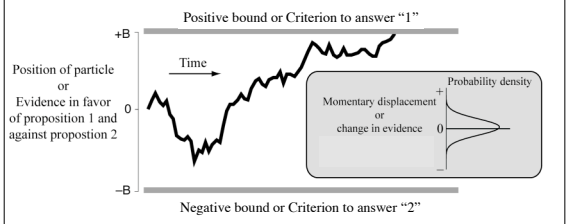




Diffusion to bound model

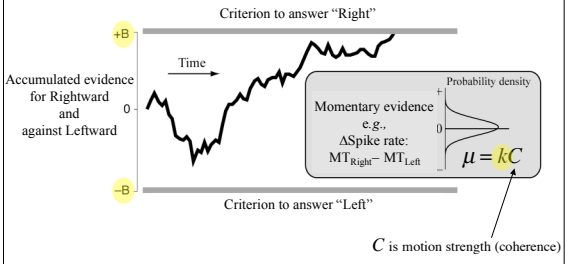


Diffusion to bound model



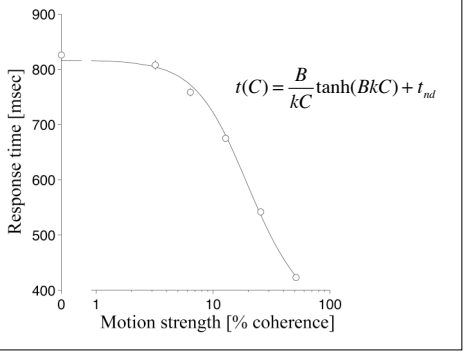
Proposed by Wald, 1947 and Turing (WW II, classified);
Stone, 1960; then Laming, Link, Ratcliff, Smith, . . .

Diffusion to bound model

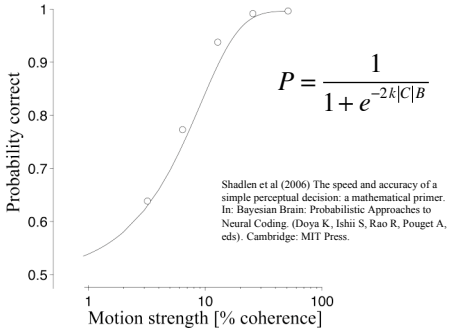


Palmer et al (2005)
Shadlen et al (2006)

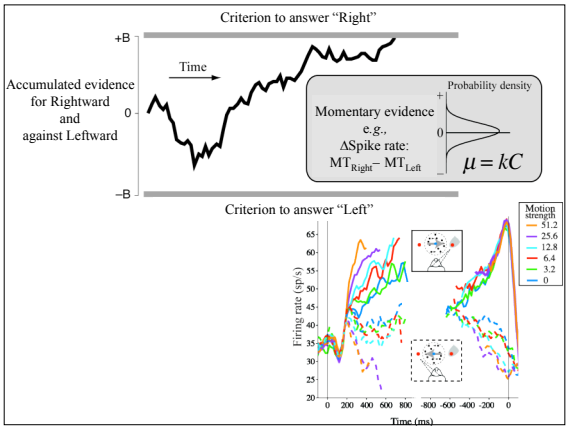
Best fitting chronometric function "Diffusion to bound"

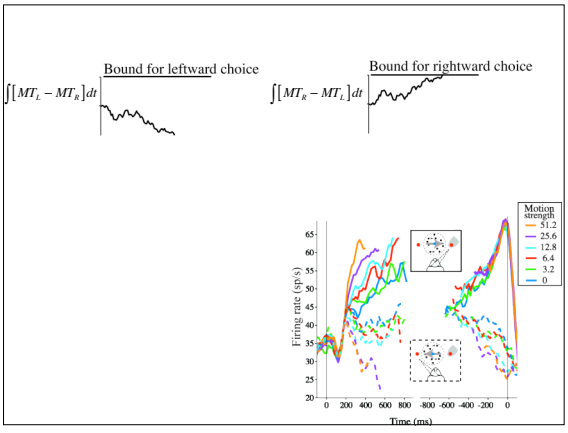


Predicted psychometric function "Diffusion to bound"

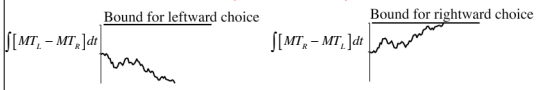


Shadlen et al (2006) The speed and accuracy of a simple perceptual decision: a mathematical primer. In: Bayesian Brain: Probabilistic Approaches to Neural Coding. (Doya K, Ishii S, Rao R, Pouget A, eds). Cambridge: MIT Press.

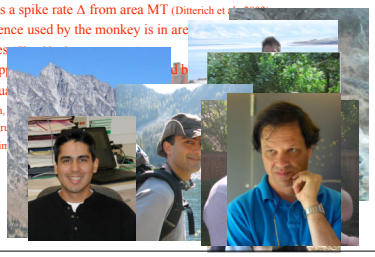




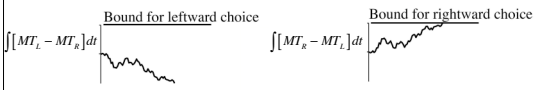
What we (think we) know…



- LIP represents $\int dt$ of momentary motion evidence (Huk & Shadlen, 2005)
- Momentary evidence is a spike rate Δ from area MT (Ditterich et al., 2003)
- The accumulated evidence used by the monkey is in are
- Extends to N>2 choices
- Bound (termination) app
- LIP represents other qu
  - Time (Leon & Shadlen,
  - Value (Newsome, Sugru
  - Prior probability (Glim



Lots we don't know…



- How and where is the integral computed? (Seung, Koulakov, Goldman, …)
- How is the bound set? (XJ Wang, Palmer, Holmes, Cohen)
- How is a bound crossing detected? (Brody, Wang, …)
- How/whether mechanism extends to other tasks:
  - *e.g.*, when *t* uncertain (Cook, Maunsell)

Sequential analysis (Wald)
Banburismus (Turing)

Good IJ. Studies in the history of probability and statistics. XXXVII A.M. Turing's statistical work in World War II. Biometrika 66:393-396, 1979

Gold & Shadlen. Neuron 36:299-308, 2002

Turing's strategy: sequential analysis

Weight of evidence in favor of common rotor setting $=$ match

Hypothesis: *Messages encrypted by Enigma devices in same state*

K C Y W D K D O P E D B A I Q S D F M K C N F A E O I E N C V N S D F N
E N C H P D N C O E N A S H Q E N D N C K R N D N Q I O M Z F J K C P Q

Turing's strategy: sequential analysis

Weight of evidence in favor of common rotor setting $=$

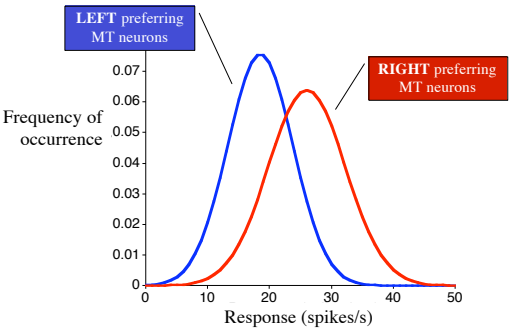
$$10 \log_{10}\left[\frac{\left(\frac{1}{13}\right)}{\left(\frac{1}{26}\right)}\right] = +3.0\ db \quad \text{match}$$

$$10 \log_{10}\left[\frac{\left(\frac{12}{13}\right)}{\left(\frac{25}{26}\right)}\right] = -0.17\ db \quad \text{non-match}$$

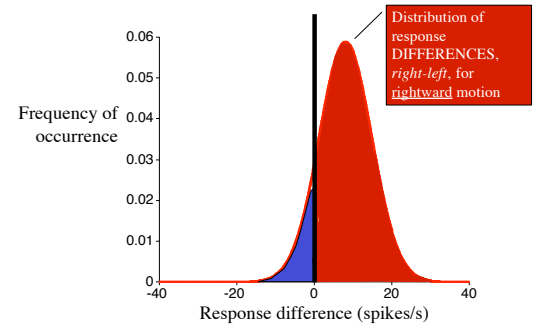
K C Y W D K D O P E D B A I Q S D F M K C N F A E O I E N C V N S D F N
E N C H P D N C O E N A S H Q E N D N C K R N D N Q I O M Z F J K C P Q

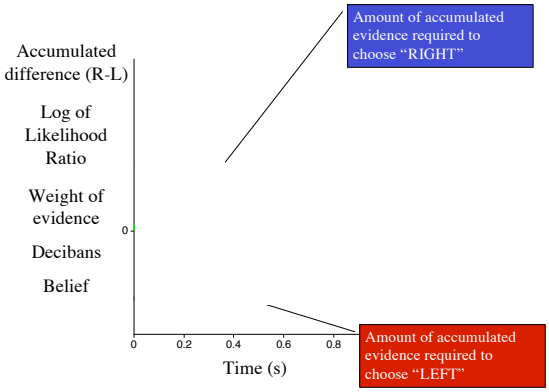
Weight of evidence in favor of common settings (decibans)

Variable response to weak RIGHTWARD motion



Difference in *spike rate* is proportional to the *logarithm of the likelihood ratio*

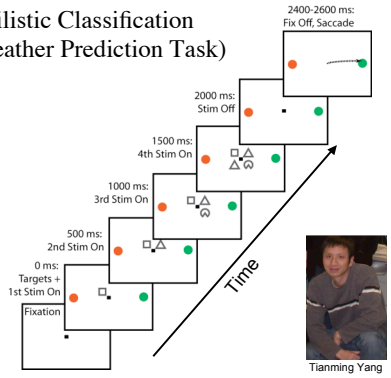


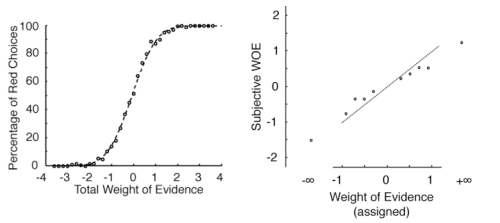


Outline

- A neural mechanism of a simple perceptual decision
- Combining probabilistic information: reasoning

Probabilistic Classification (*a.k.a.*, Weather Prediction Task)



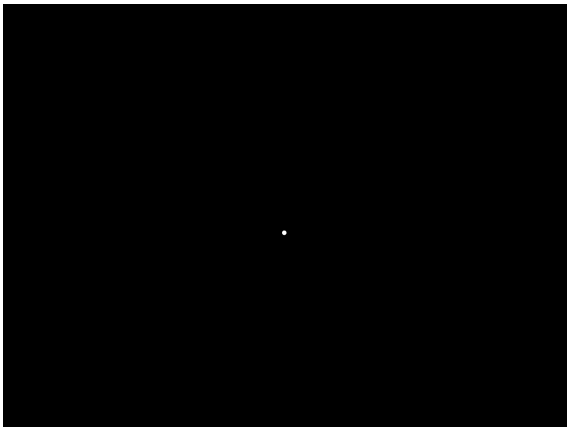


$$z = \log\frac{P(\text{red})}{P(\text{green})} = \beta + \alpha_{\diamond} I_{\diamond} + \alpha_{\triangle} I_{\triangle} + \ldots + \alpha_{\square} I_{\square} + \varepsilon$$

$$P(\text{red}) = \frac{10^{z}}{1+10^{z}}$$

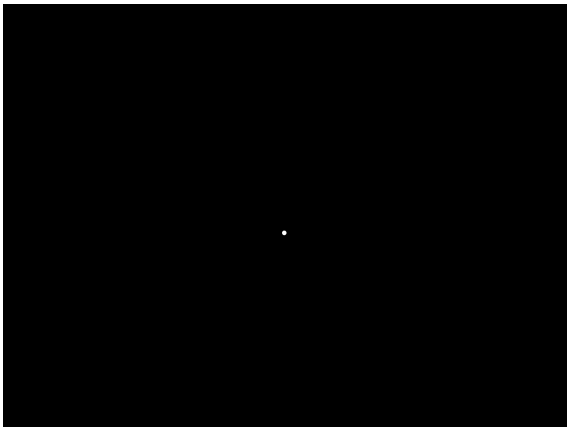
1st shape favors RF target
Next three add evidence for opposite target

Response Field

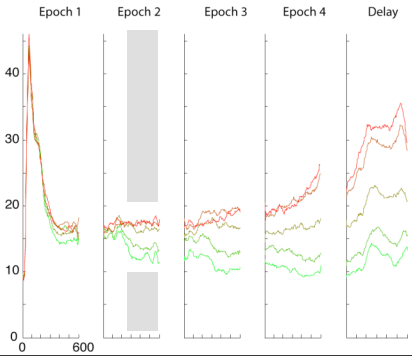


1st shape favors target outside RF
Next two add strong evidence for target in RF
Last shape favors target outside RF

Response Field

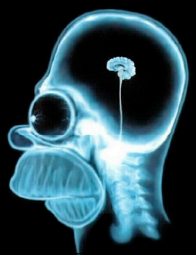


Firing rate is proportional to logLR

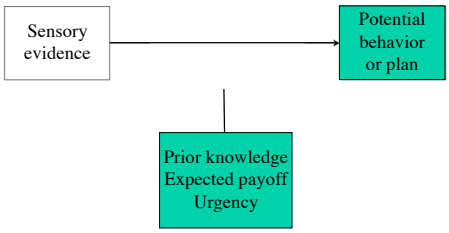


Main points from experiments

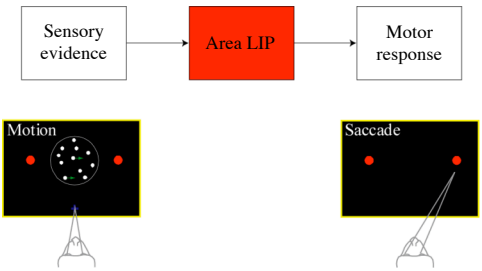
- LIP "interprets" sensory evidence in the way a statistician might
  - Accumulates log probability ⇒ rationality
  - Applies a termination rule ⇒ deliberation & commitment



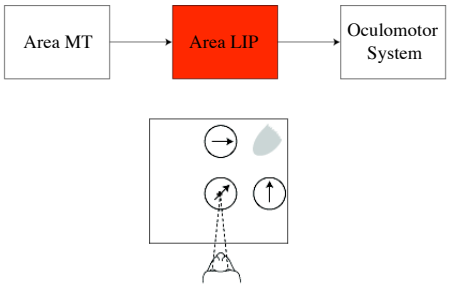
From sensorimotor integration to cognition



From sensorimotor integration to cognition



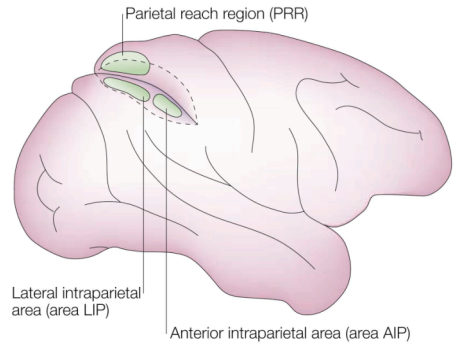
From sensorimotor integration to cognition



"In the gaze we have at our disposal, a natural instrument analogous to the blind man, the gaze gets more or less from things according to the way in which it questions them, ranges over, or dwells on them."

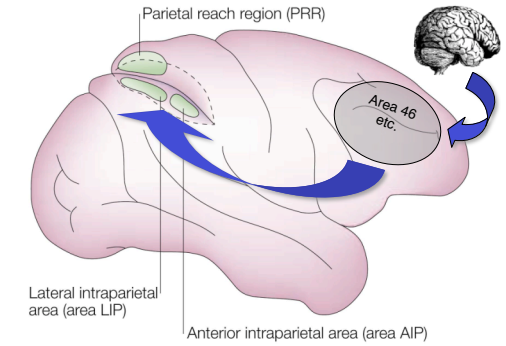
Merleau-Ponty, Phenomenology of Perception.

From sensorimotor integration to cognition

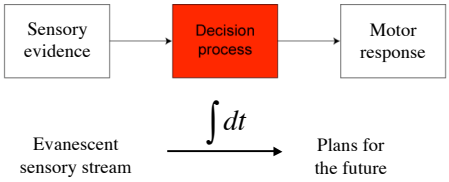


from Richard Andersen

From sensorimotor integration to cognition



From sensorimotor integration to cognition



Leaky integration ⇨ confusion

Summary

- It is possible to study decision-making at the neuronal level
- Neurons in association cortex combine evidence…
  - rationally (*e.g.*, adding log P)
  - intentionally (*e.g.*, in the context of a goal or action)
  - terminably (*e.g.*, with an eye for time and long term goals)
- Permits behavior on a flexible time frame
  - The basis of all higher brain function
  - A key to future treatments of neurological & psychiatric disease