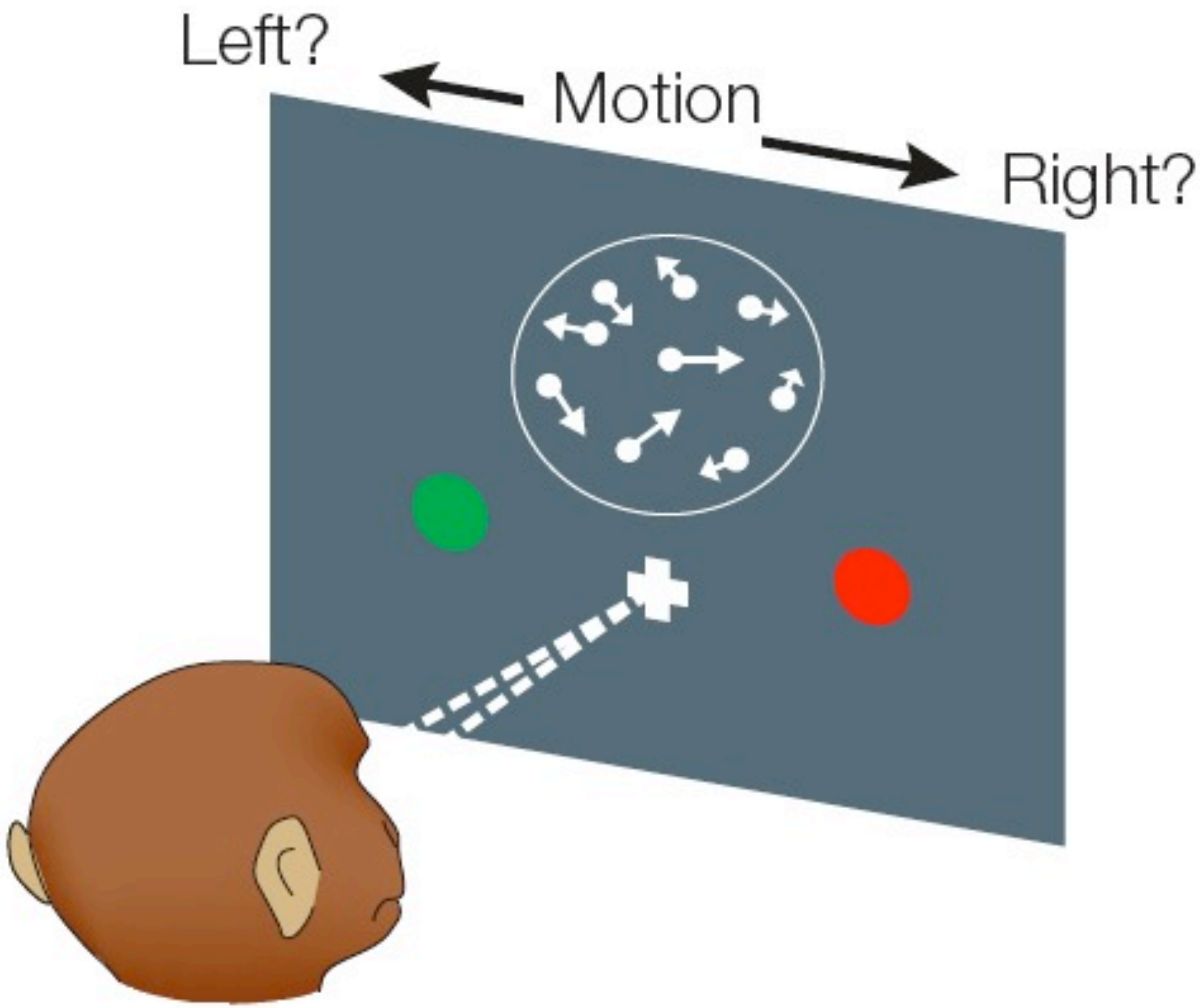
Part 2.3

Simple Decision-Making

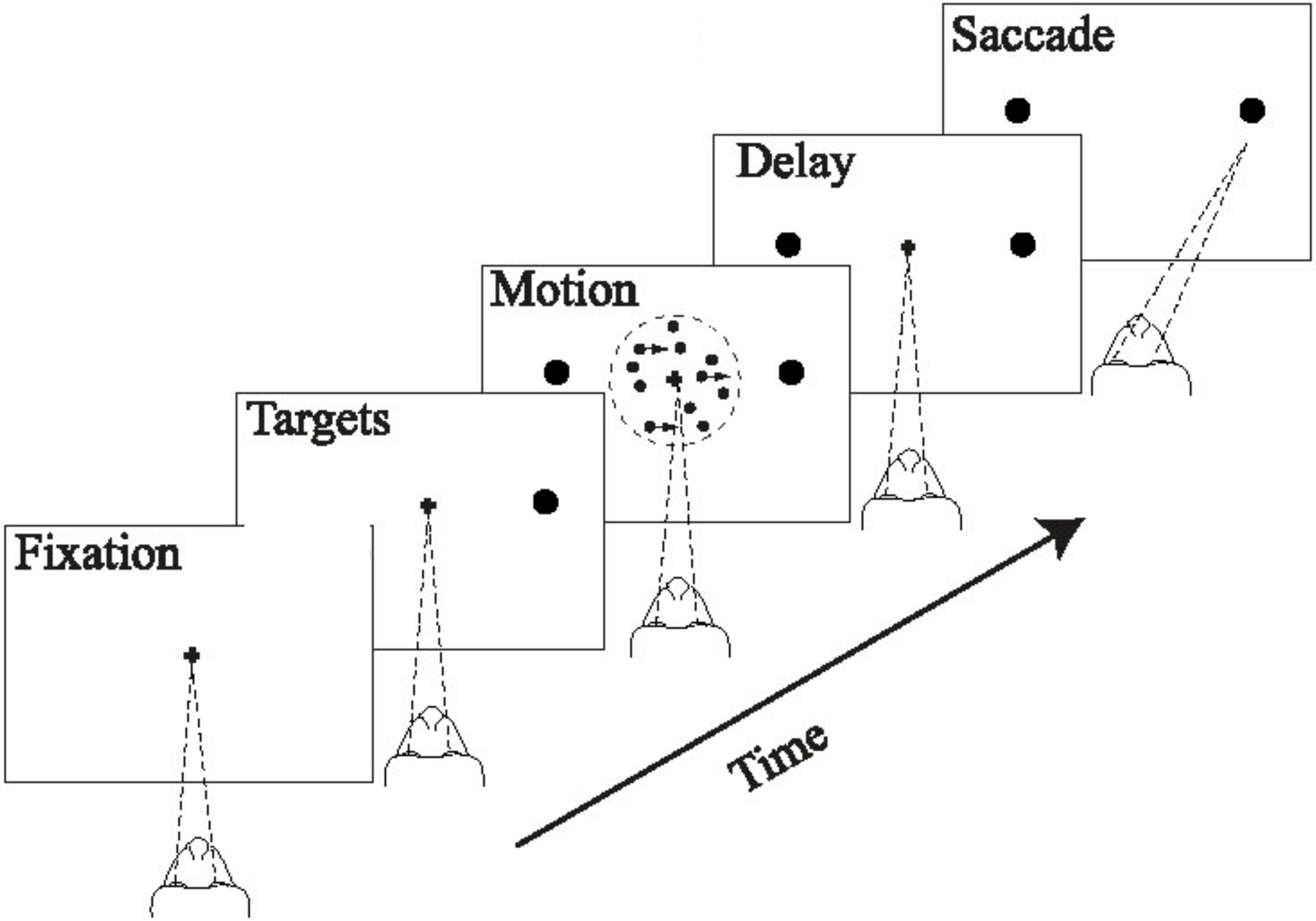
How neural activities relate to an animal's behavior

Cogmaster CO6 / Christian Machens

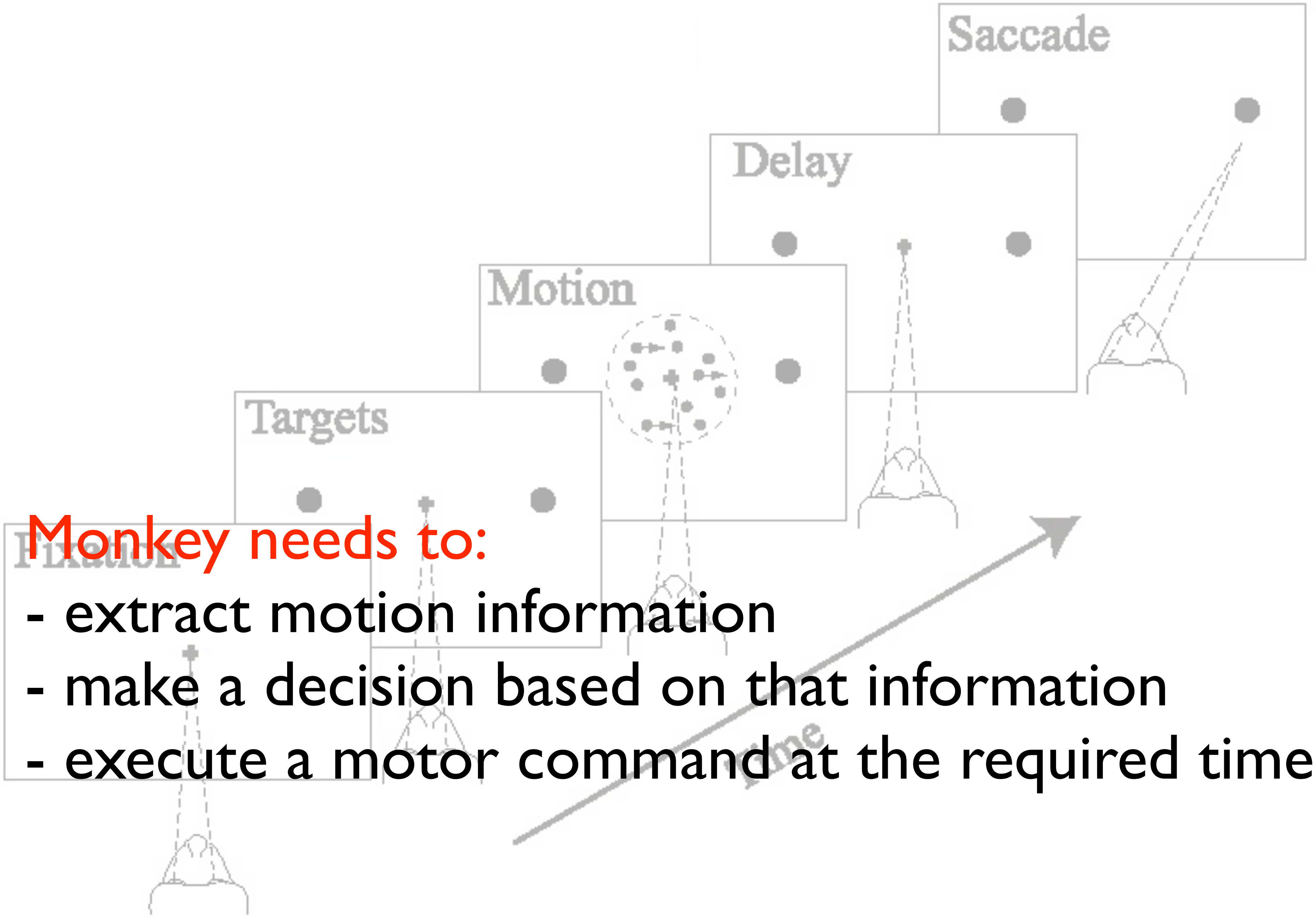
Motion discrimination task



Fixed viewing duration paradigm



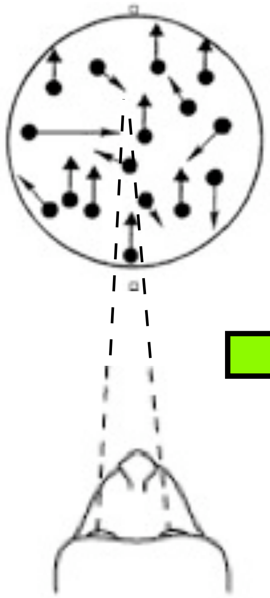
Fixed viewing duration paradigm



Monkey needs to:

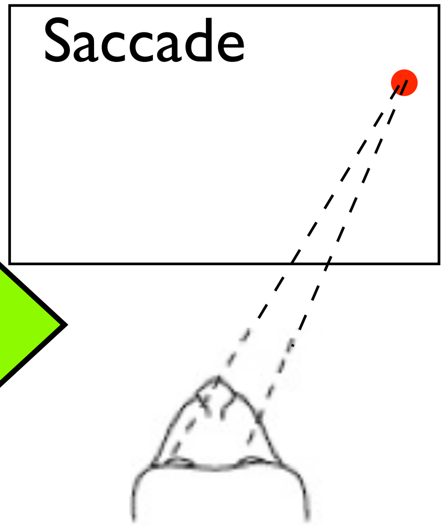
- extract motion information
- make a decision based on that information
- execute a motor command at the required time

From sensory to motor systems



BRAIN

various areas involved in the task:
visual system / frontal areas / motor systems



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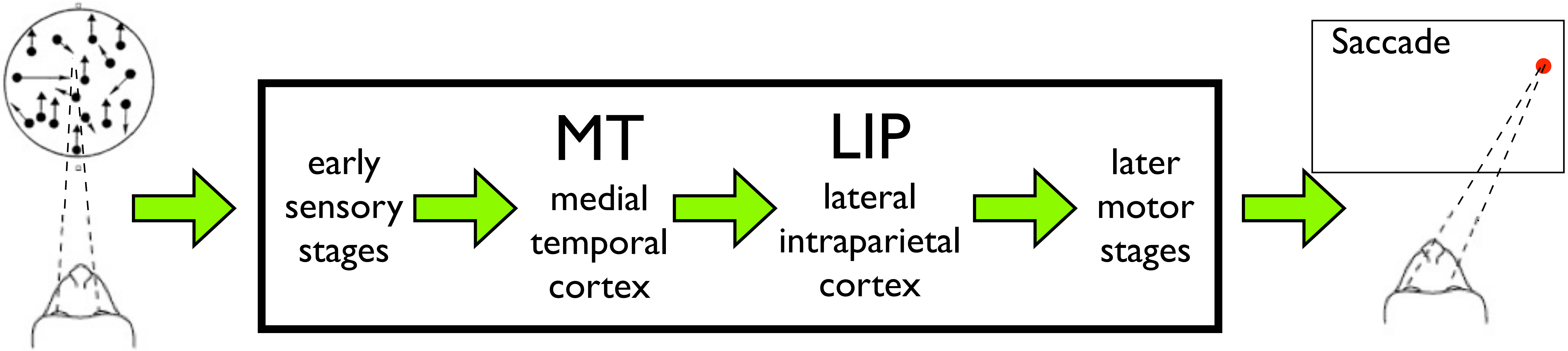

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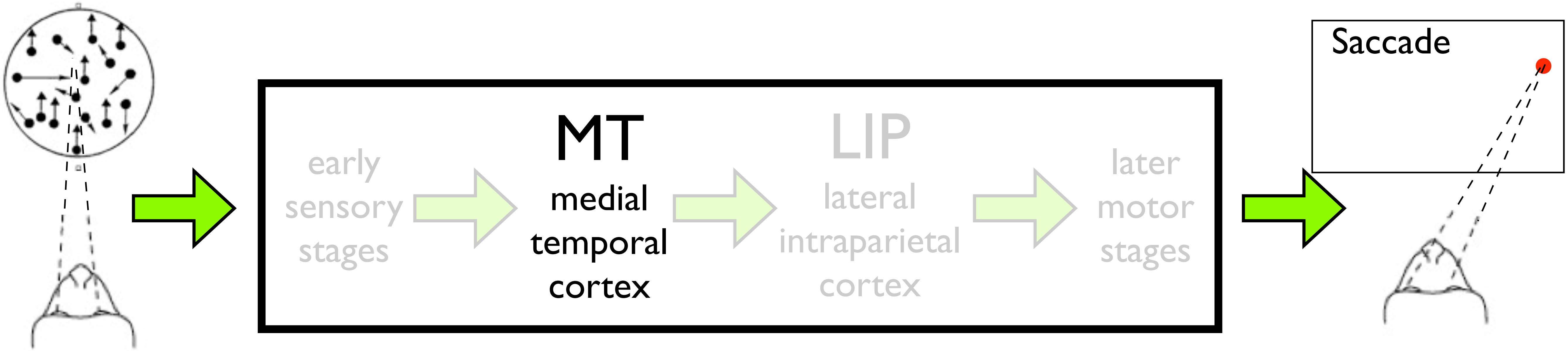
From sensory to motor systems



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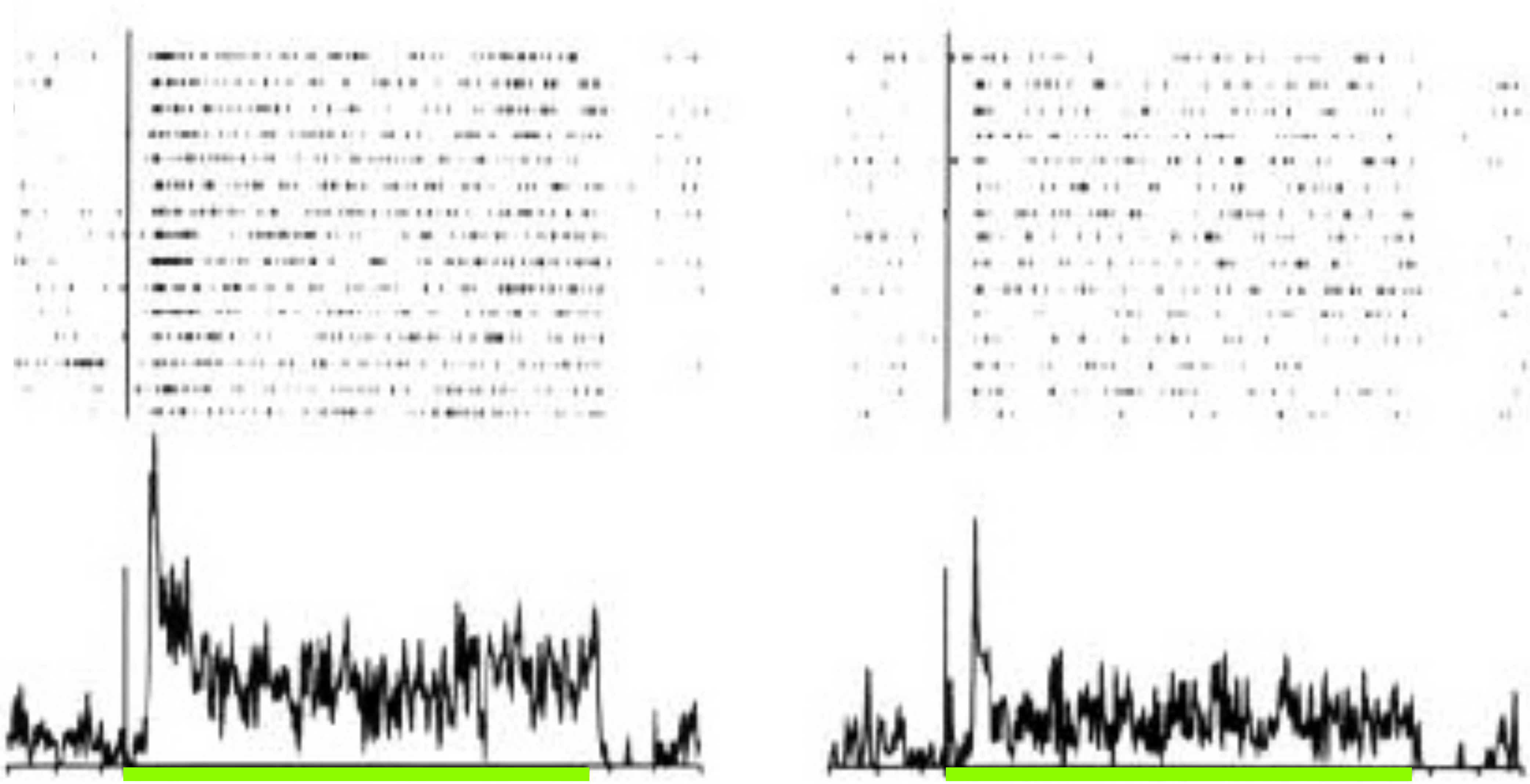
Responses of MT neurons

MT neuron spike raster, 25.6 % motion coherence

preferred direction (+) | null direction (-)



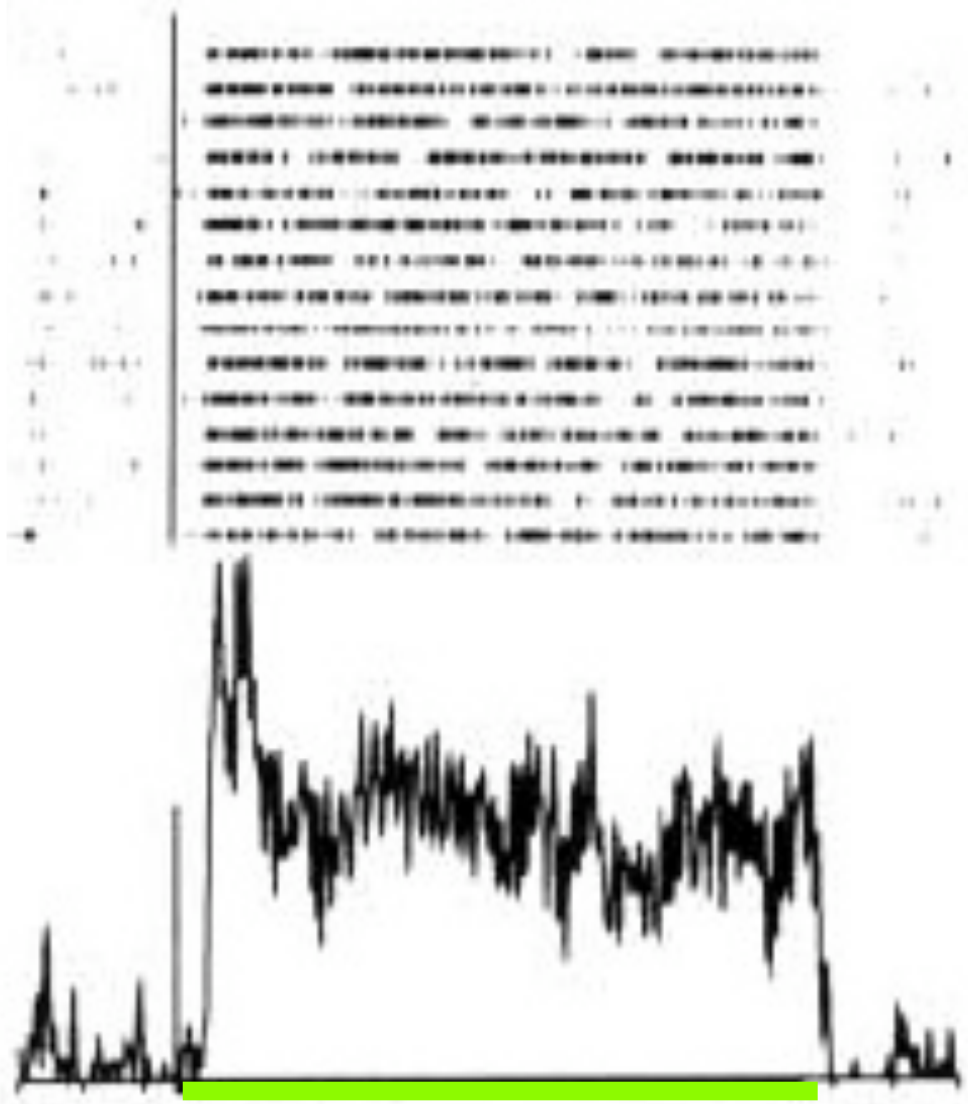
time: 2 seconds | time: 2 seconds

Britten, Shadlen et al. 2003

Responses of MT neurons

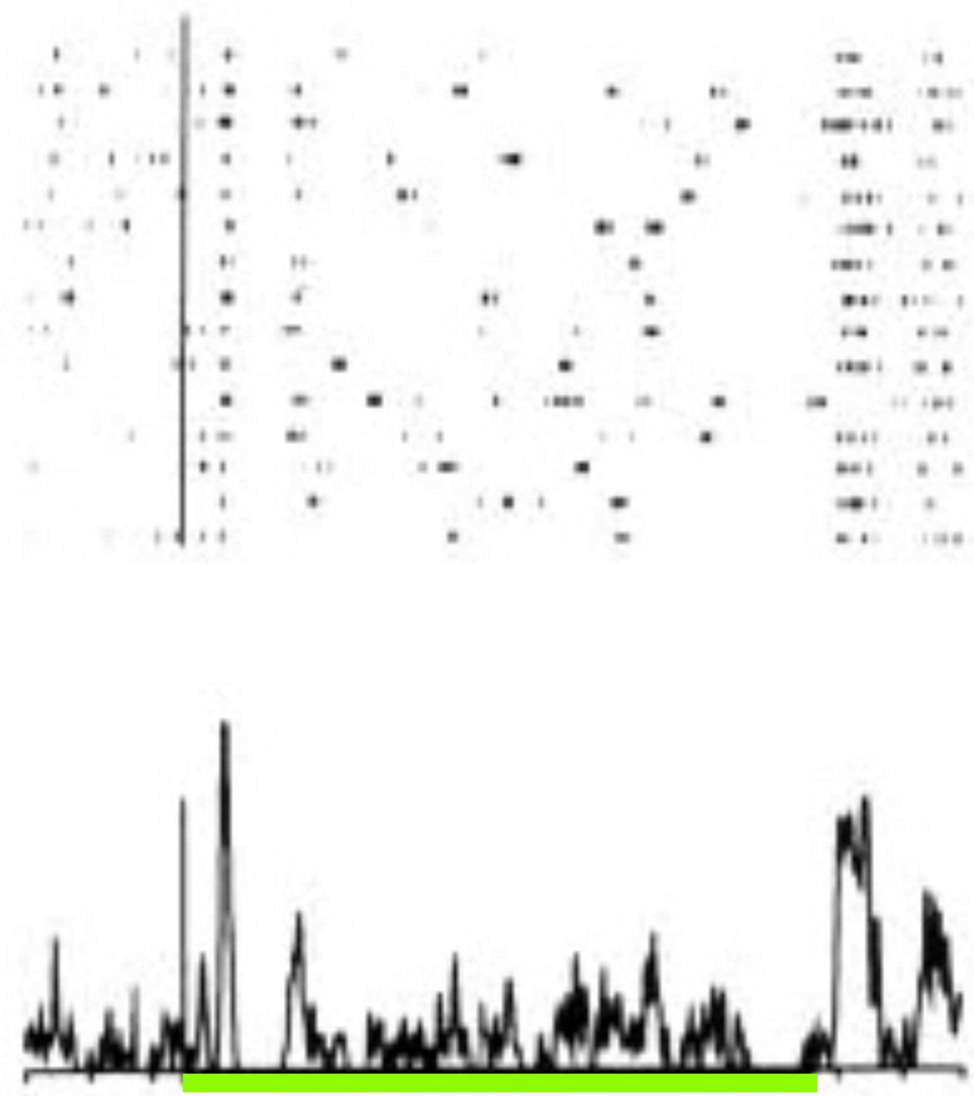
MT neuron spike raster, 99.9 % motion coherence

preferred direction (+)



time: 2 seconds

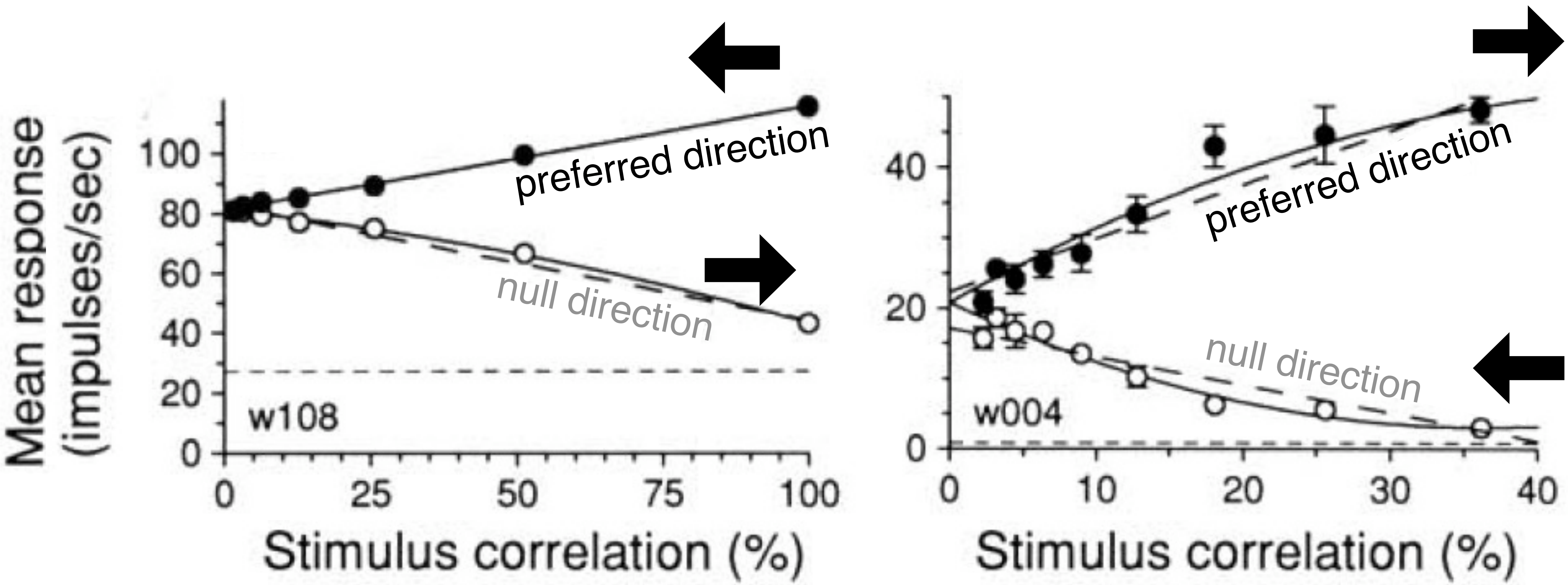
null direction (-)



time: 2 seconds

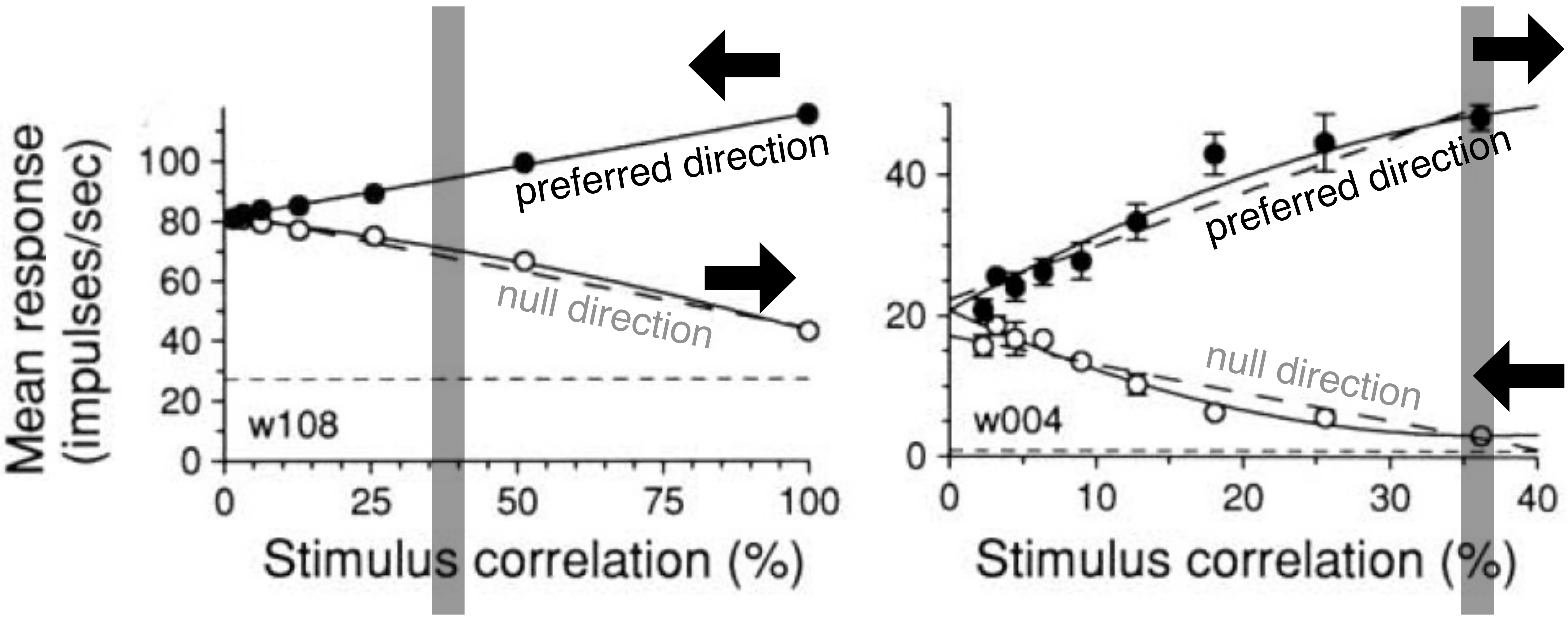
Britten, Shadlen et al. 2003

Responses of MT neurons



Britten, Shadlen, Newsome, Movshon (1993)

Responses of MT neurons



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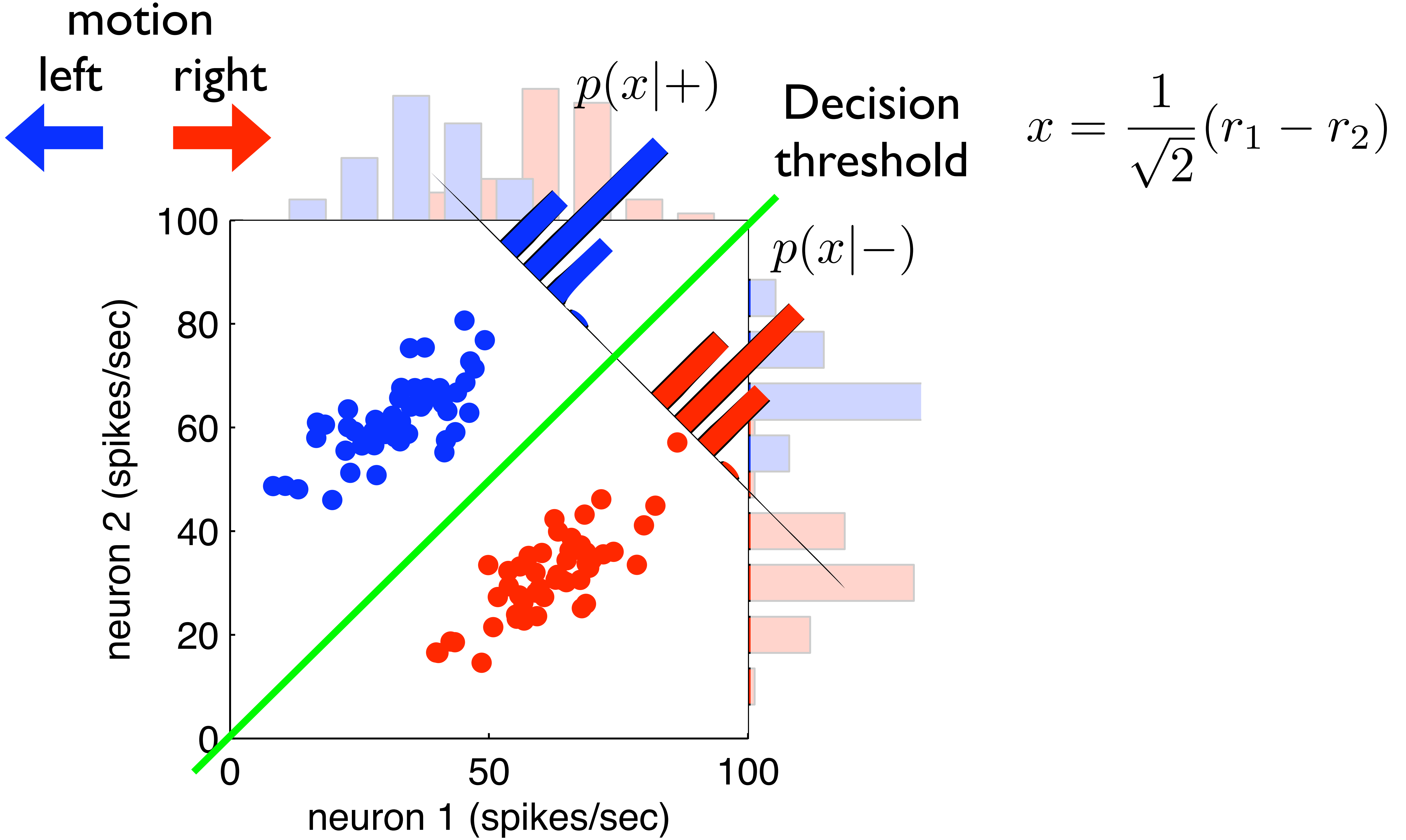
Decision strategy revisited



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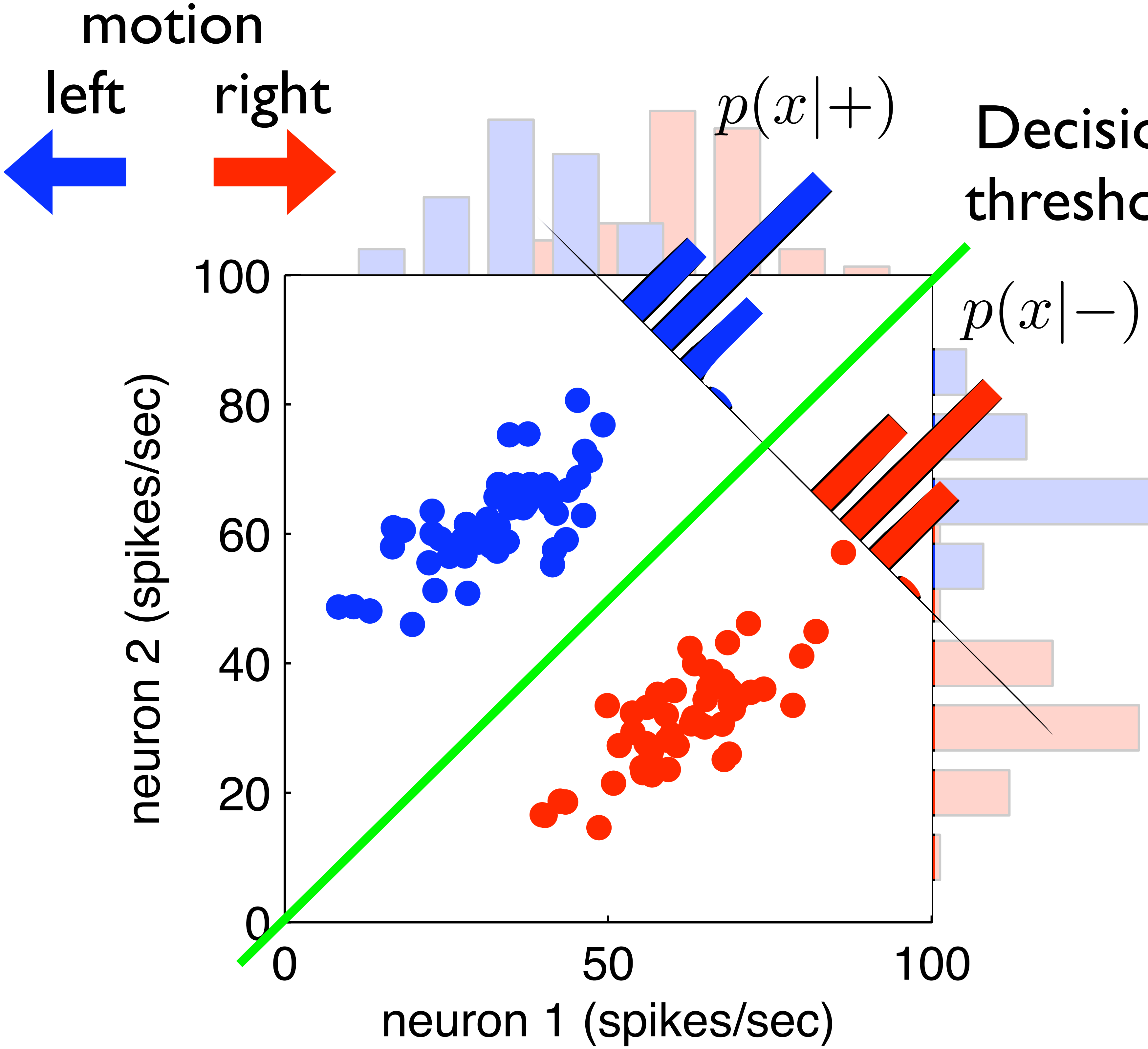


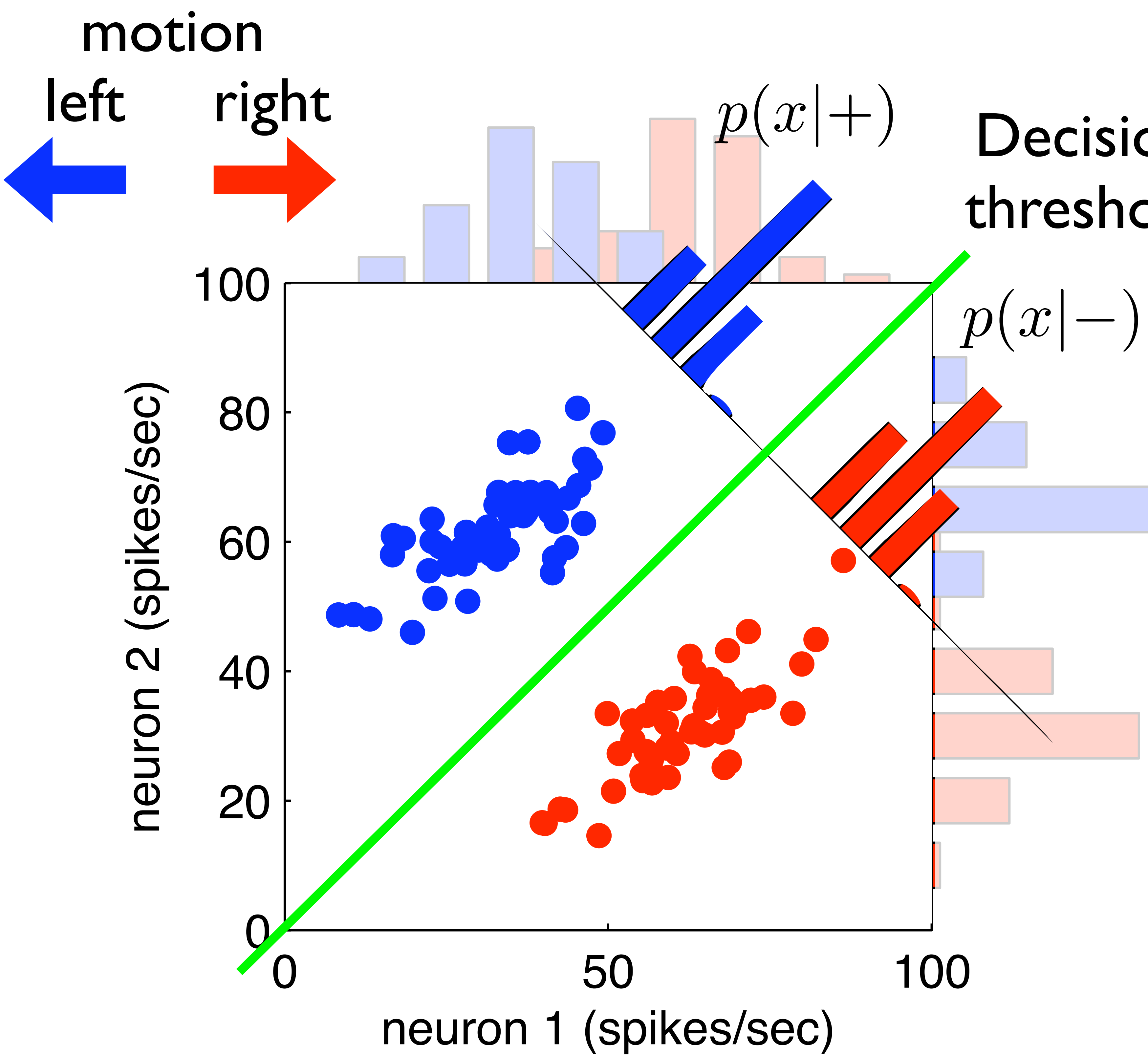
Decision threshold

$$x = \frac{1}{\sqrt{2}}(r_1 - r_2)$$

Which motion?

$p(x|+) > p(x|-)$?

Decision strategy revisited



Decision threshold

$$x = \frac{1}{\sqrt{2}}(r_1 - r_2)$$

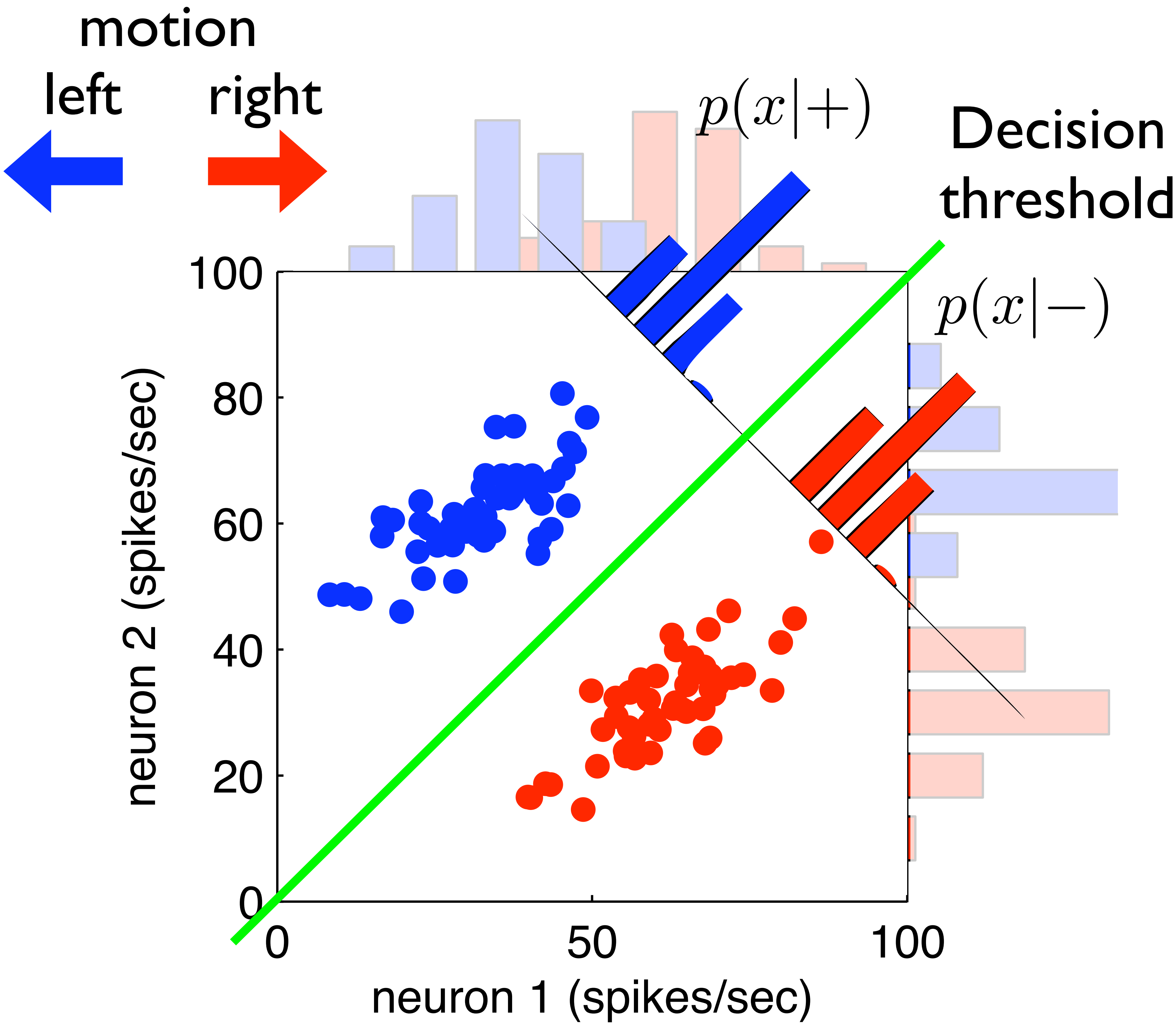
Which motion?

$$p(x|+) > p(x|-) \ ?$$

Likelihood ratio

$$l(x) = \frac{p(x|+)}{p(x|-)}$$

Decision strategy revisited



$$x = \frac{1}{\sqrt{2}}(r_1 - r_2)$$

Which motion?

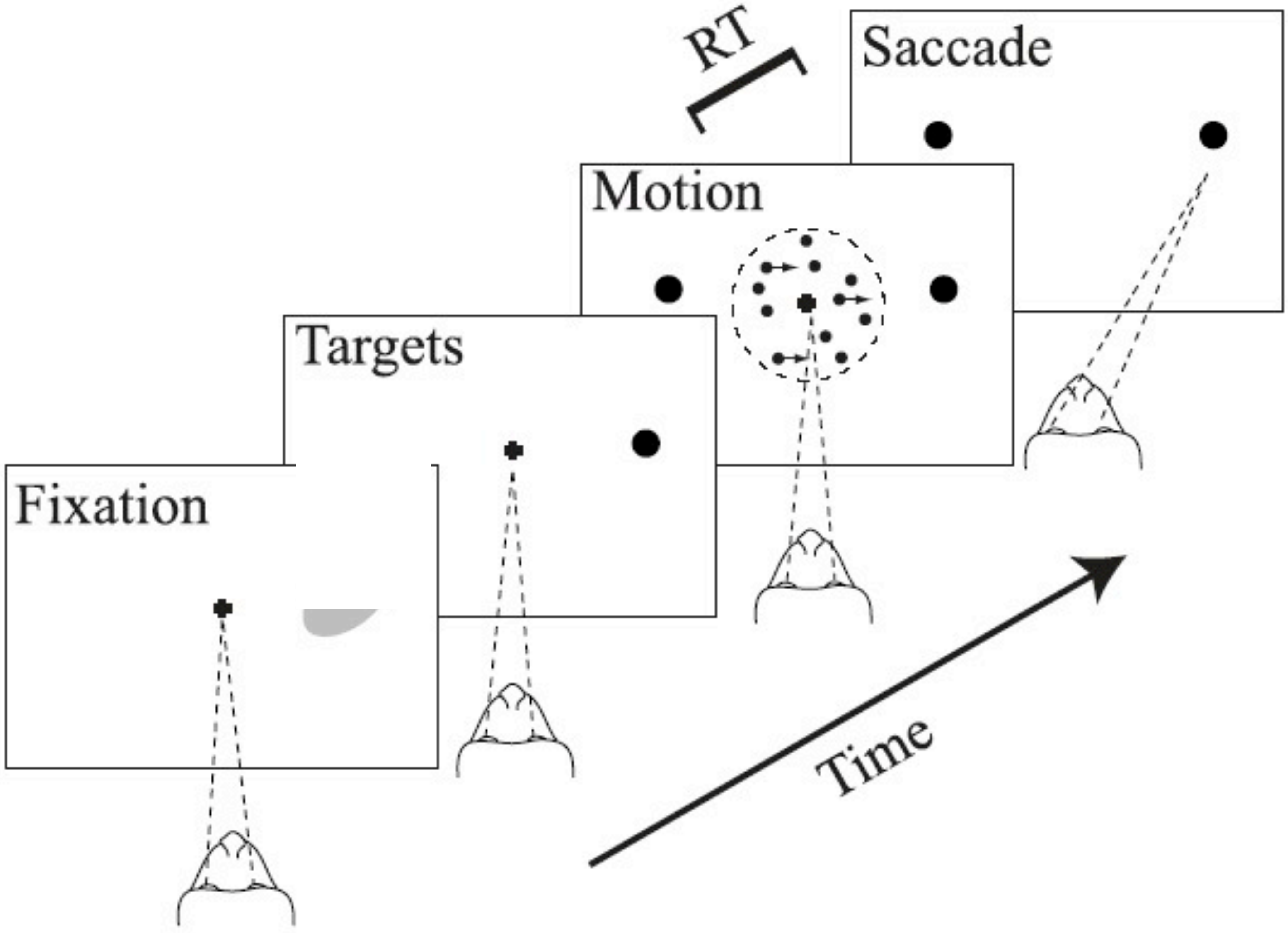
$$p(x|+) > p(x|-) \;?$$

Likelihood ratio

$$l(x) = \frac{p(x|+)}{p(x|-)}$$

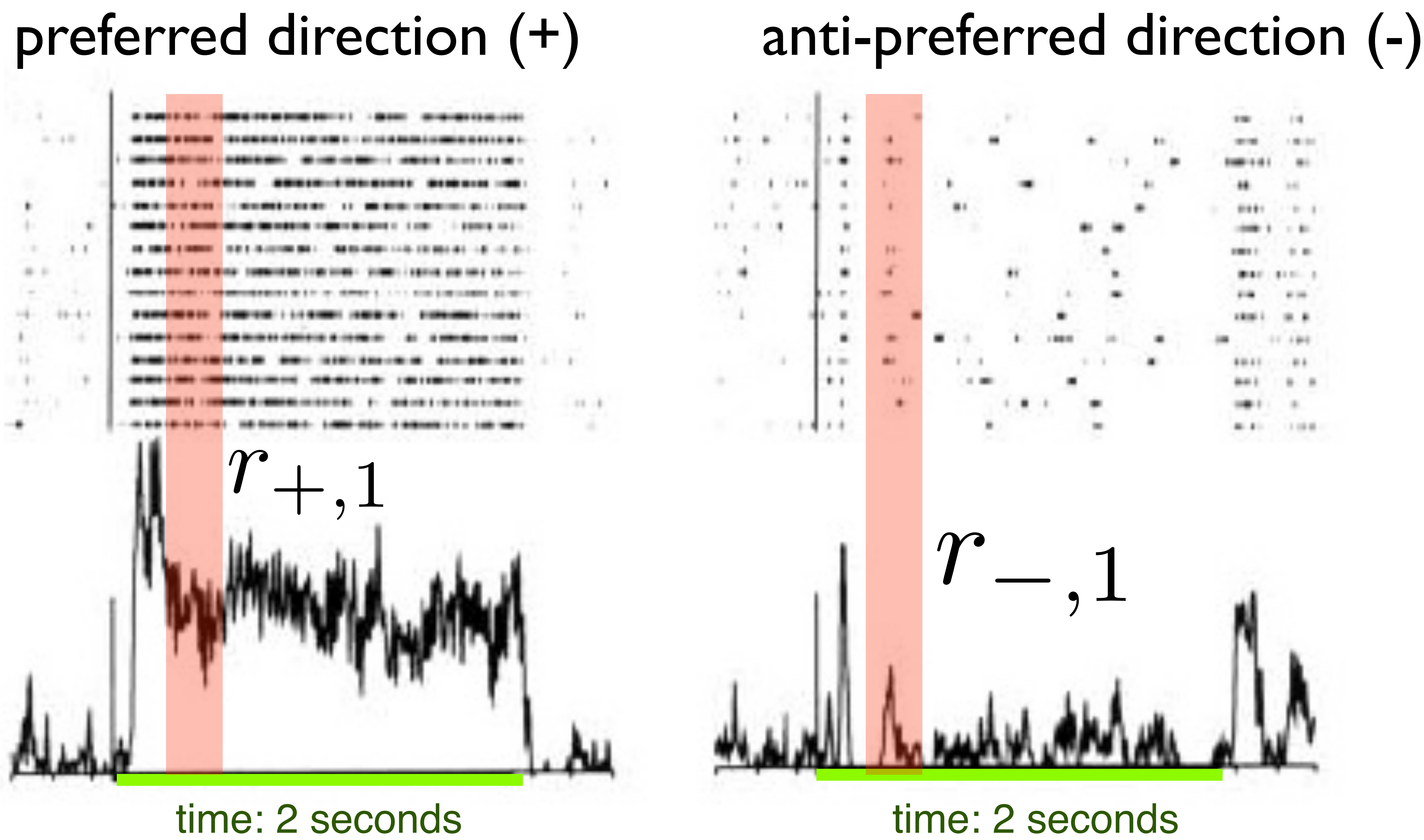
$$l(x) > 1 \;?$$

Reaction time (RT) task



Stimulus presented over time

MT neuron spike raster, 99.9 % motion coherence

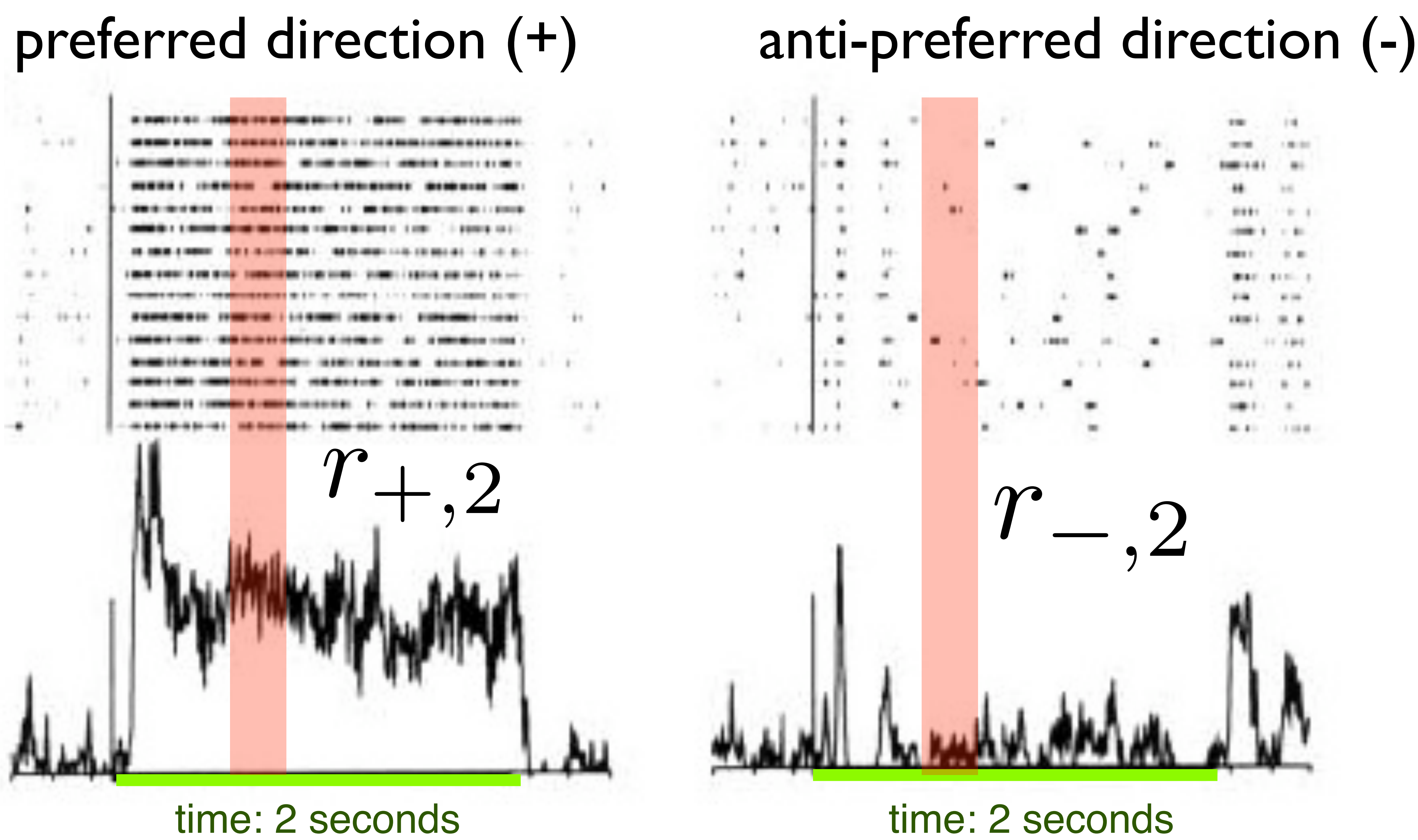


$$x_1 = r_{+,1} - r_{-,1}$$

Britten, Shadlen et al. 2003

Stimulus presented over time

MT neuron spike raster, 99.9 % motion coherence

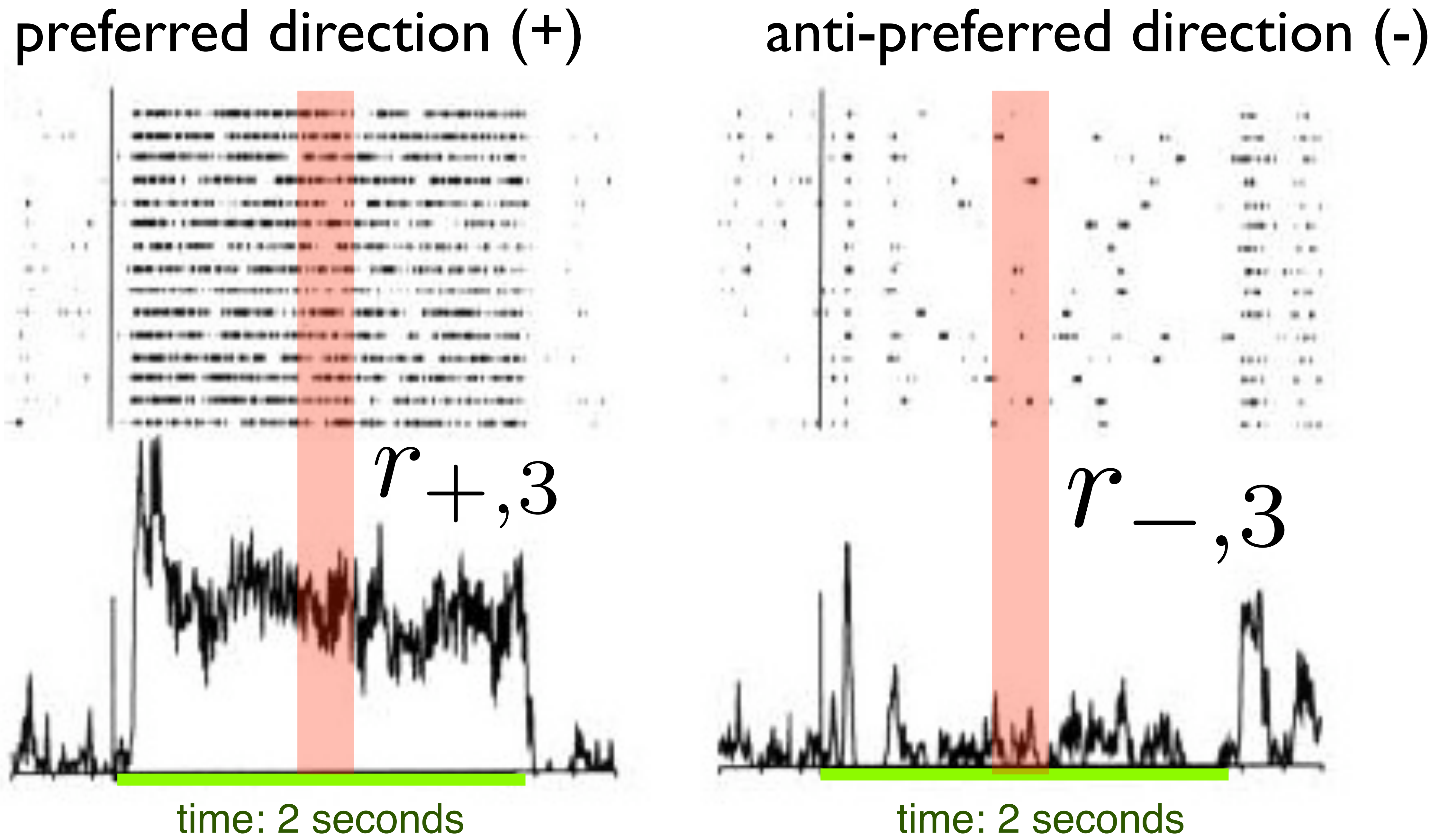


$$x_2 = r_{+,2} - r_{-,2}$$

Britten, Shadlen et al. 2003

Stimulus presented over time

MT neuron spike raster, 99.9 % motion coherence



$$x_3 = r_{+,3} - r_{-,3}$$

Britten, Shadlen et al. 2003

Optimal decision and likelihood ratio

Observations of firing rate differences over discrete time steps:

$$\mathbf{x} = (x_1, x_2, \ldots, x_N)$$

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Likelihood ratio:

$$l(\mathbf{x}) = l(x_1, x_2, \ldots, x_N)$$

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Likelihood ratio:

$$l(\mathbf{x}) = l(x_1, x_2, \ldots, x_N)$$

$$= \frac{p(x_1, x_2, \ldots, x_N | +)}{p(x_1, x_2, \ldots, x_N | -)}$$

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$$= \frac{p(x_1, x_2, \ldots, x_N|+)}{p(x_1, x_2, \ldots, x_N|-)}$$

$$= \frac{p(x_1|+)}{p(x_1|-)} \frac{p(x_2|+)}{p(x_2|-)} \cdots \frac{p(x_N|+)}{p(x_N|-)}$$

Optimal decision and likelihood ratio

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$$\mathbf{x} = (x_1, x_2, \ldots, x_N)$$

Likelihood ratio:

$$\begin{aligned} l(\mathbf{x}) &= l(x_1, x_2, \ldots, x_N) \\ &= \frac{p(x_1, x_2, \ldots, x_N | +)}{p(x_1, x_2, \ldots, x_N | -)} \\ &= \frac{p(x_1 | +)}{p(x_1 | -)} \frac{p(x_2 | +)}{p(x_2 | -)} \cdots \frac{p(x_N | +)}{p(x_N | -)} \end{aligned}$$

When should we take the decision?

Optimal decision and likelihood ratio

Observations of firing rate differences over discrete time steps:

$$\mathbf{x} = (x_1, x_2, \ldots, x_N)$$

Likelihood ratio:

$$l(\mathbf{x}) = l(x_1, x_2, \ldots, x_N)$$
$$= \frac{p(x_1, x_2, \ldots, x_N|+)}{p(x_1, x_2, \ldots, x_N|-)}$$
$$= \frac{p(x_1|+)}{p(x_1|-)} \frac{p(x_2|+)}{p(x_2|-)} \cdots \frac{p(x_N|+)}{p(x_N|-)}$$

When should we take the decision?

Ideal: decide as soon as a certain reliability has been met.

$$l(\mathbf{x}) < Z_1 \quad \vee \quad l(\mathbf{x}) > Z_2$$

The drift-diffusion model

Log-Likelihood ratio:

$$y_N = \log l(\mathbf{x}_N)$$

$$\mathbf{x}_N = (x_1, x_2, \ldots, x_N)$$

The drift-diffusion model

Log-Likelihood ratio:

$$\mathbf{x}_N = (x_1, x_2, \ldots, x_N)$$

$$\begin{aligned} y_N &= \log l(\mathbf{x}_N) \\ &= \log \left[\frac{p(x_1|+)}{p(x_1|-)} \frac{p(x_2|+)}{p(x_2|-)} \cdots \frac{p(x_N|+)}{p(x_N|-)} \right] \end{aligned}$$

The drift-diffusion model

Log-Likelihood ratio:

$$\mathbf{x}_N = (x_1, x_2, \ldots, x_N)$$

$$\begin{aligned}
y_N &= \log l(\mathbf{x}_N) \\
&= \log \left[\frac{p(x_1|+)}{p(x_1|-)} \frac{p(x_2|+)}{p(x_2|-)} \cdots \frac{p(x_N|+)}{p(x_N|-)} \right] \\
&= \log \frac{p(x_1|+)}{p(x_1|-)} + \log \frac{p(x_2|+)}{p(x_2|-)} + \cdots + \log \frac{p(x_N|+)}{p(x_N|-)}
\end{aligned}$$

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Log-Likelihood ratio:

$$\mathbf{x}_N = (x_1, x_2, \ldots, x_N)$$

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&= \log \frac{p(x_1|+)}{p(x_1|-)} + \log \frac{p(x_2|+)}{p(x_2|-)} + \cdots + \log \frac{p(x_N|+)}{p(x_N|-)} \\
&= \log \frac{p(x_1|+)}{p(x_1|-)} + \log \frac{p(x_2|+)}{p(x_2|-)} + \cdots + \log \frac{p(x_{N-1}|+)}{p(x_{N-1}|-)} \\
&\qquad + \log \frac{p(x_N|+)}{p(x_N|-)} \\
&= y_{N-1} + \log \frac{p(x_N|+)}{p(x_N|-)}
\end{aligned}$$

The drift-diffusion model

Optimal strategy:
Decide as soon as a certain reliability has been met.

$$y_N = y_{N-1} + \log \frac{p(x_N|+)}{p(x_N|-)} \qquad y_N < -\Theta \quad \vee \quad y_N > \Theta$$

The drift-diffusion model

Optimal strategy:
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$$y_N = y_{N-1} + \log \frac{p(x_N|+)}{p(x_N|-)} \qquad y_N < -\Theta \quad \vee \quad y_N > \Theta$$

Define:

$$m = E\left[\log \frac{p(x|+)}{p(x|-)}\right] \qquad \sigma^2 = \mathrm{Var}\left[\log \frac{p(x|+)}{p(x|-)}\right]$$

The drift-diffusion model

Optimal strategy:
Decide as soon as a certain reliability has been met.

$$y_N = y_{N-1} + \log \frac{p(x_N|+)}{p(x_N|-)} \qquad y_N < -\Theta \quad \vee \quad y_N > \Theta$$

Define:

$$m = E\left[\log \frac{p(x|+)}{p(x|-)}\right] \qquad \sigma^2 = \mathrm{Var}\left[\log \frac{p(x|+)}{p(x|-)}\right]$$

Then approximately:

$$\log \frac{p(x_N|+)}{p(x_N|-)} = m + \sigma\eta$$

random Gaussian number with zero mean and variance σ^2

average log-likelihood ratio

The drift-diffusion model

Optimal strategy:
Decide as soon as a certain reliability has been met.

$$y_N = y_{N-1} + \log \frac{p(x_N|+)}{p(x_N|-)}$$

$$= y_{N-1} + m + \sigma\eta$$

$$y_N < -\Theta \quad \vee \quad y_N > \Theta$$

Random walk with drift
(drift-diffusion model)

$$\log \frac{p(x_N|+)}{p(x_N|-)} = m + \sigma\eta$$

random Gaussian number with zero mean and variance σ^2

average log-likelihood ratio

The drift-diffusion model

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Decide as soon as a certain reliability has been met.

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$$= y_{N-1} + m + \sigma\eta$$

$$y_N < -\Theta \quad \vee \quad y_N > \Theta$$

Random walk with drift
(drift-diffusion model)

In the limit of continuous time

$$\dot{y}(t) = m + \sigma\eta(t)$$

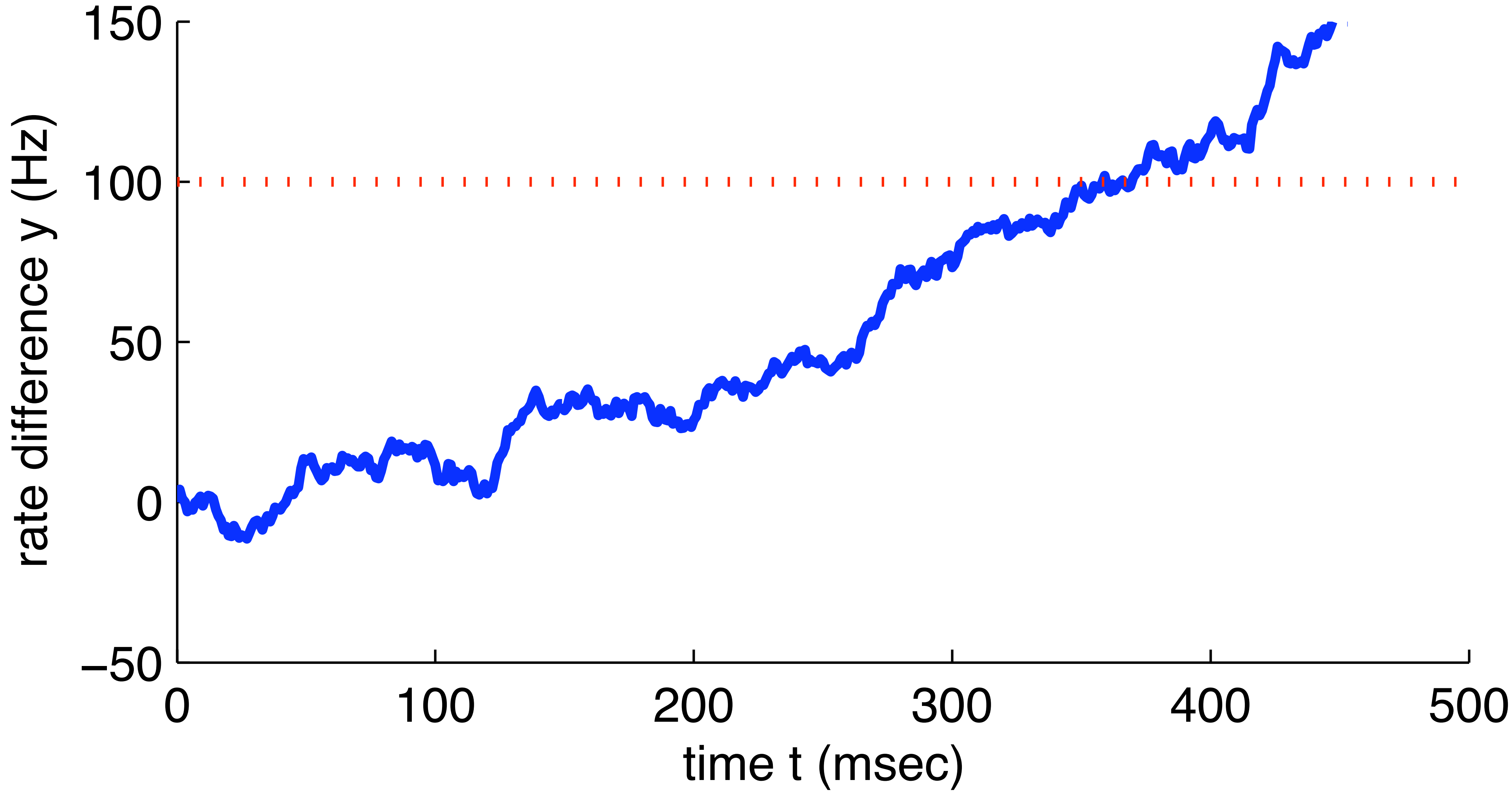
$$y(t) < -\Theta \quad \vee \quad y(t) > \Theta$$

noise term

The drift-diffusion model

$$\dot{y}(t) = m + \sigma\eta(t) \qquad\qquad y(t) < -\Theta \quad \vee \quad y(t) > \Theta$$

$$m = 0.3 \qquad \sigma = 2 \qquad \Theta = 100$$



The drift-diffusion model

$$\dot{y}(t) = m + \sigma\eta(t) \qquad\qquad y(t) < -\Theta \quad \vee \quad y(t) > \Theta$$

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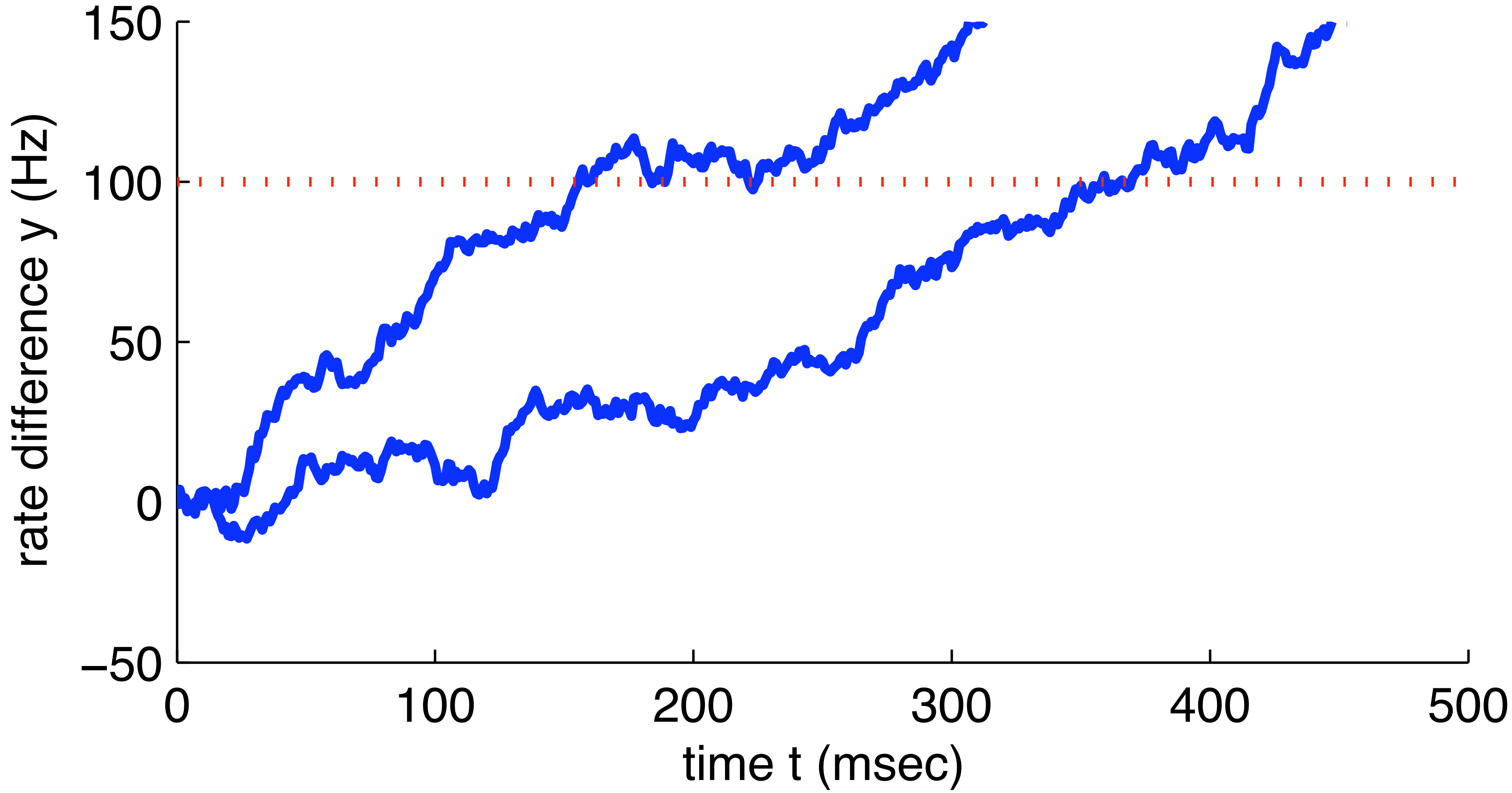

The drift-diffusion model

$$\dot{y}(t) = m + \sigma\eta(t) \qquad y(t) < -\Theta \quad \vee \quad y(t) > \Theta$$

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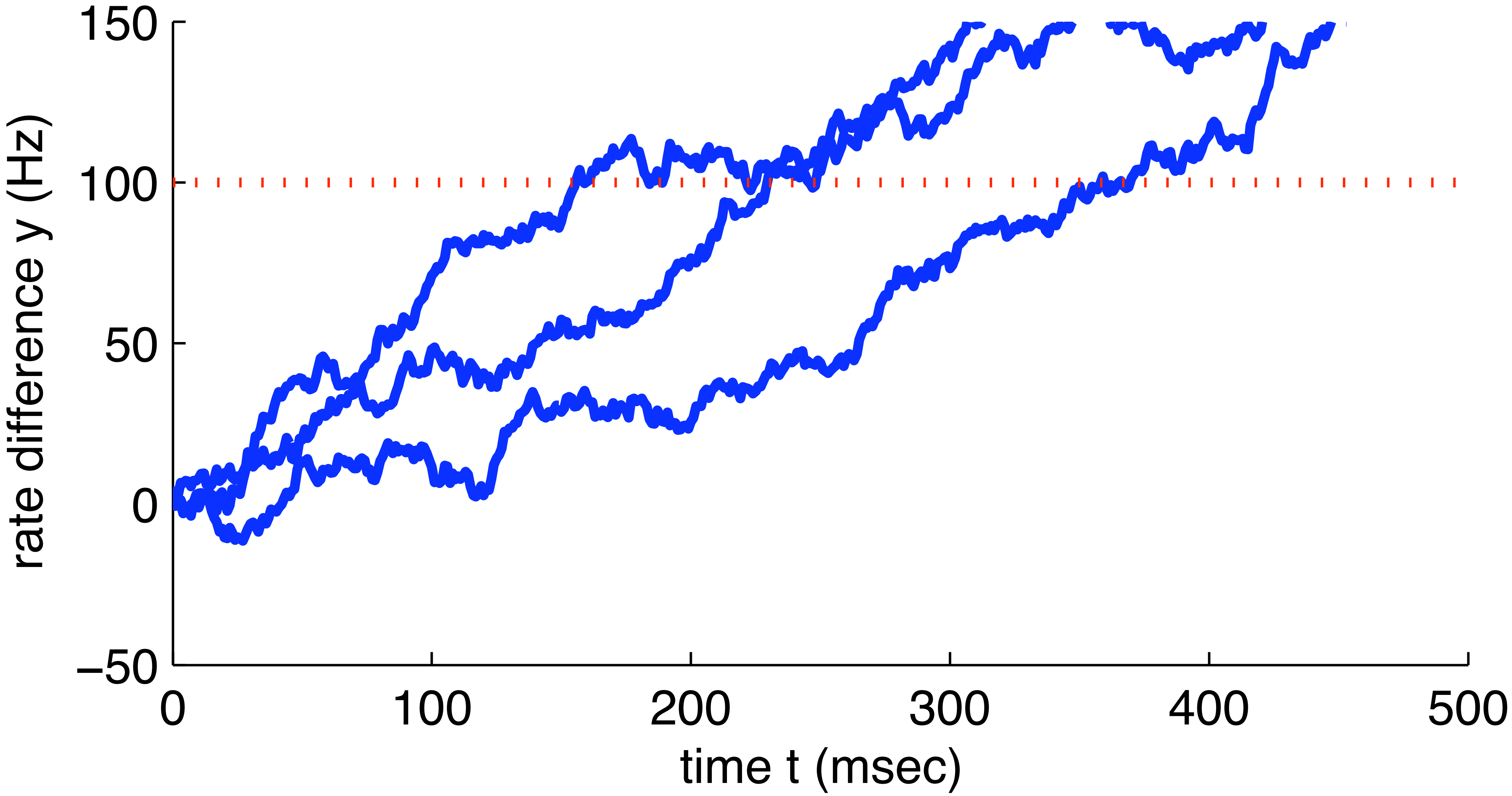
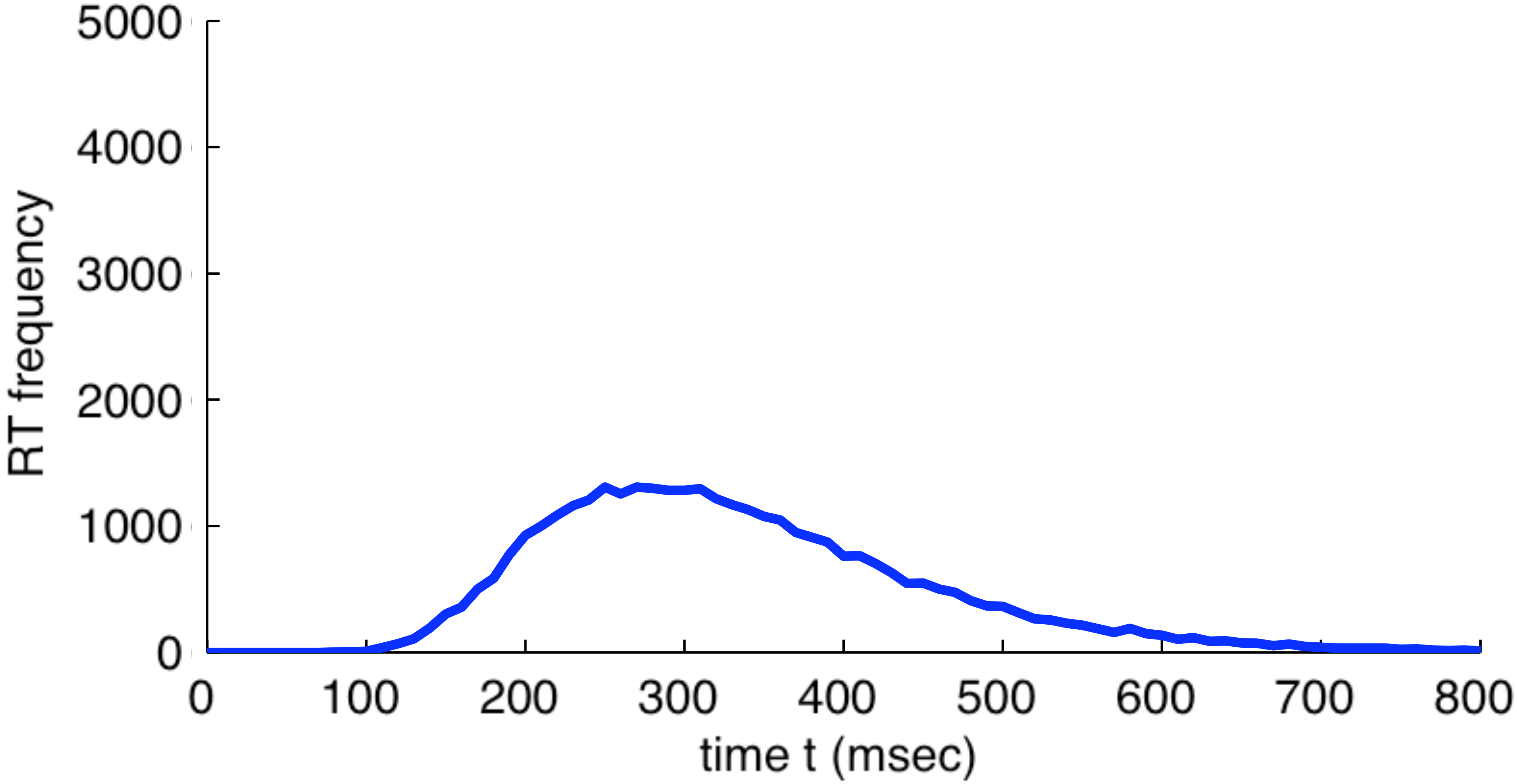


Reaction-time distribution

$$\mathrm{RT} = \mathrm{DT} + T_0$$



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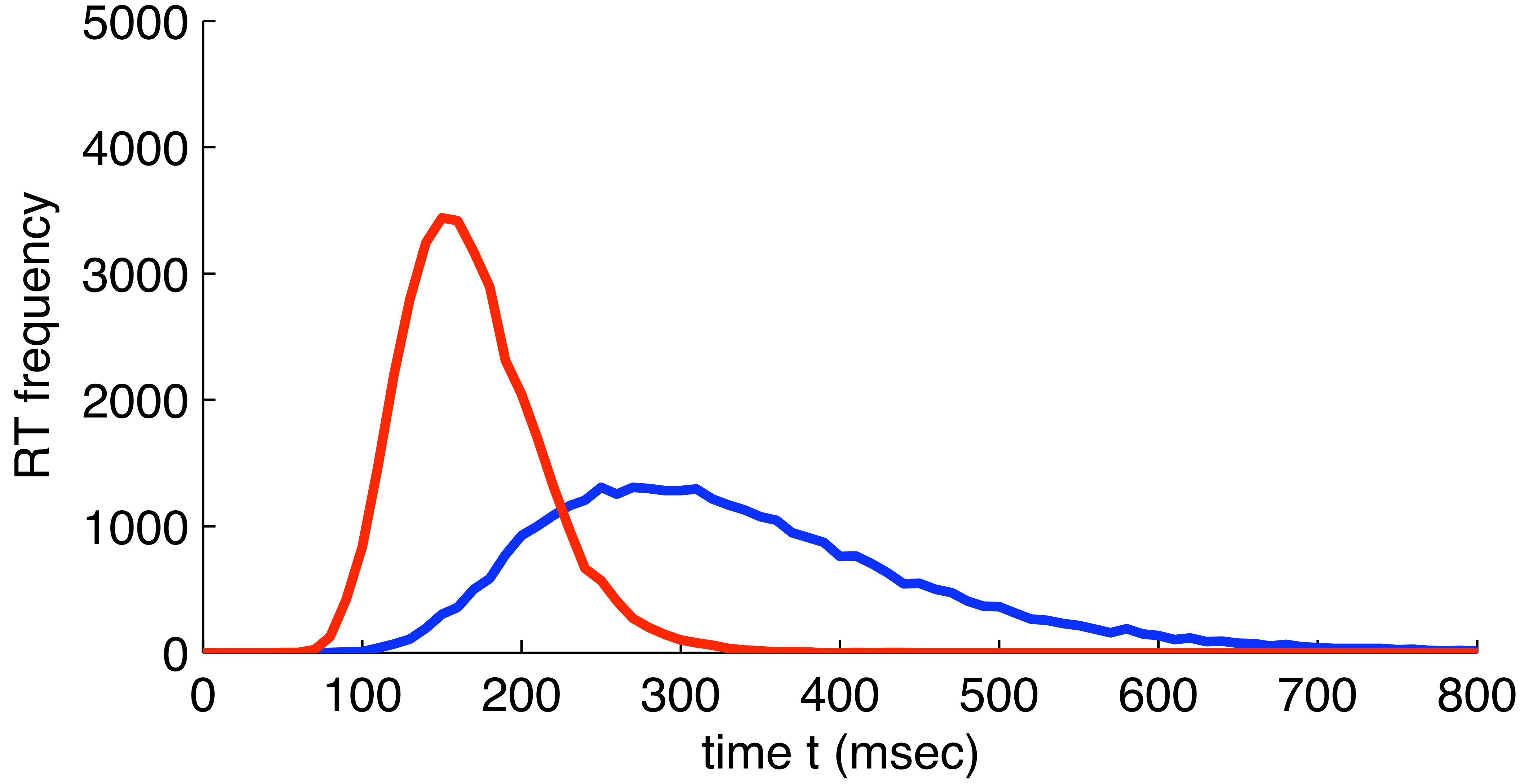
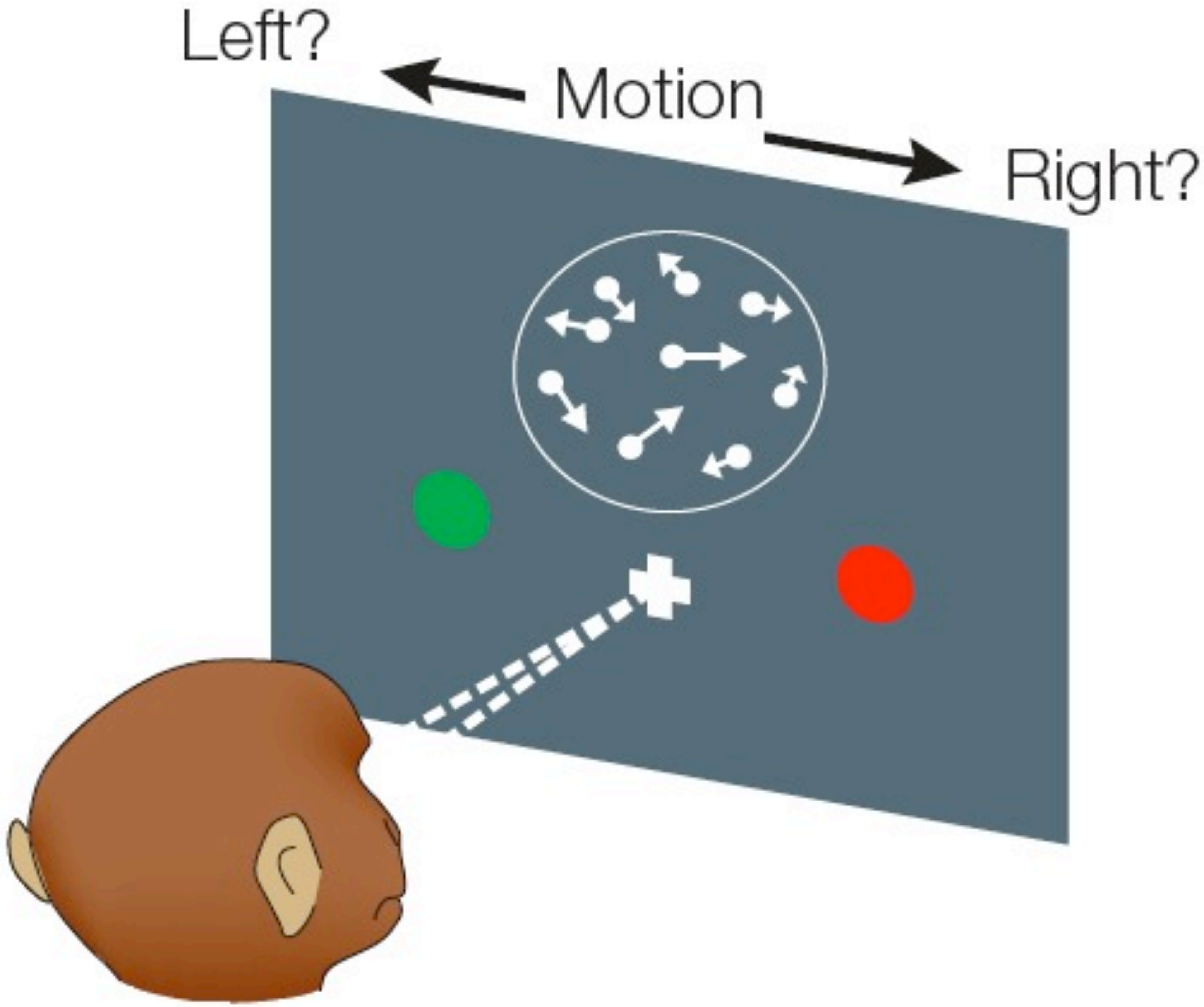
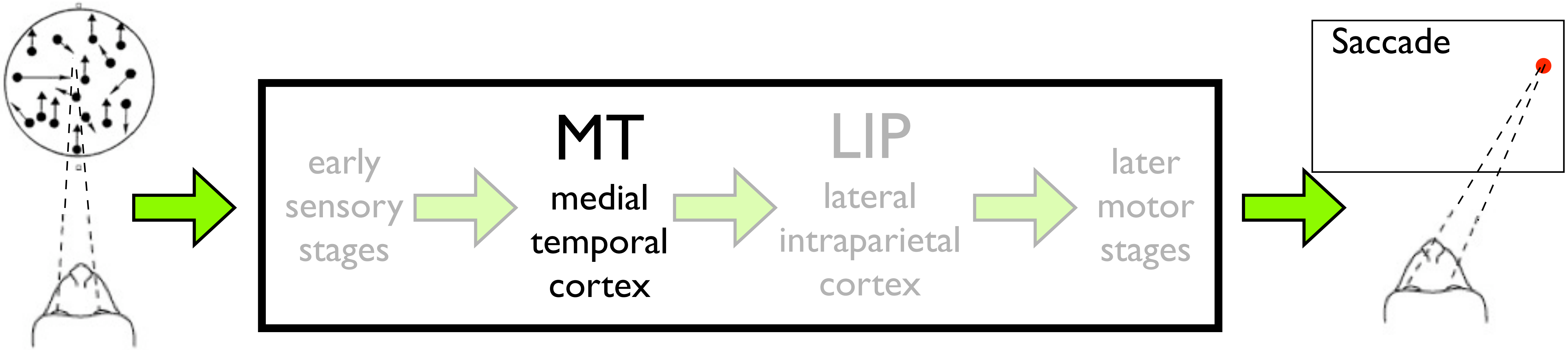


Experimental Evidence



Evidence in MT



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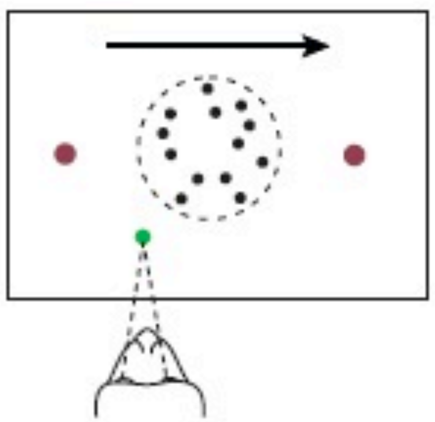
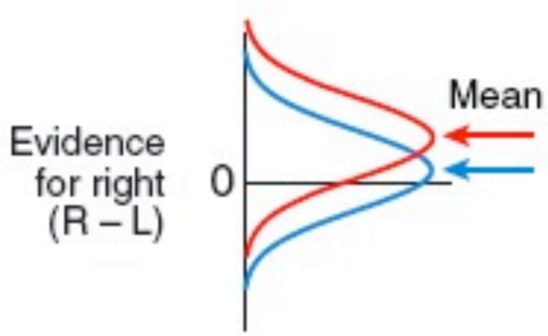
Microstimulation in MT

Stimulate rightward MT neurons

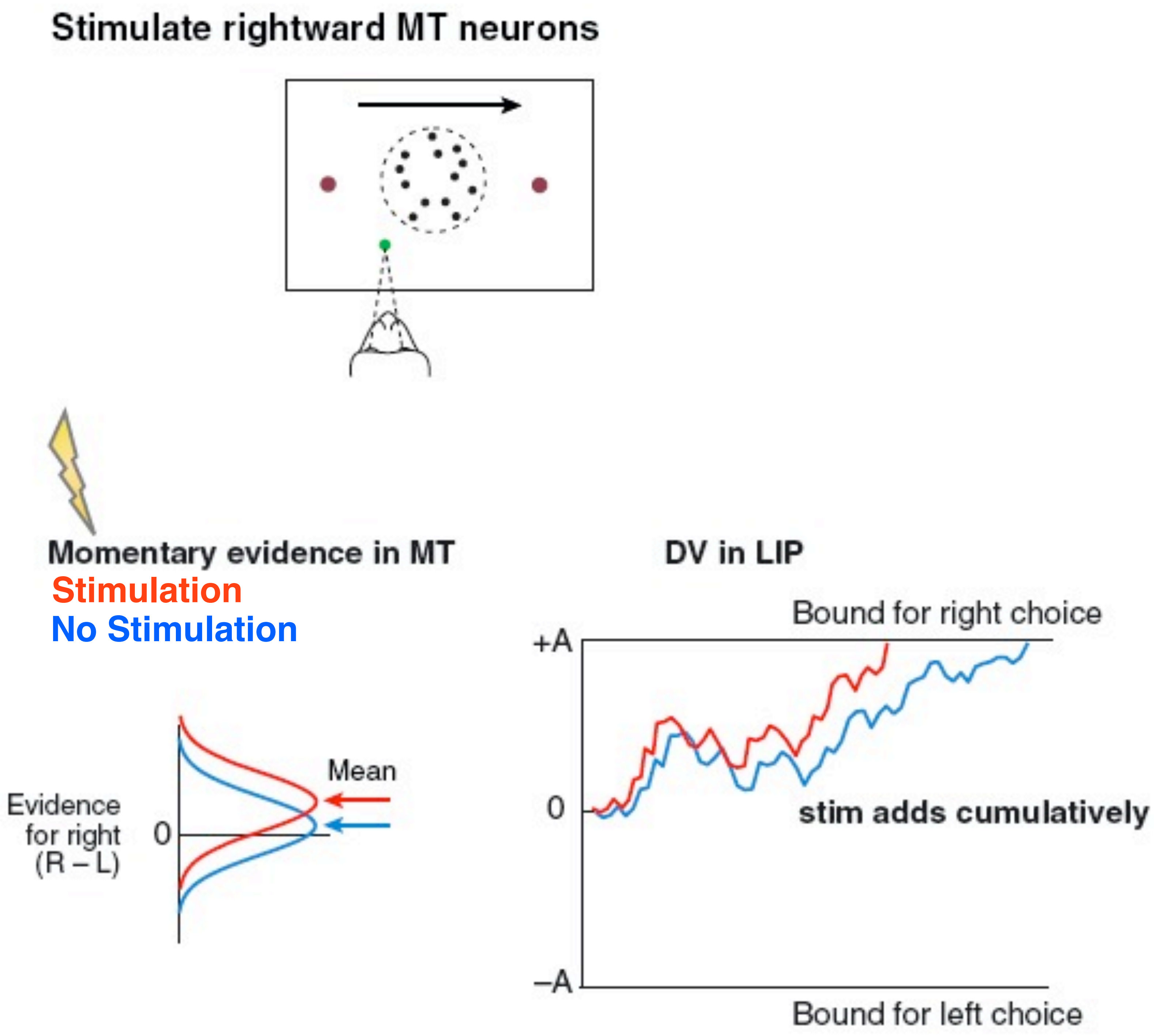


Momentary evidence in MT
Stimulation
No Stimulation



Gold & Shadlen (2007). Ann. Rev. Neurosci.

Microstimulation in MT



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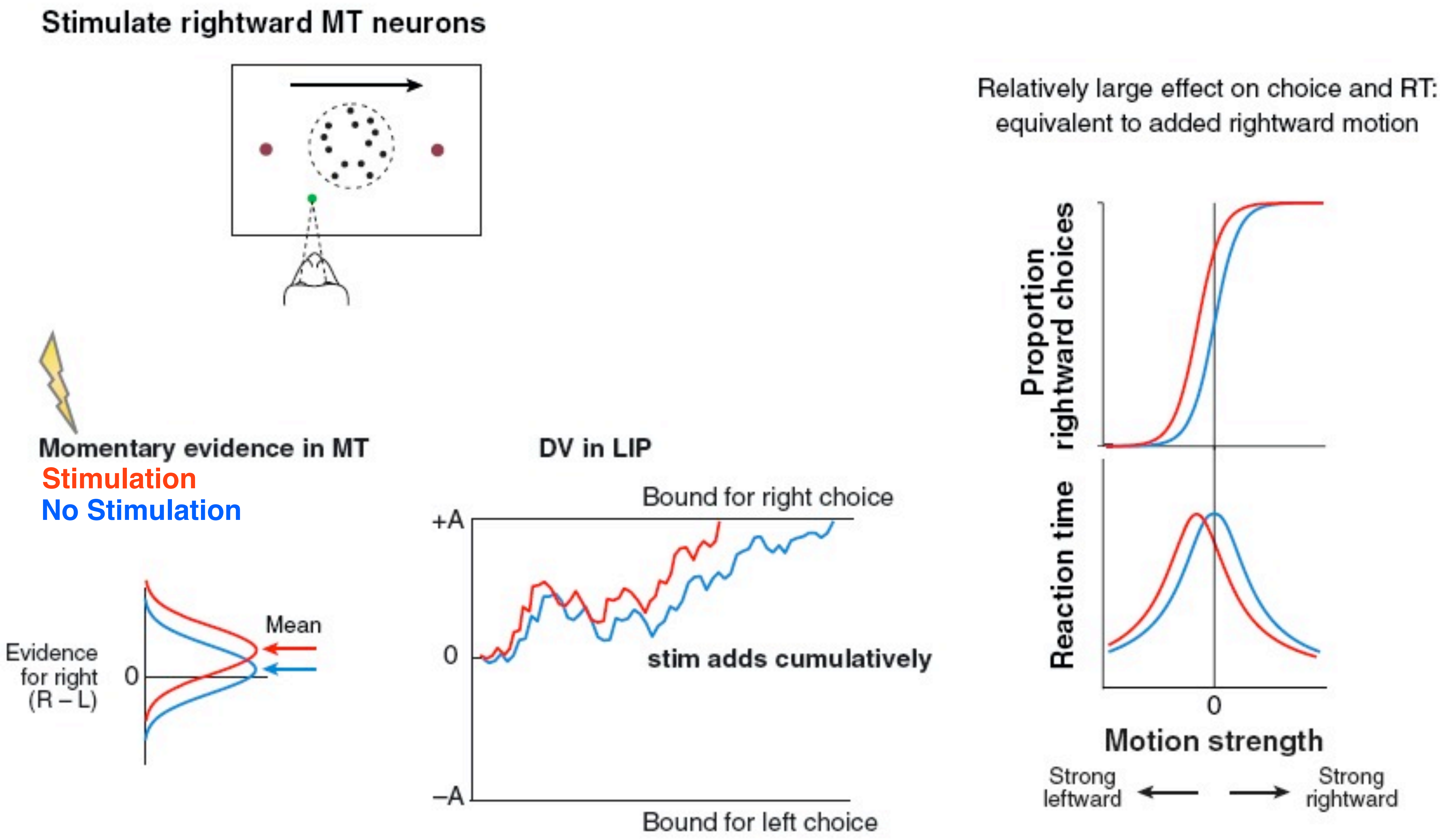
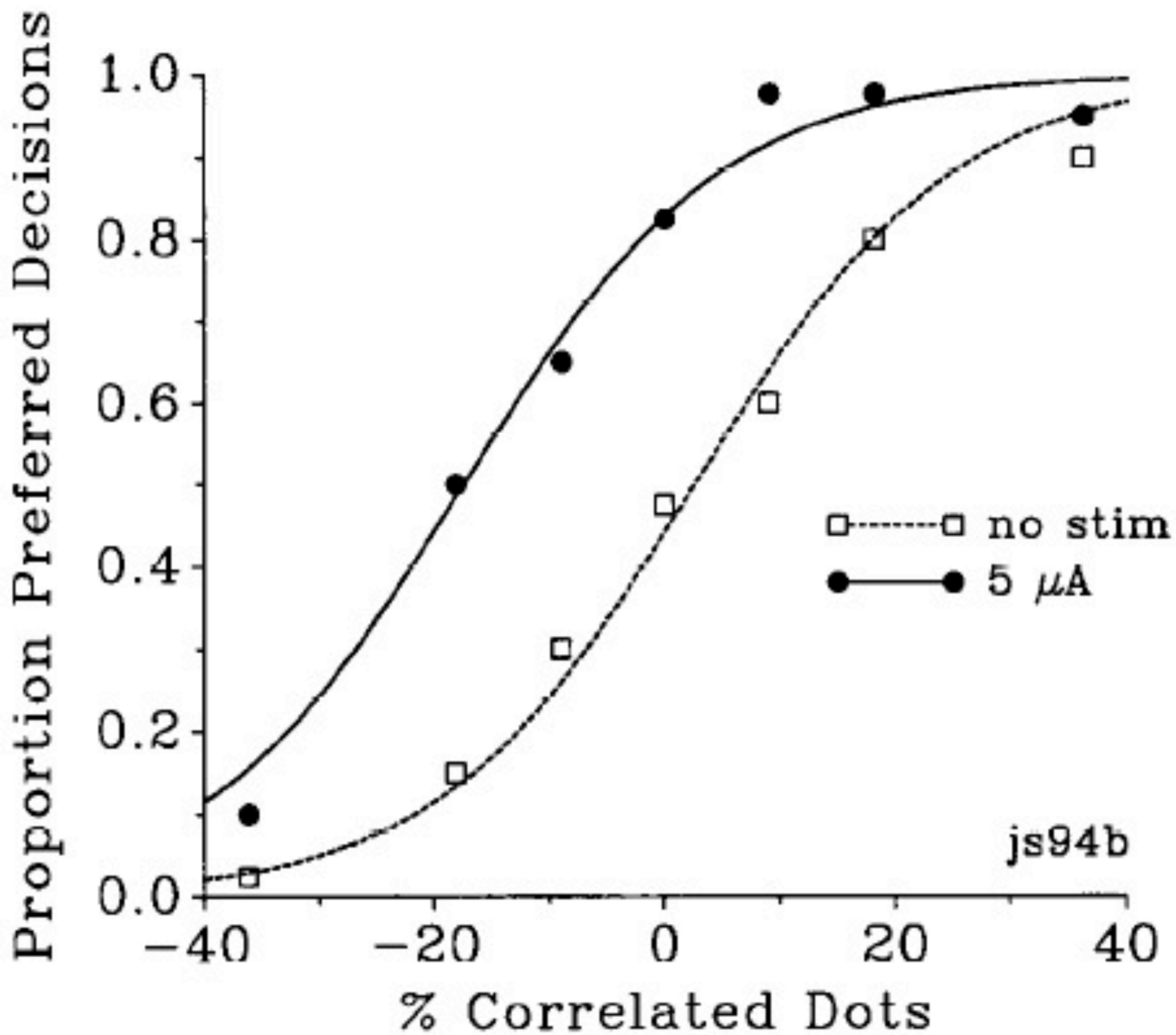
Microstimulation in MT



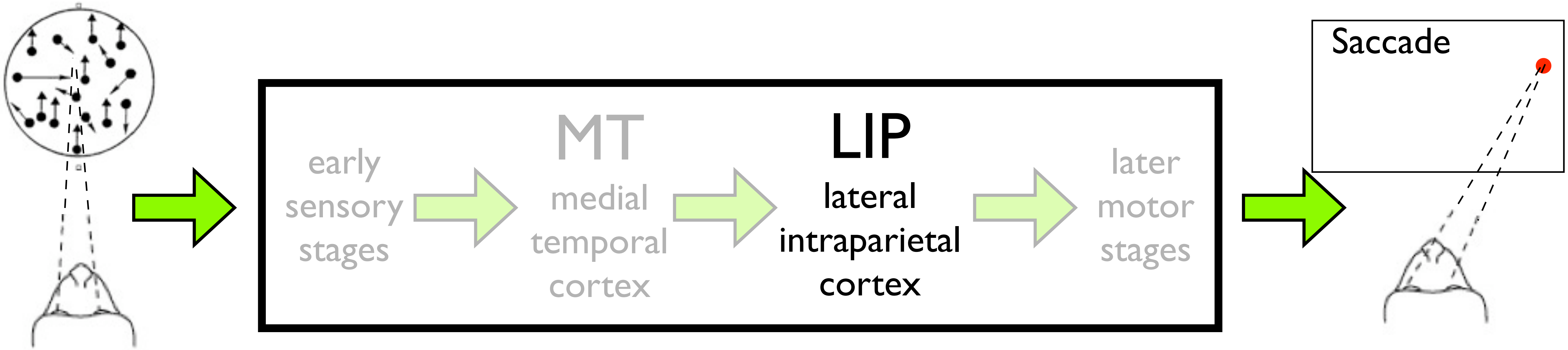
Gold & Shadlen (2007). Ann. Rev. Neurosci.

Shift in psychometric curve



Murasugi, Salzman, Newsome (1993). J. Neurosci.

Evidence in LIP



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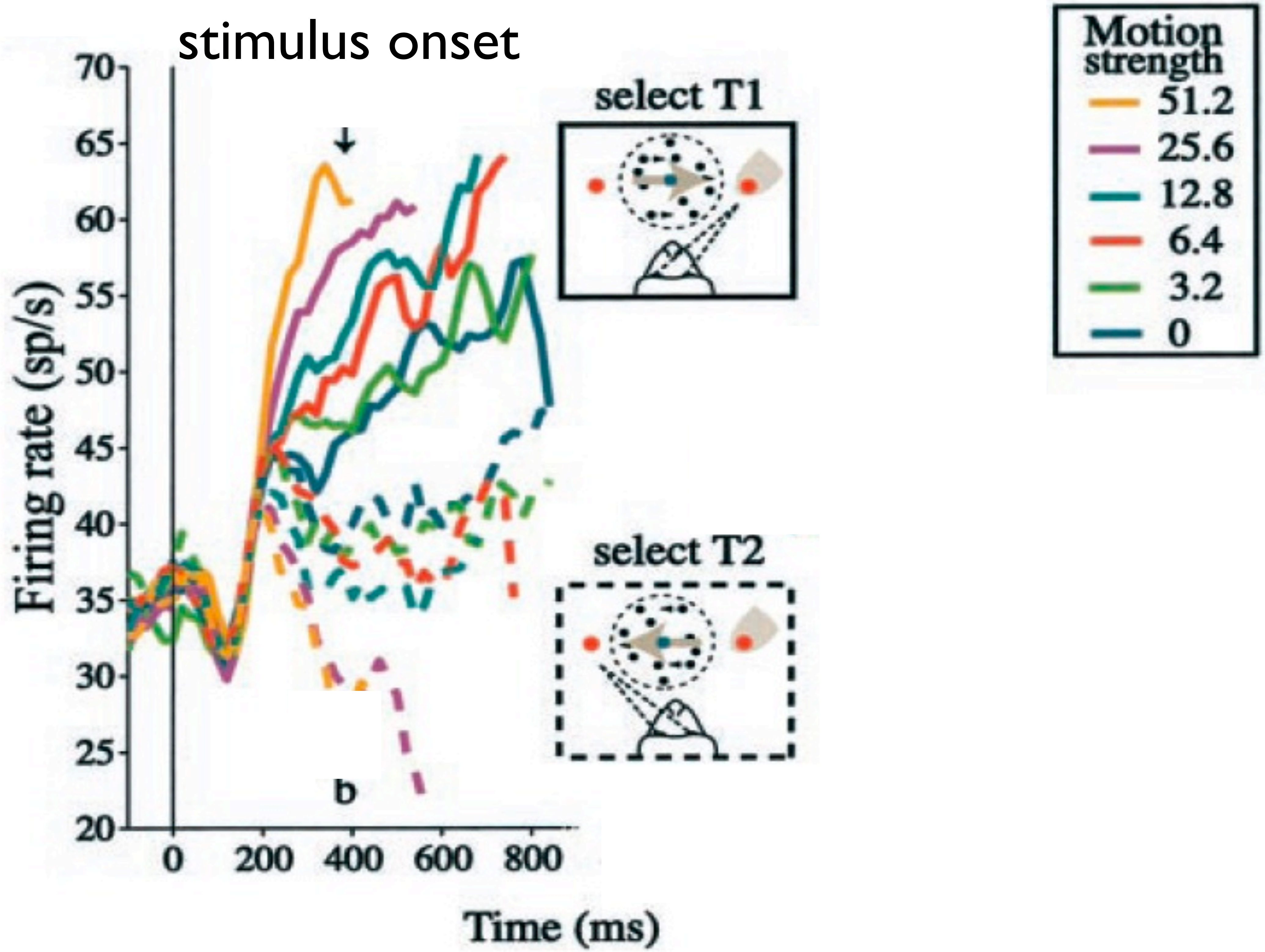
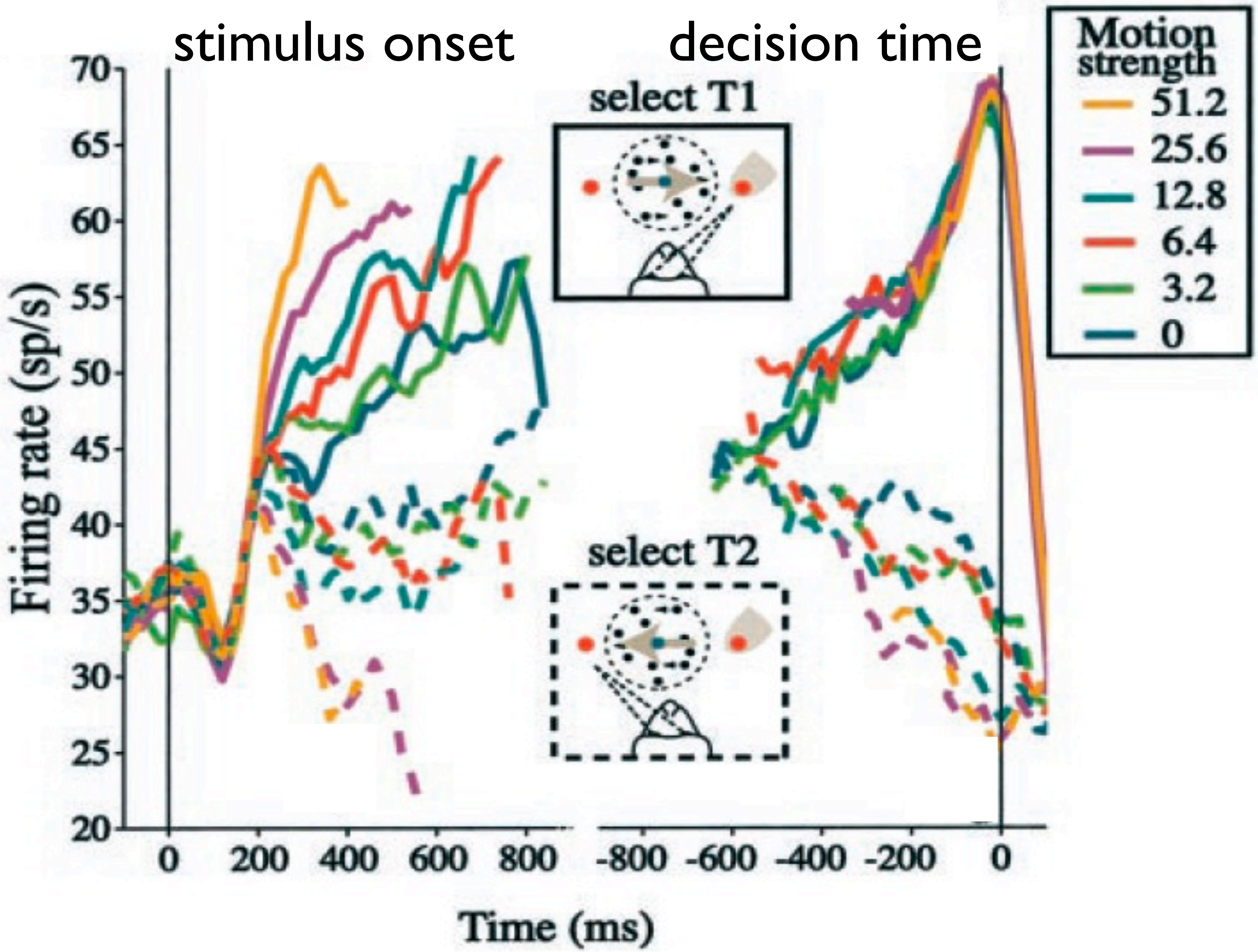
Single neuron in LIP



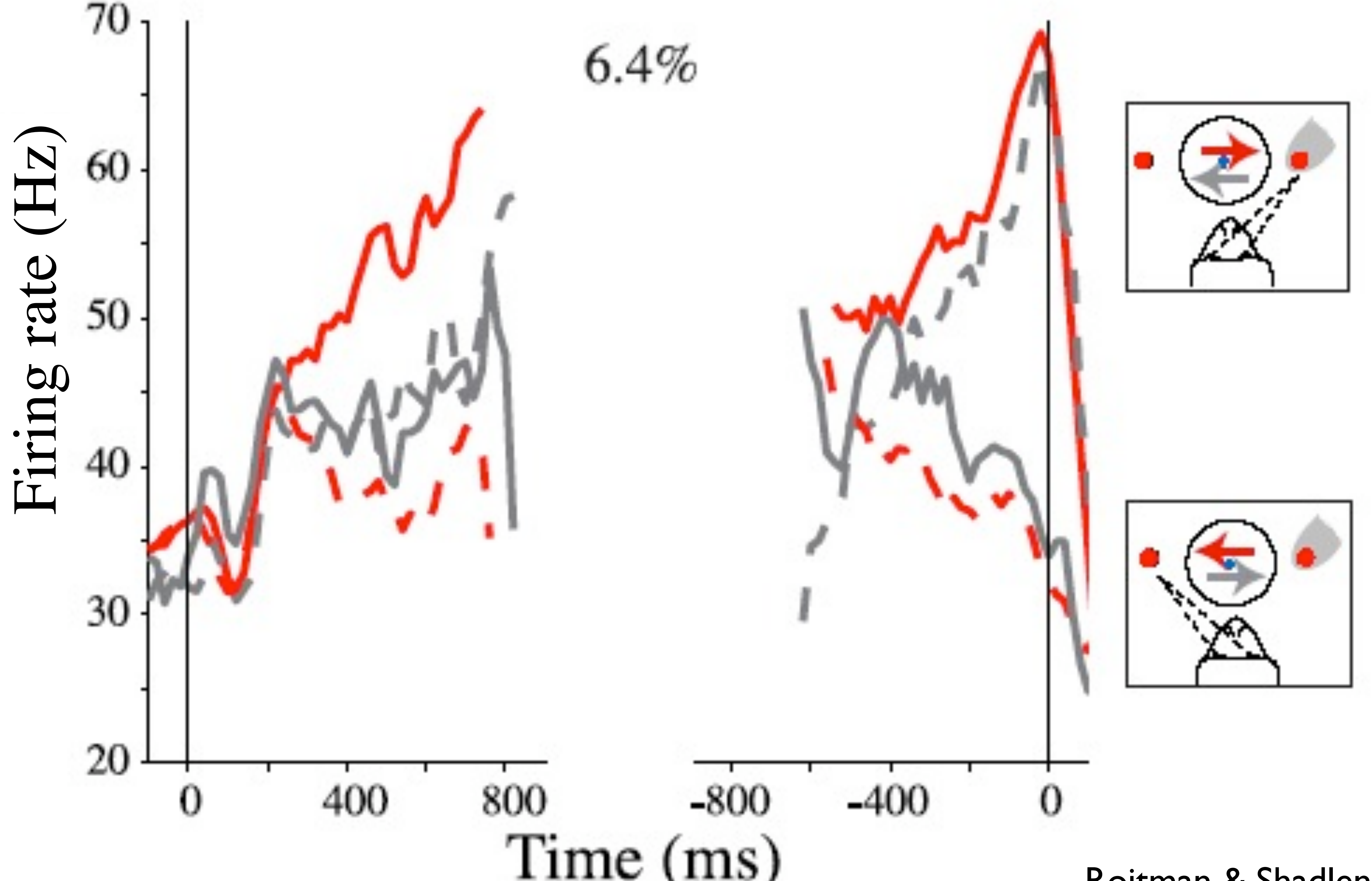
Roitman & Shadlen, 2002

Single neuron in LIP



Roitman & Shadlen, 2002

Error trials



Roitman & Shadlen, 2002