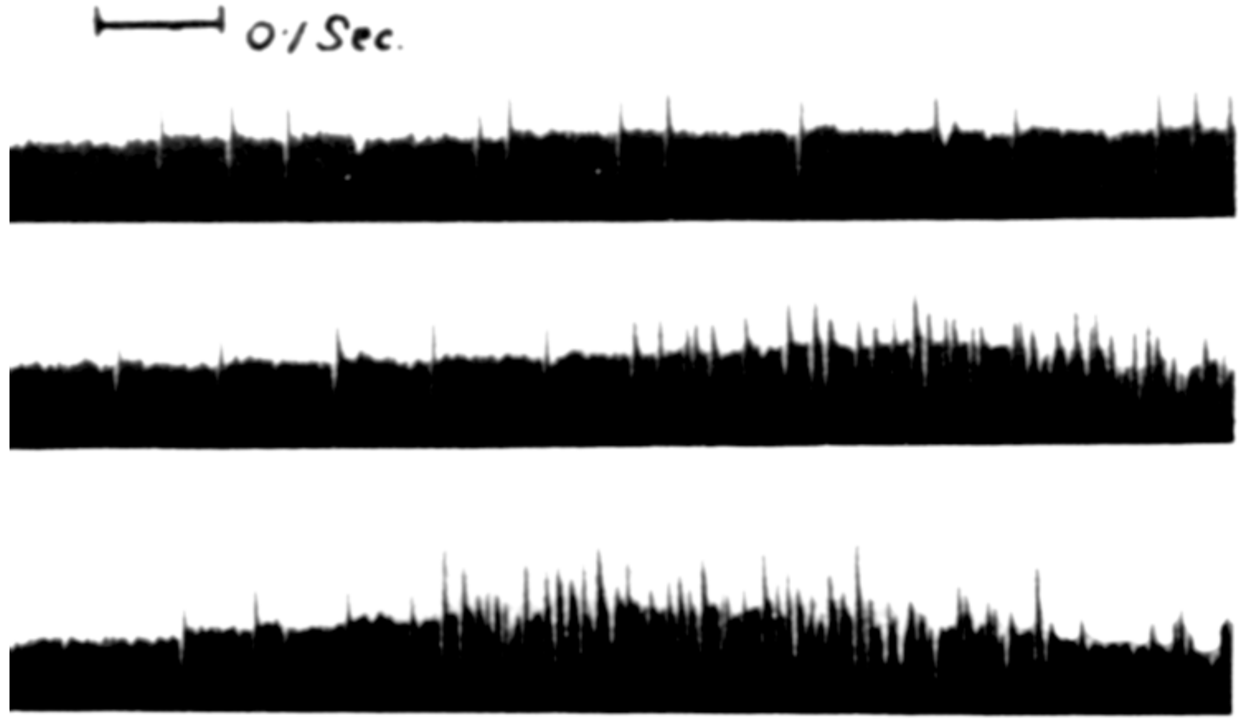
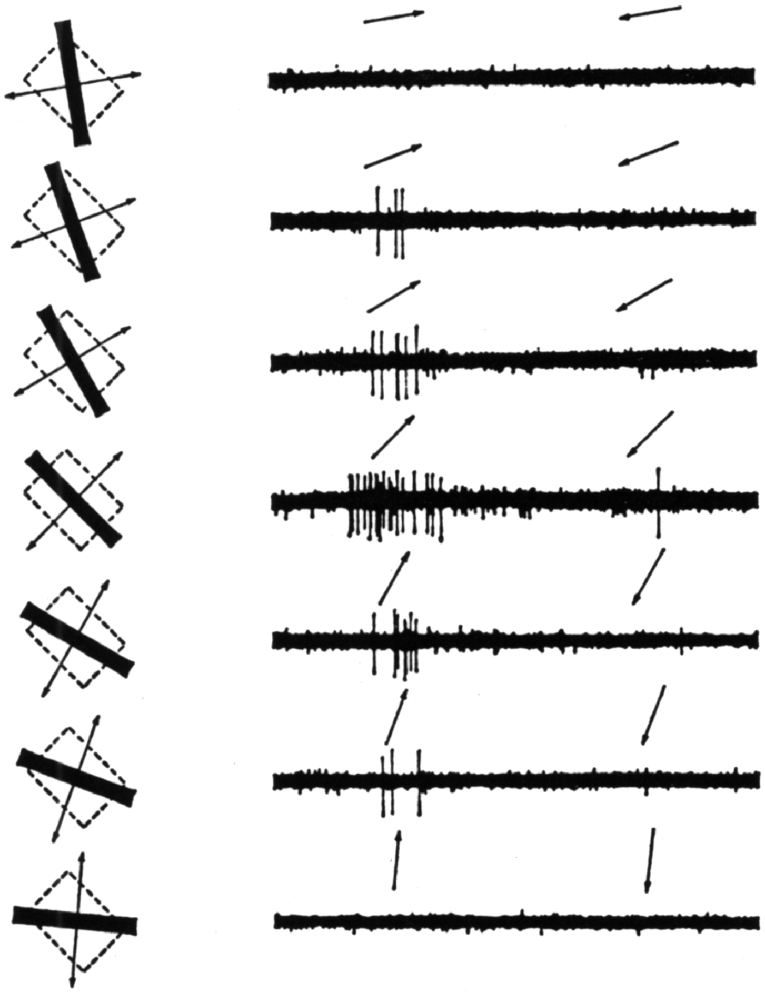
Lord Adrian of Cambridge (1889–1977).



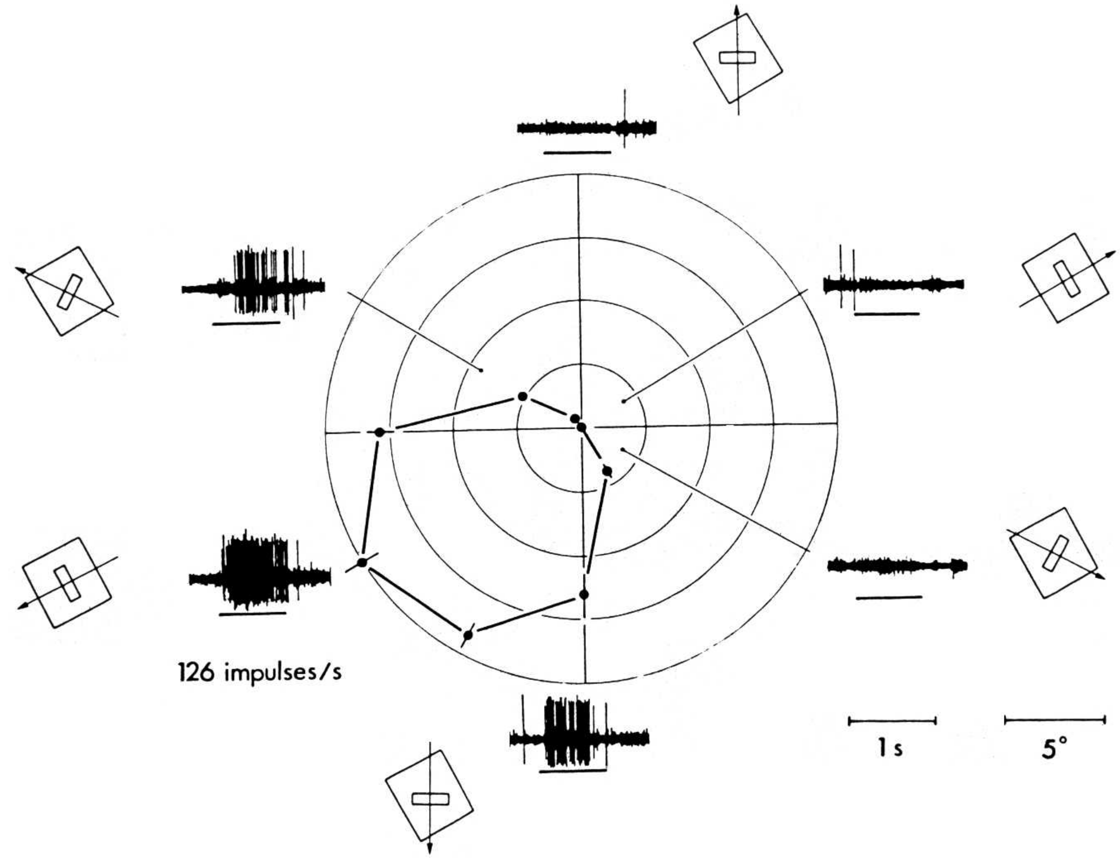
Some of Adrian's first recordings from very small numbers of individual nerve fibres. Each spiky deflection is a single nerve impulse. These records were taken from the sensory nerves of a cat's toe. The toe was flexed slowly, more quickly and very rapidly to produce these three traces. The frequency of firing depends on the strength of the stimulus – Adrian's law.

V1



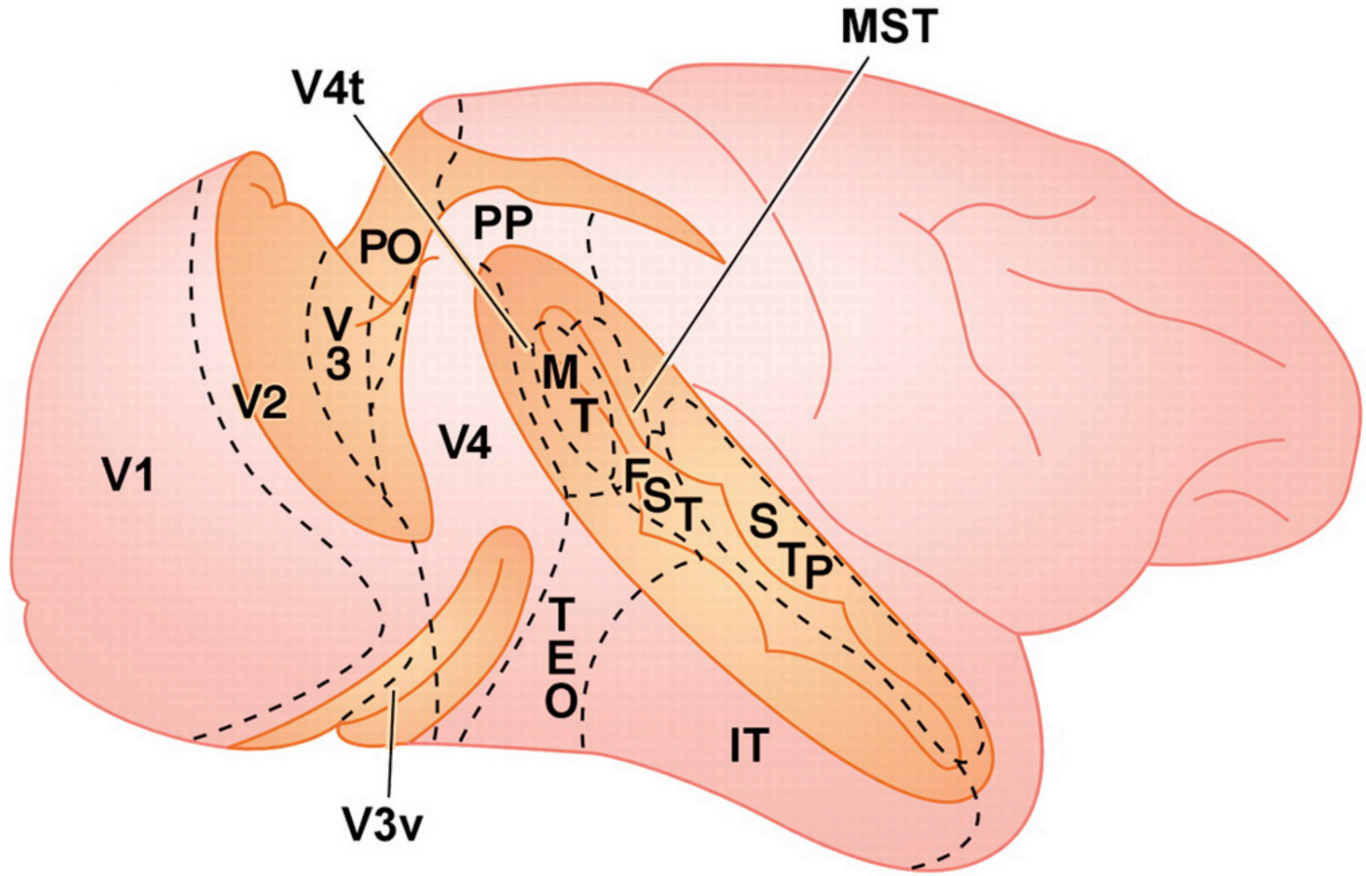
Hubel and Wiesel, 1968

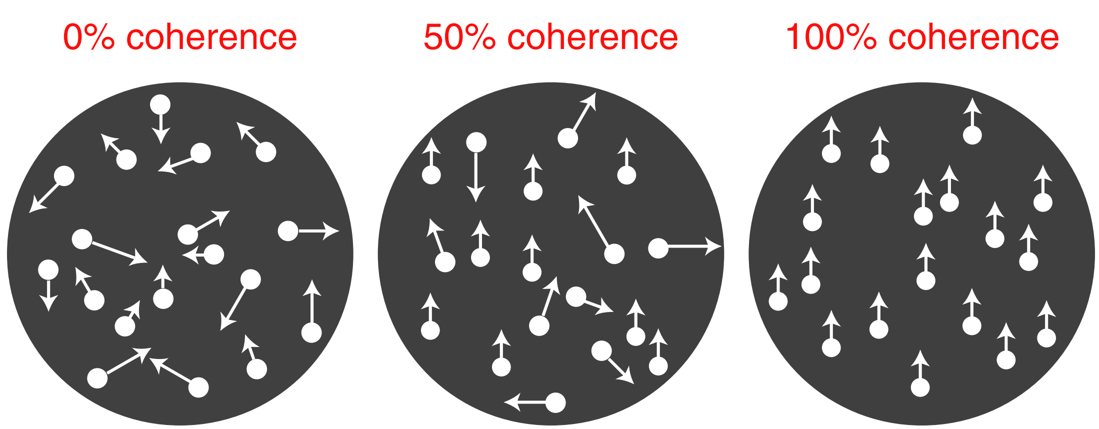
MT

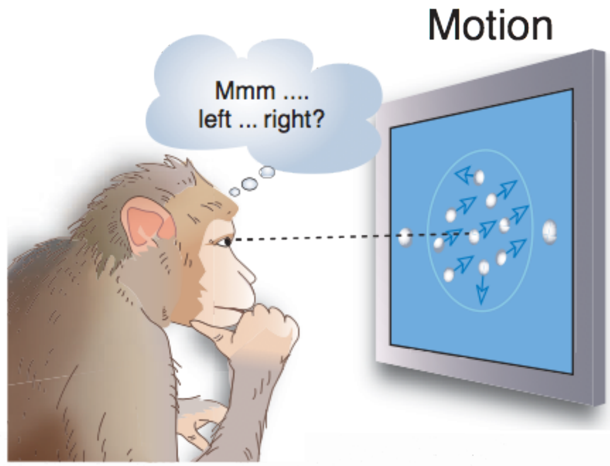


Maunsell and Van Essen, 1983

Relating MT responses to visual discrimination







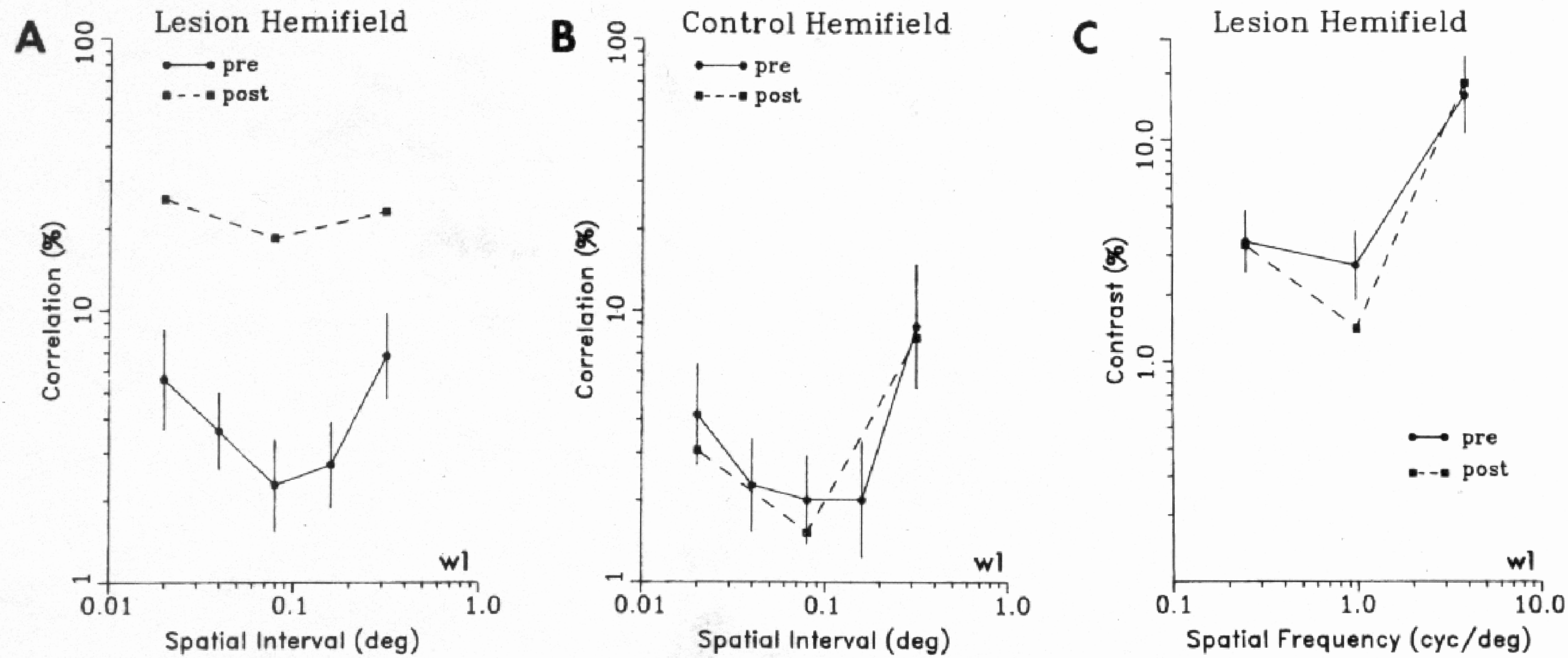
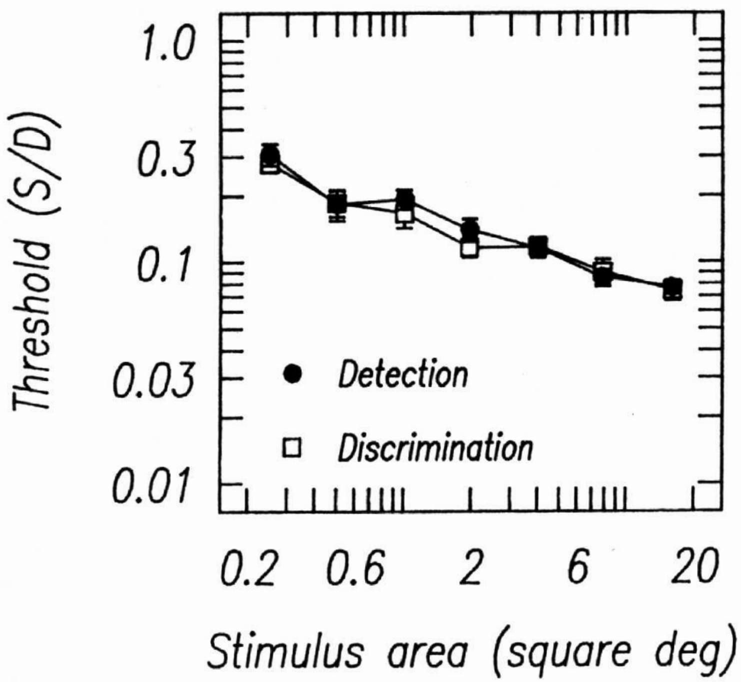
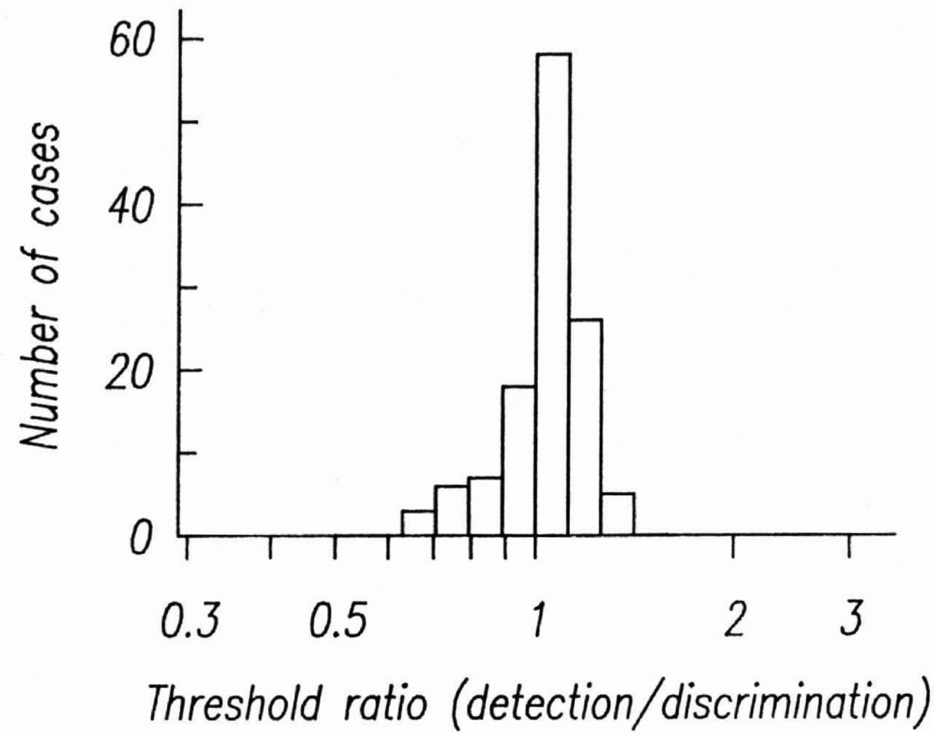


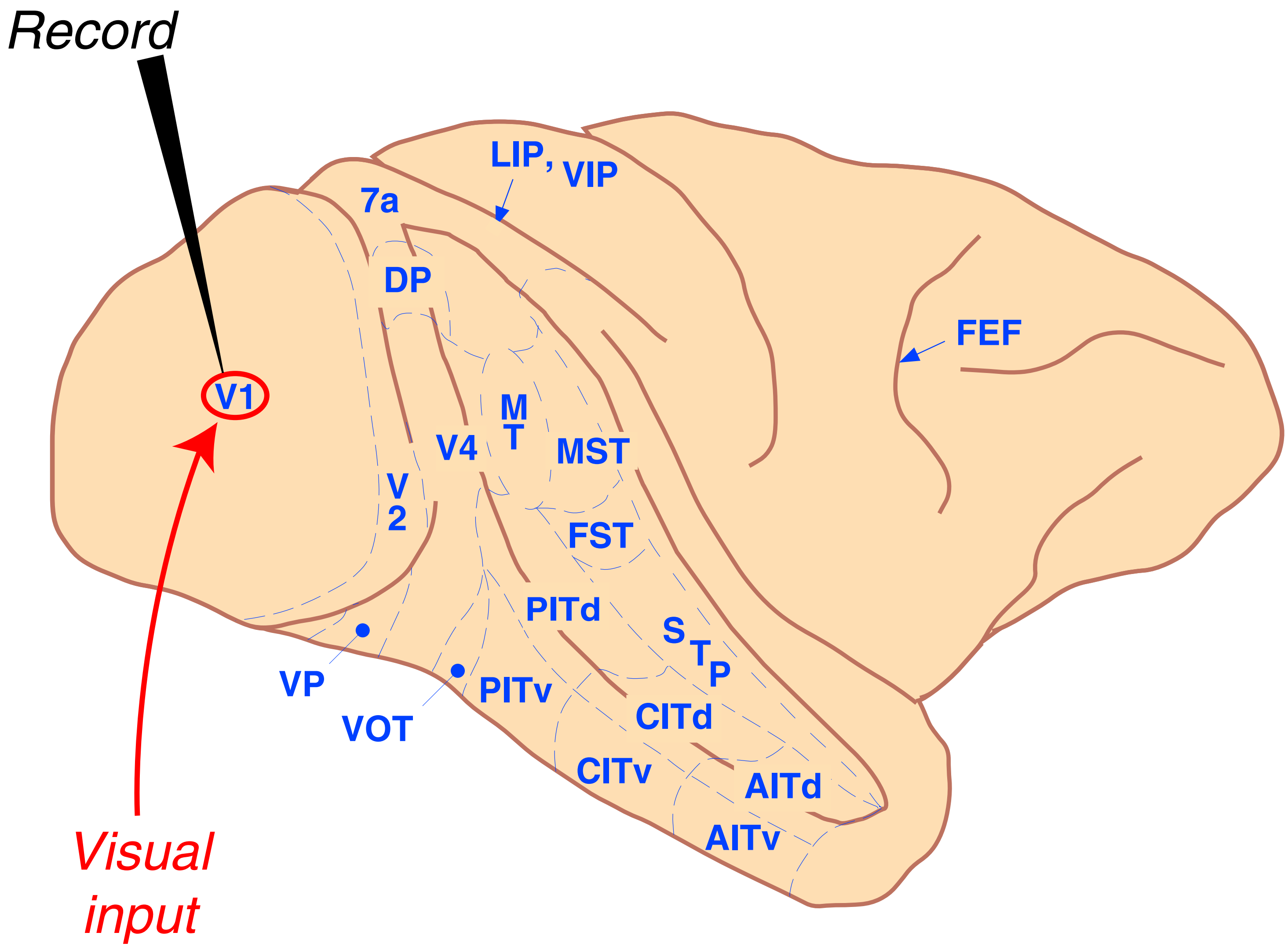
Figure 6. The psychophysical effects of an ibotenic acid injection into MT in experiment *w1*. *Solid line and error bars* in *A–D* indicate the mean prelesion threshold and standard deviation for each condition tested; *dashed line*, postlesion thresholds obtained 24 hr after the MT injection. *A*, Motion thresholds for 5 different spatial intervals in the test (contralateral) hemifield. Again, the MT lesion caused striking elevations of motion thresholds in the test hemifield. *B*, Motion thresholds were within the normal range in the control (ipsilateral) hemifield. *C*, The MT injection had no effect on contrast thresholds in the test hemifield.

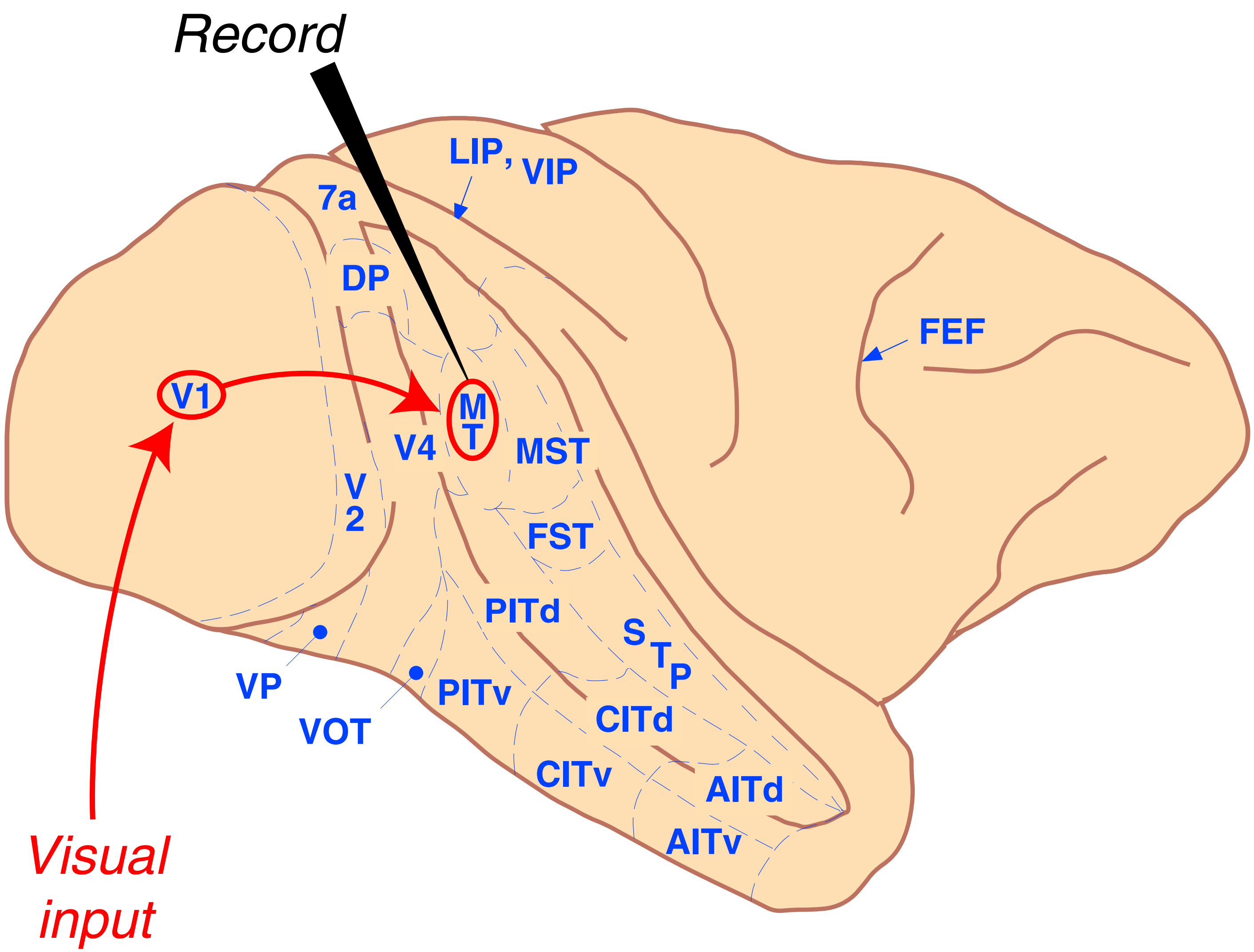
Newsome and Paré, 1988

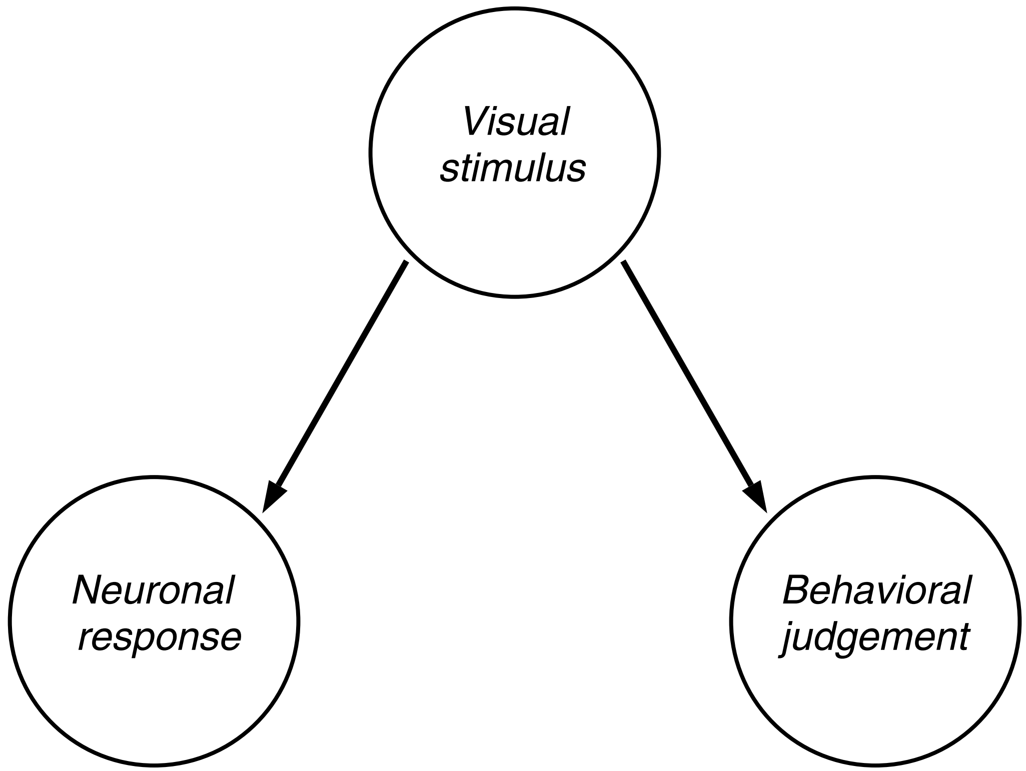


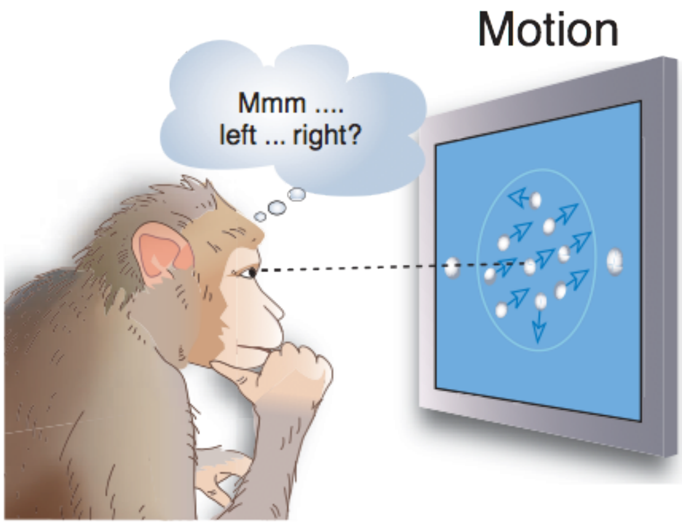


Downing & Movshon, 1989

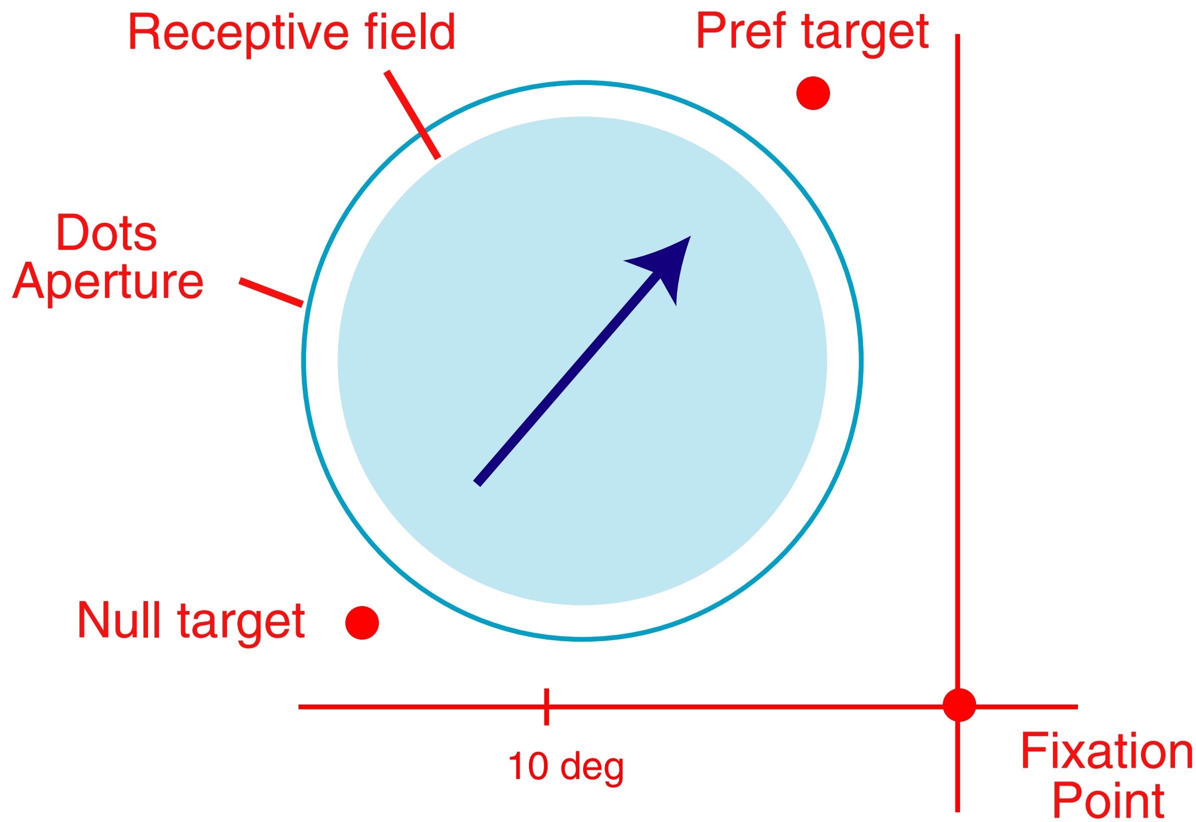

Record
V1
Visual input
7a
LIP, VIP
DP
FEF
M T
V4
MST
V 2
FST
PITd
S T P
VP
PITv
VOT
CITd
CITv
AITd
AITv

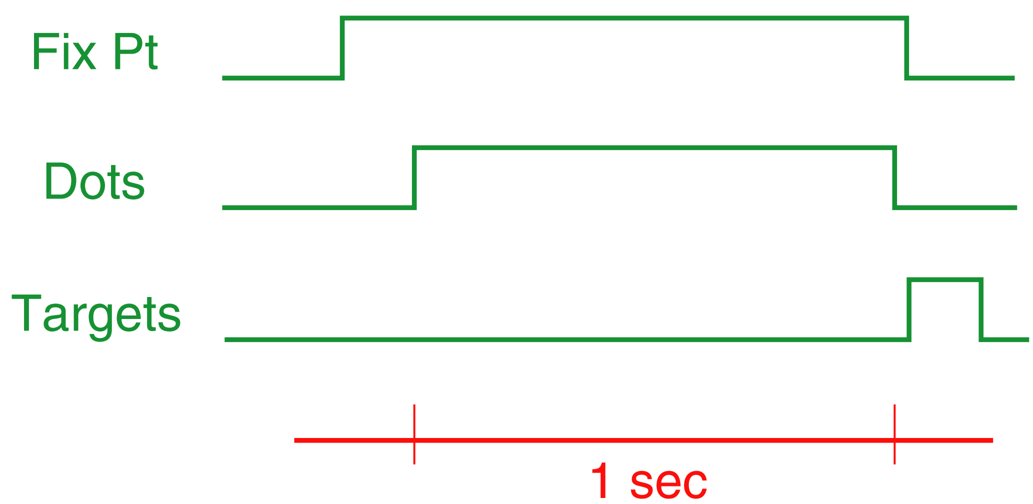

Record
LIP, VIP
7a
DP
FEF
V1
MT
V4
MST
V2
FST
PITd
STP
VP
PITv
VOT
CITd
CITv
AITd
AITv
Visual input


Visual stimulus
Neuronal response
Behavioral judgement

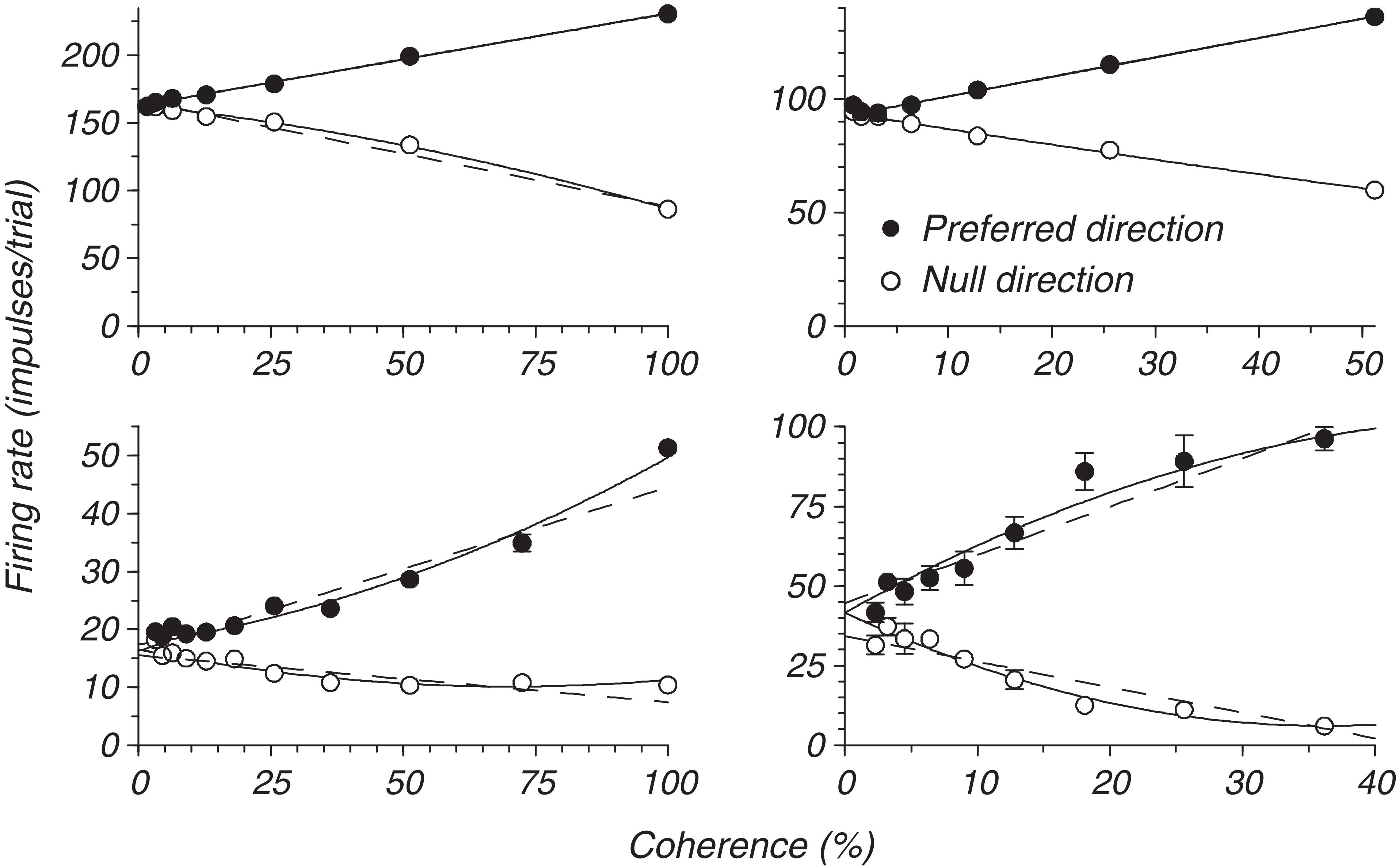


+ recording in MT



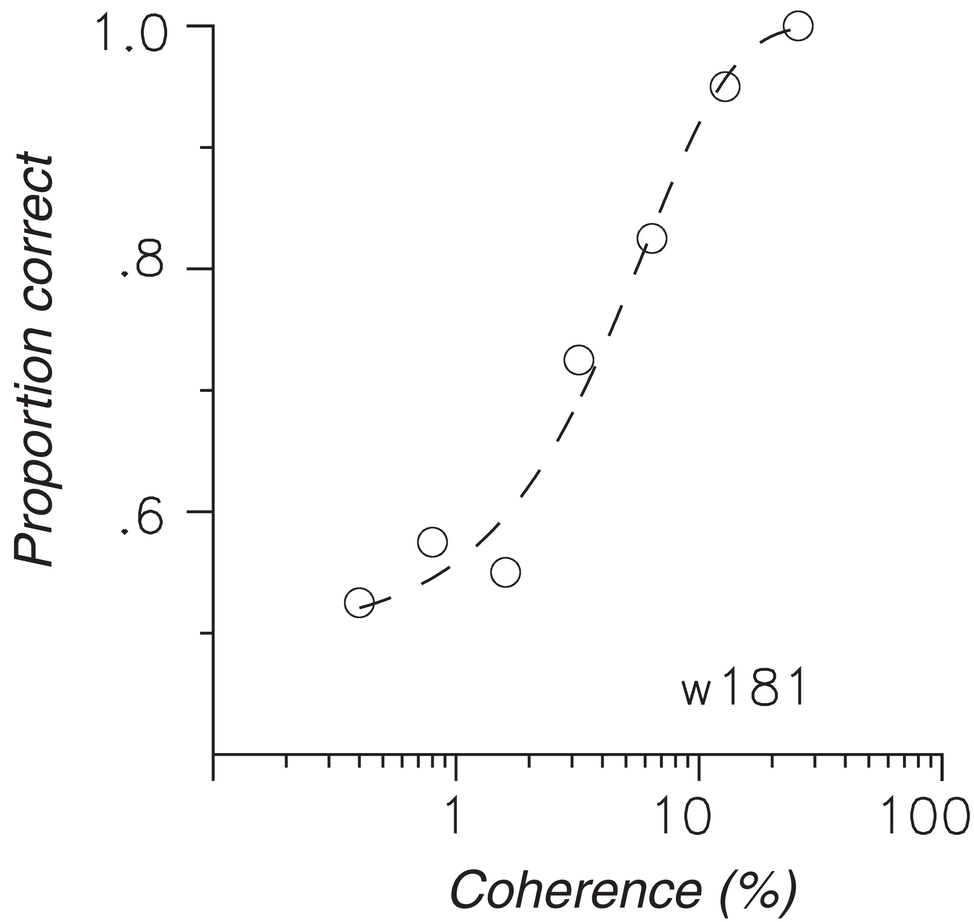


MT responses depend on motion coherence

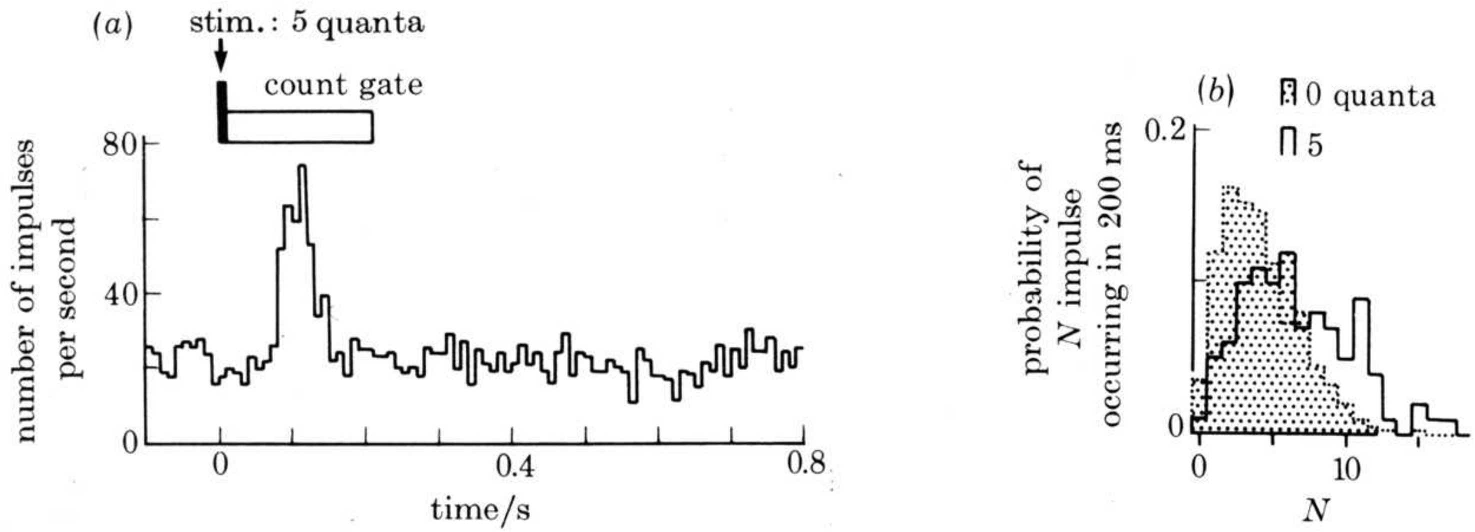


Britten, Shadlen, Newsome & Movshon, 1993

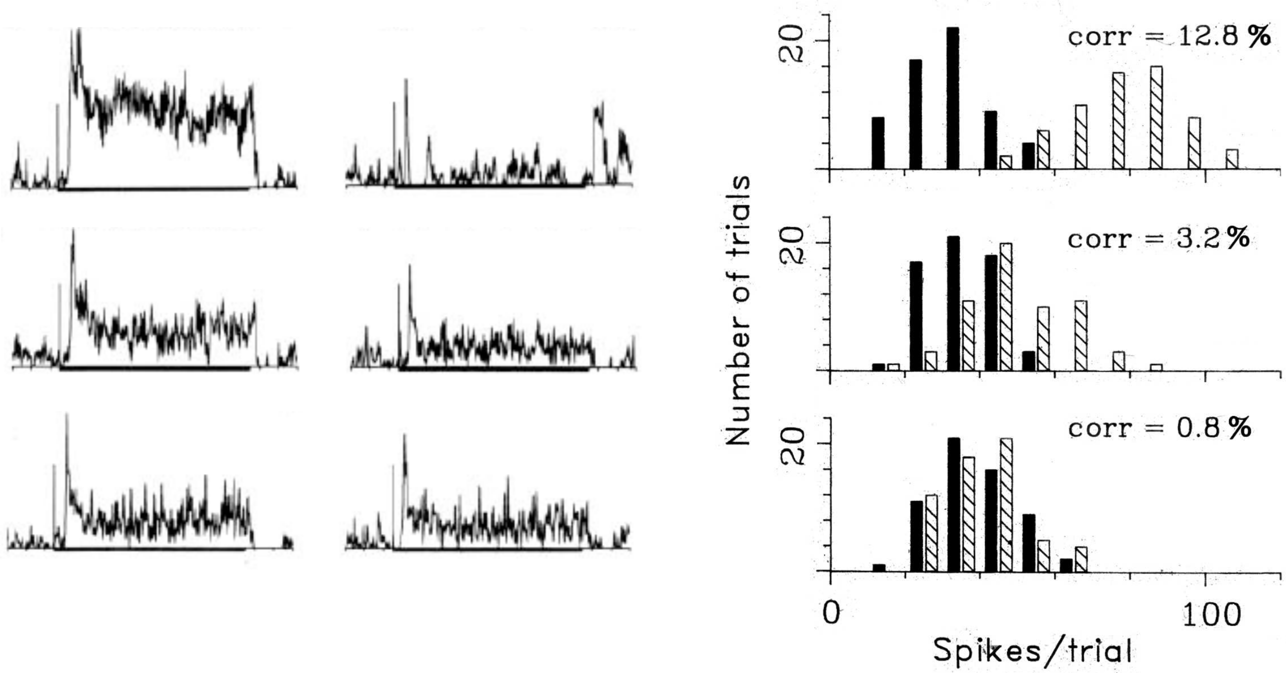
Behavioral performance from one session



Britten, Shadlen, Newsome & Movshon, 1992

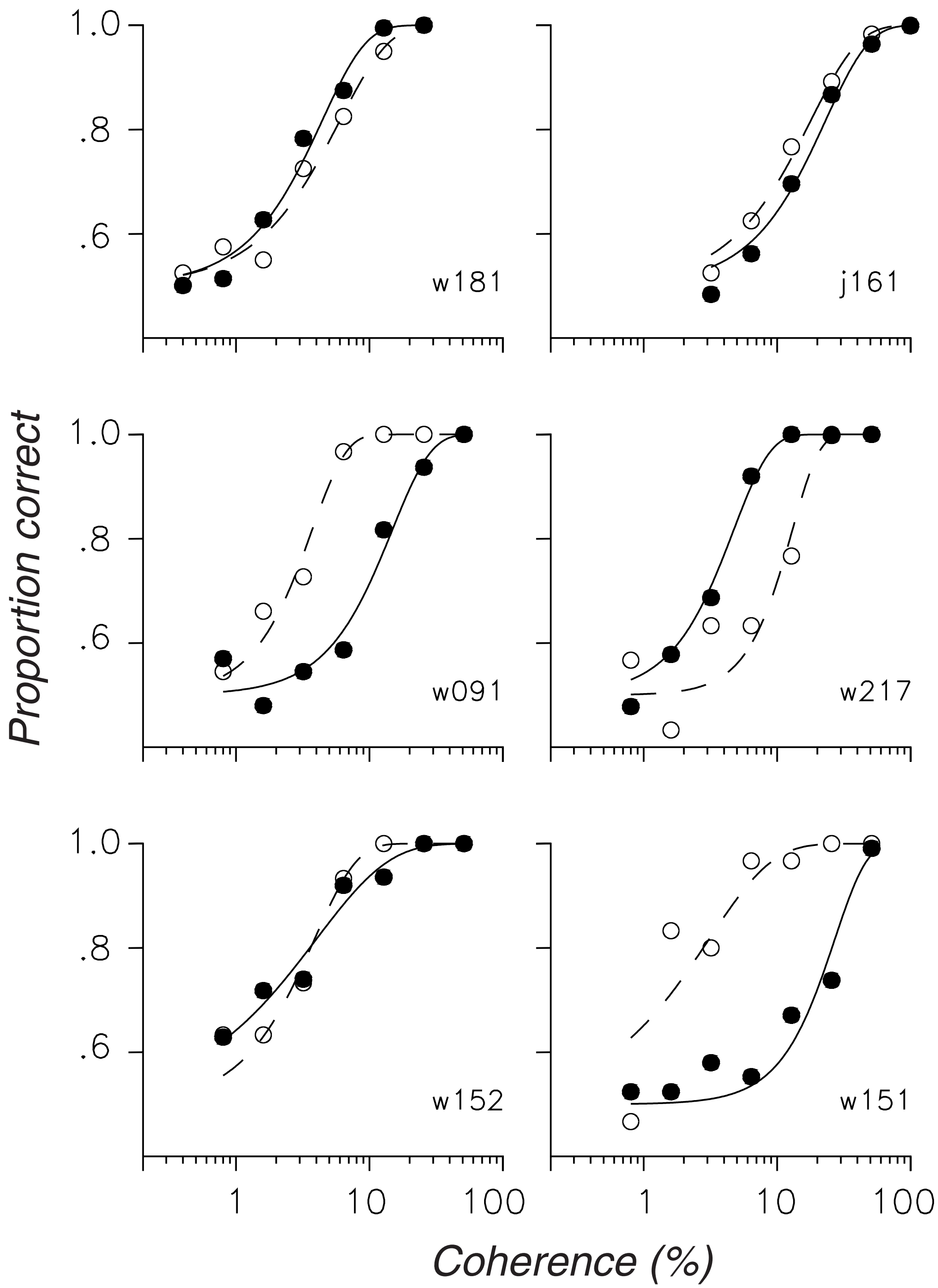


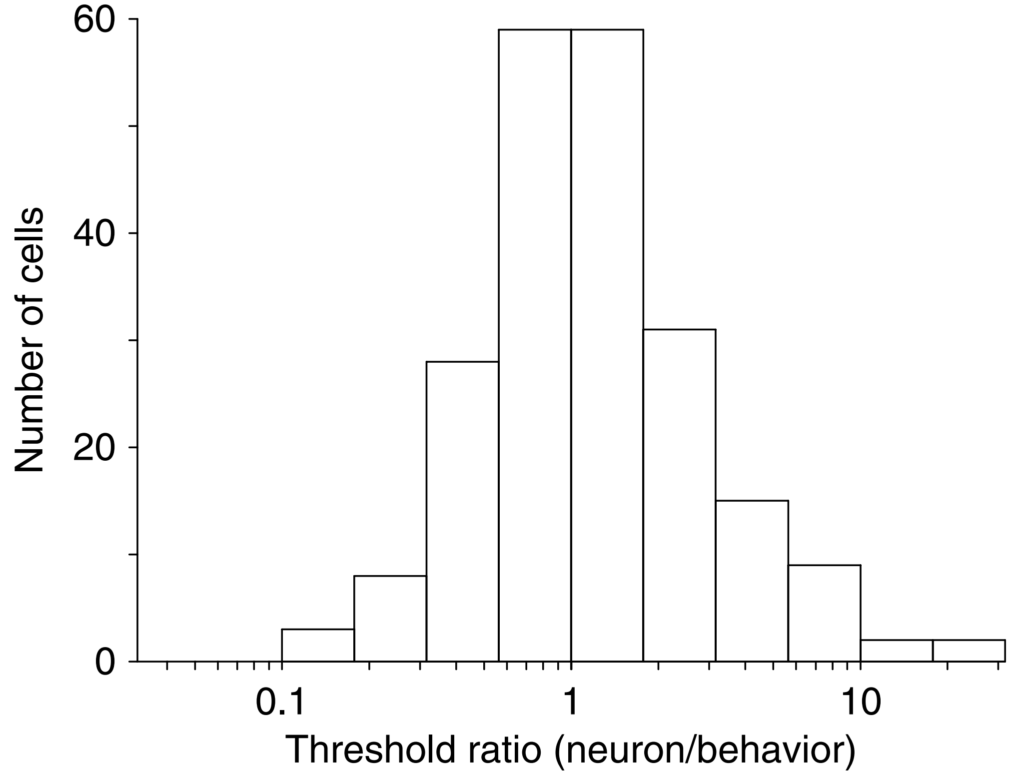
Barlow, Levick and Yoon, 1971



Britten, Shadlen, Newsome & Movshon, 1992

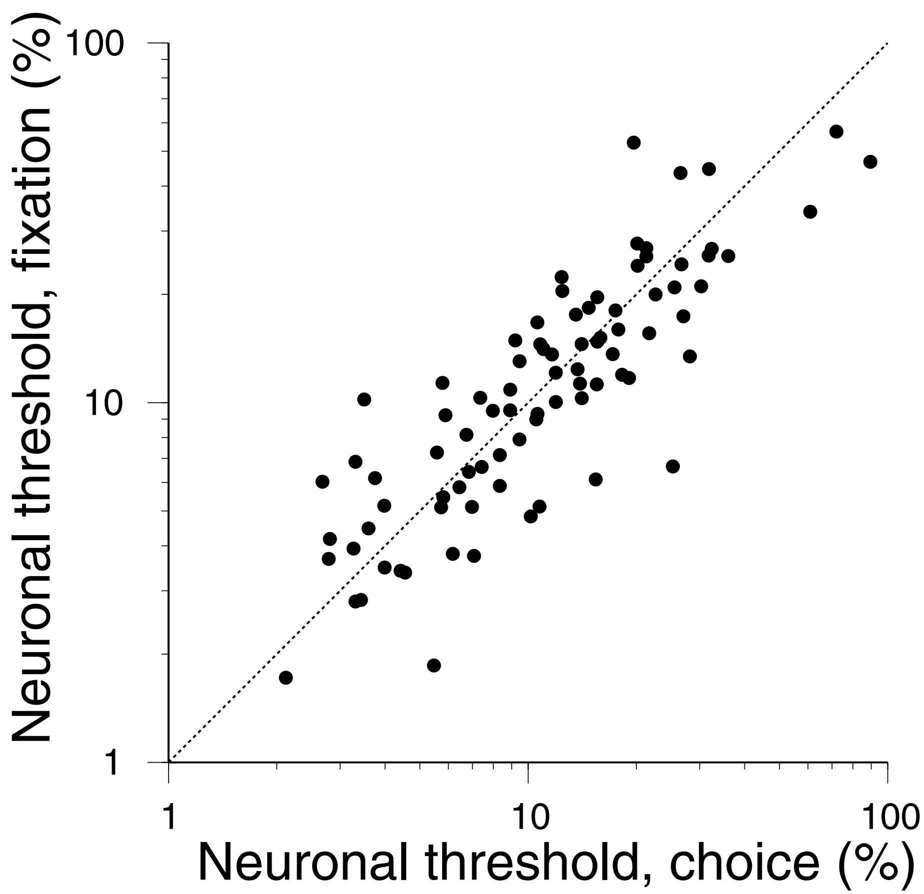
MT cells are as sensitive as monkeys to visual motion



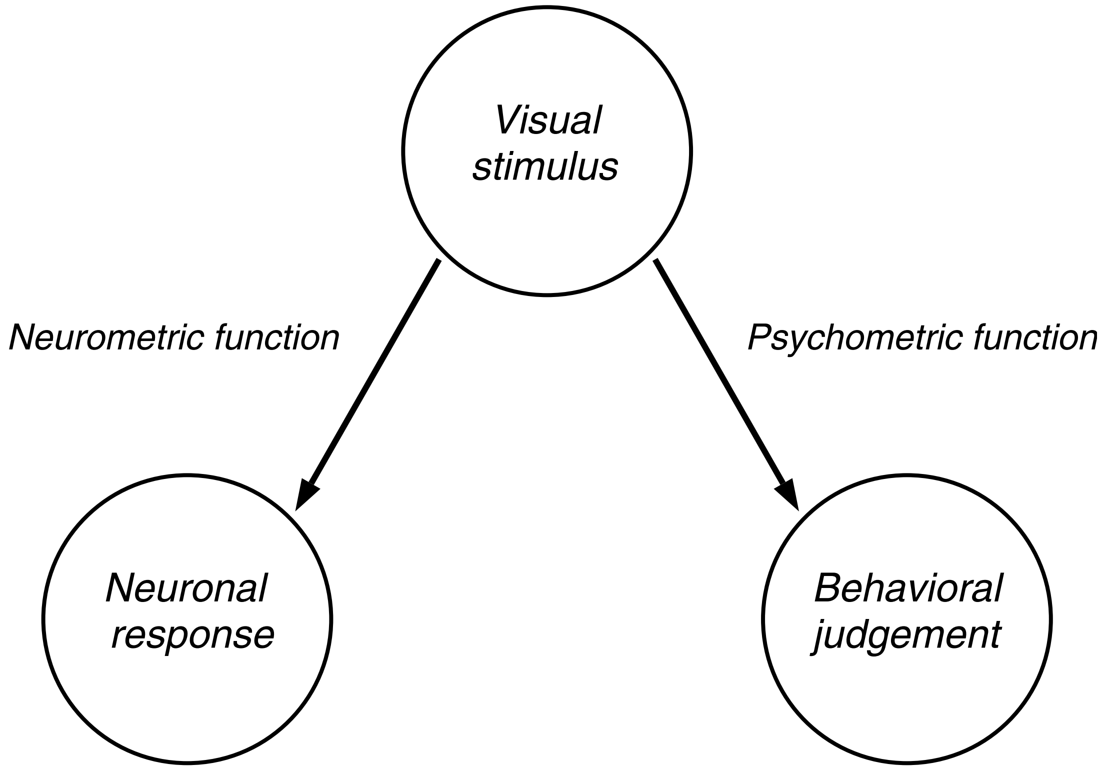


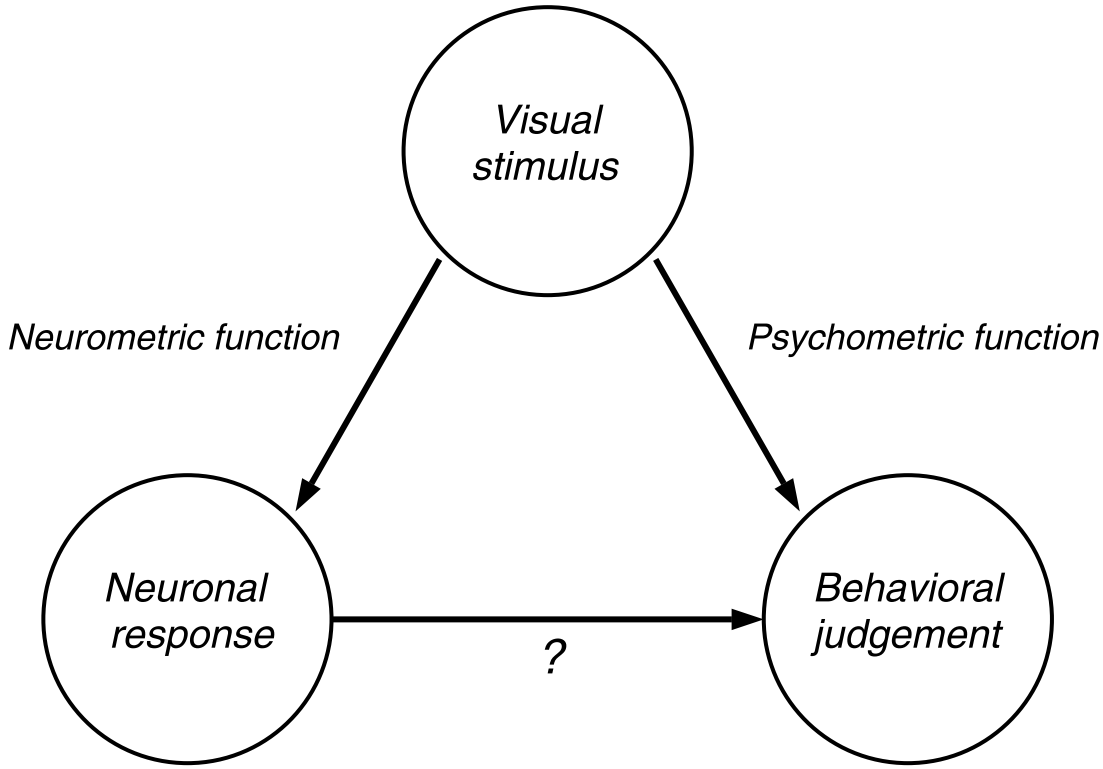
Britten, Shadlen, Newsome & Movshon, 1992

MT cell firing does not require the observer to make a decision

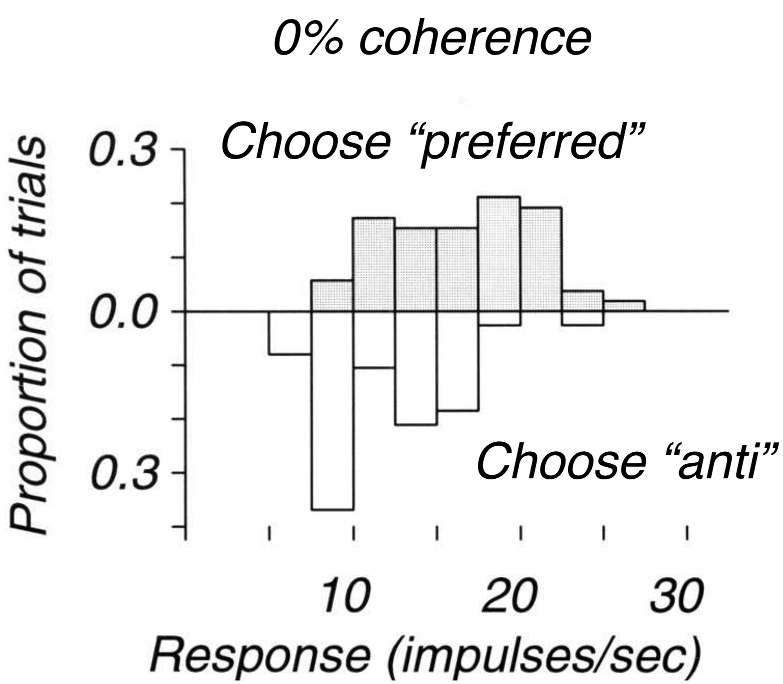


Britten, Shadlen, Newsome & Movshon, 1992


Visual stimulus
Neurometric function
Psychometric function
Neuronal response
Behavioral judgement

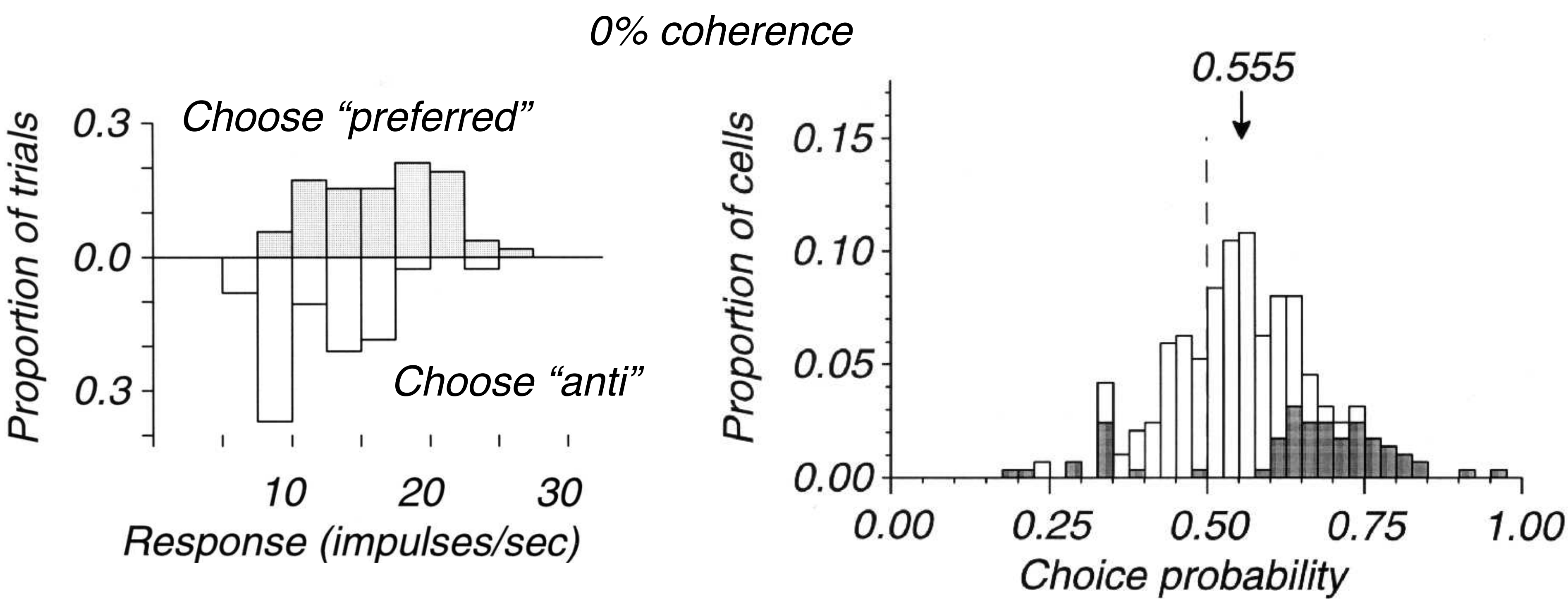

Visual stimulus
Neurometric function
Psychometric function
Neuronal response
Behavioral judgement
?

MT cell firing is correlated with behavioral choice



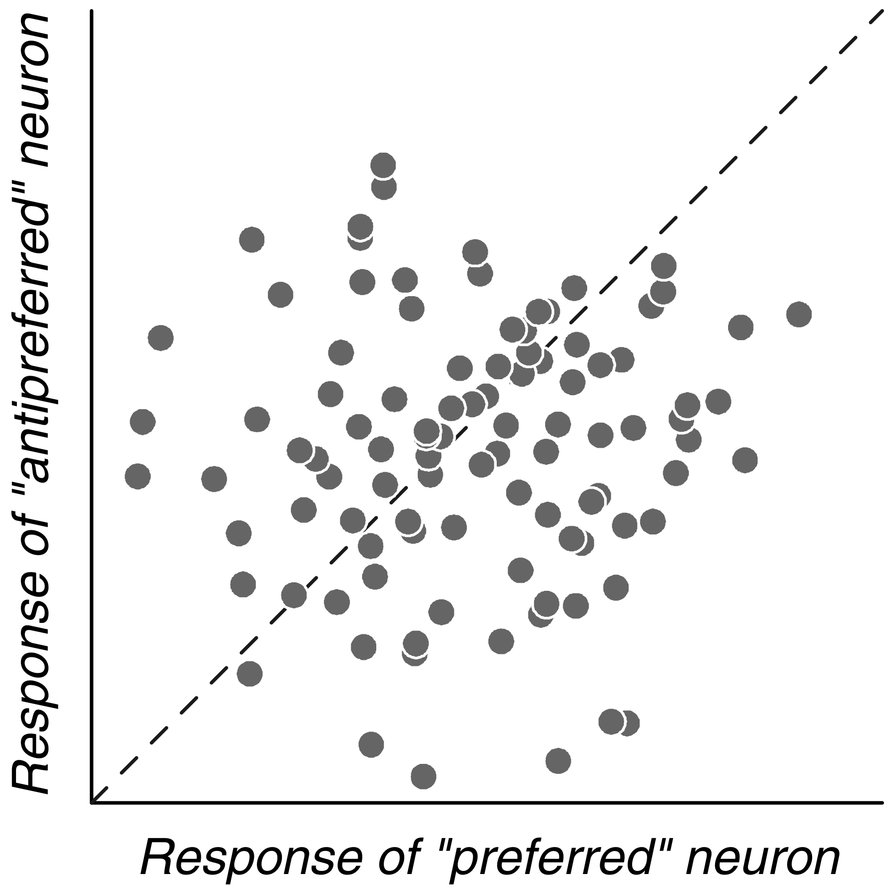
Britten, Newsome, Shadlen, Celebrini & Movshon, 1996

MT cell firing is correlated with behavioral choice

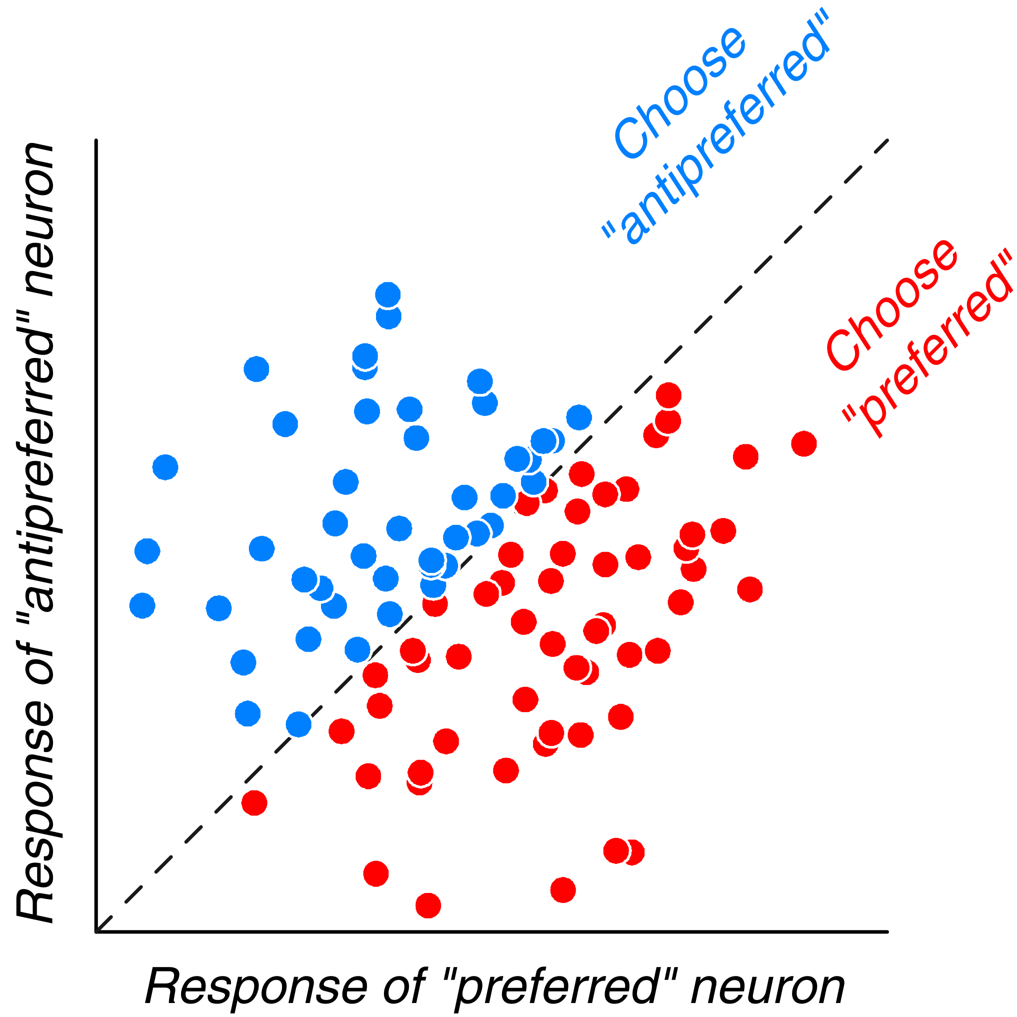


Britten, Newsome, Shadlen, Celebrini & Movshon, 1996

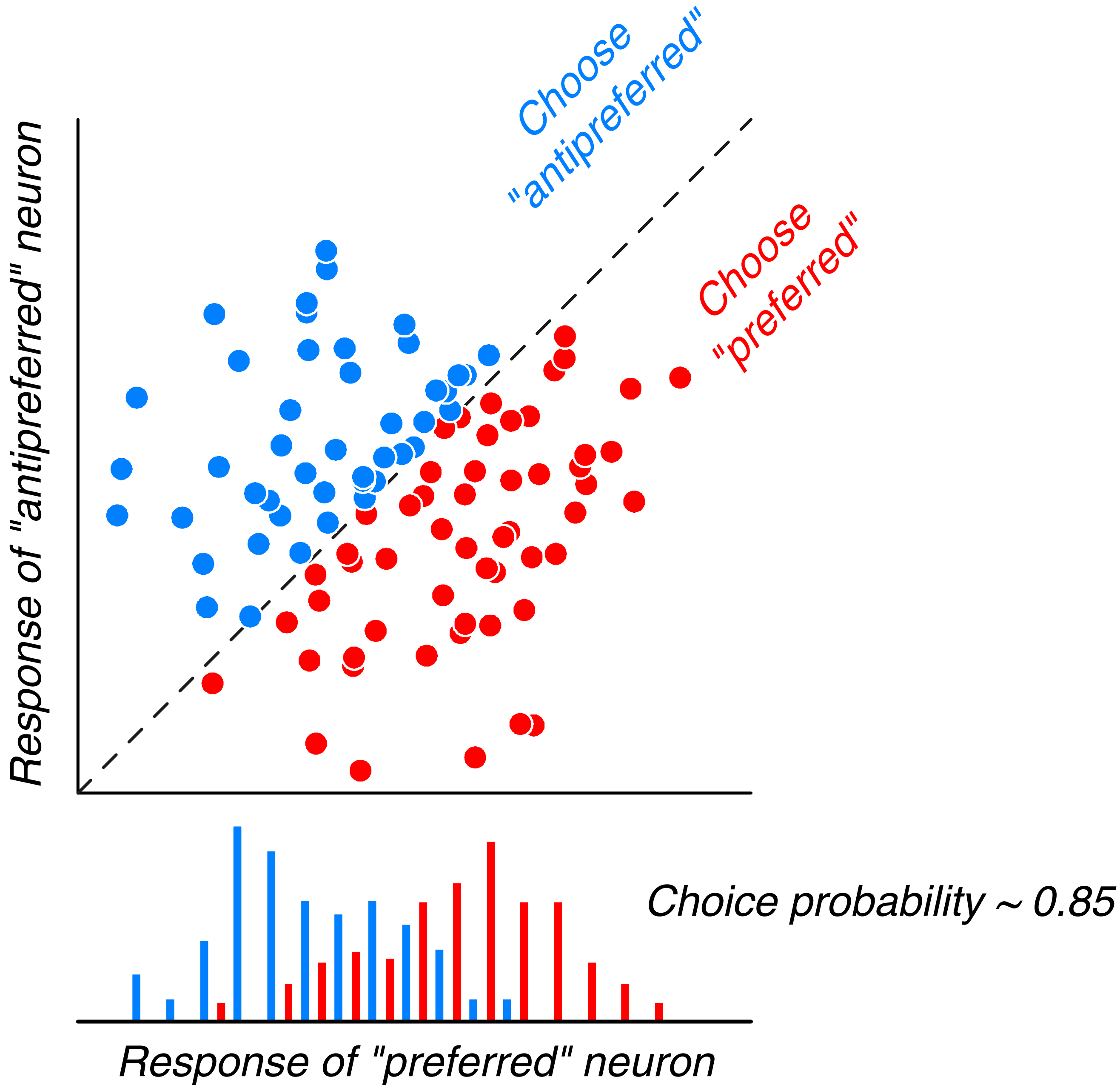
MT cell firing is correlated with behavioral choice



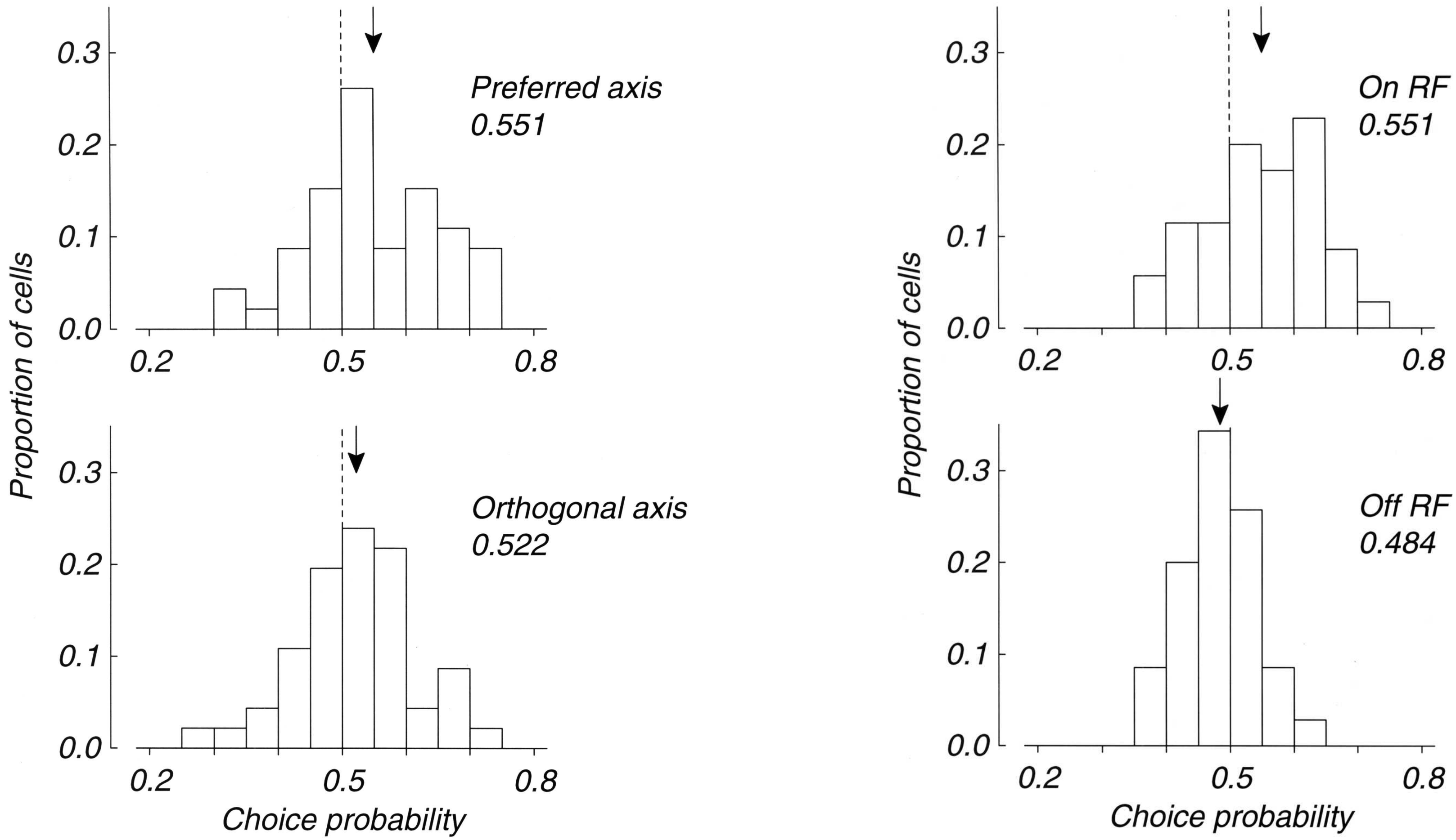
MT cell firing is correlated with behavioral choice



MT cell firing is correlated with behavioral choice

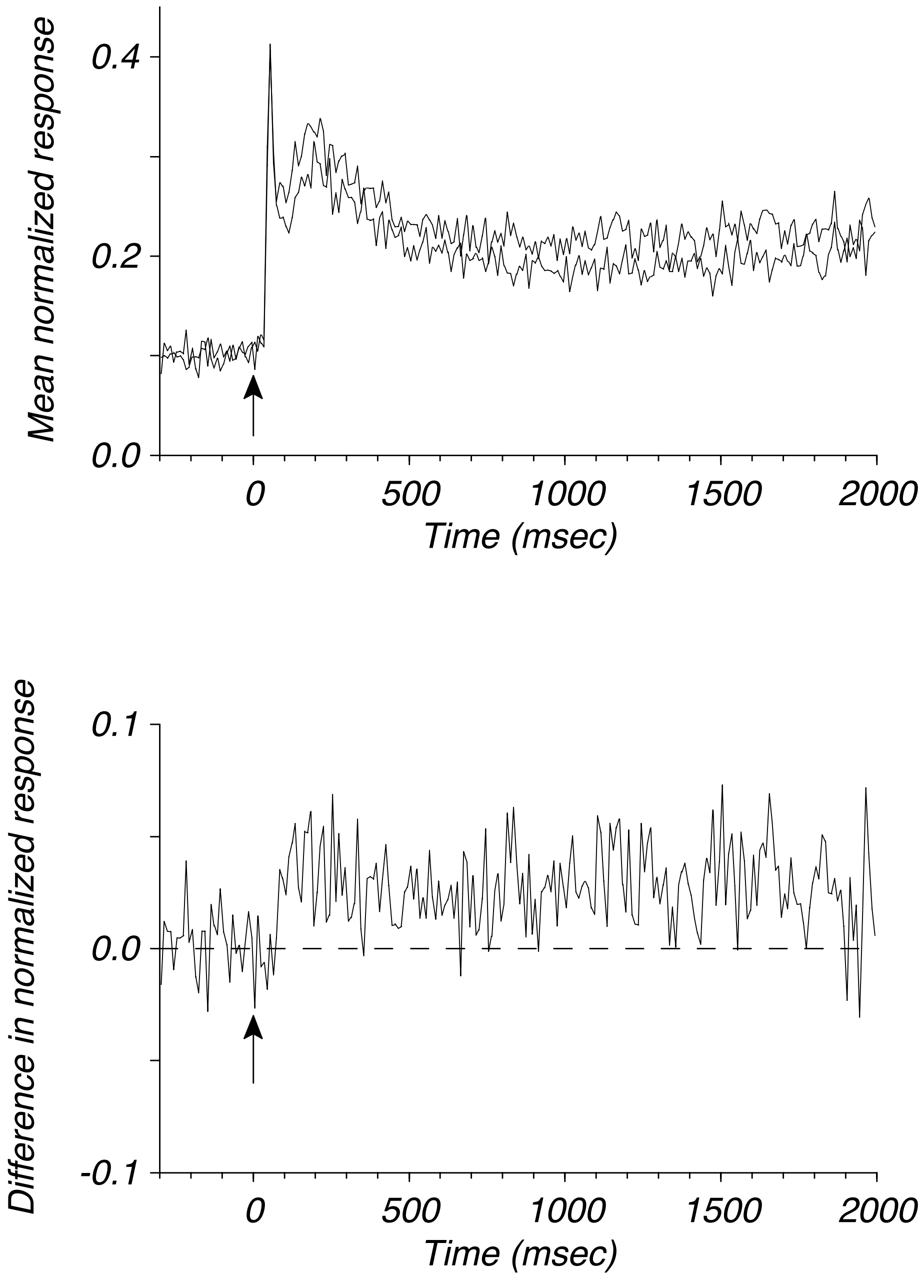


Correlation of activity to choice is not accidental



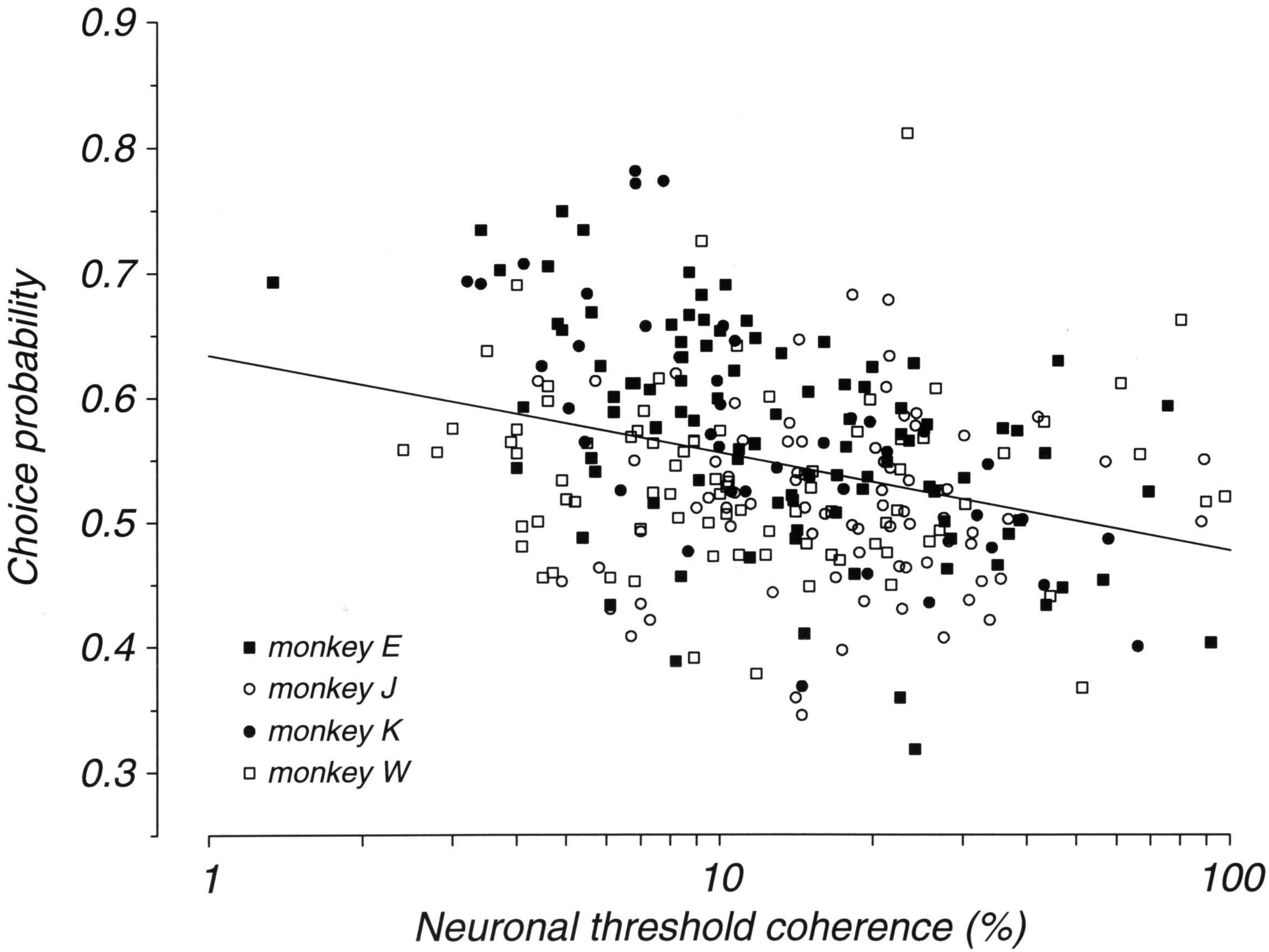
Britten, Newsome, Shadlen, Celebrini & Movshon, 1996

Choice-related activity has a "forward" time course



Britten, Newsome, Shadlen, Celebrini & Movshon, 1996

The most sensitive neurons are most correlated to choice



Britten, Newsome, Shadlen, Celebrini & Movshon, 1996

Choice probability for depth discrimination in V2

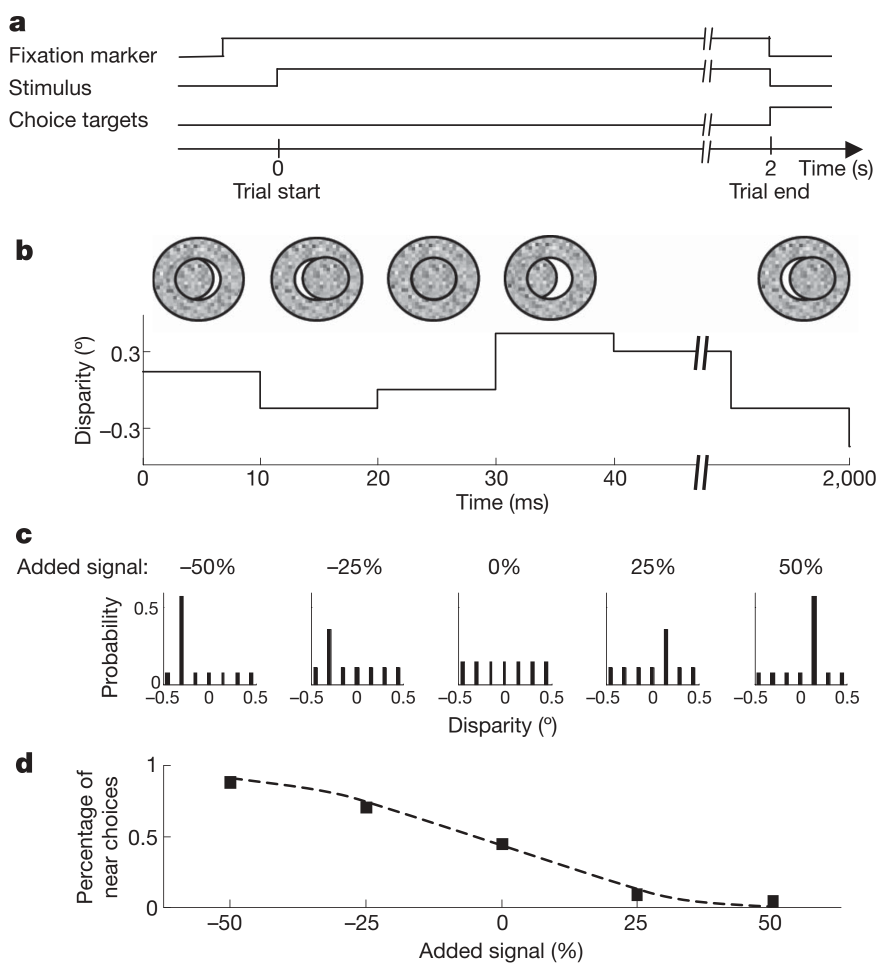


Figure 1 | Methods. **a**, Sketch of the sequence of events during one trial. **b**, Example time series of the stimulus. **c**, Probability mass distributions of the stimuli for one experiment (probability as a function of disparity), with signal disparities of -0.3° and 0.15°. Each plot depicts one signal condition (negative percentages indicate near signal disparities). **d**, The monkey's performance for this experiment (in percentage 'near' choices as a function of percentage added signal).

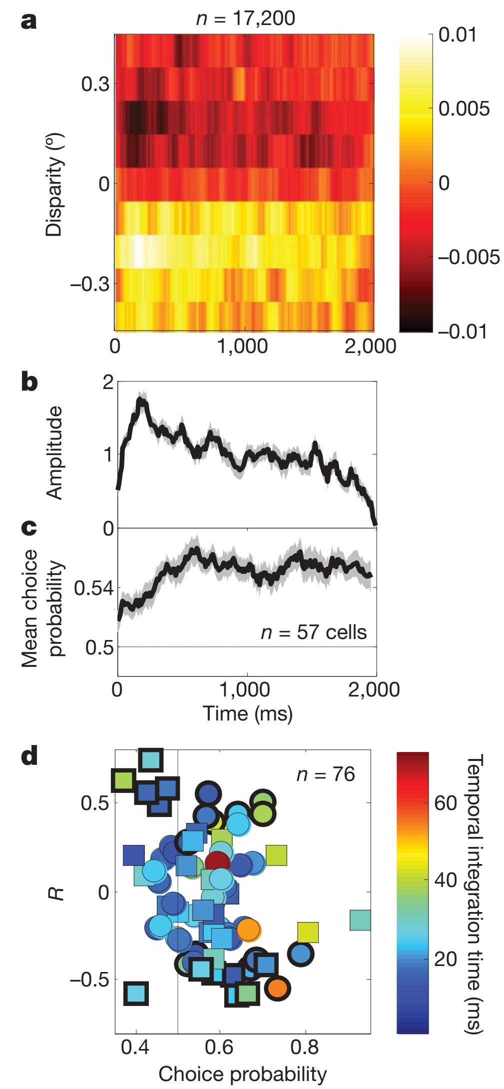
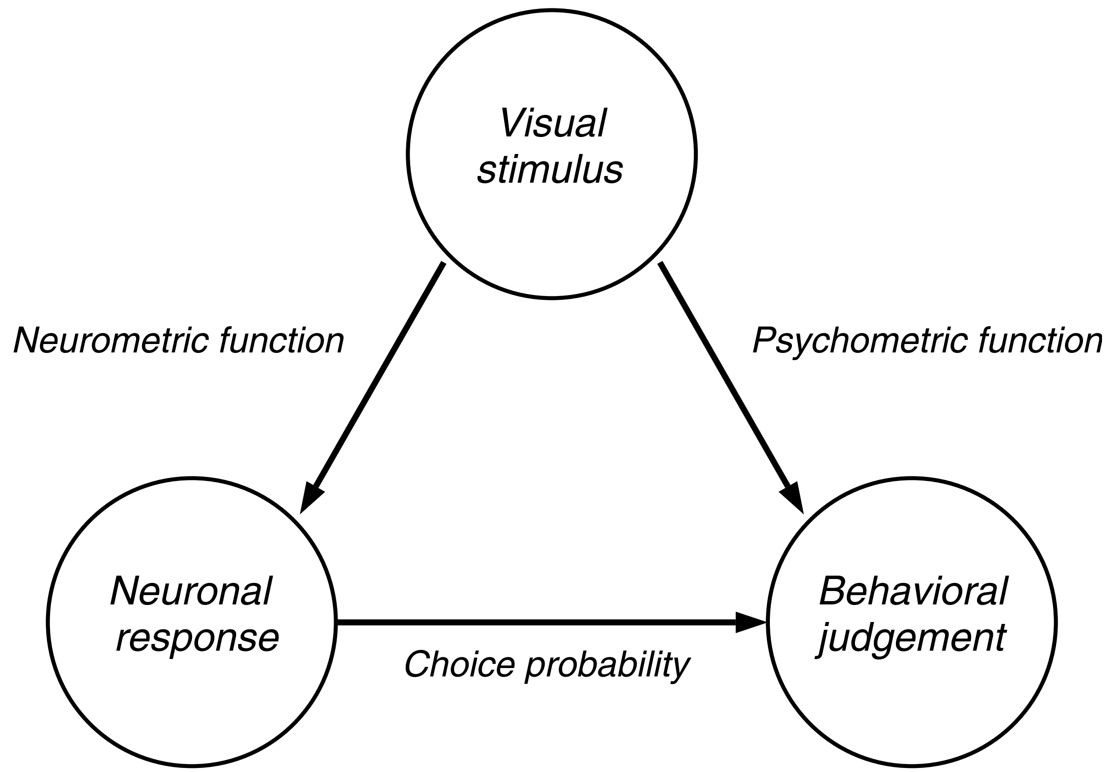
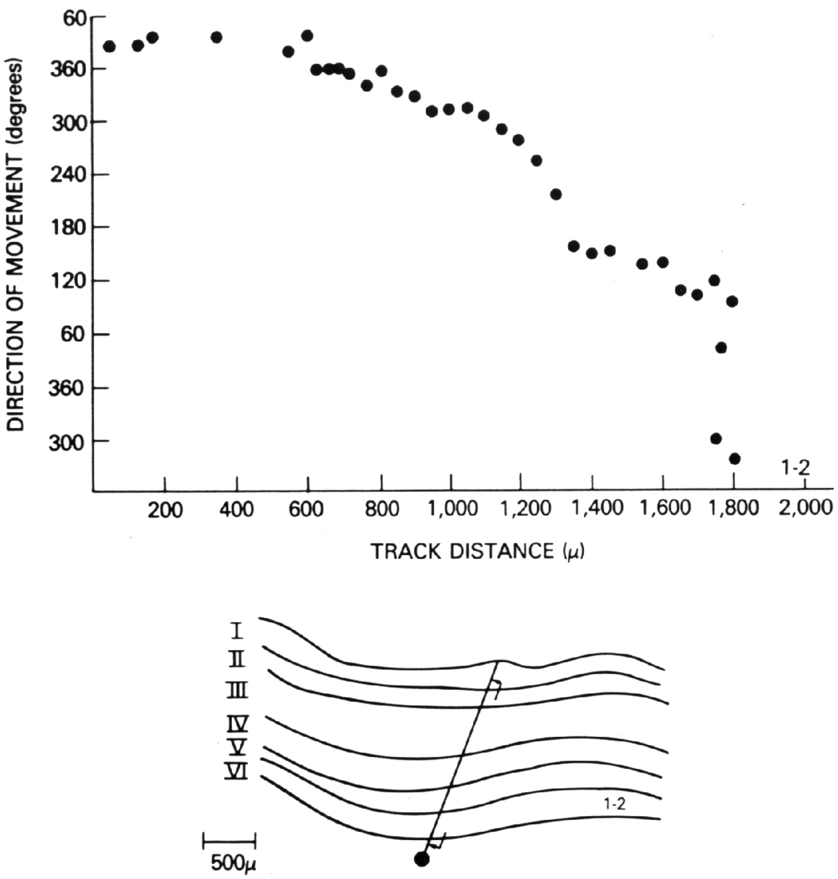
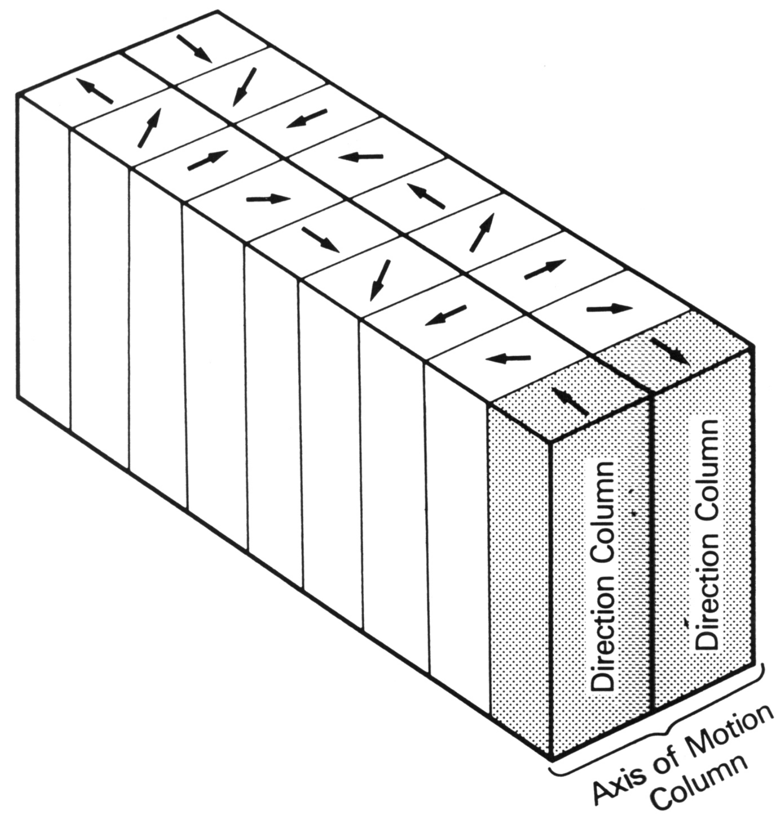


Figure 2 | Psychophysical kernel and choice-related signal have different time courses. **a**, Psychophysical kernel (averaged over 76 experiments; $n = 17{,}200$ trials; two monkeys) as a function of disparity and time. Colour represents amplitude (in occurrences per frame). **b**, Normalized amplitude of the psychophysical kernels decreases over time. **c**, Averaged choice-related signal over time. Shaded grey areas in **b** and **c**, ± 1 standard error. **d**, The correlation coefficient, *R*, over time between choice probability (for individual neurons) and the amplitude of the mean psychophysical kernel, plotted against a neuron's mean choice probability. Colour represents temporal integration time (Supplementary Methods); bold symbols, significant R ($P < 0.05$, by resampling); circles, data from monkey 1; squares, data from monkey 2.

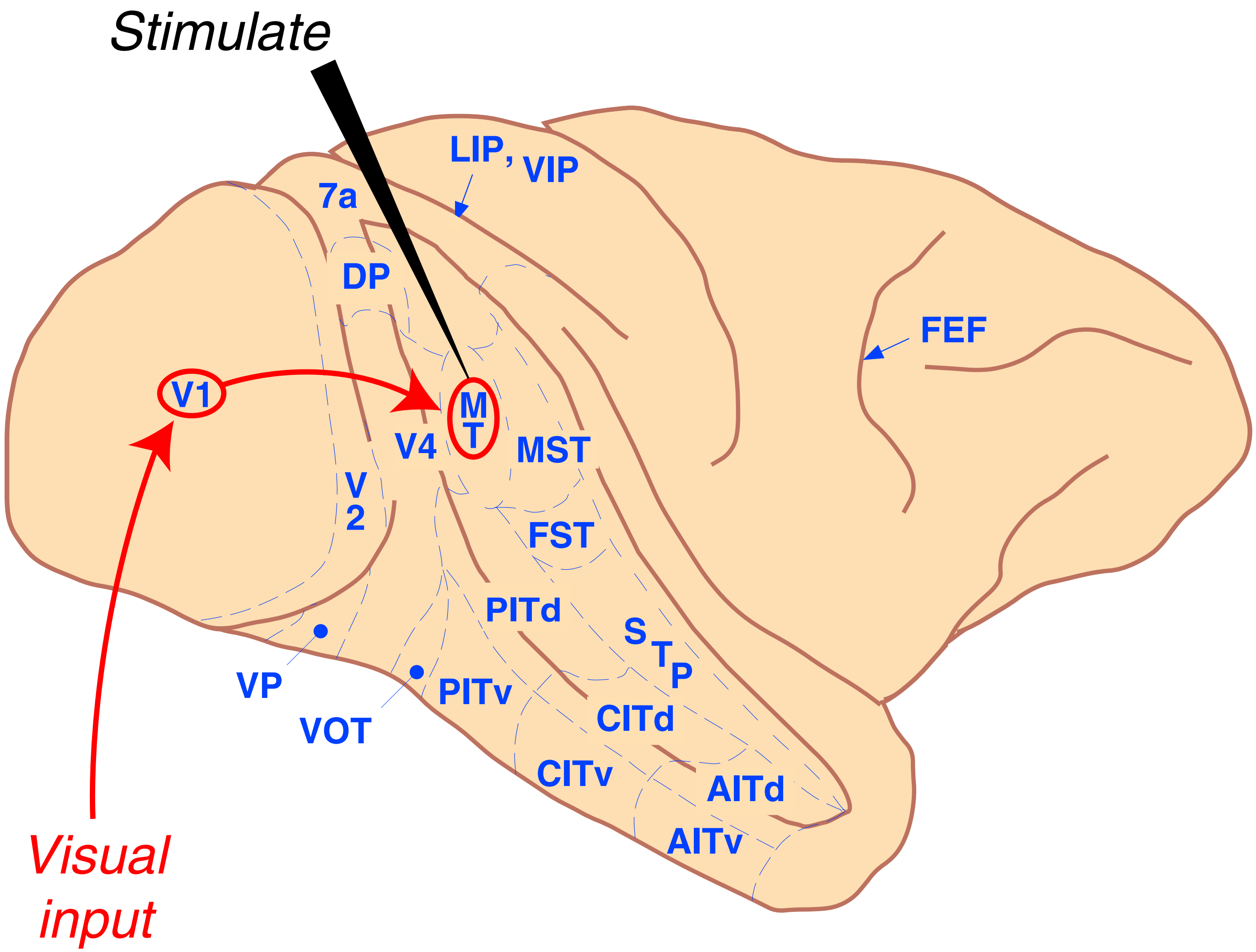

Visual stimulus
Neurometric function
Psychometric function
Neuronal response
Behavioral judgement
Choice probability

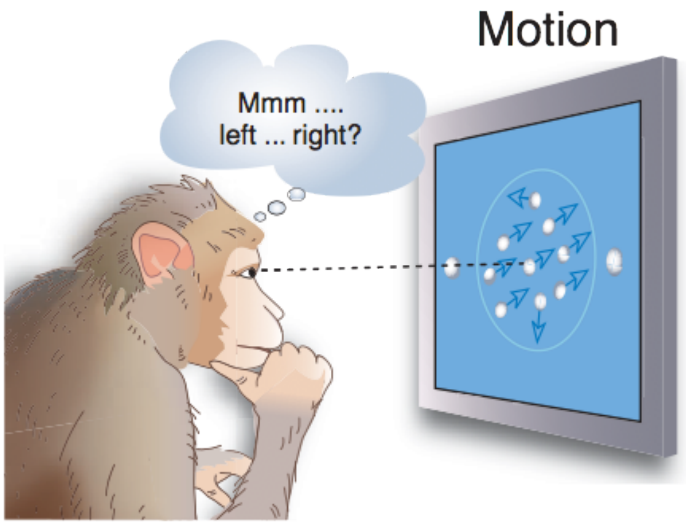
COLUMNAR ORGANIZATION OF MT IN MACAQUE



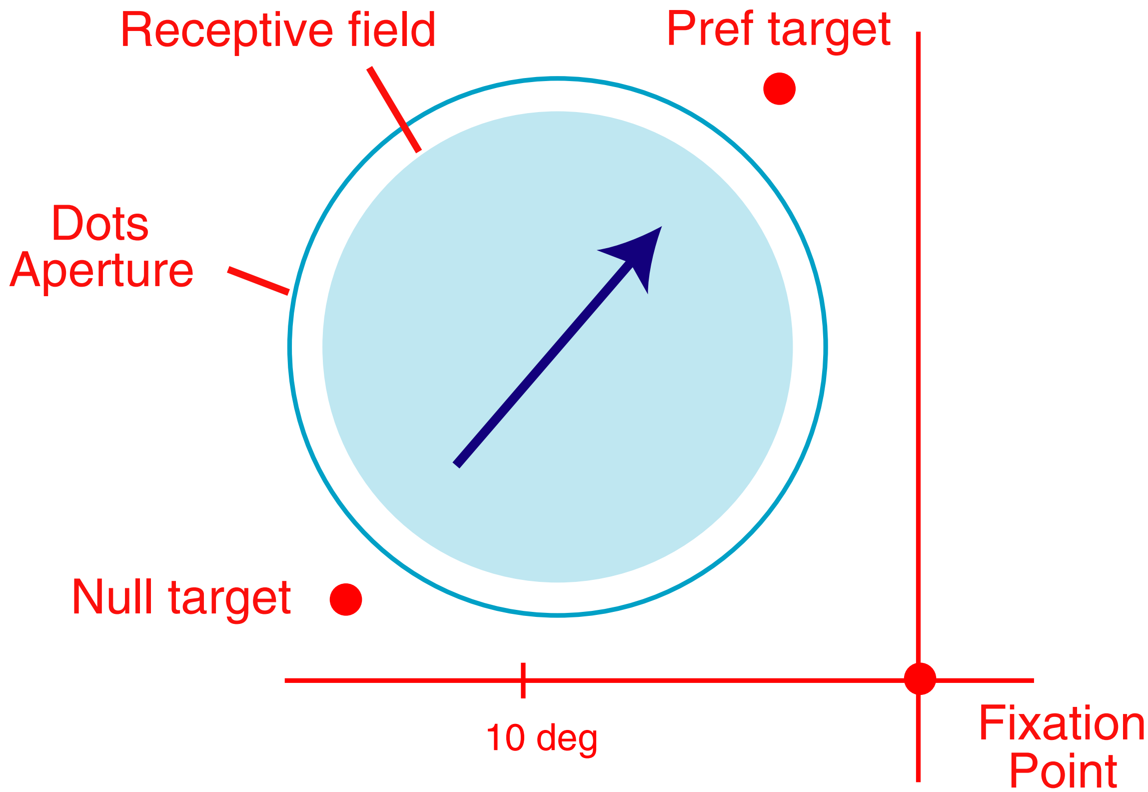


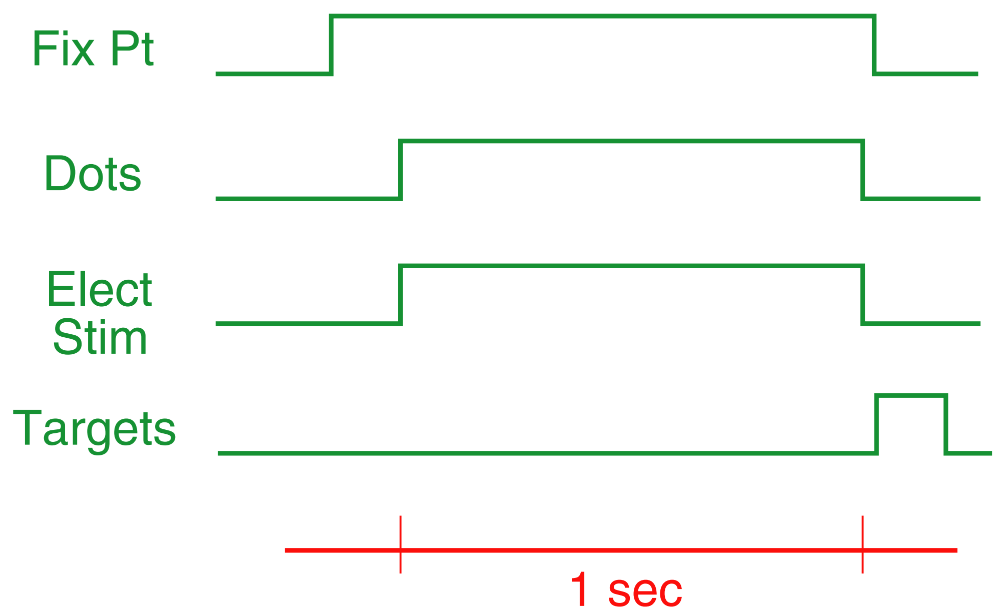
Albright, 1984

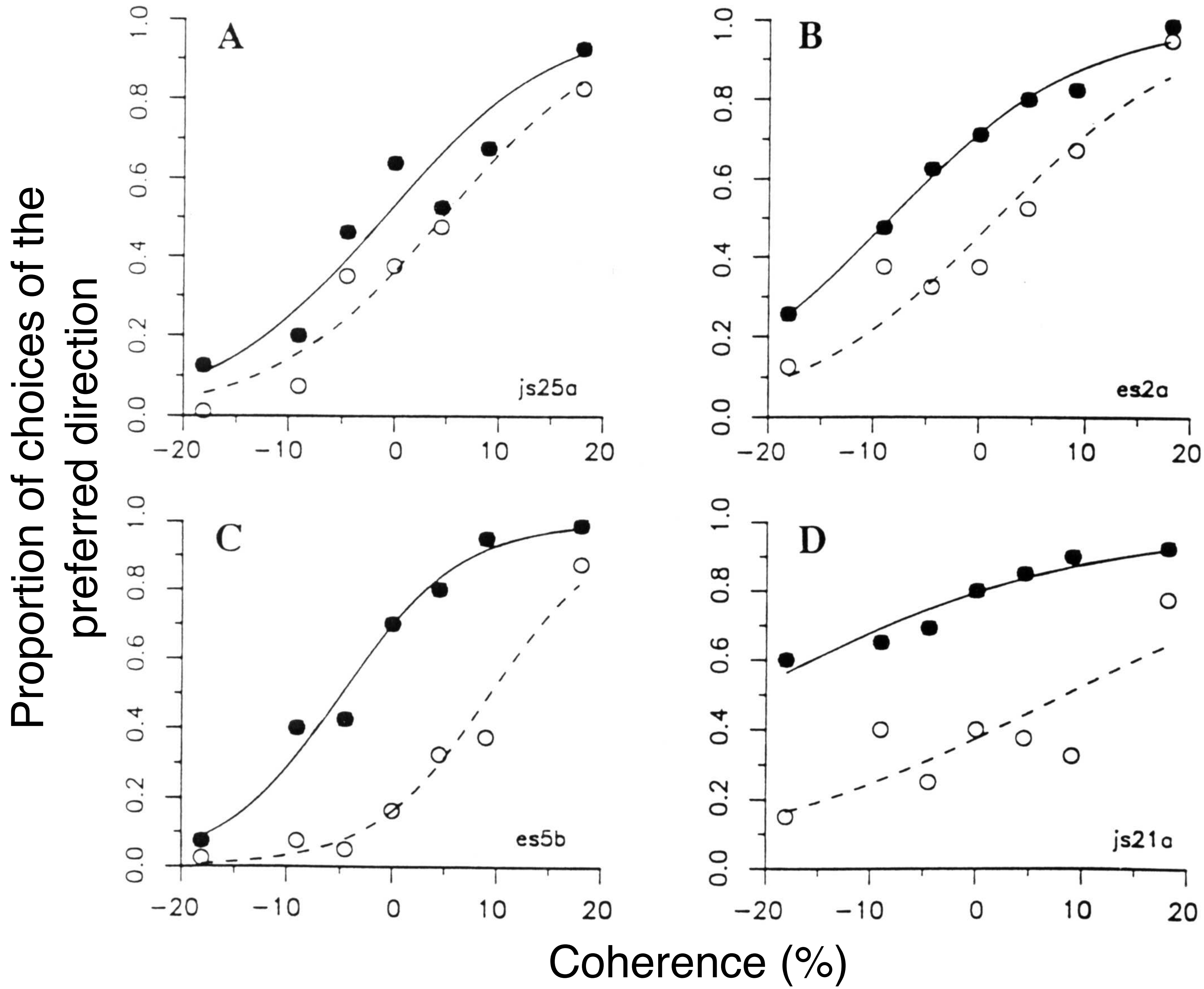

Stimulate
LIP, VIP
7a
DP
V1
MT
V4
MST
V2
FST
FEF
PITd
STP
VP
PITv
VOT
CITd
CITv
AITd
AITv
Visual input



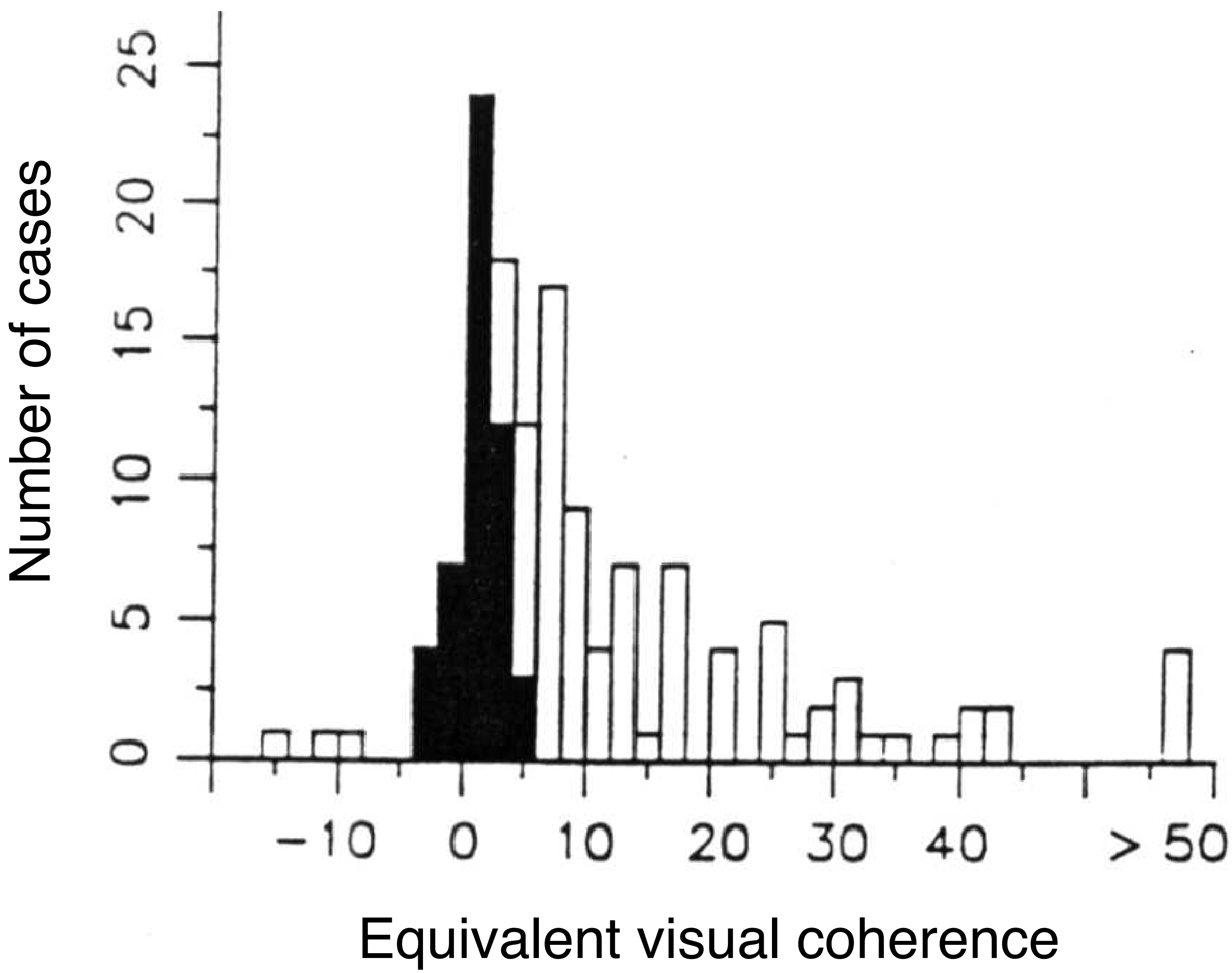
+ microstimulation in MT



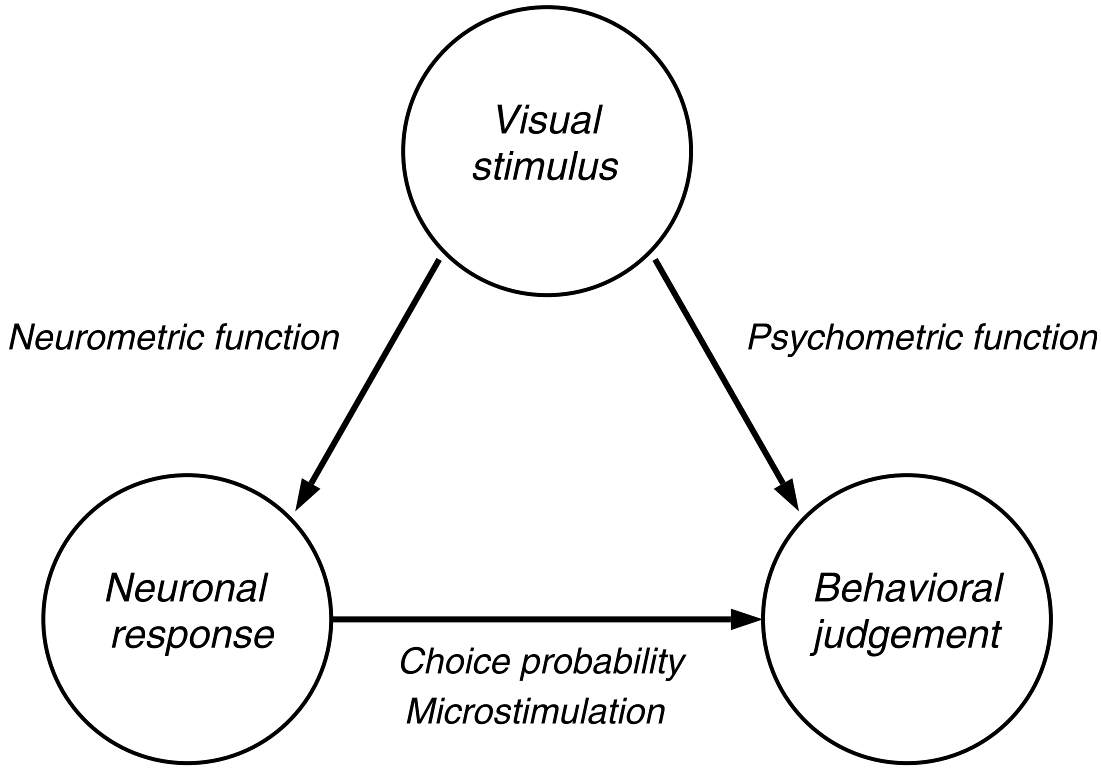




Salzman, Murasugi, Britten and Newsome, 1992

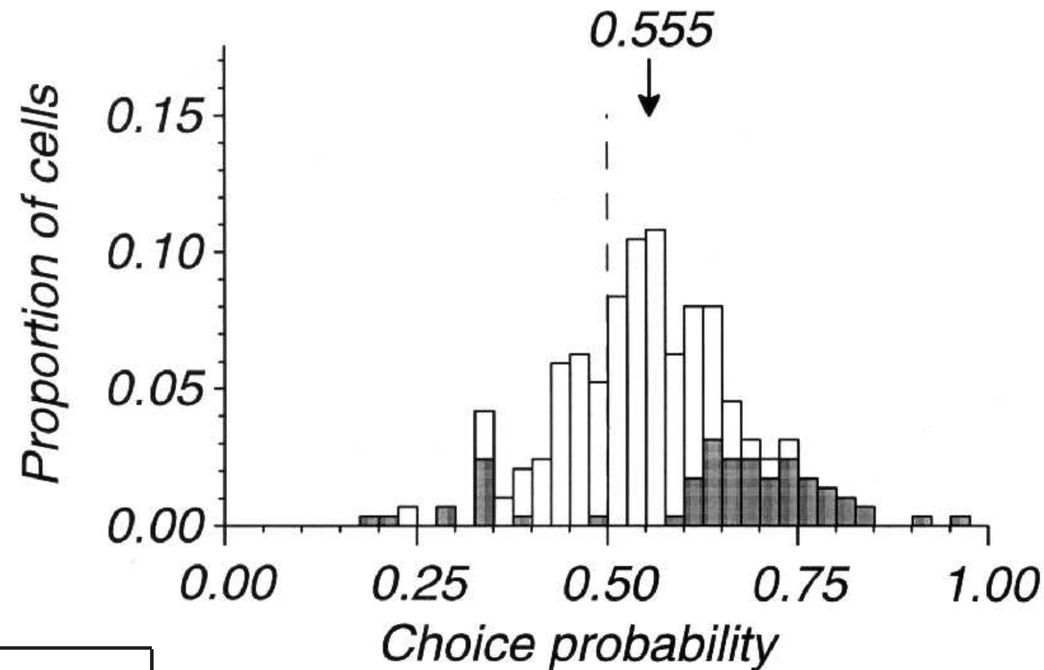


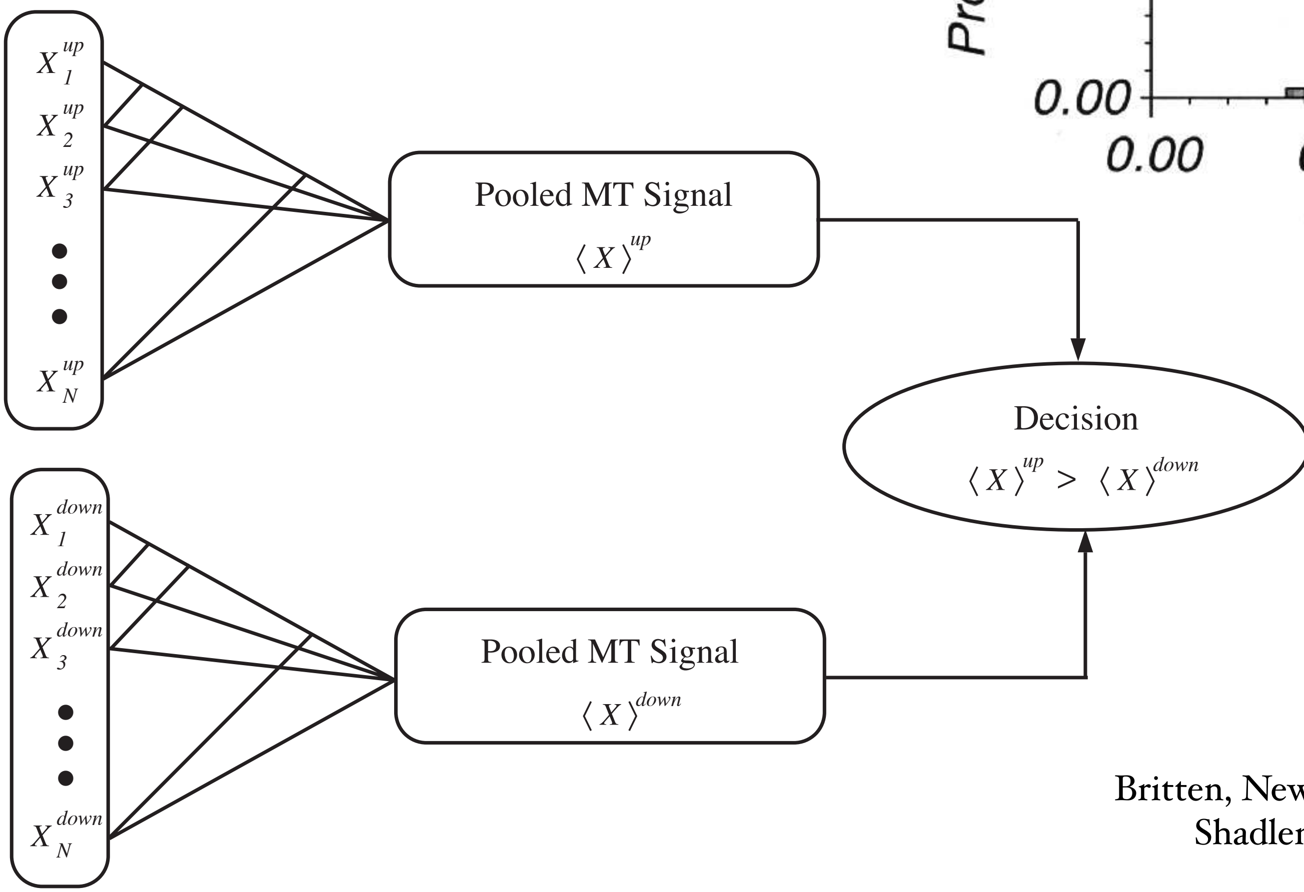
Salzman, Murasugi, Britten and Newsome, 1992



Visual stimulus
Neurometric function
Psychometric function
Neuronal response
Behavioral judgement
Choice probability
Microstimulation

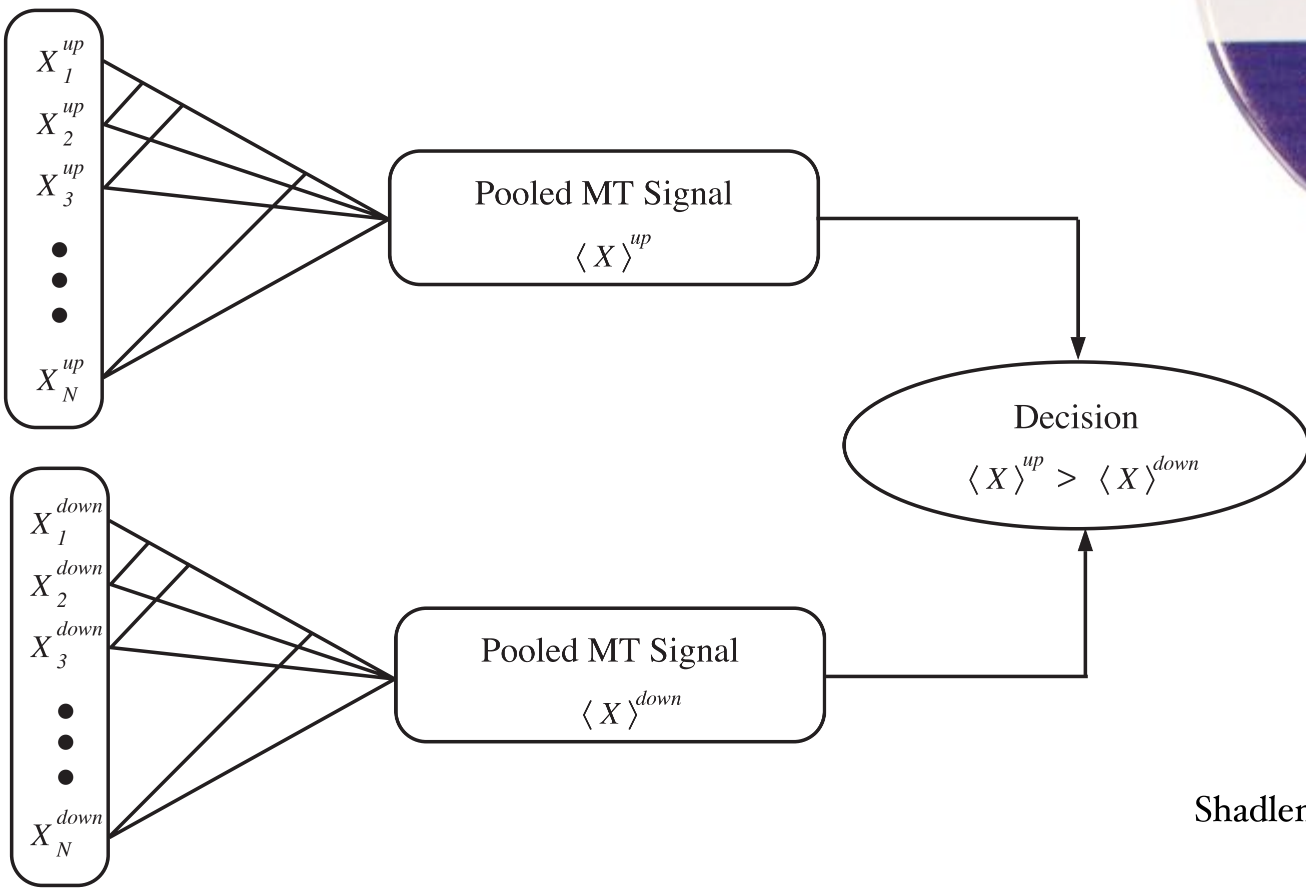
Decoding MT neurons for visual motion discrimination





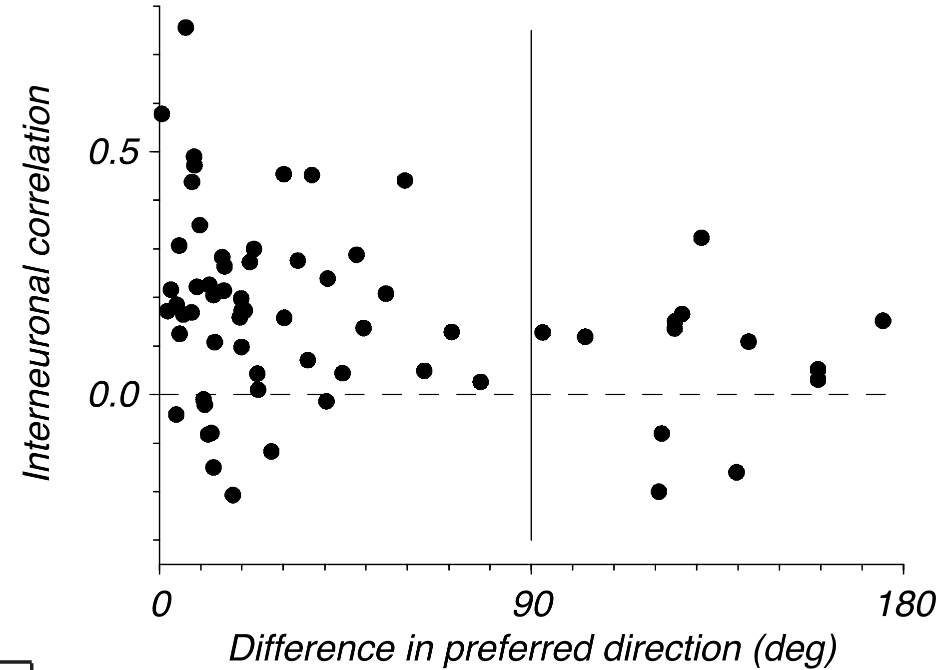
Britten, Newsome, Shadlen, Celebrini & Movshon, 1996
Shadlen, Britten, Newsome & Movshon, 1996
Cohen & Newsome, 2009

Decoding MT neurons for visual motion discrimination

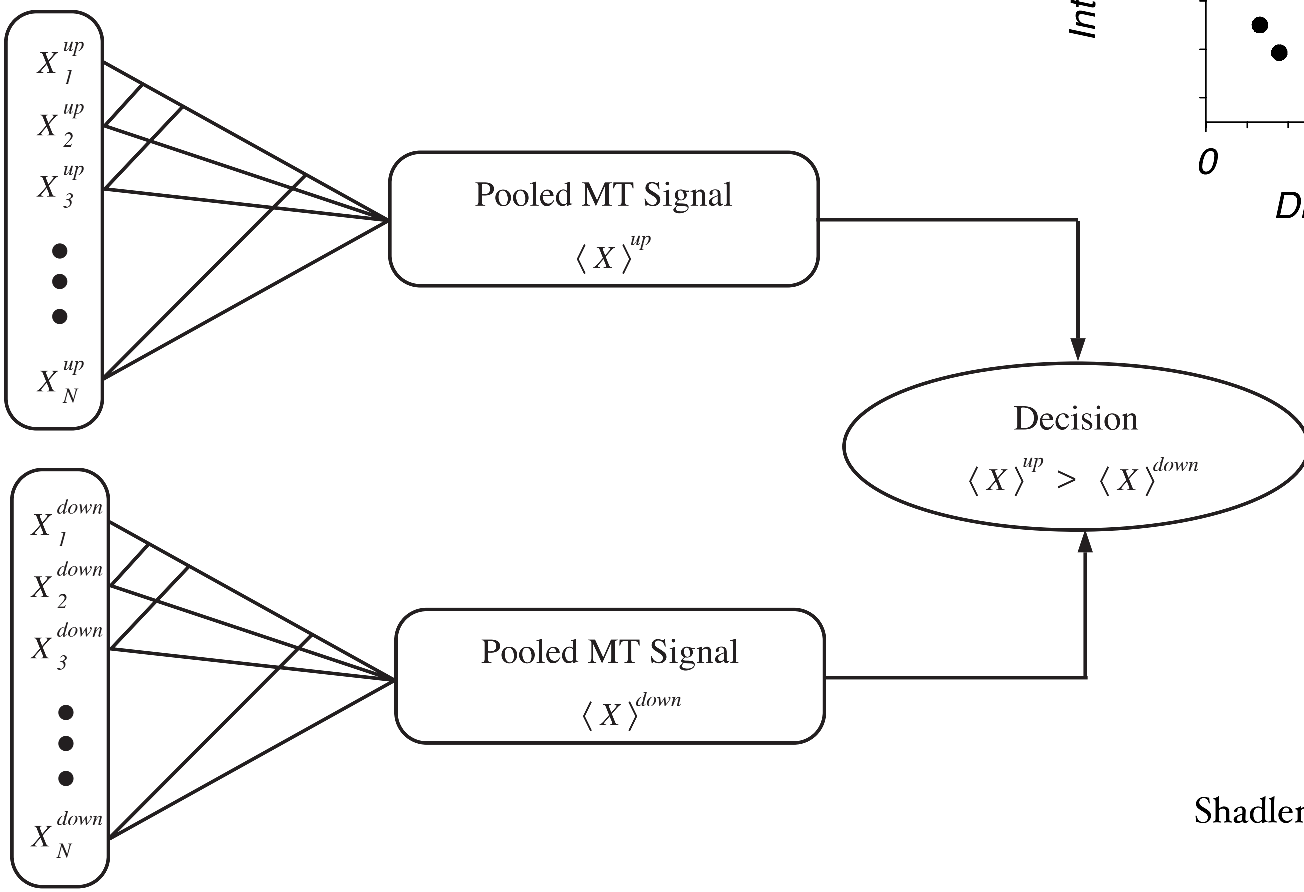


Shadlen, Britten, Newsome & Movshon, 1996
Cohen & Newsome, 2009

Decoding MT neurons for visual motion discrimination

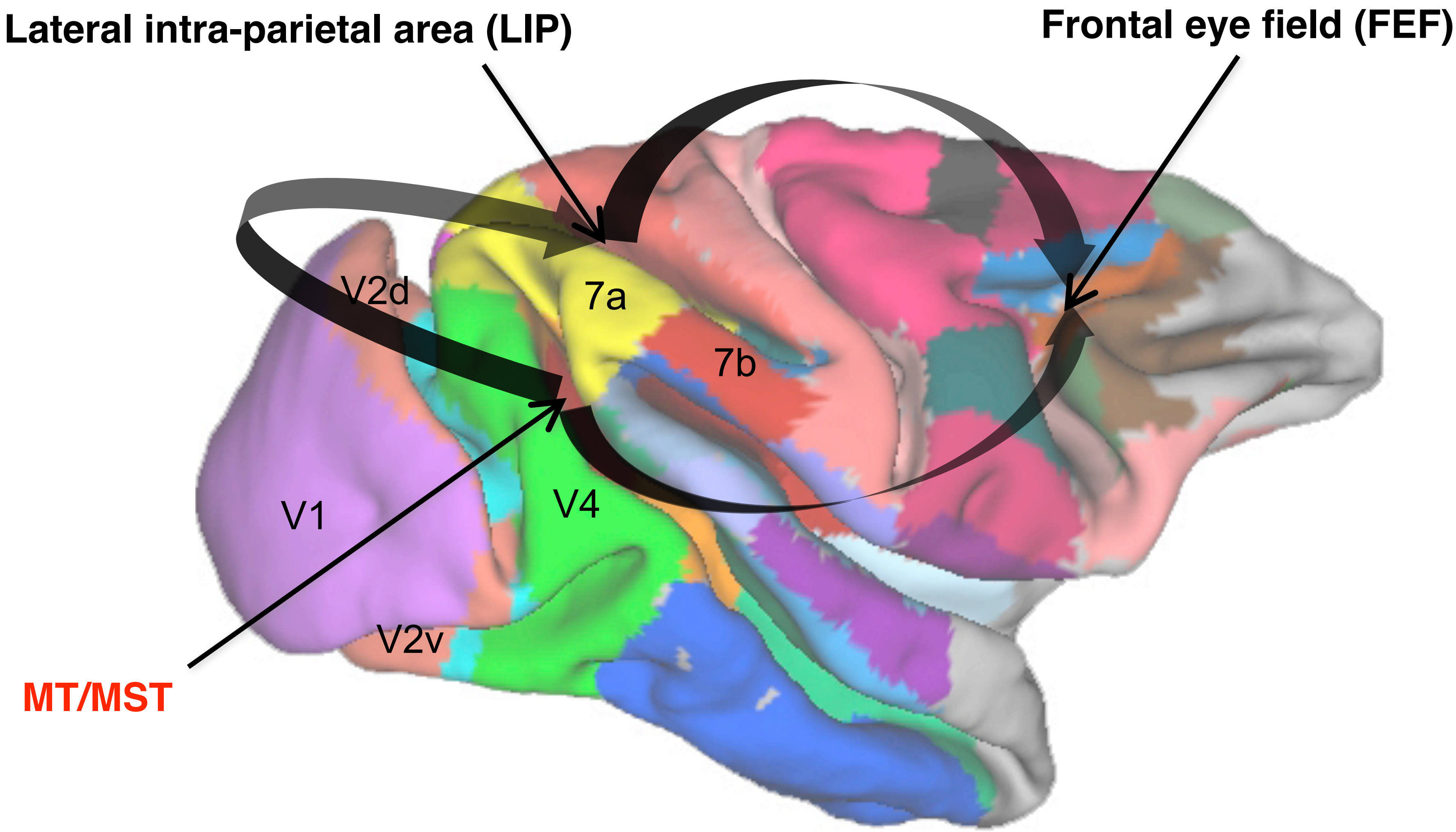


Zohary, Shadlen & Newsome, 1994

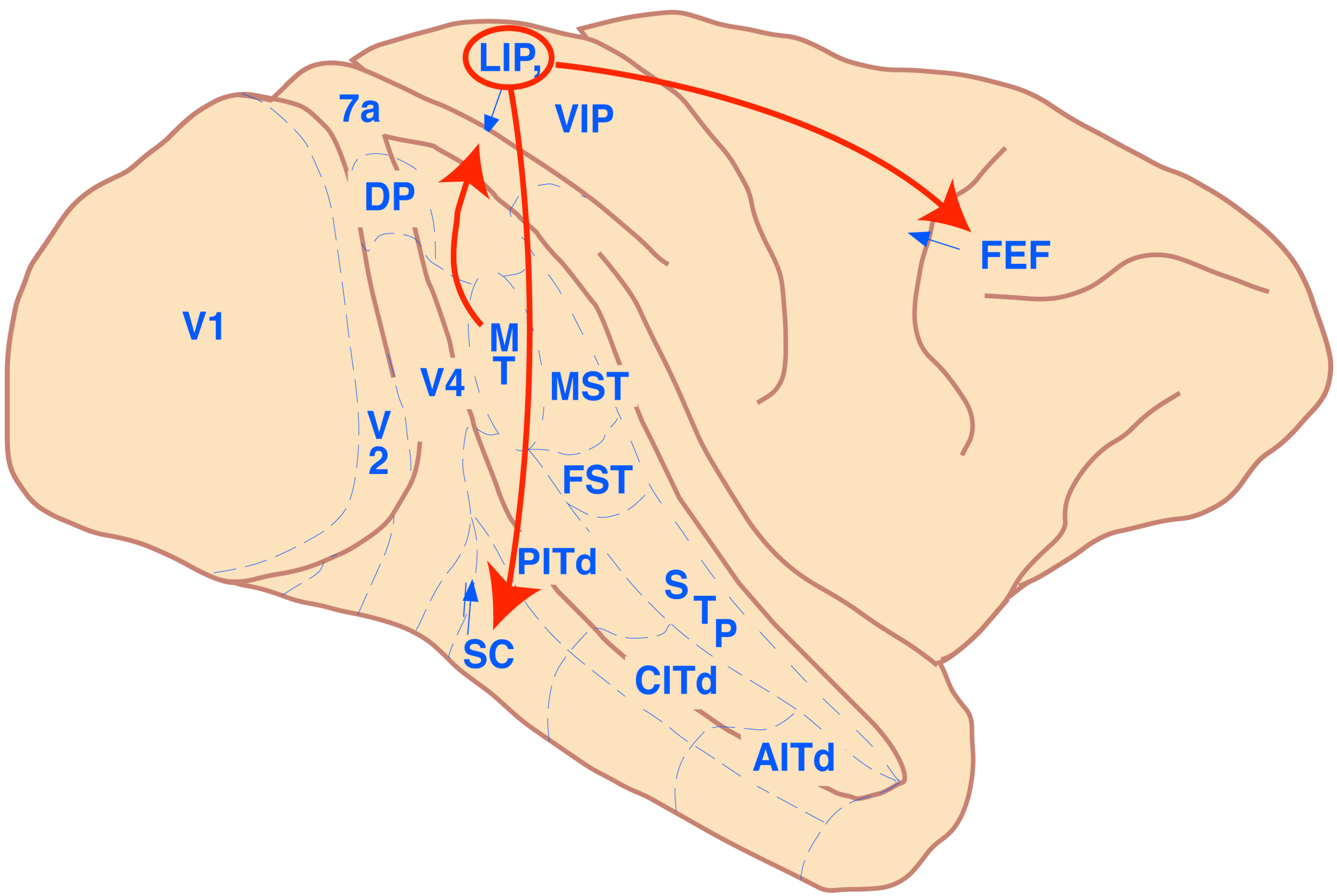


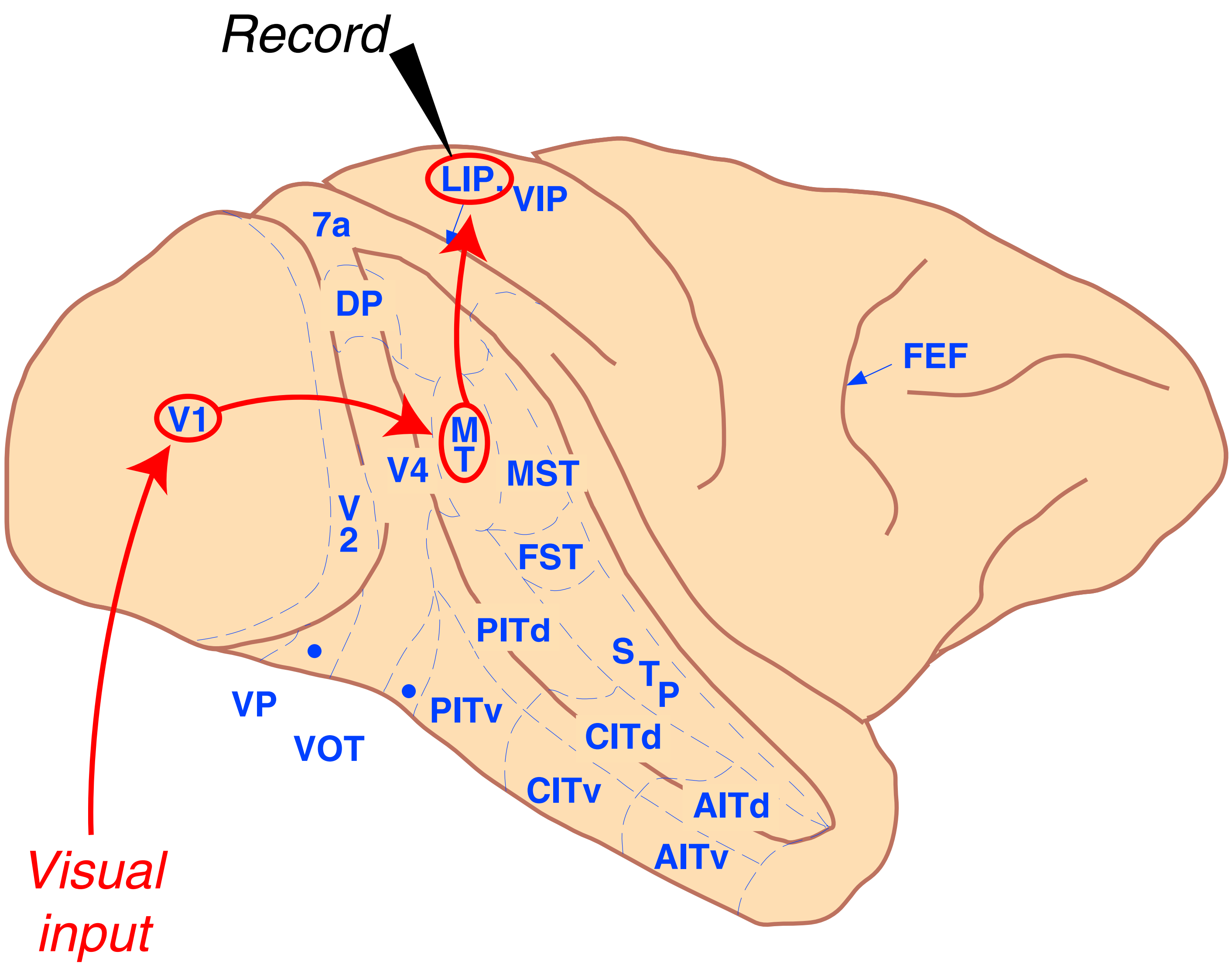
Shadlen, Britten, Newsome & Movshon, 1996
Cohen & Newsome, 2009

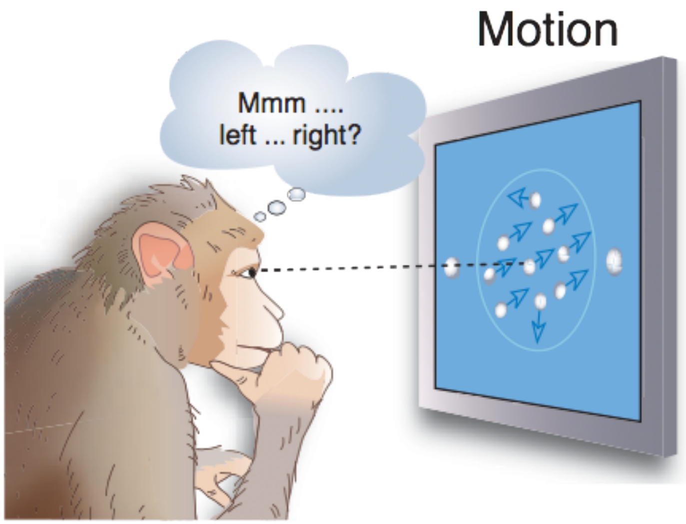
Where is sensory activity converted into decision and actions?



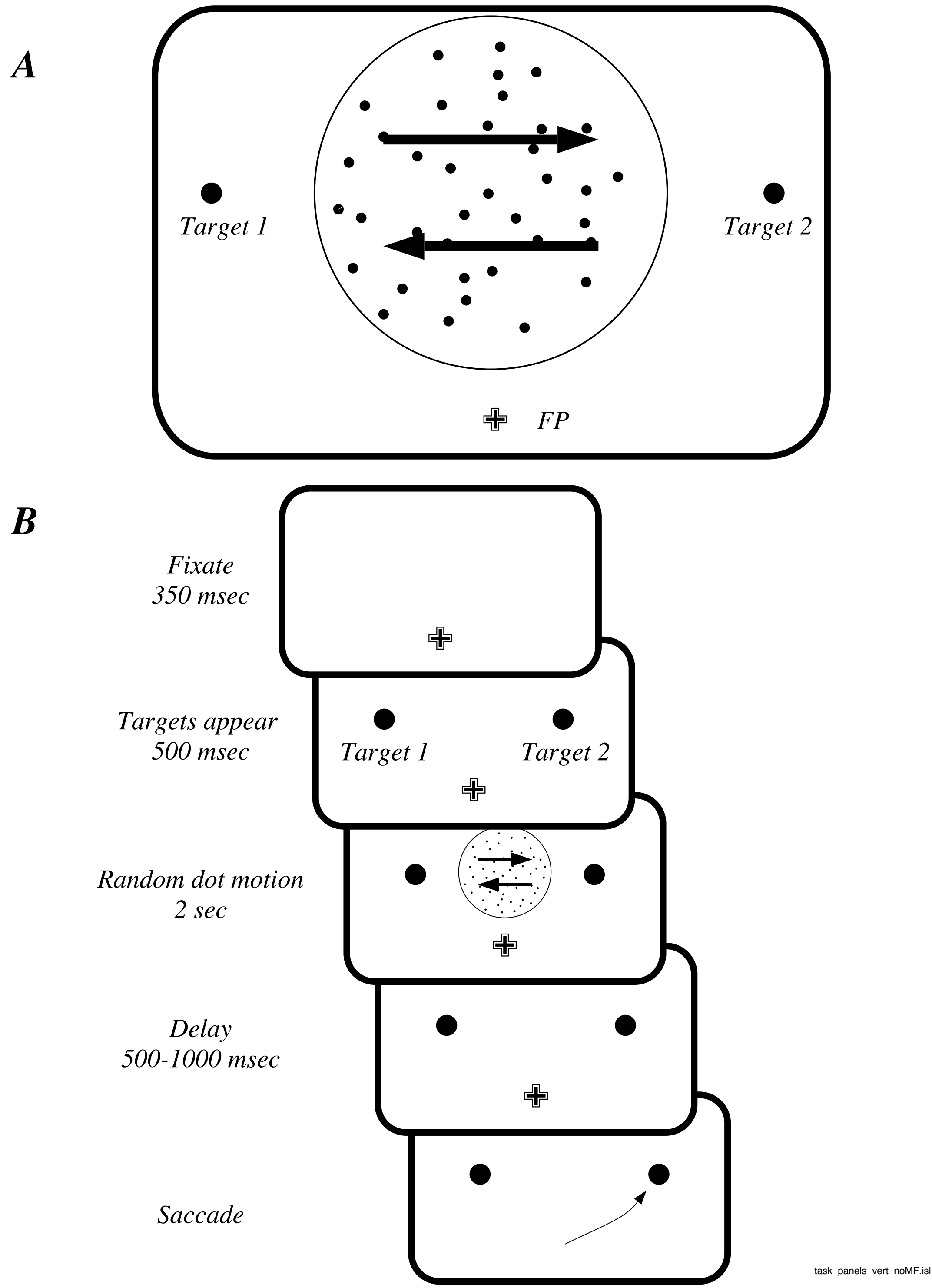
LIP receives projections from MT and projects to areas that are known to contribute to the generation of saccadic eye movements



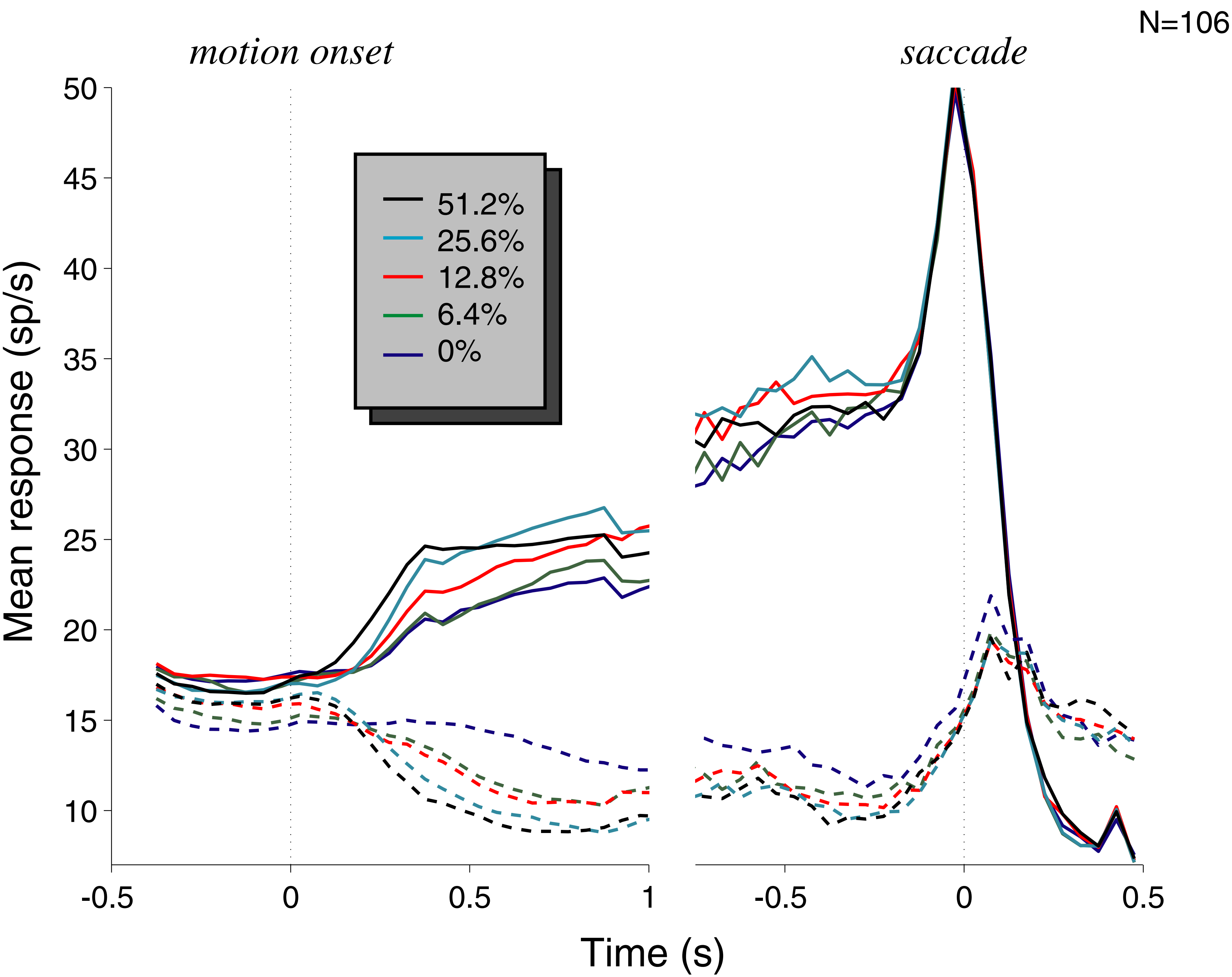

Record
LIP
VIP
7a
DP
FEF
V1
MT
V4
MST
V2
FST
PITd
STP
VP
PITv
CITd
VOT
CITv
AITd
AITv
Visual input



+ recording in LIP

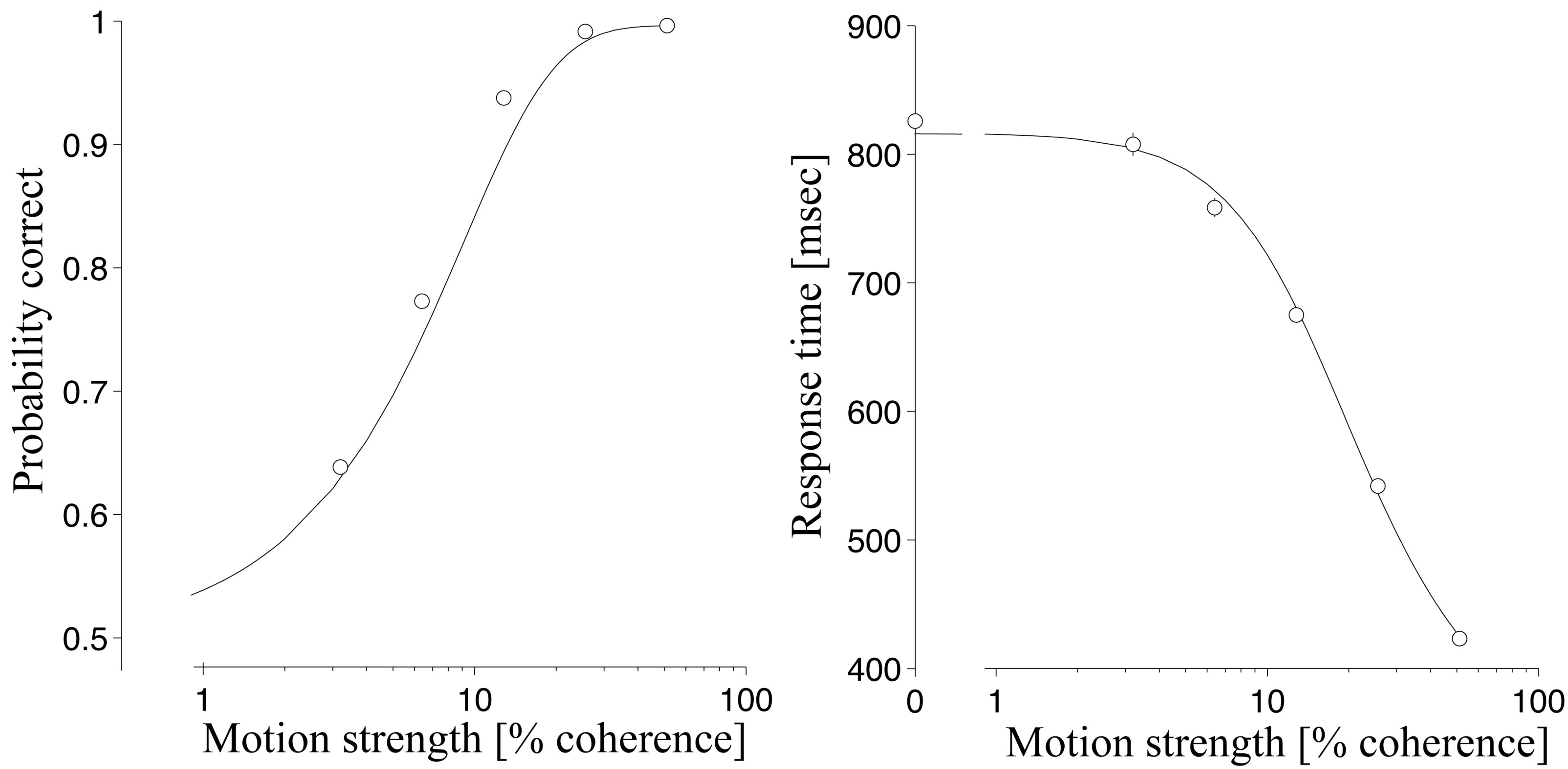


Shadlen and Newsome, 2001



Mike Shadlen

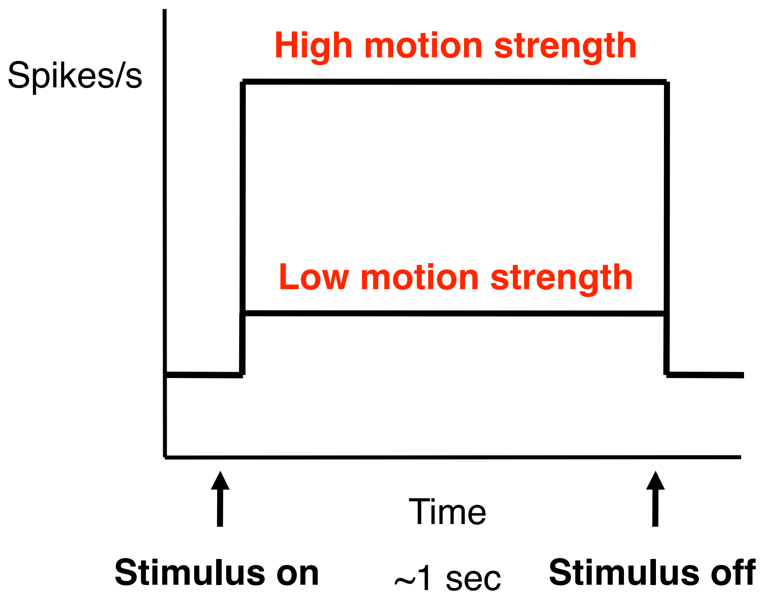
Responses in a reaction-time version of the direction discrimination task



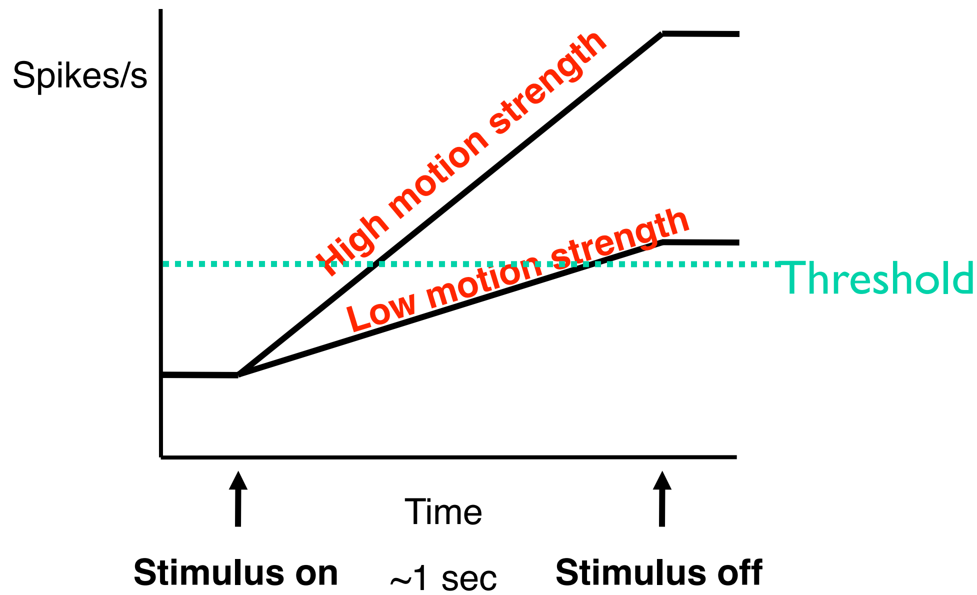
Mike Shadlen

Bounded accumulation of evidence

MT – sensory evidence
Motion energy "step"

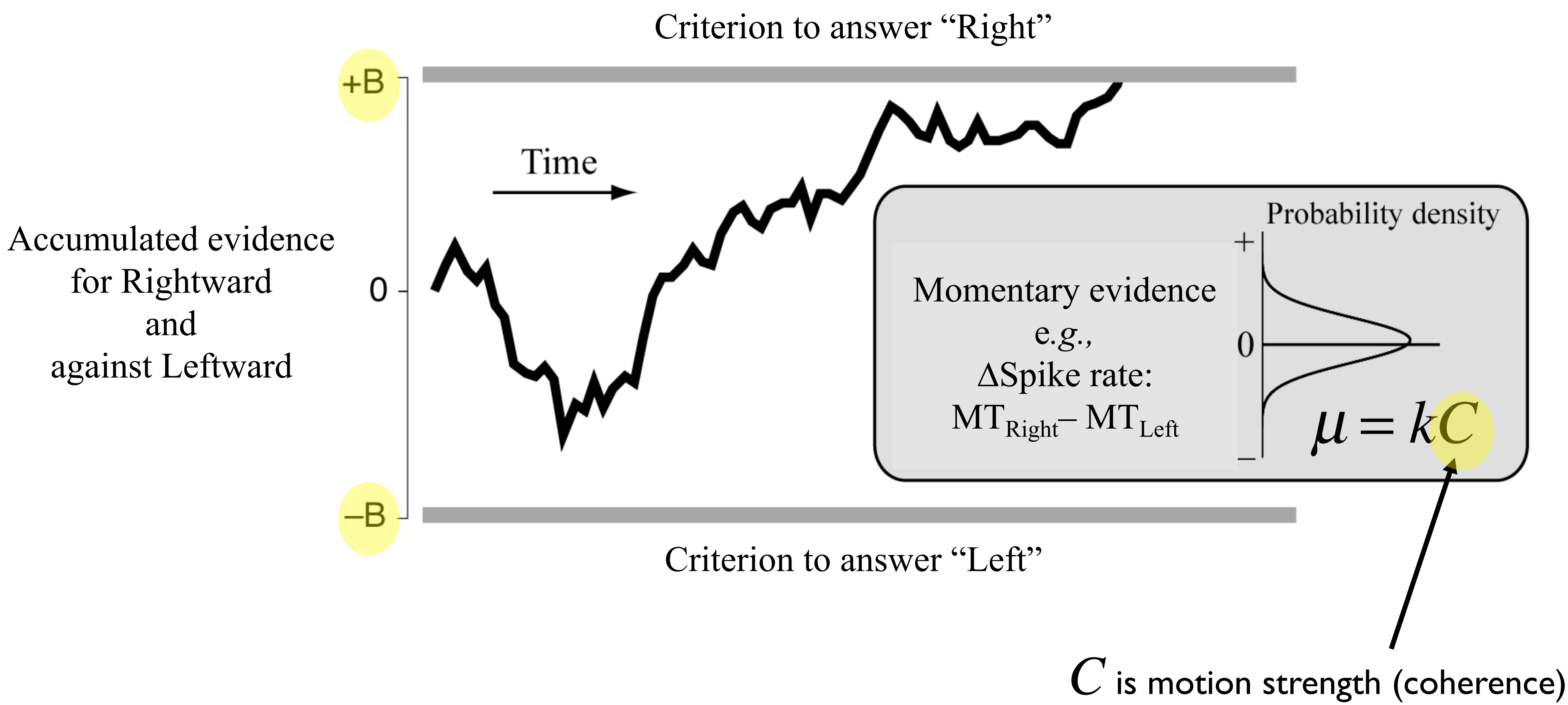


LIP – decision formation
Accumulation of evidence "ramp"



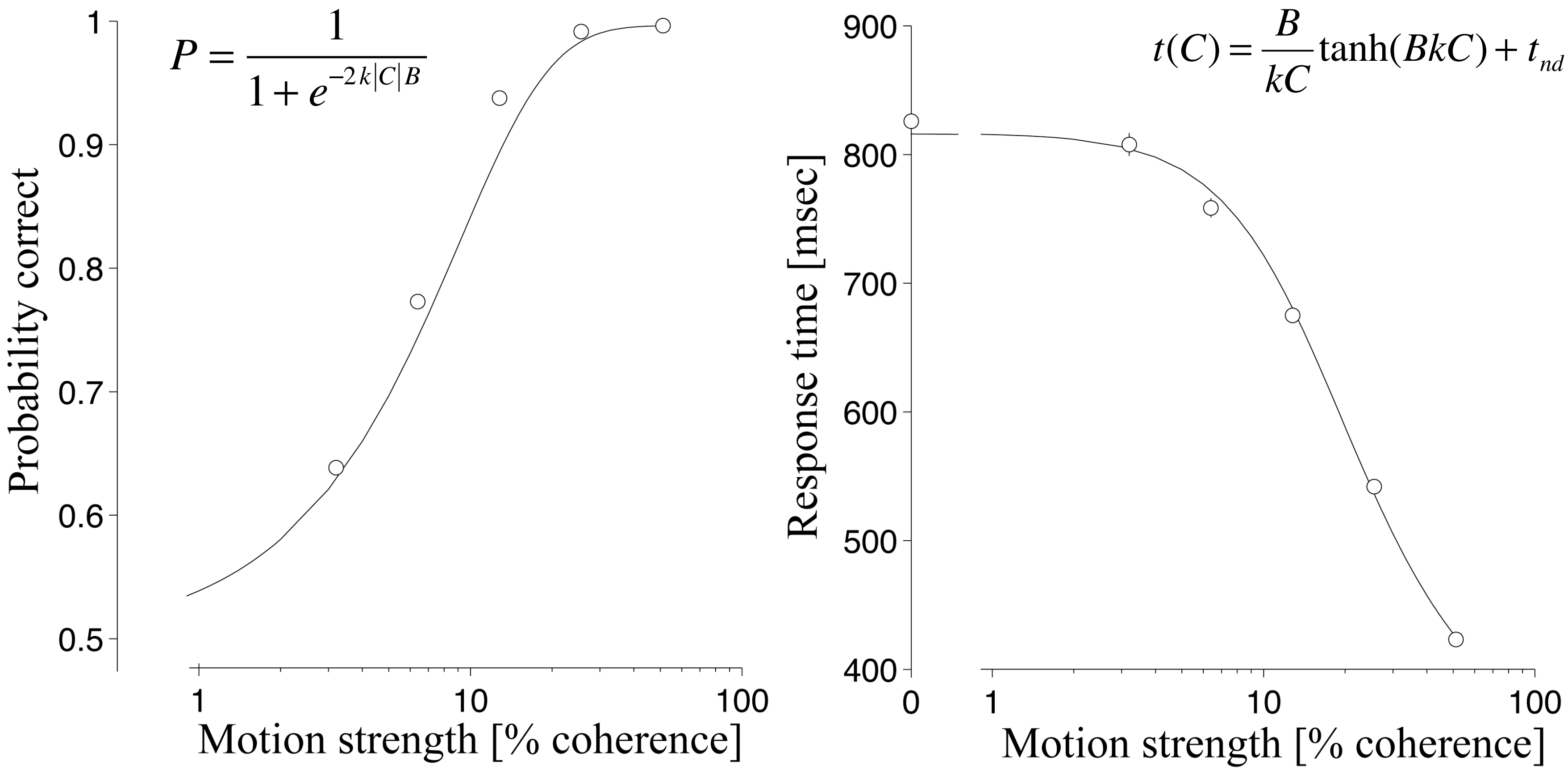
Mike Shadlen

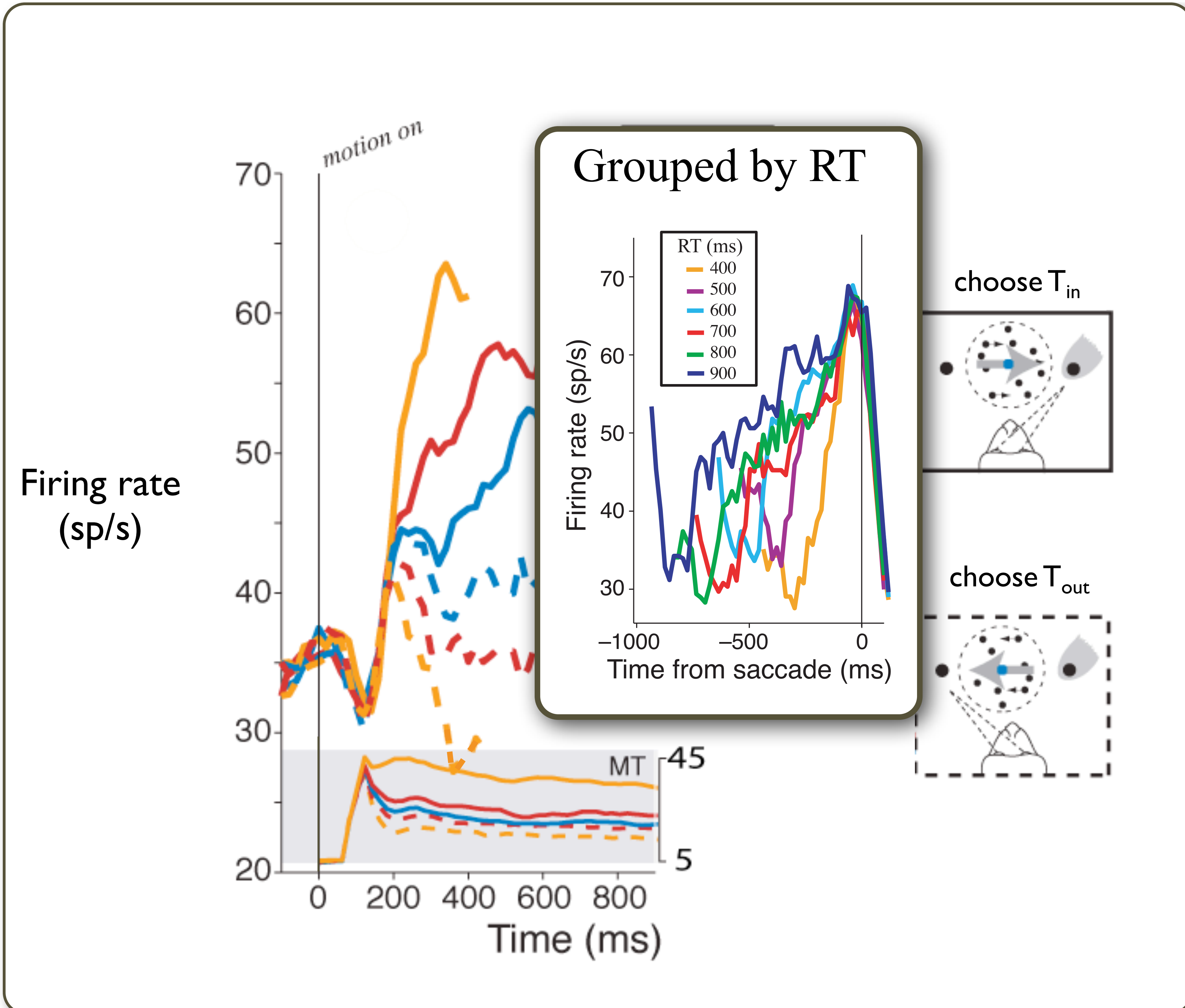
Diffusion to bound model



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

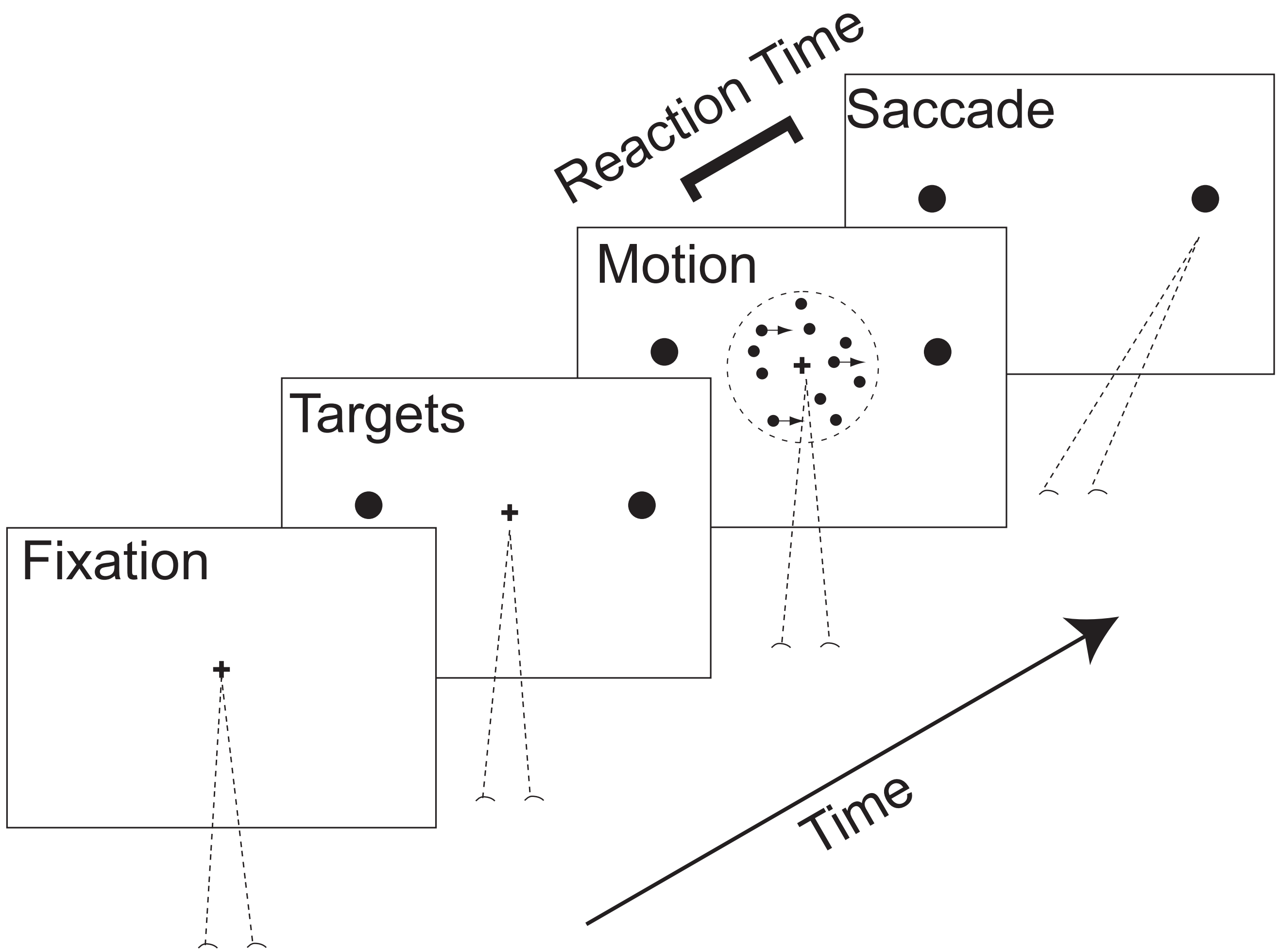
Responses in a reaction-time version of the direction discrimination task
are well described by the "race" model of integration to a decision boundary





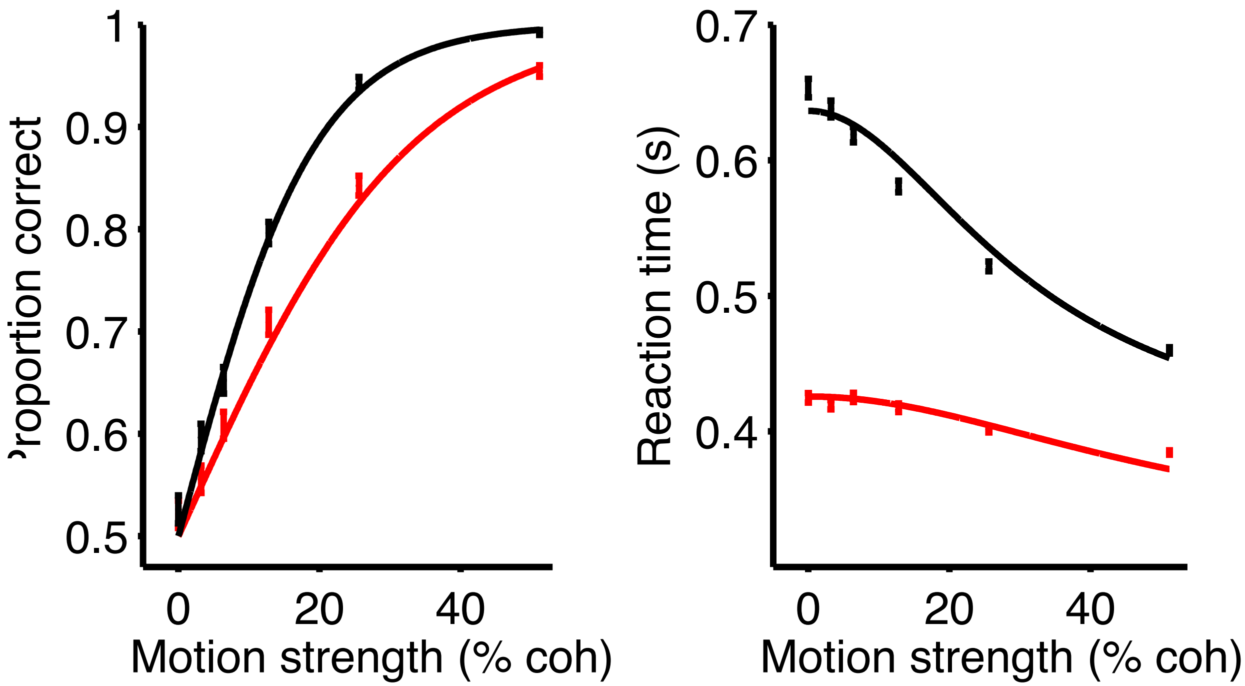
Roitman & Shadlen, 2002

Speed-Accuracy Tradeoff



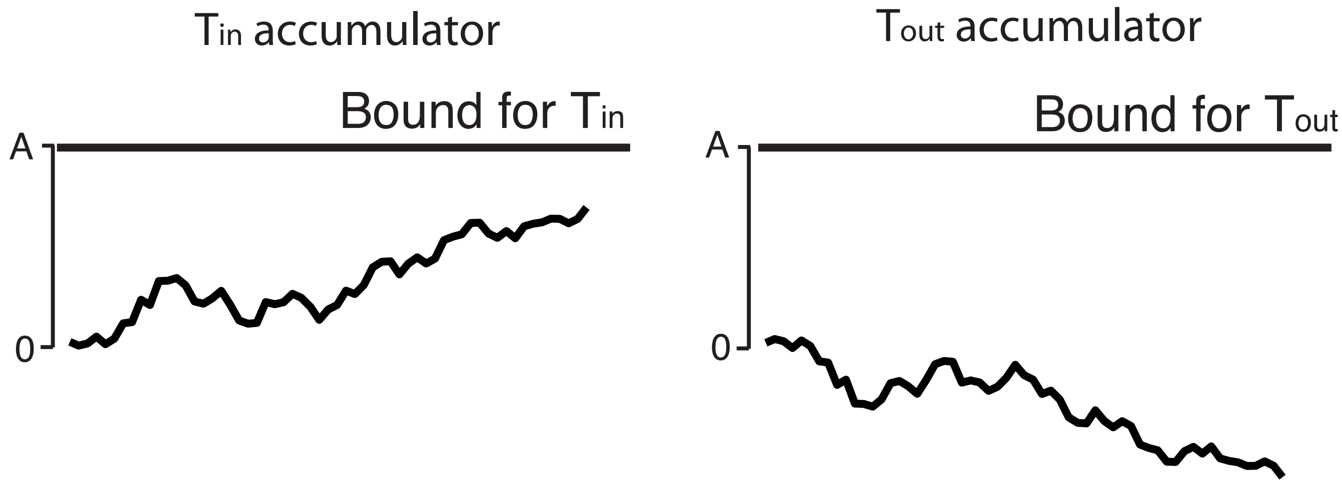
Hanks, Kiani & Shadlen, 2014

Speed-Accuracy Tradeoff



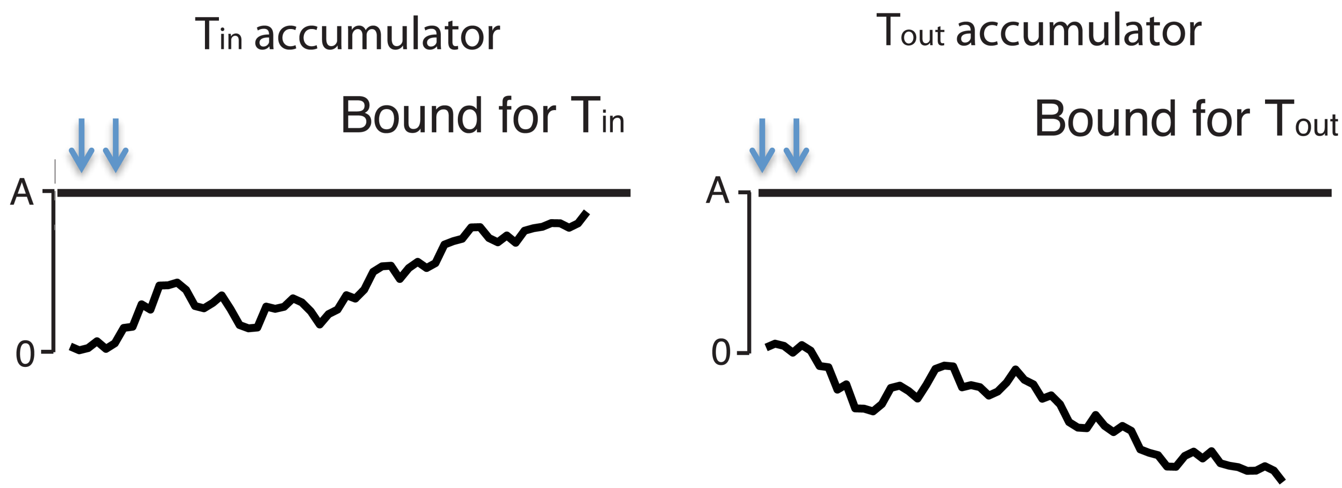
Hanks, Kiani & Shadlen, 2014

Speed-Accuracy Tradeoff

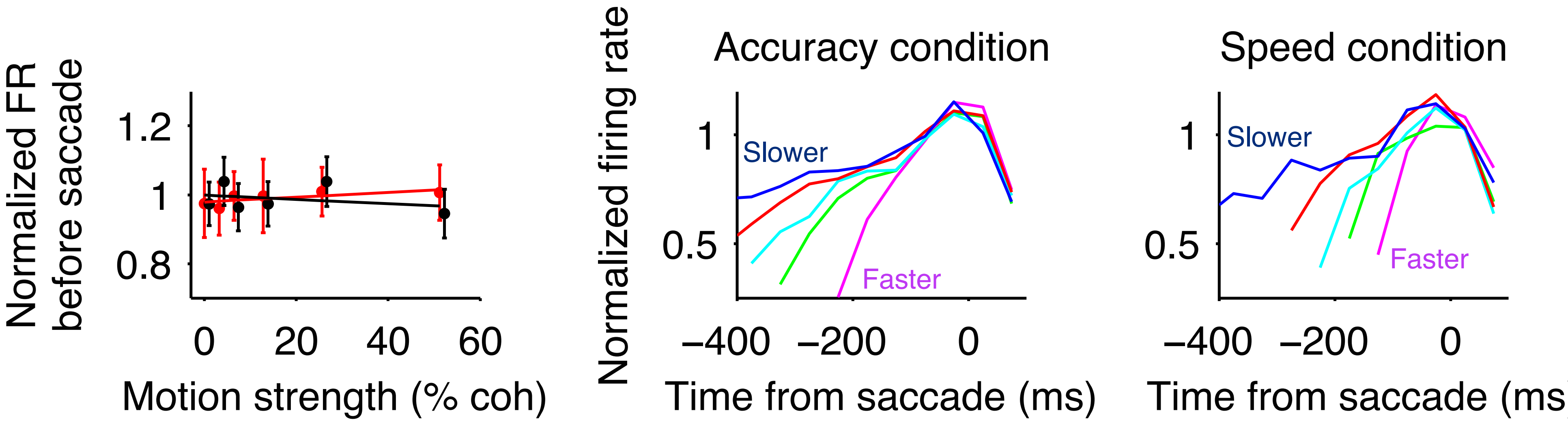


Hanks, Kiani & Shadlen, 2014

Speed-Accuracy Tradeoff

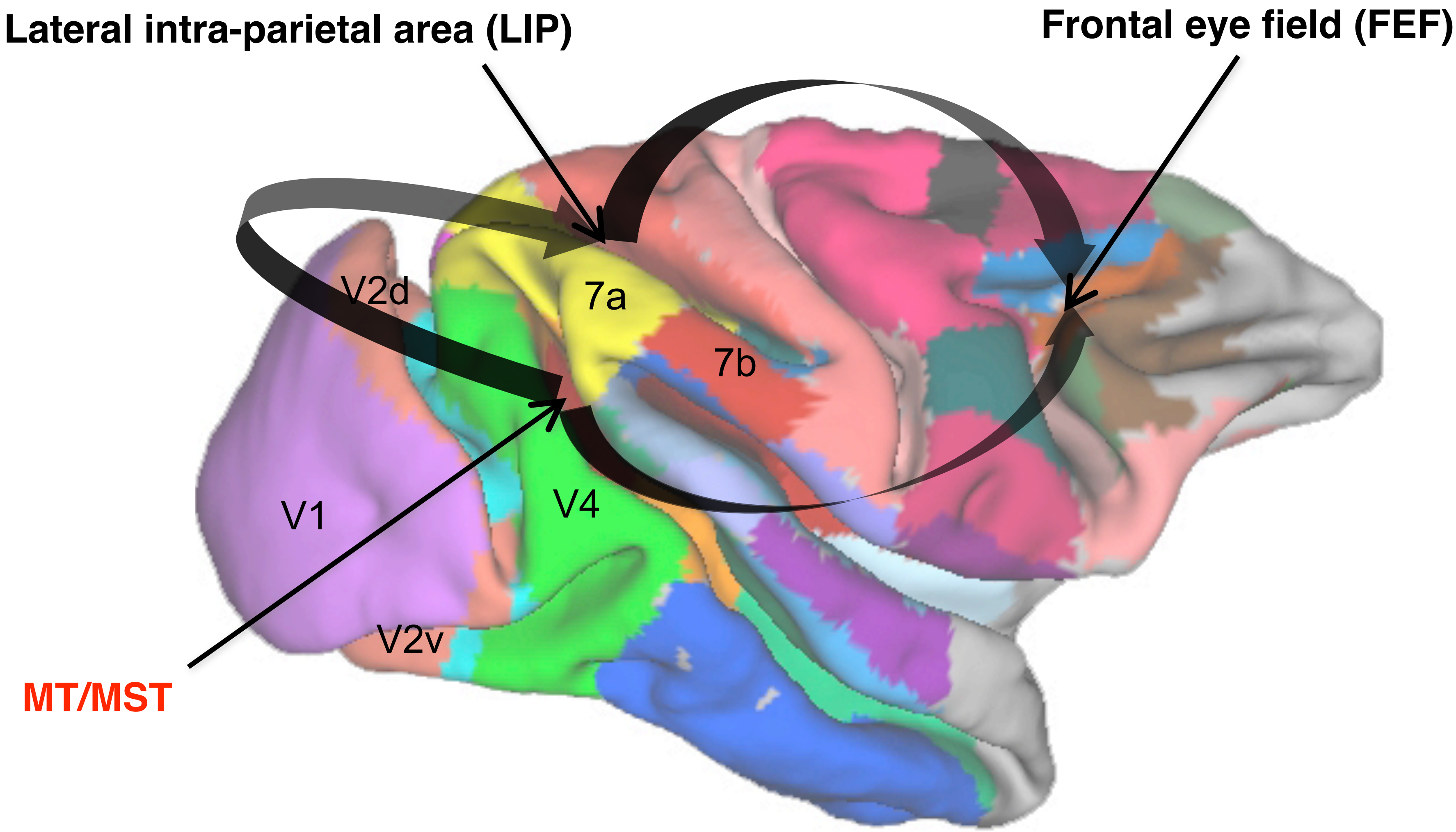


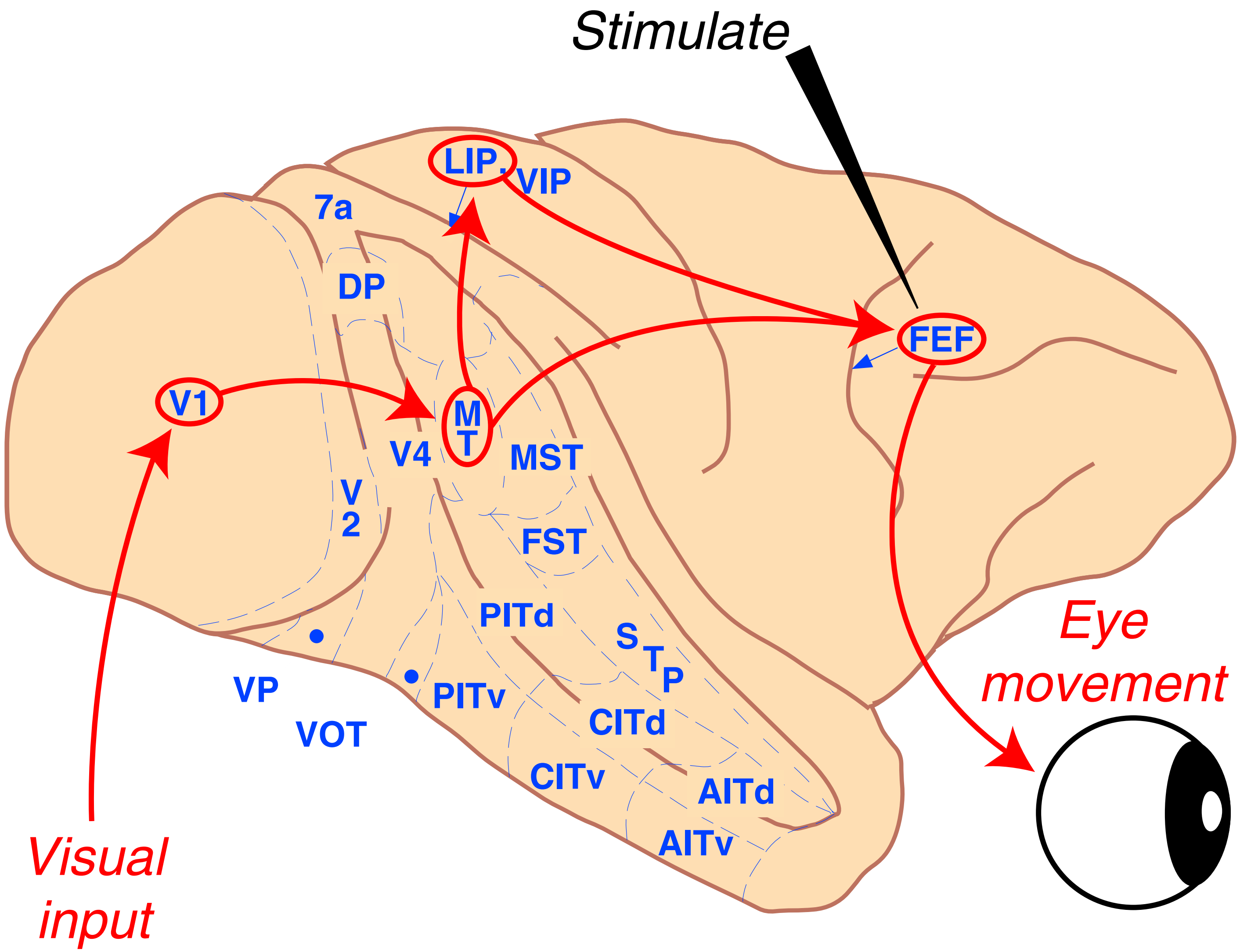
Speed-Accuracy Tradeoff



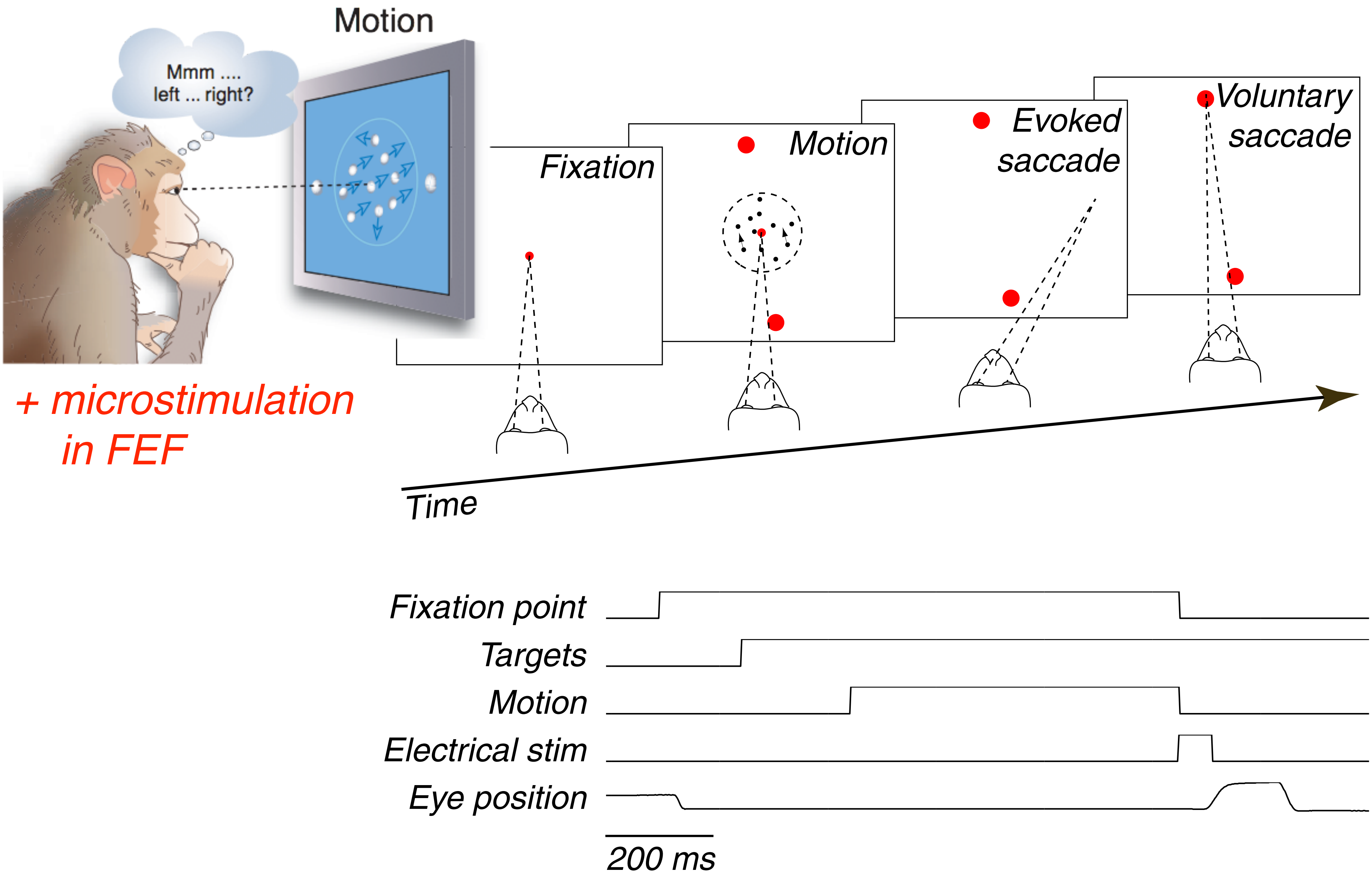
Hanks, Kiani & Shadlen, 2014

Where is sensory activity converted into decision and actions?

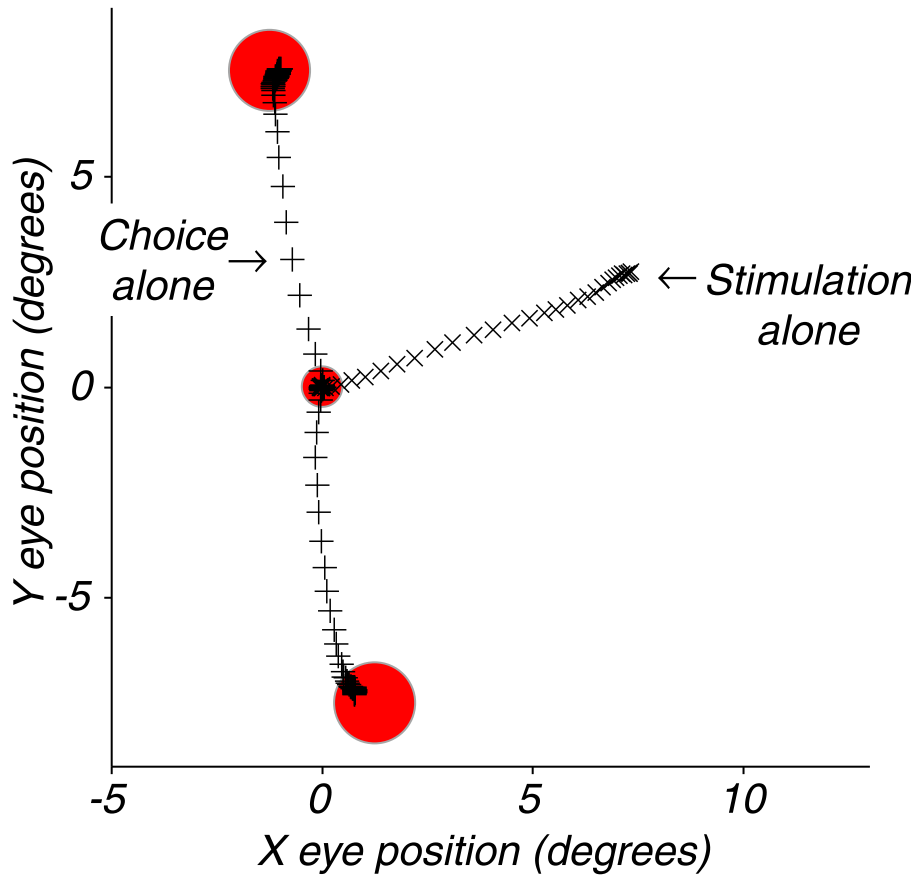




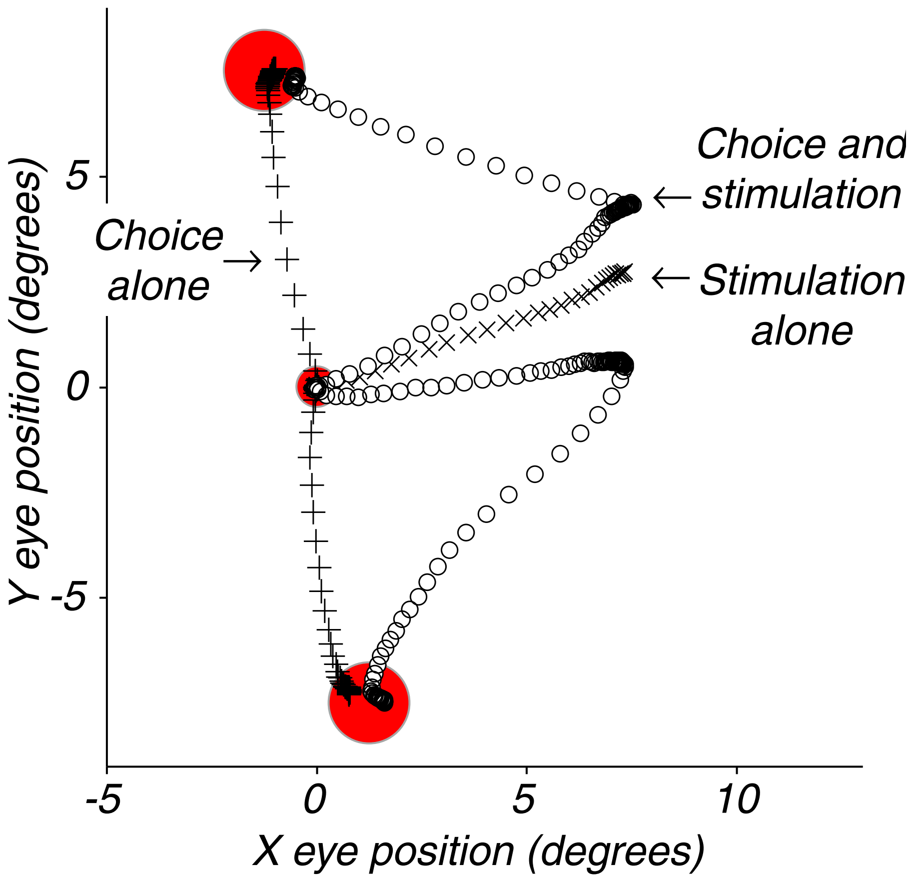
Stimulate
LIP
VIP
7a
DP
V1
M
T
V4
MST
V
2
FST
PITd
S
T
P
VP
VOT
PITv
CITd
CITv
AITd
AITv
FEF
Eye
movement
Visual
input



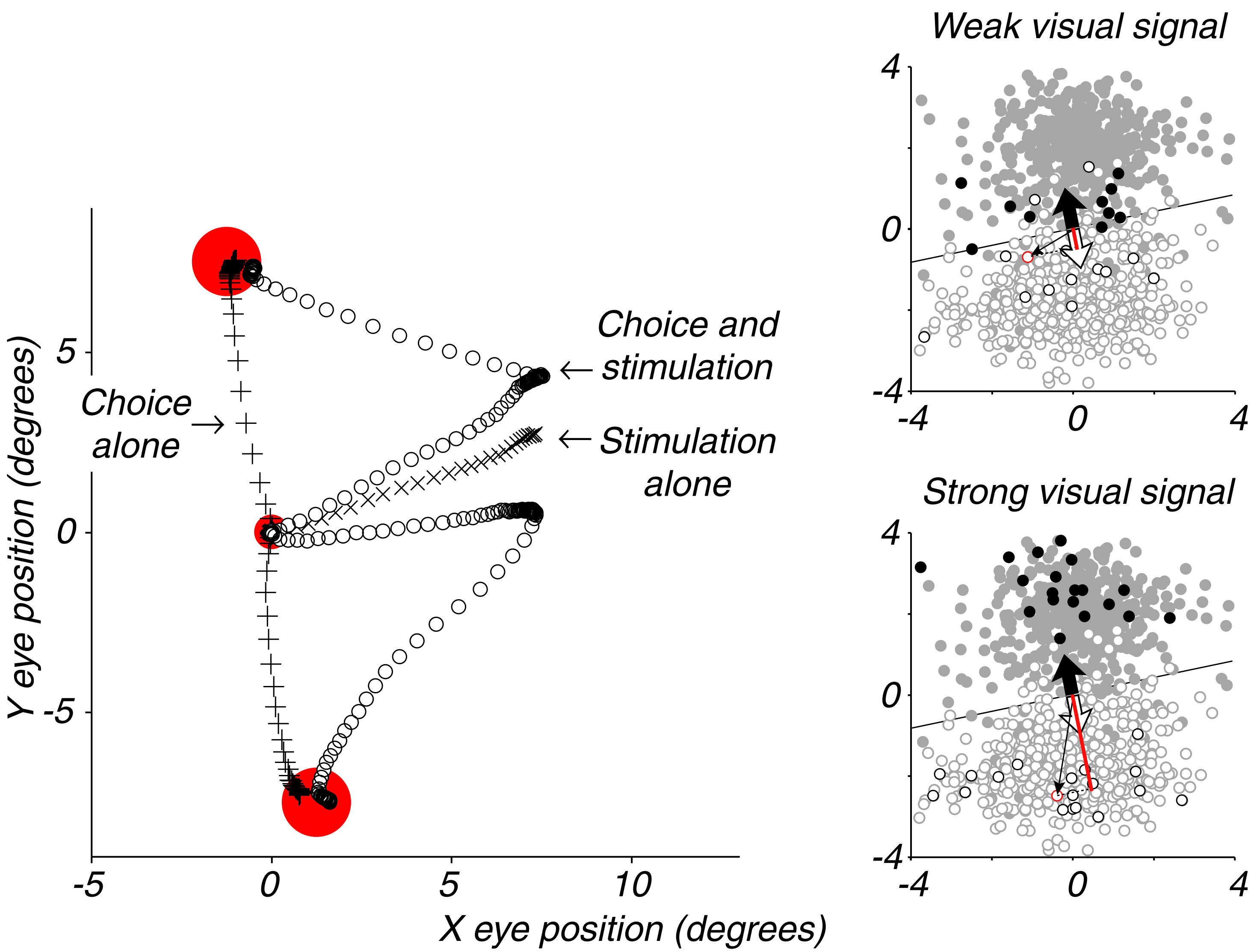
Gold and Shadlen, 2000



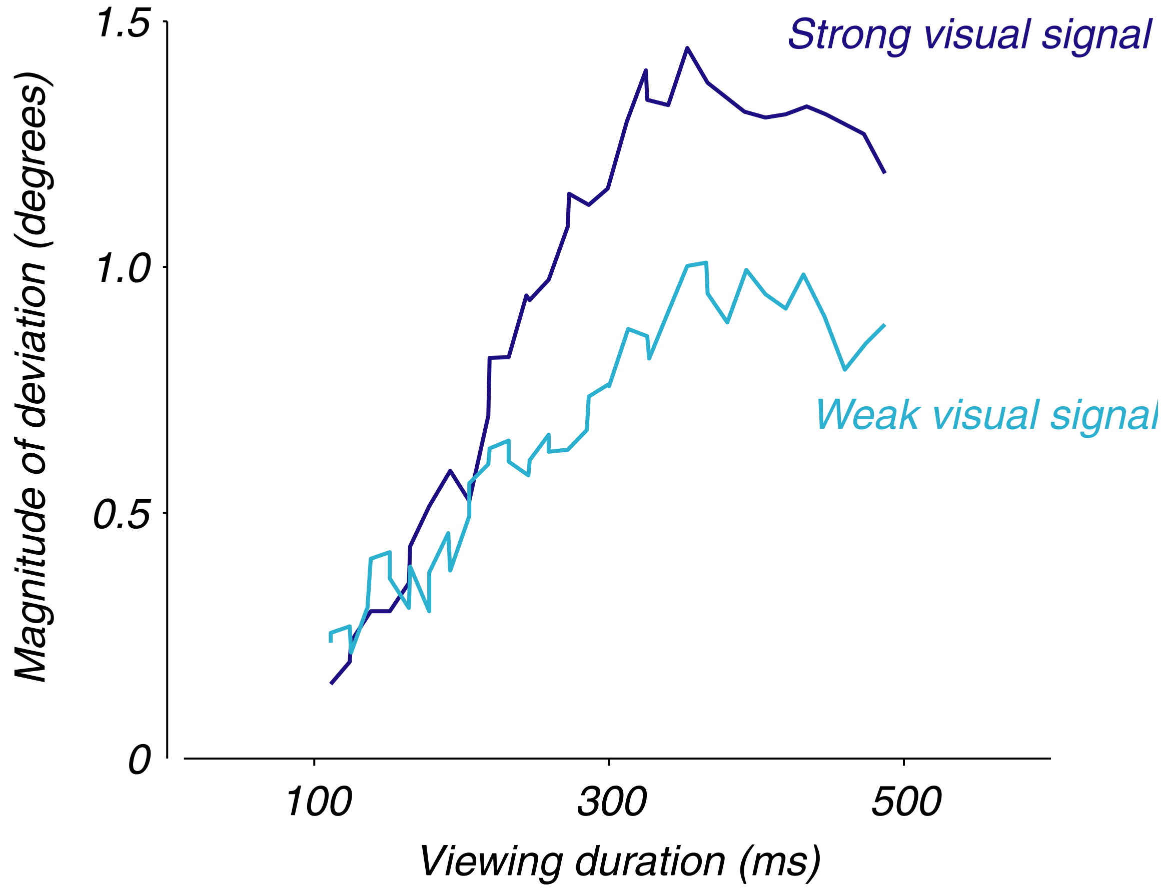
Gold and Shadlen,
2000



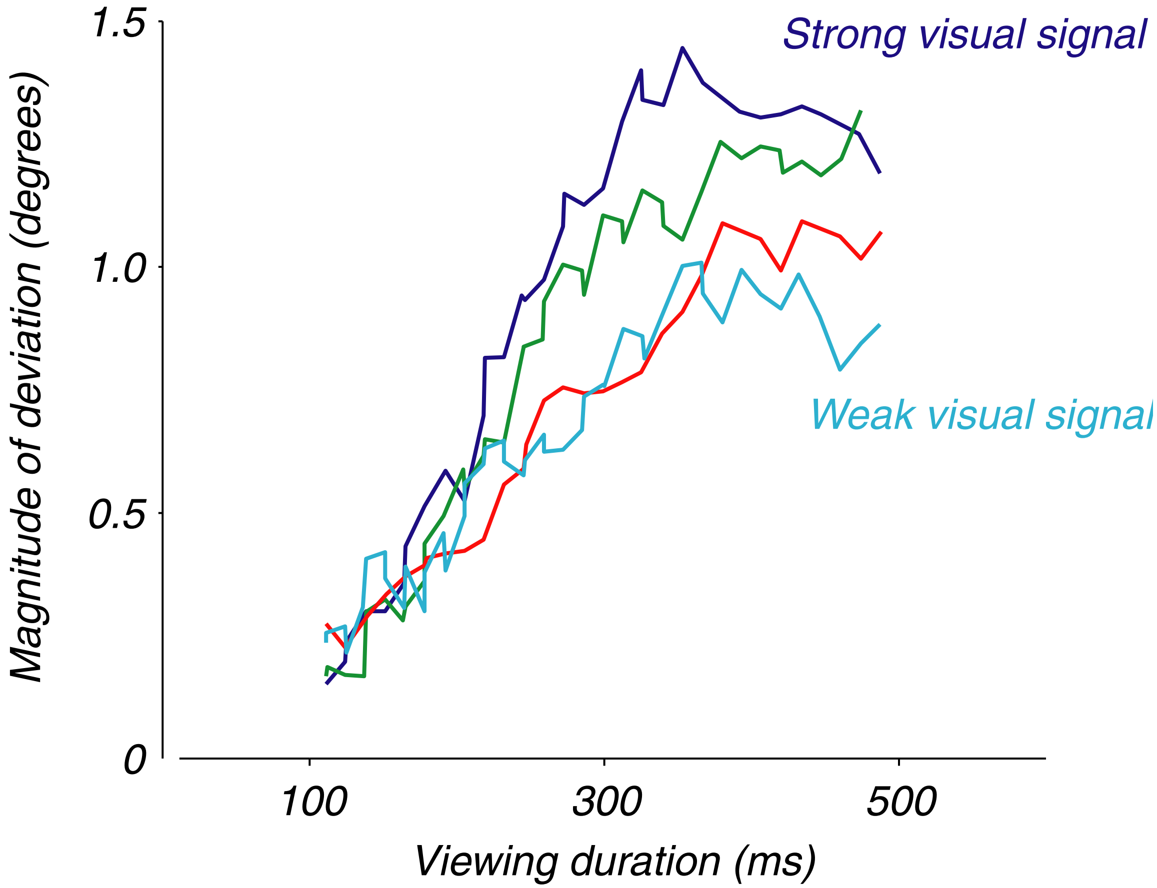
Gold and Shadlen, 2000



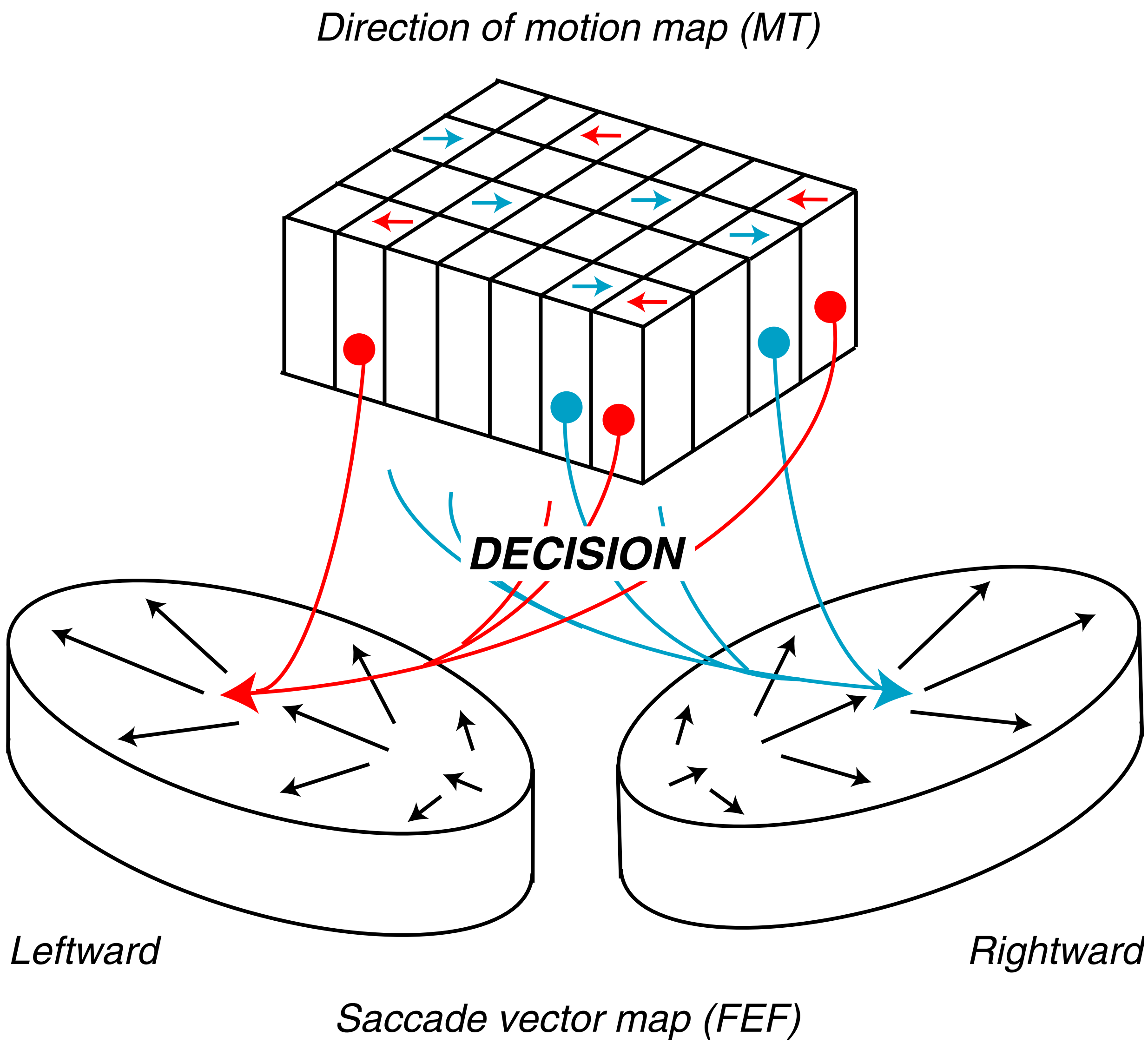
Gold and Shadlen, 2000

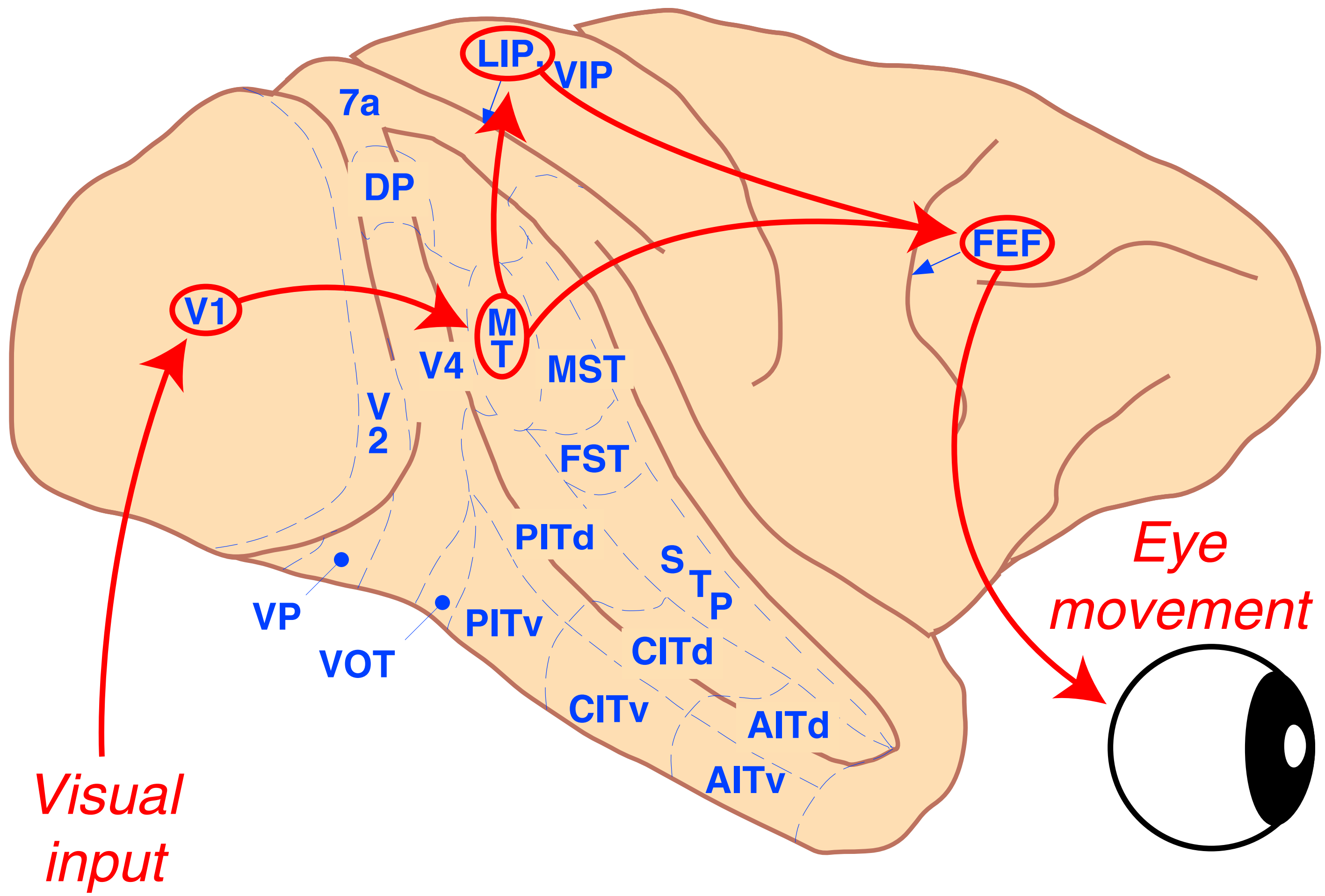


Gold and Shadlen, 2000

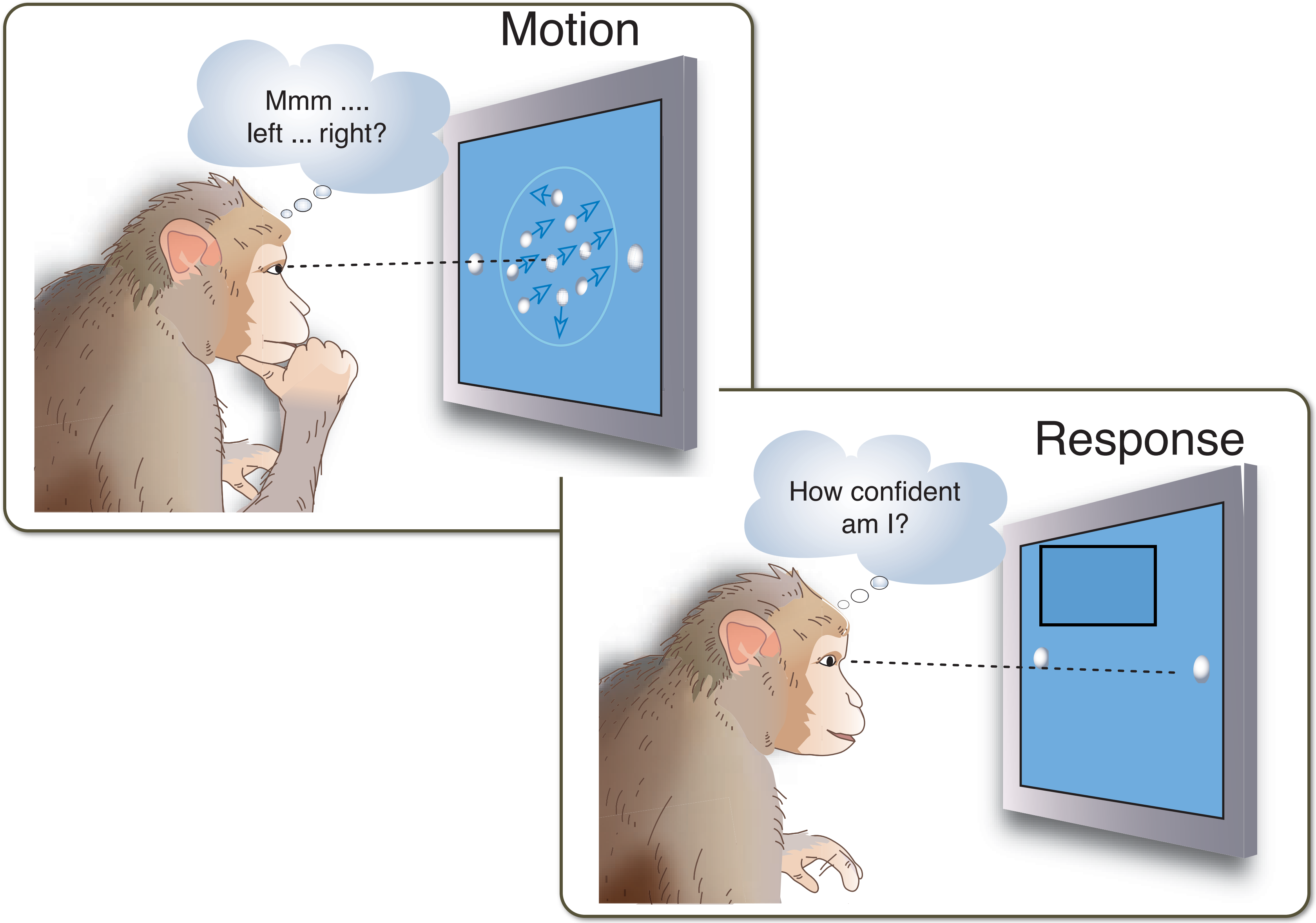


Gold and Shadlen, 2000

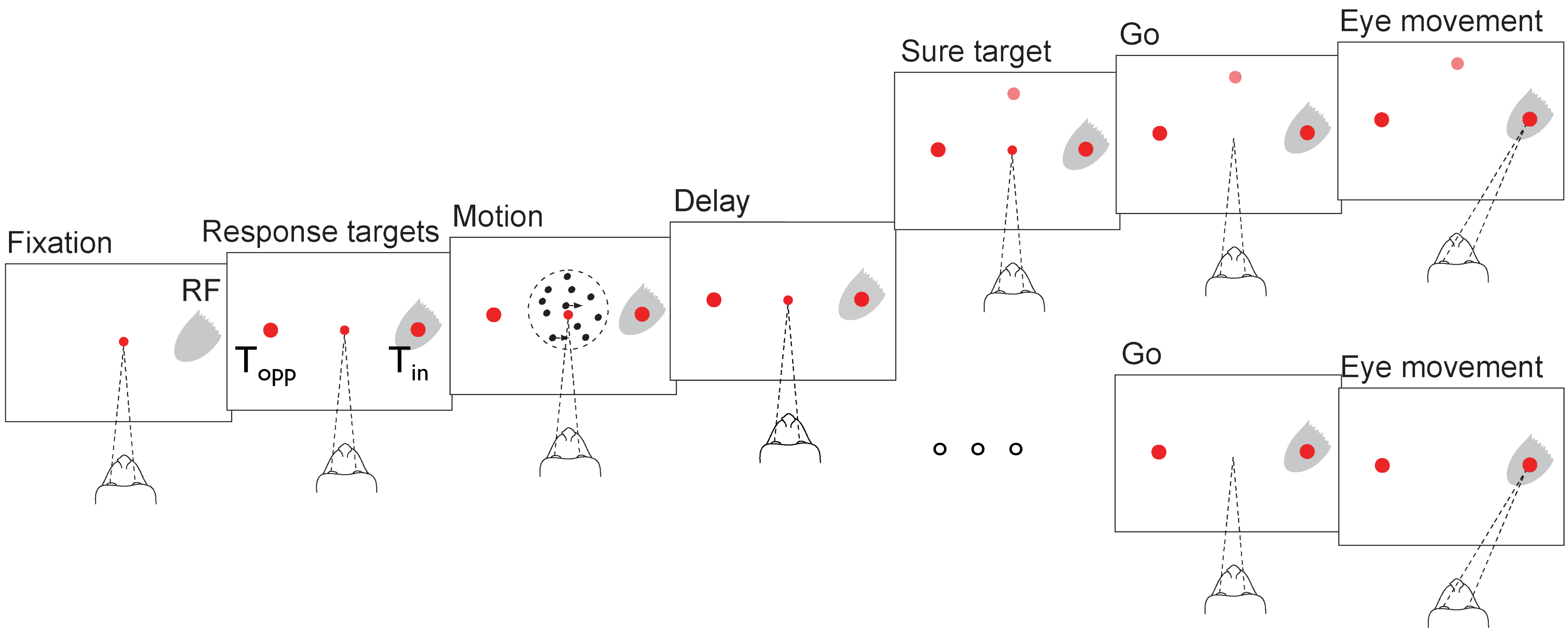

Direction of motion map (MT)
DECISION
Leftward
Rightward
Saccade vector map (FEF)



LIP
VIP
7a
DP
V1
MT
V4
MST
V2
FST
FEF
PITd
STP
VP
PITv
VOT
CITd
CITv
AITd
AITv
Eye movement
Visual input


Motion
Mmm ....
left ... right?
Response
How confident
am I?

Certainty task

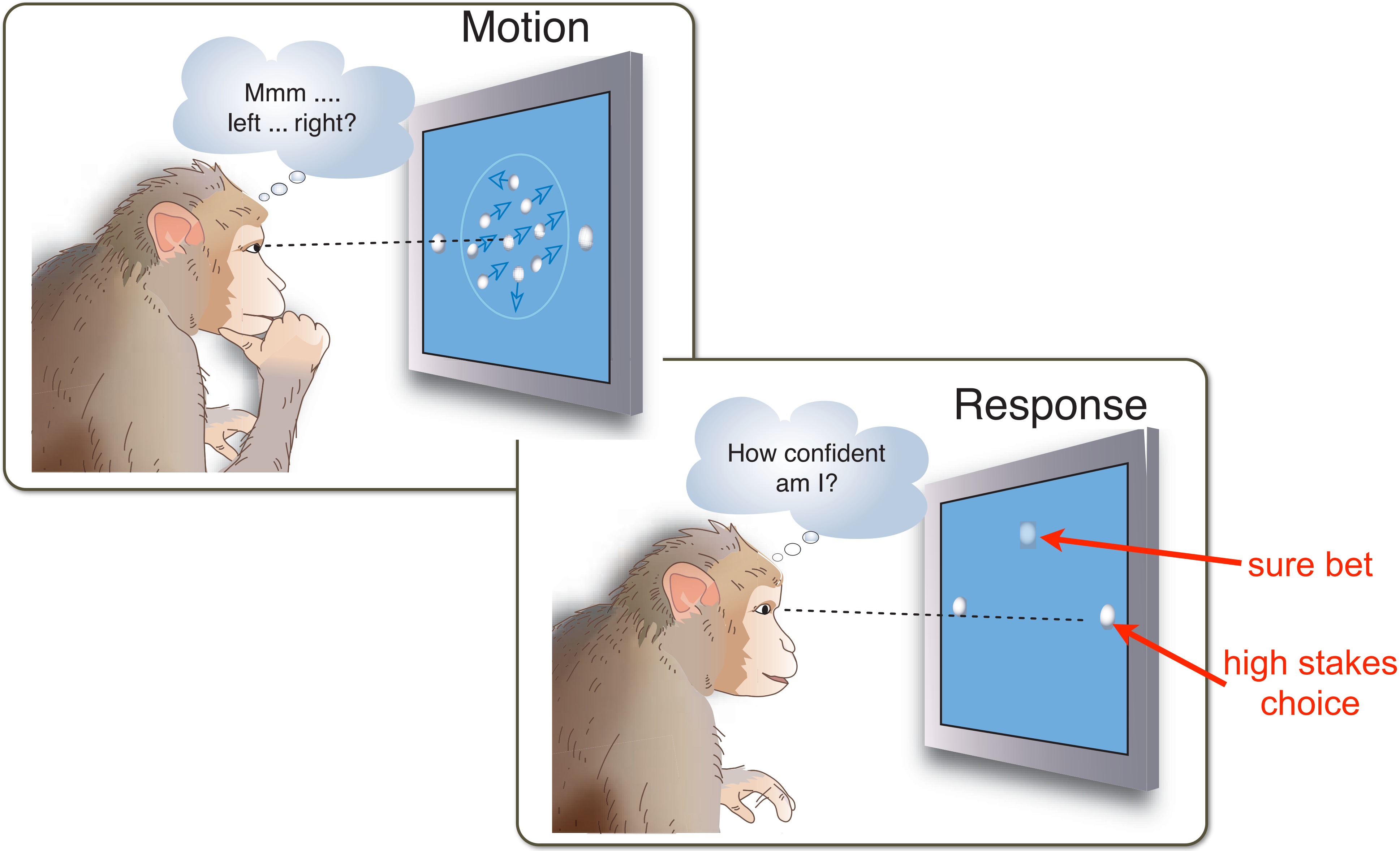


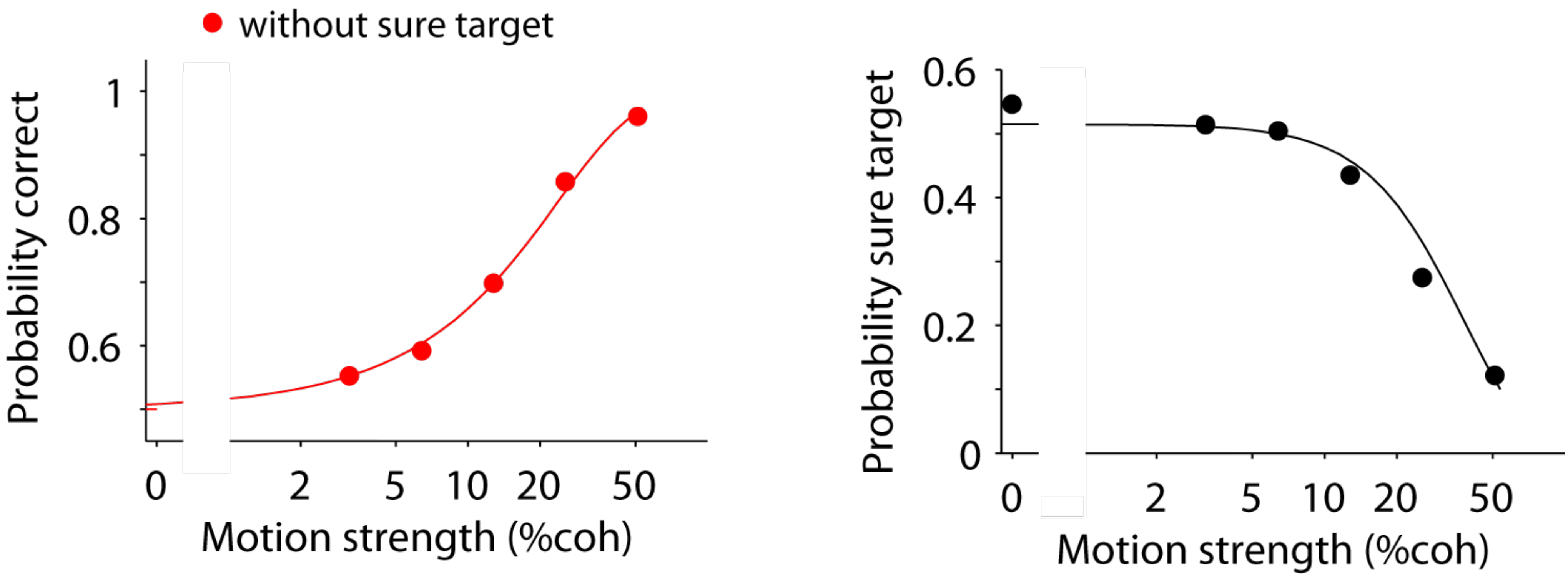
Stimulus duration: 100-900 ms (truncated exponential)

Sure target delay: 500-750 ms
Sure reward / correct reward ≈ 0.8

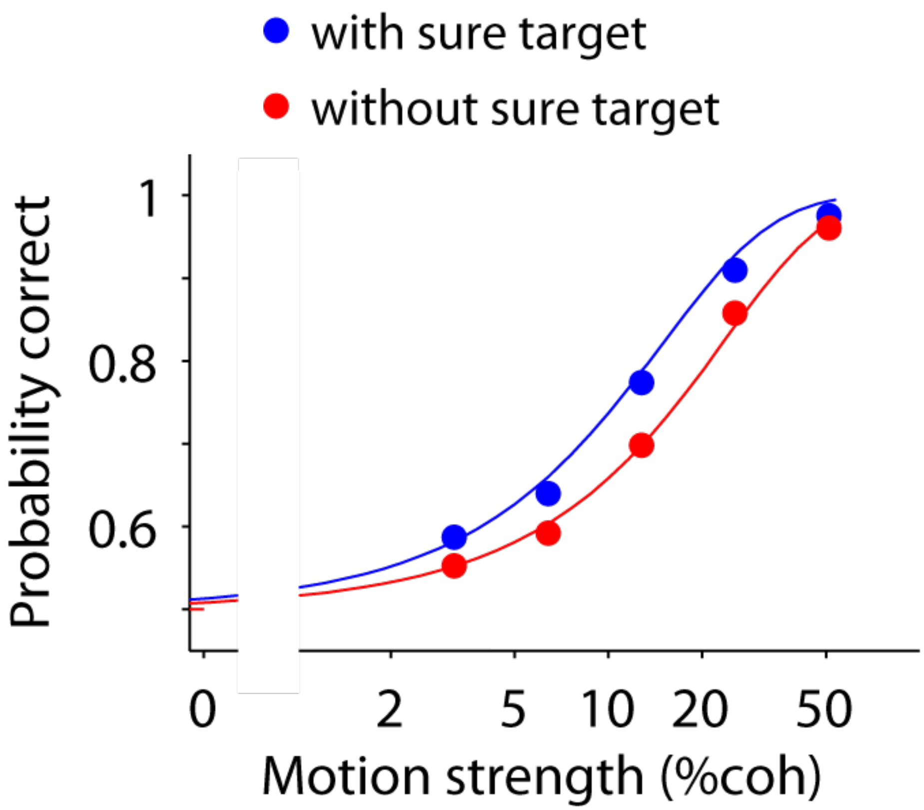
Kiani & Shadlen, 2009

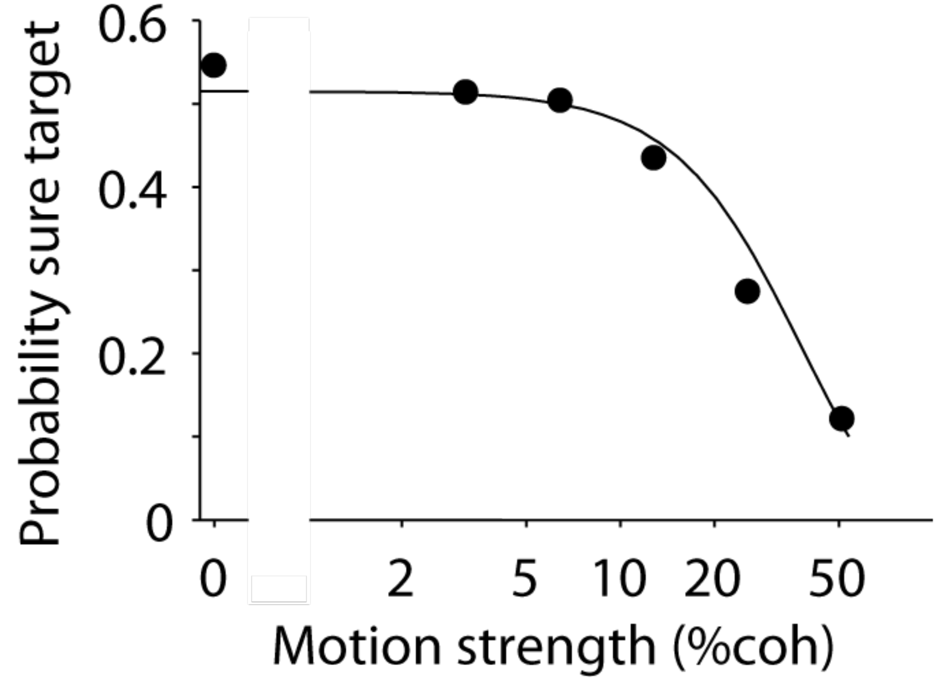
Post-decision wagering





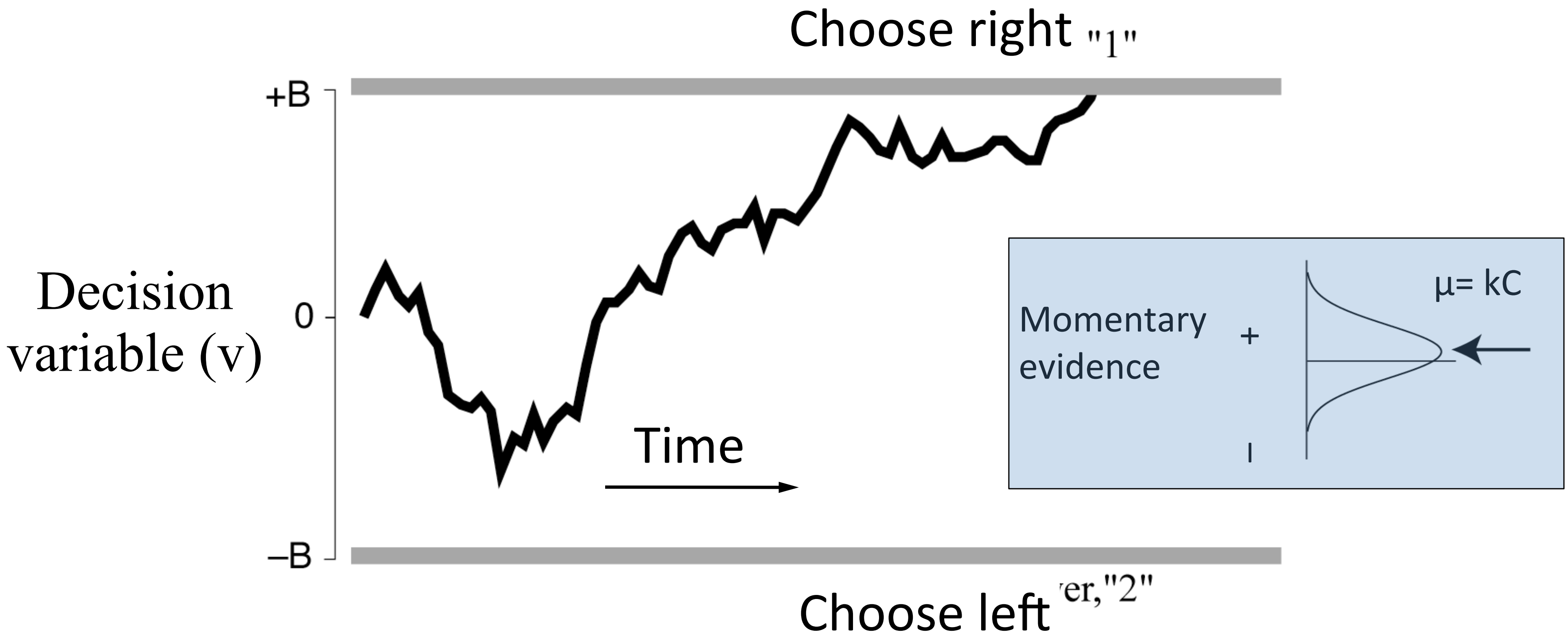
Kiani & Shadlen, 2009





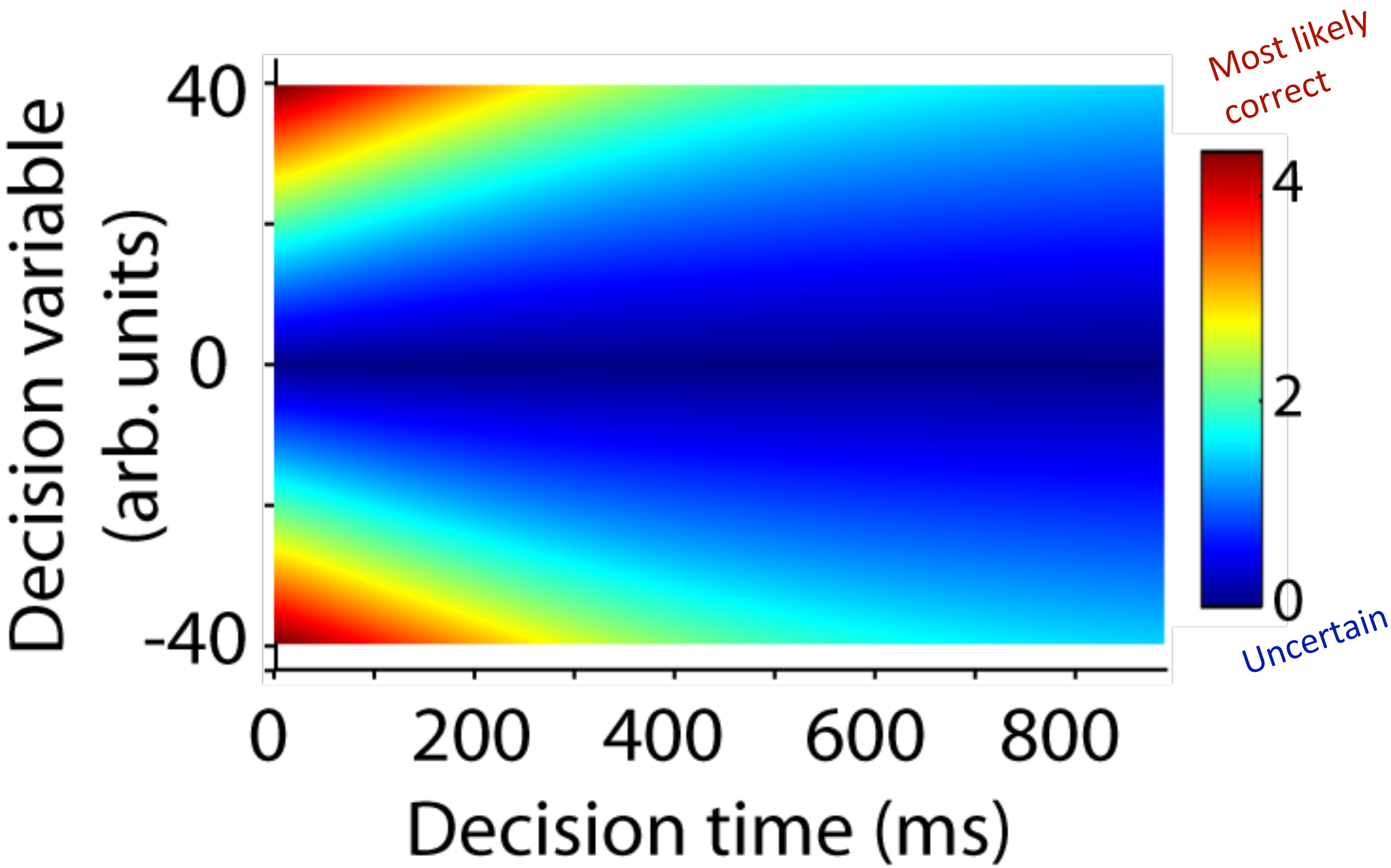
Kiani & Shadlen, 2009

accumulation-to-bound model



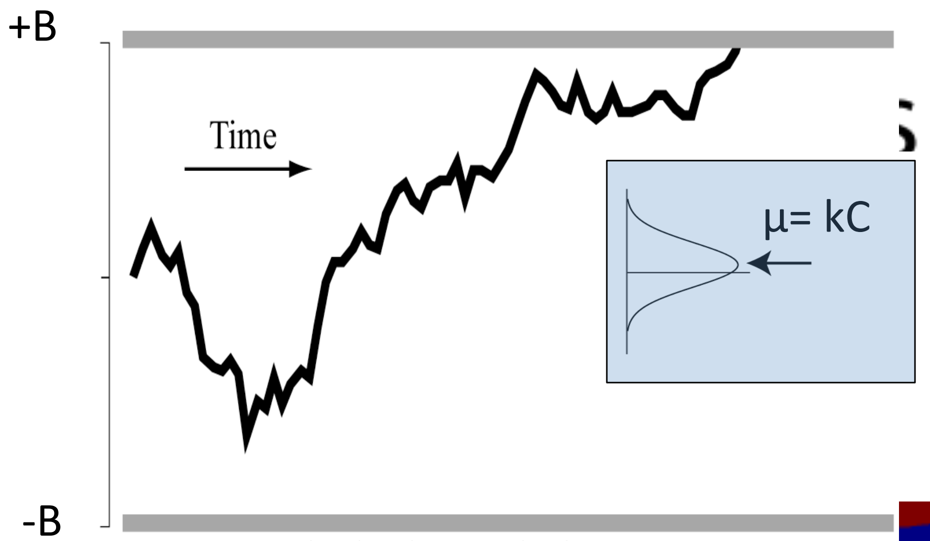
Link 1992
Ratcliff & Smith, 2004
Palmer et al, 2005
Laming, 1968
Luce, 1986

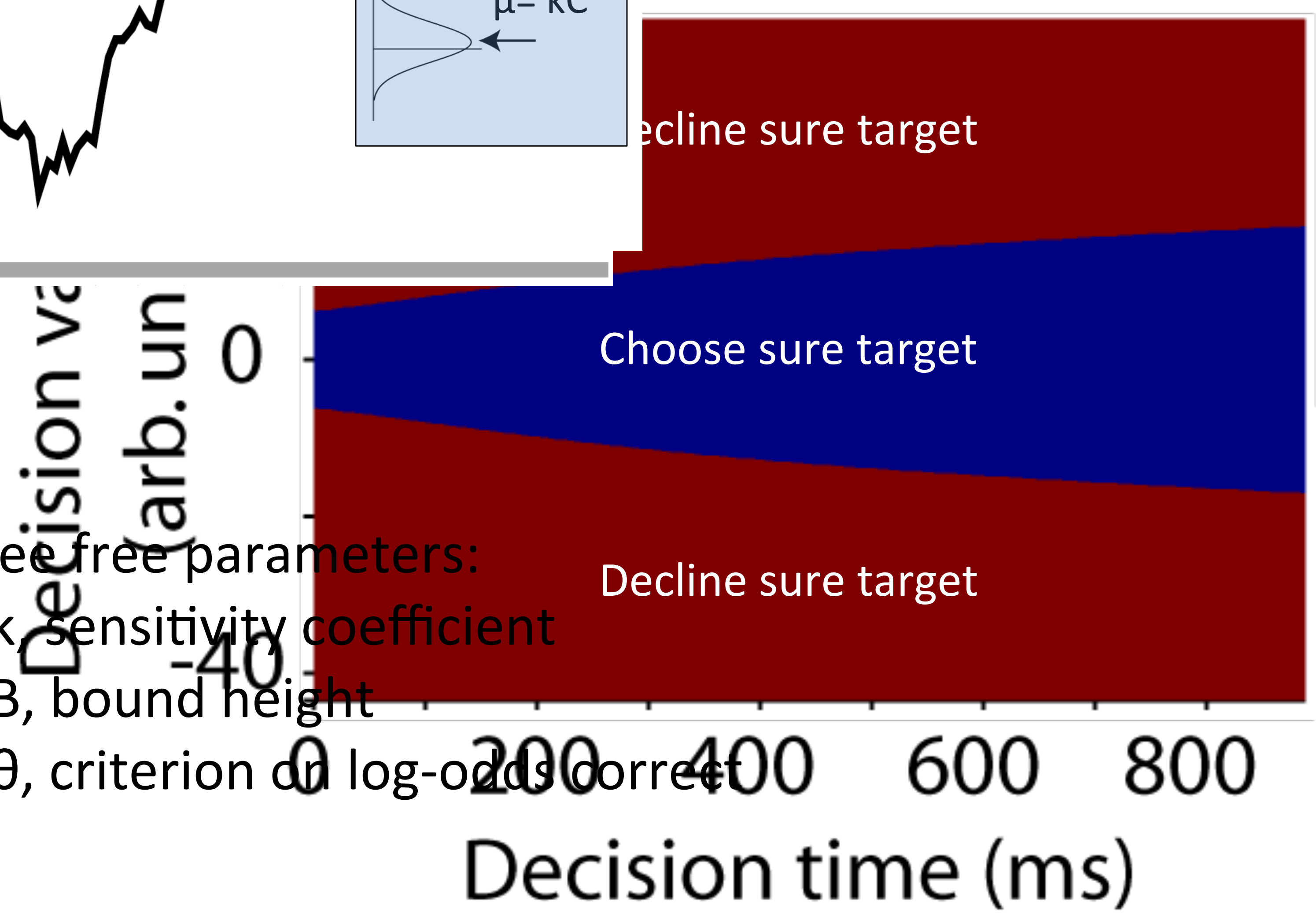
Log odds correct



Kiani & Shadlen, 2009

…s choice

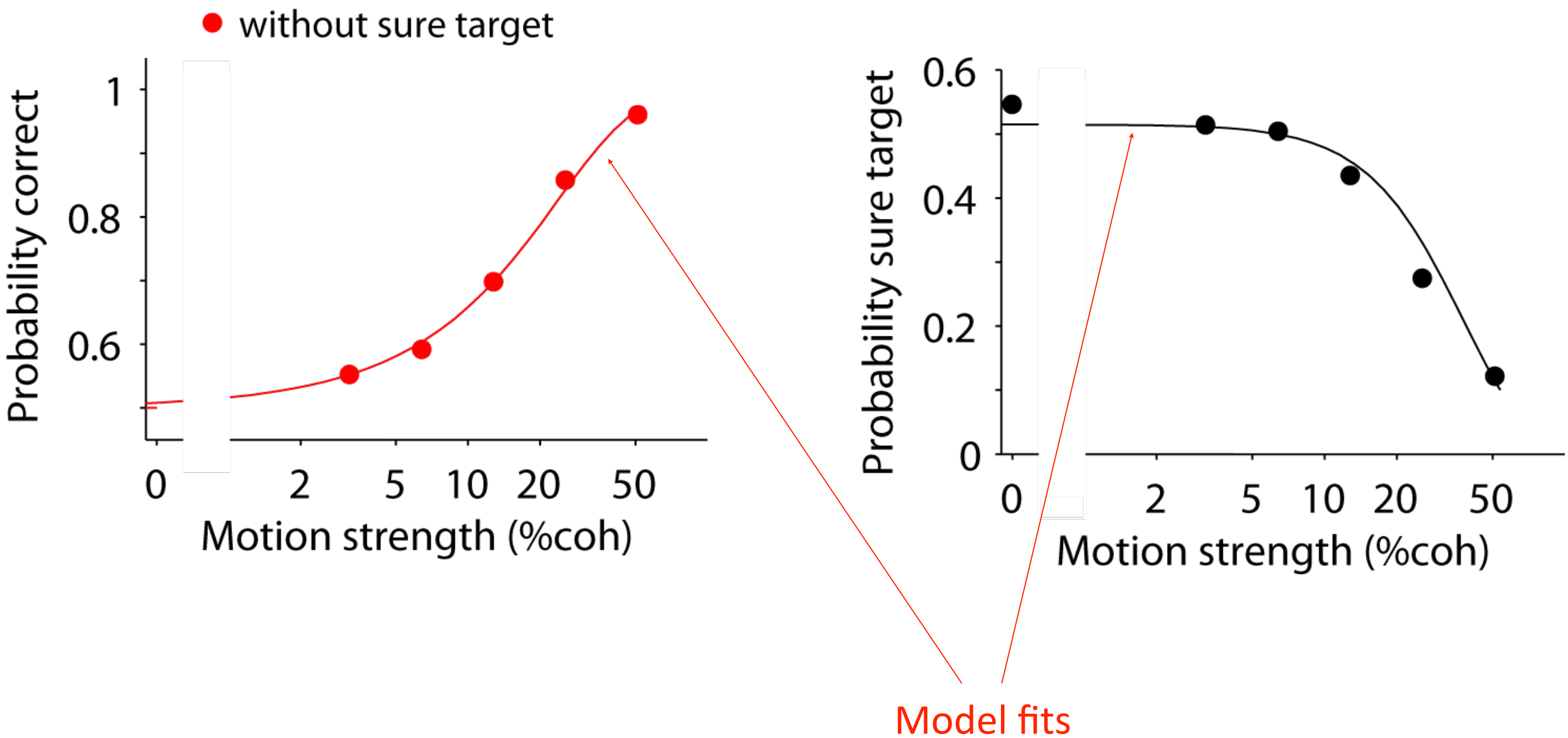




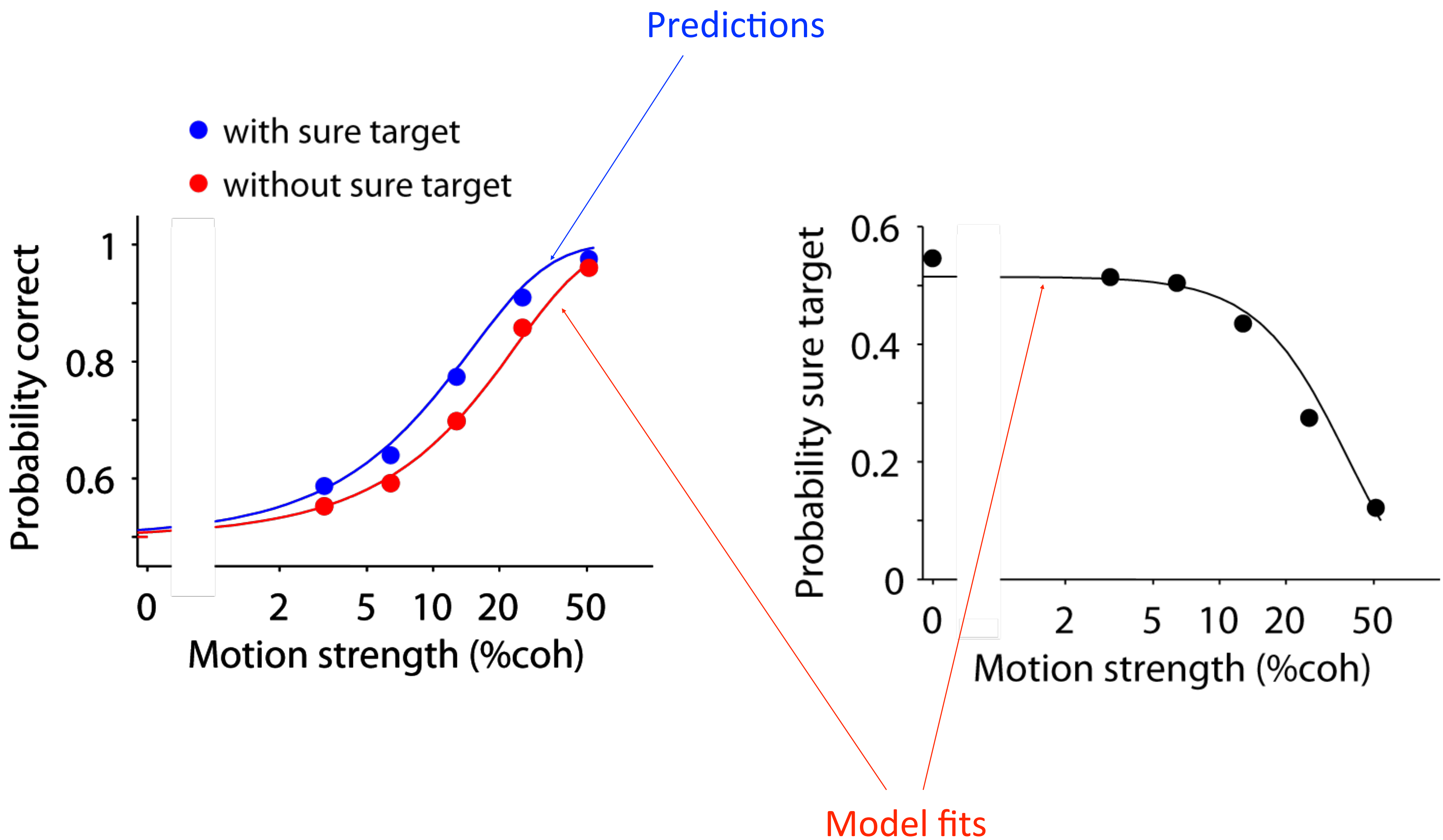
Three free parameters:

- k, sensitivity coefficient
- B, bound height
- θ, criterion on log-odds correct

Kiani & Shadlen, 2009

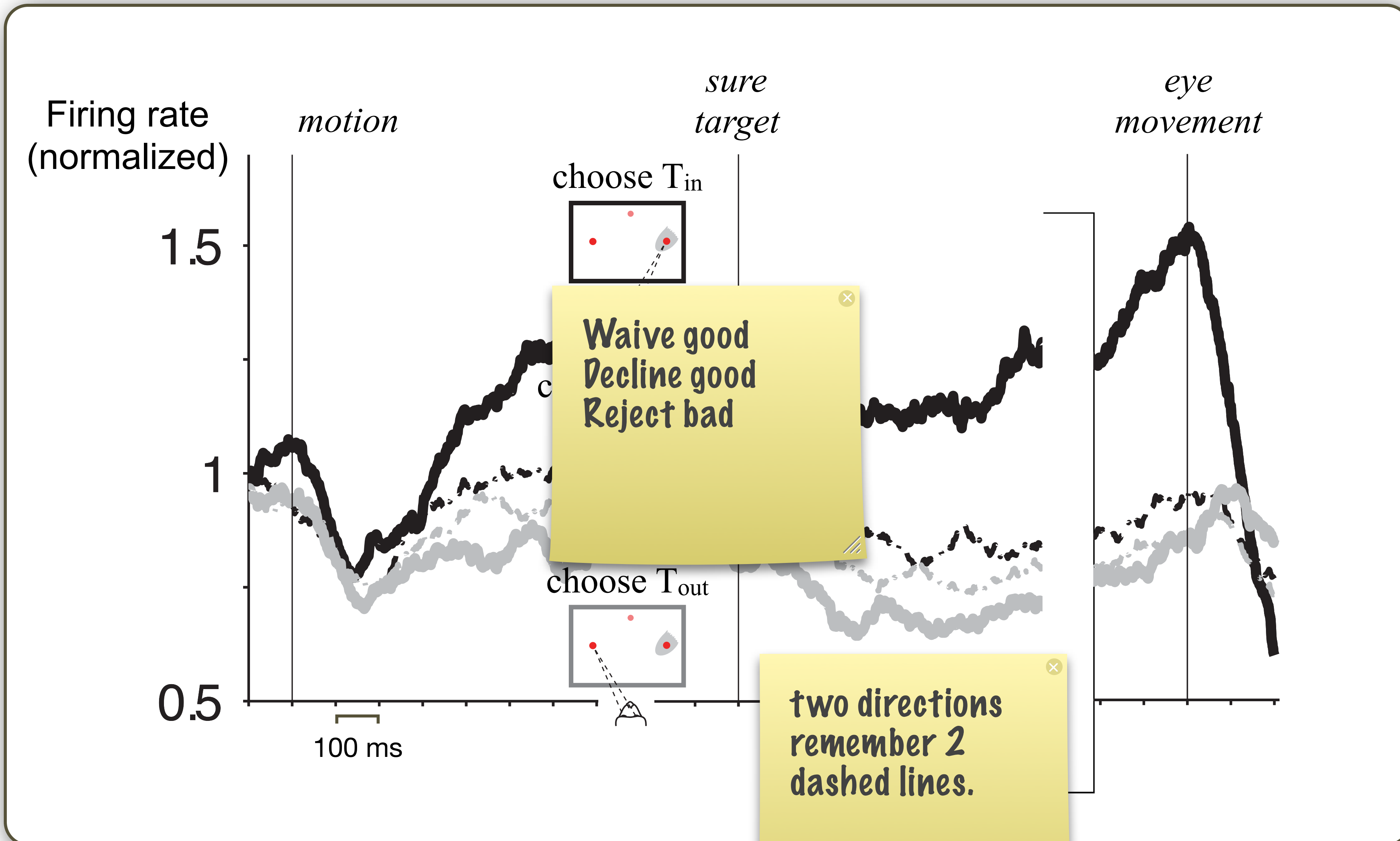


Kiani & Shadlen, 2009



Kiani & Shadlen, 2009

weak motion strength
N = 70 neurons



Waive good
Decline good
Reject bad

two directions
remember 2
dashed lines.

Kiani & Shadlen, 2009