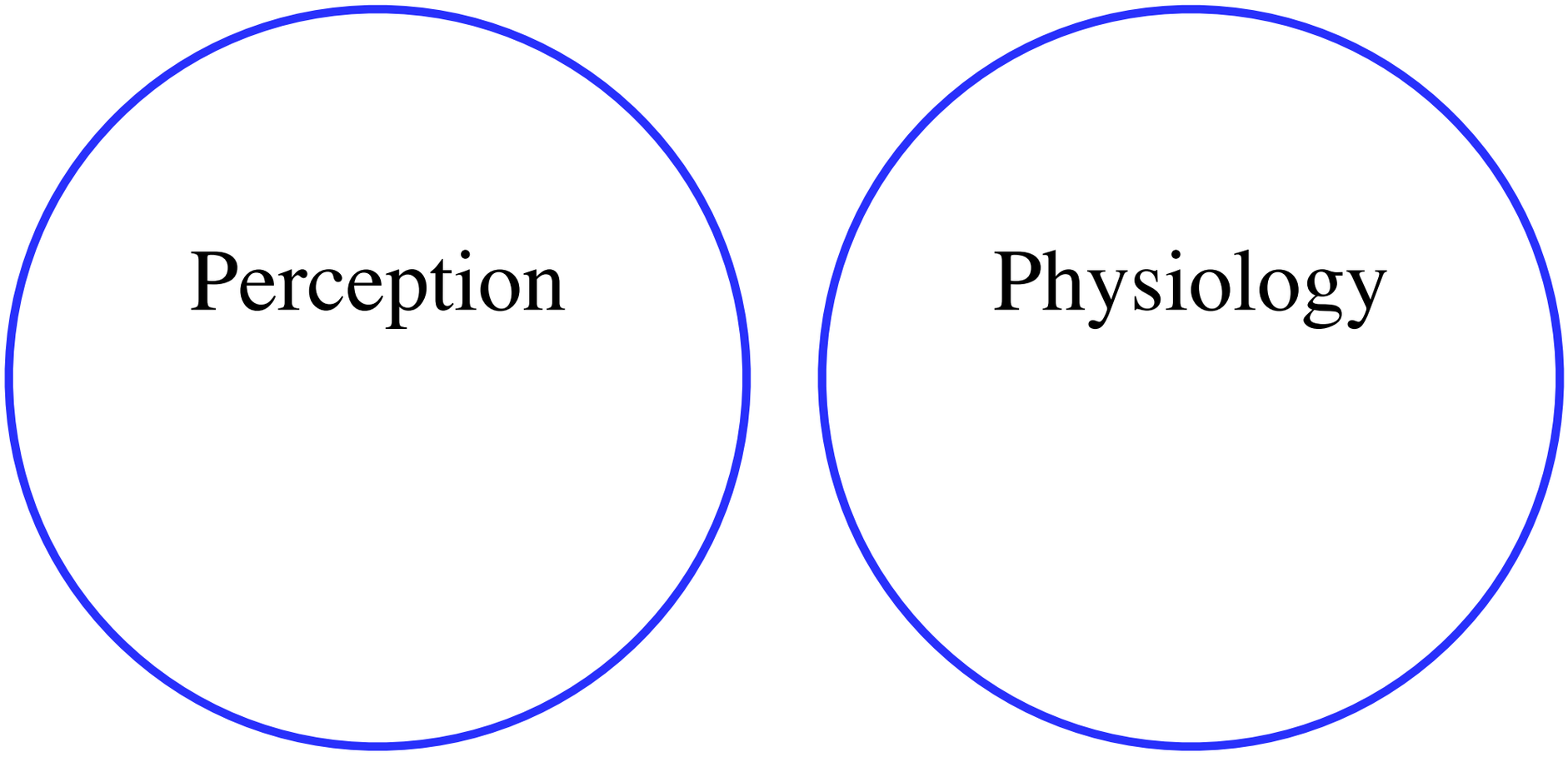
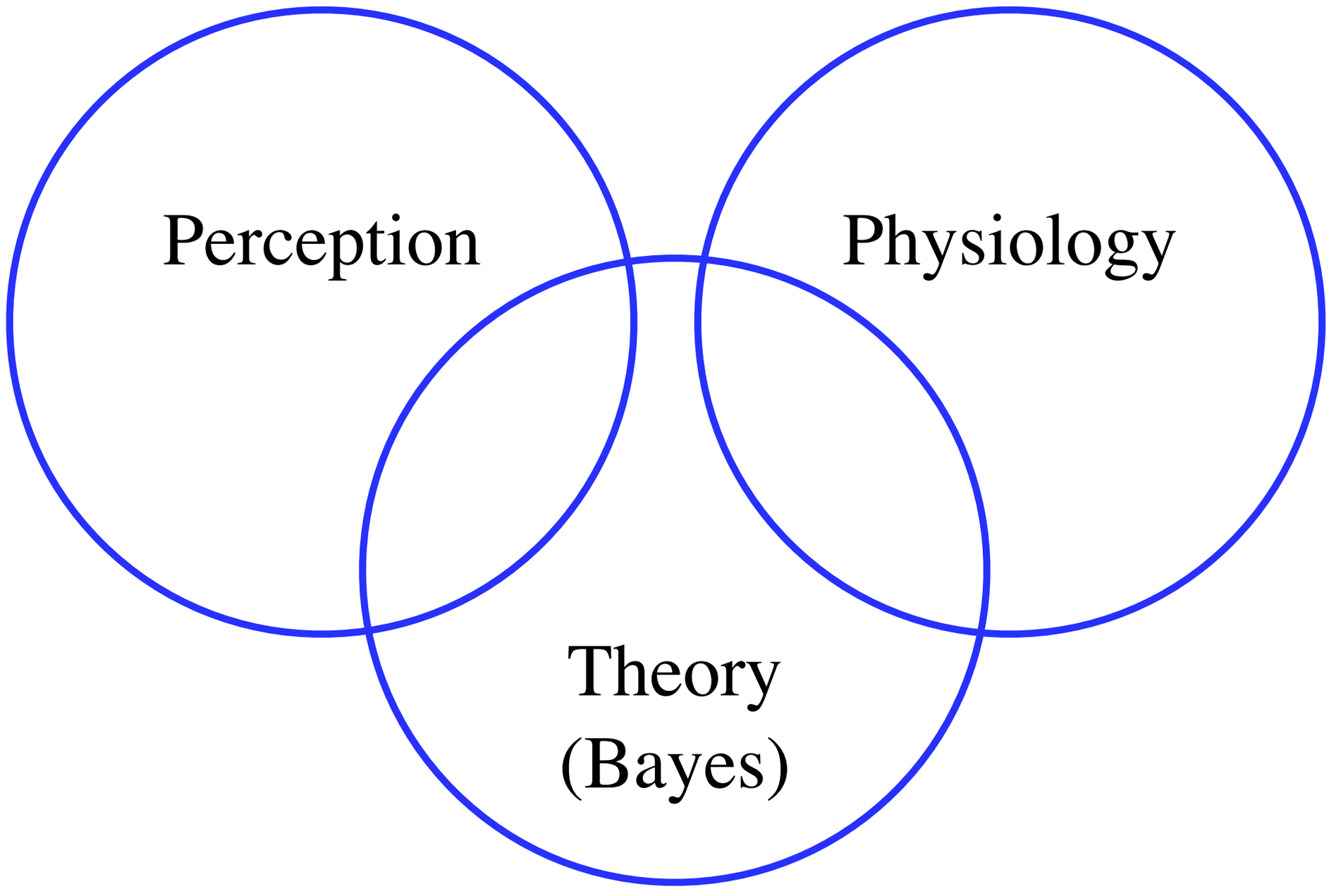
II. Bayes motion estimation

Visual motion processing



Visual motion processing



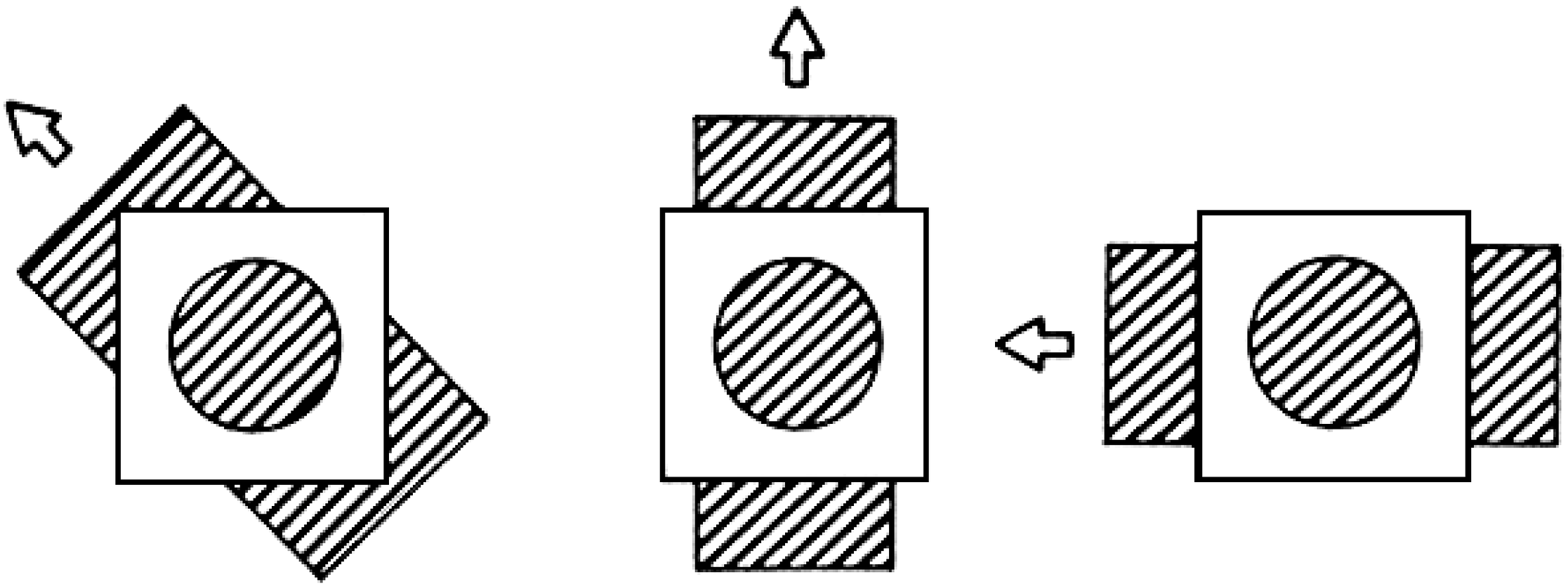
Visual motion

- Physiology: "motion pathway" heavily studied; arguably the strongest extrastriate success story

- Perception: Human motion perception heavily studied. Humans are adept at tasks which require motion processing.

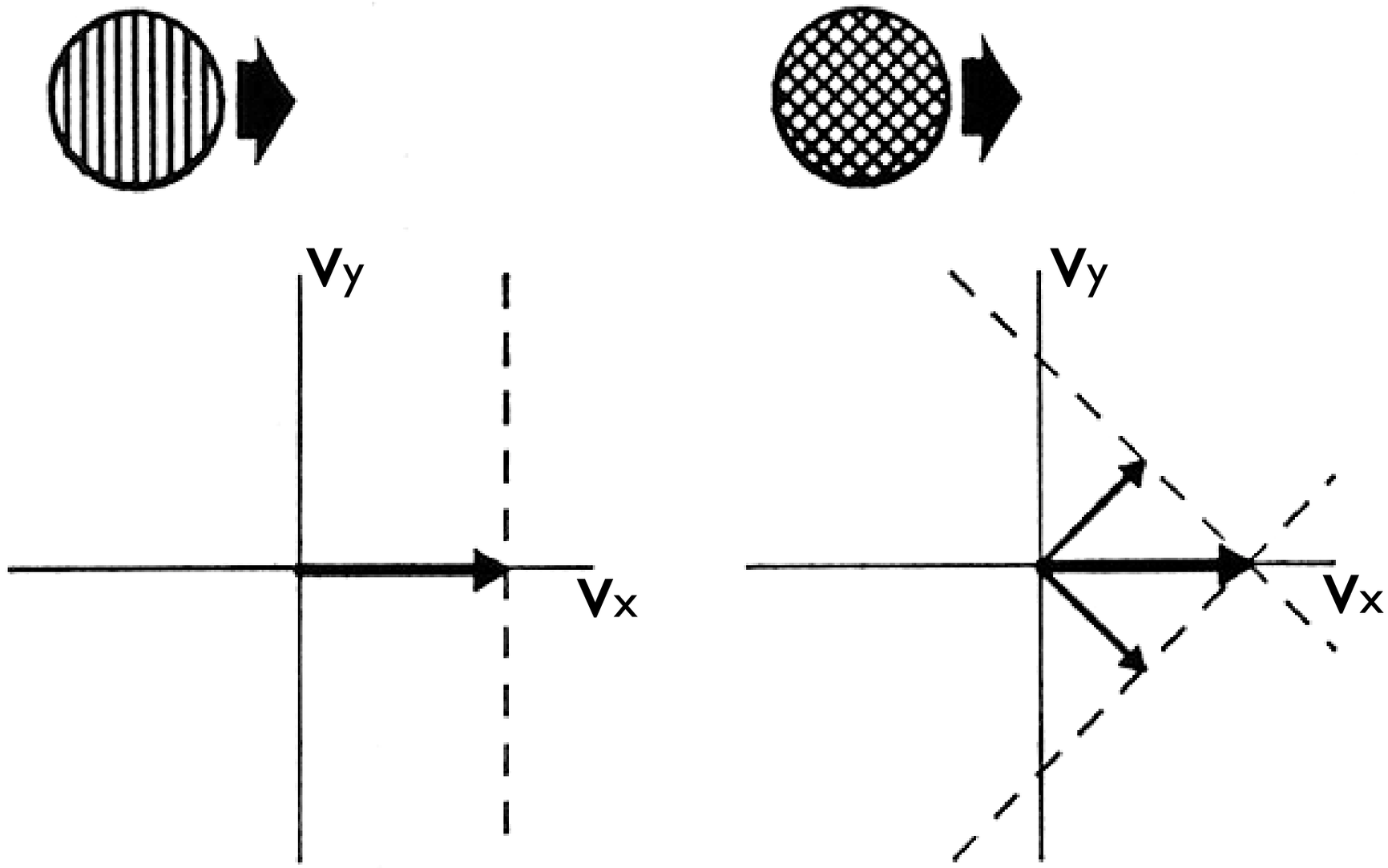
- Provides a rich source of visual information for prediction, depth perception, material properties, etc [Gibson, 1950]

“Aperture Problem”

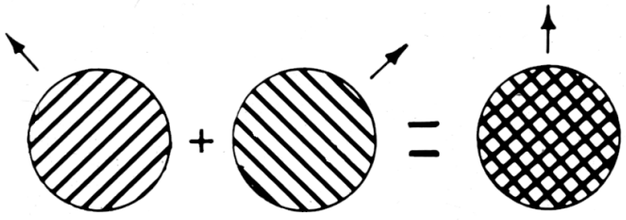


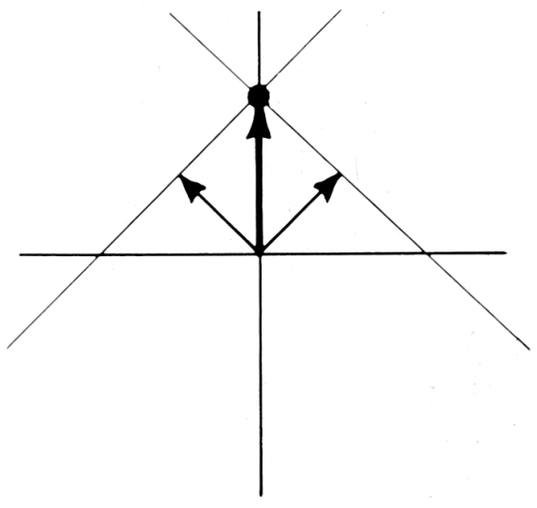
[Wallach 1935; Horn & Schunck 1981; Marr & Ullman 1981]
Figure: Movshon, Adelson, Gizzi, Newsome, 1985

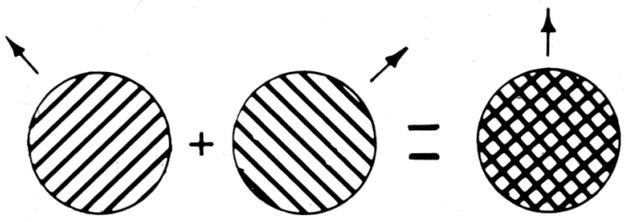
Intersection-of-constraints (IOC)

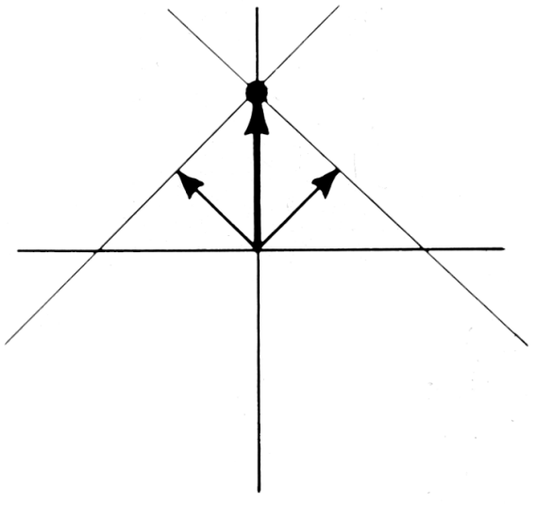


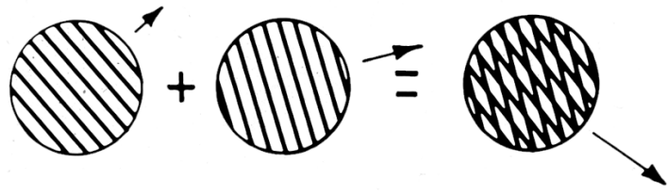
[Adelson & Movshon, 1982]

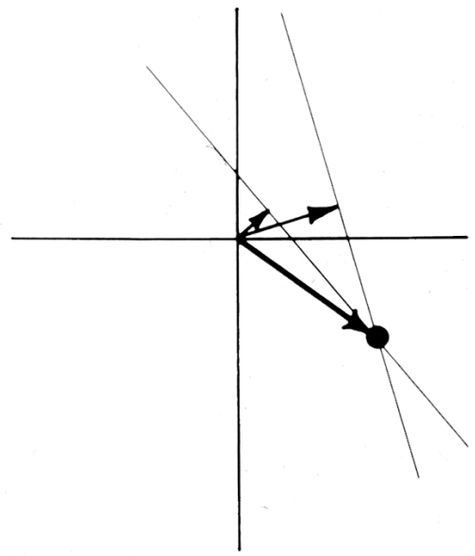


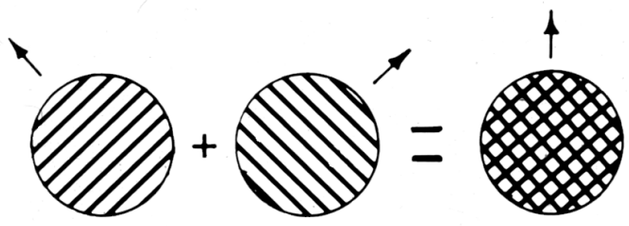


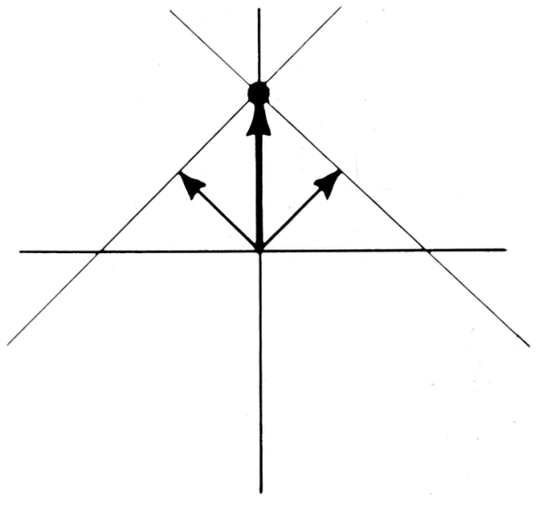


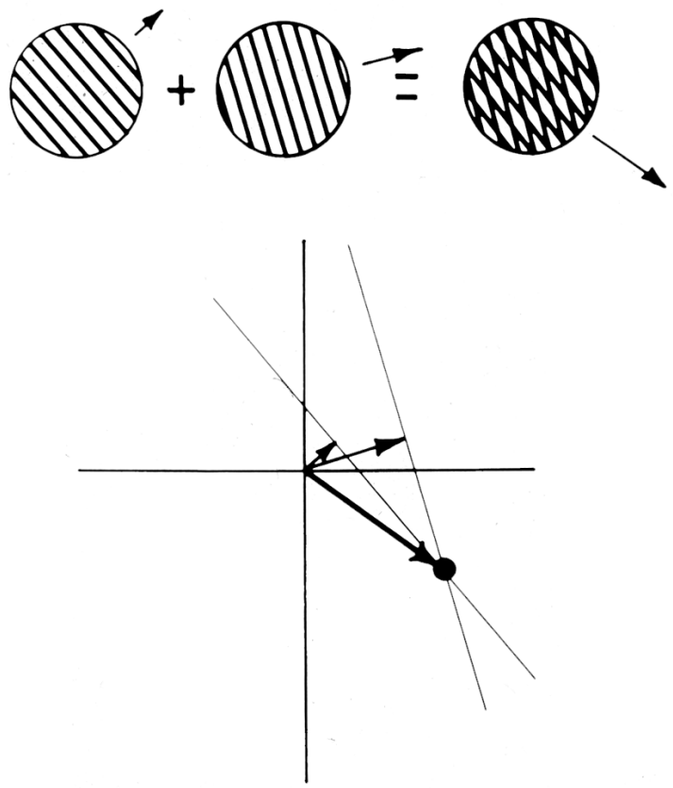


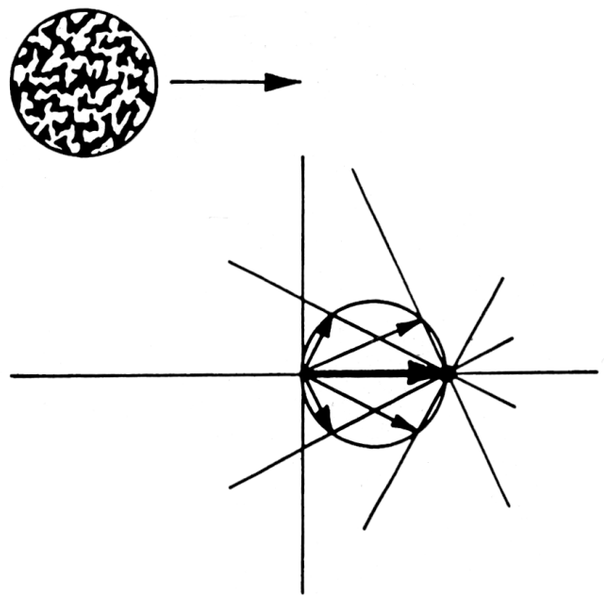




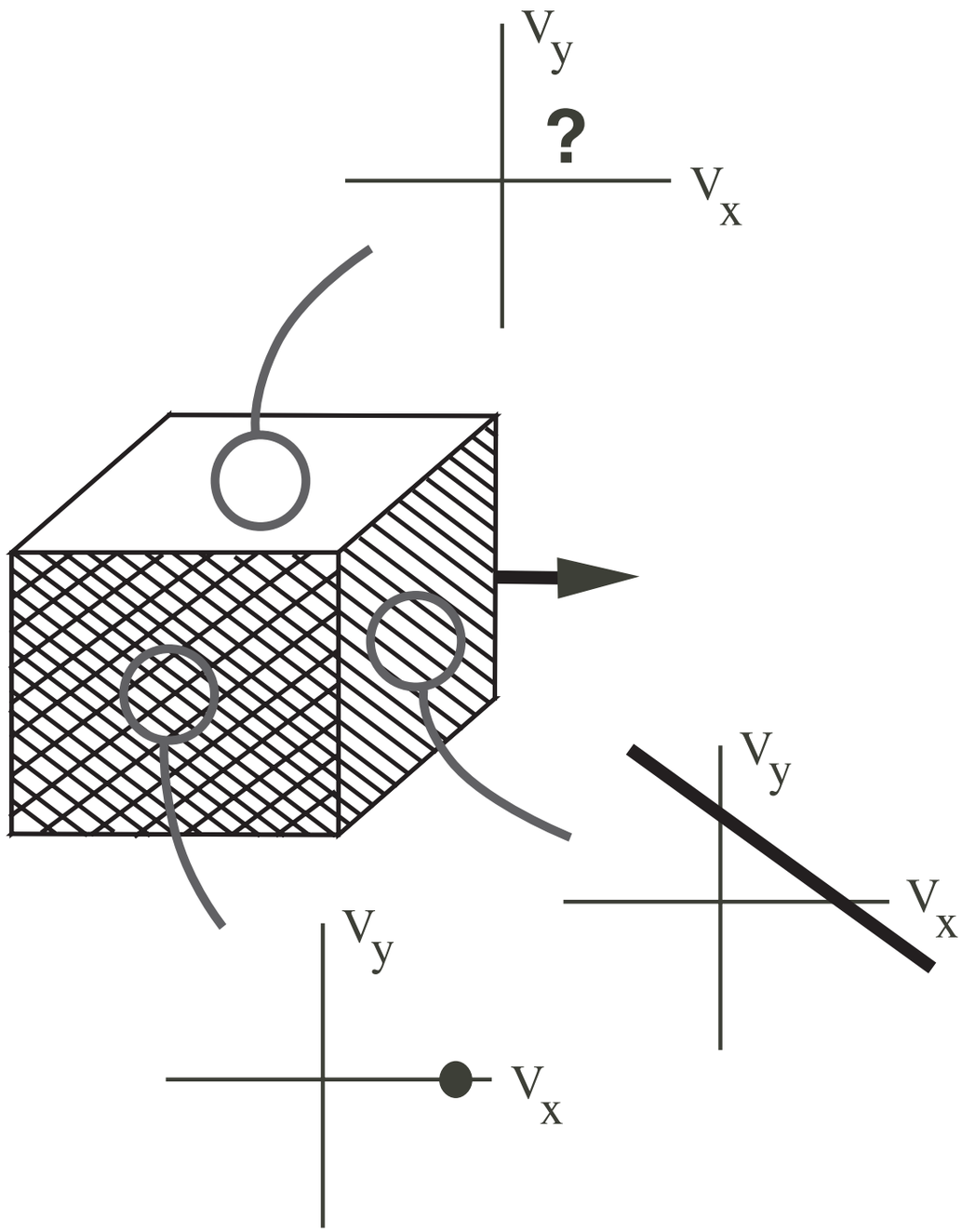








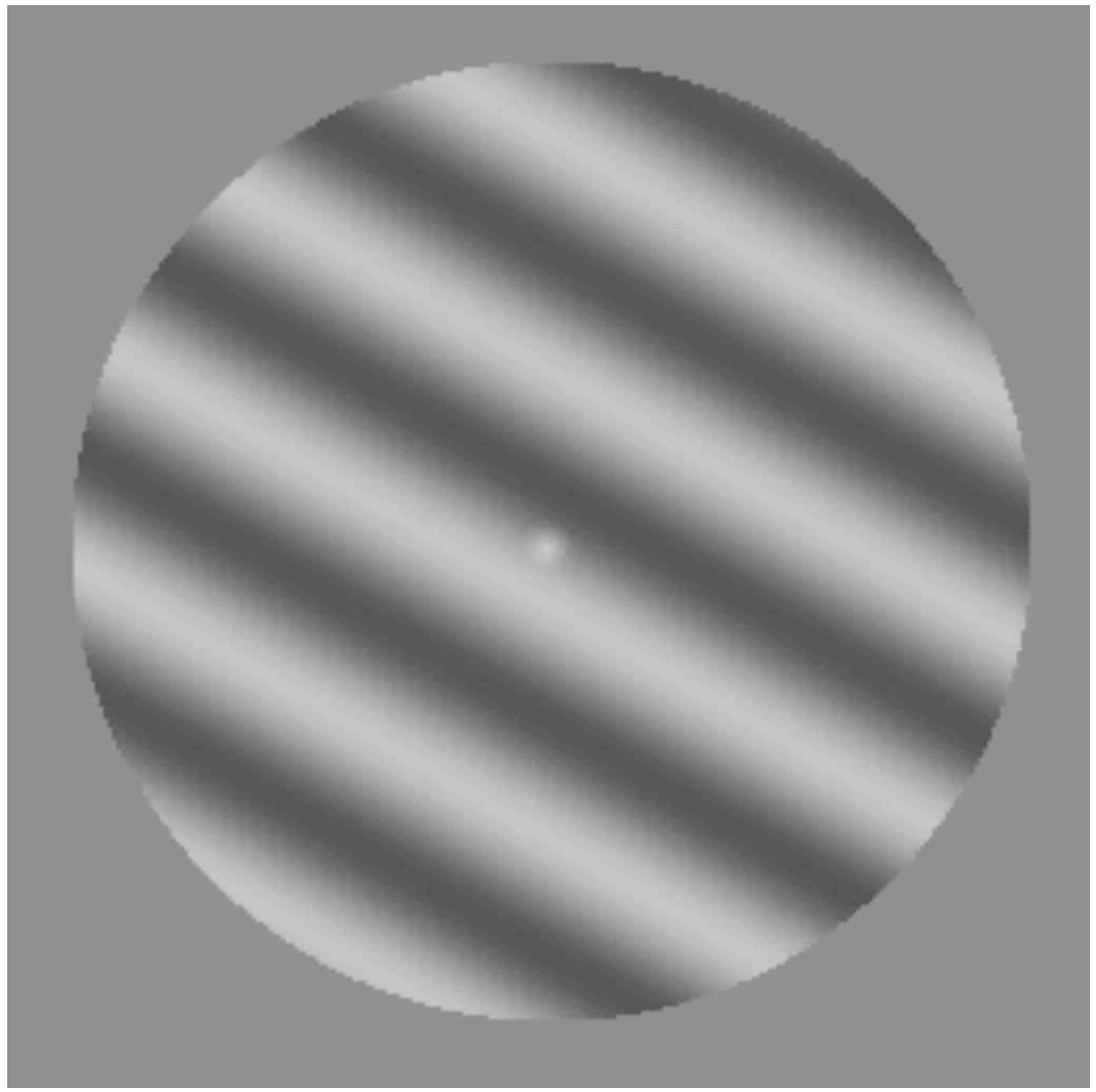
Visual motion ambiguity



Simple plaid perception = IOC

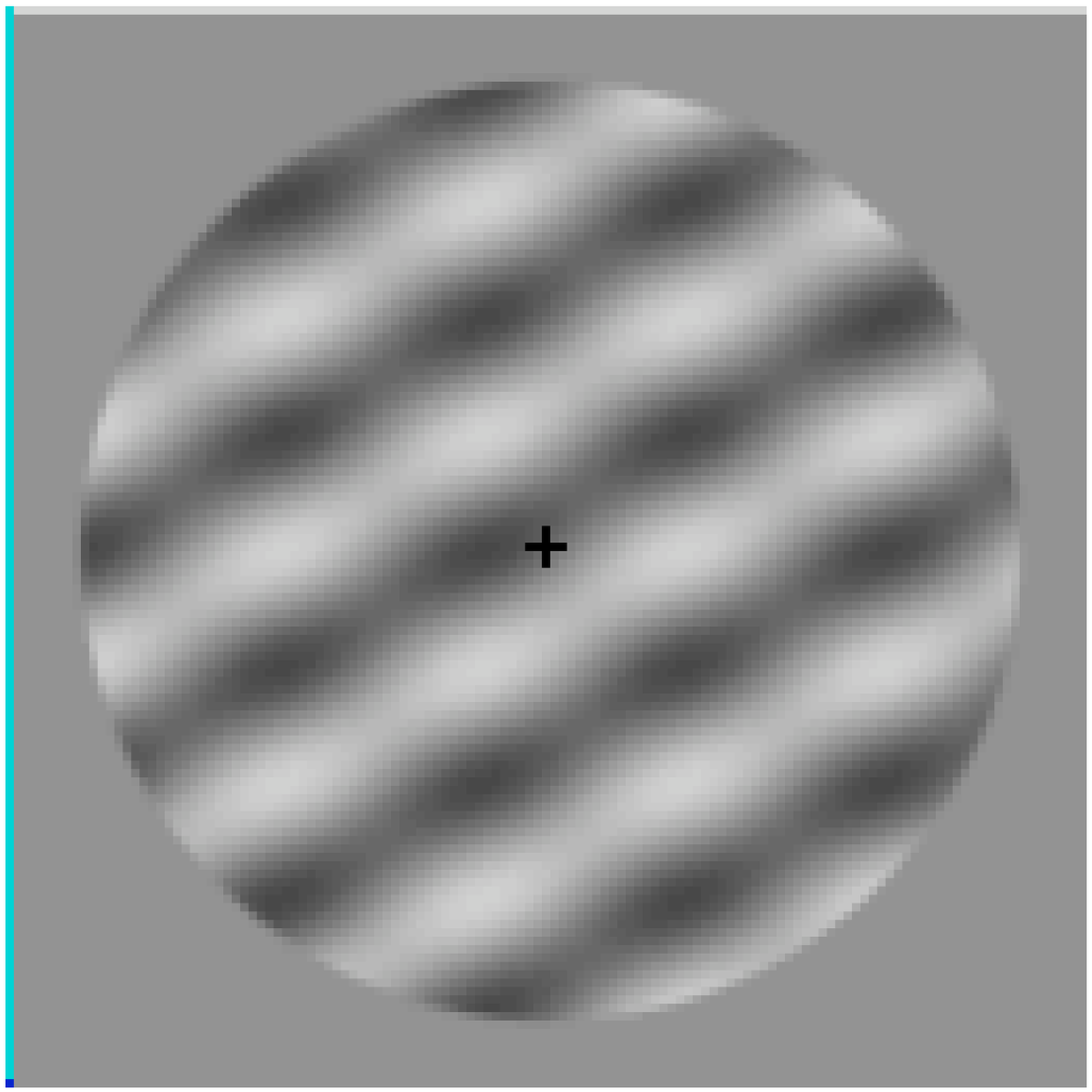
[Adelson & Movshon, 1982]

Simple plaid perception = IOC



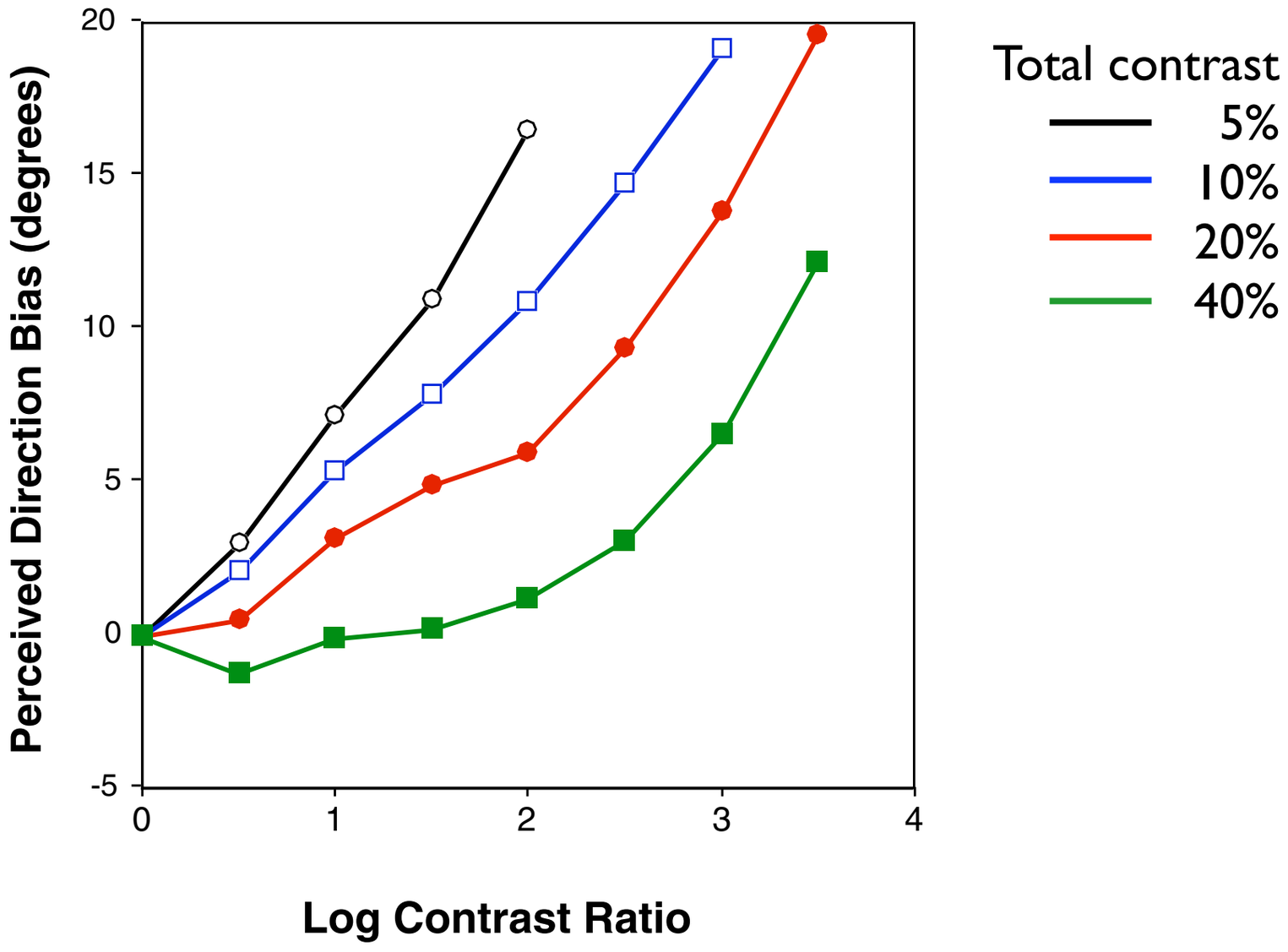
[Adelson & Movshon, 1982]

IOC failure

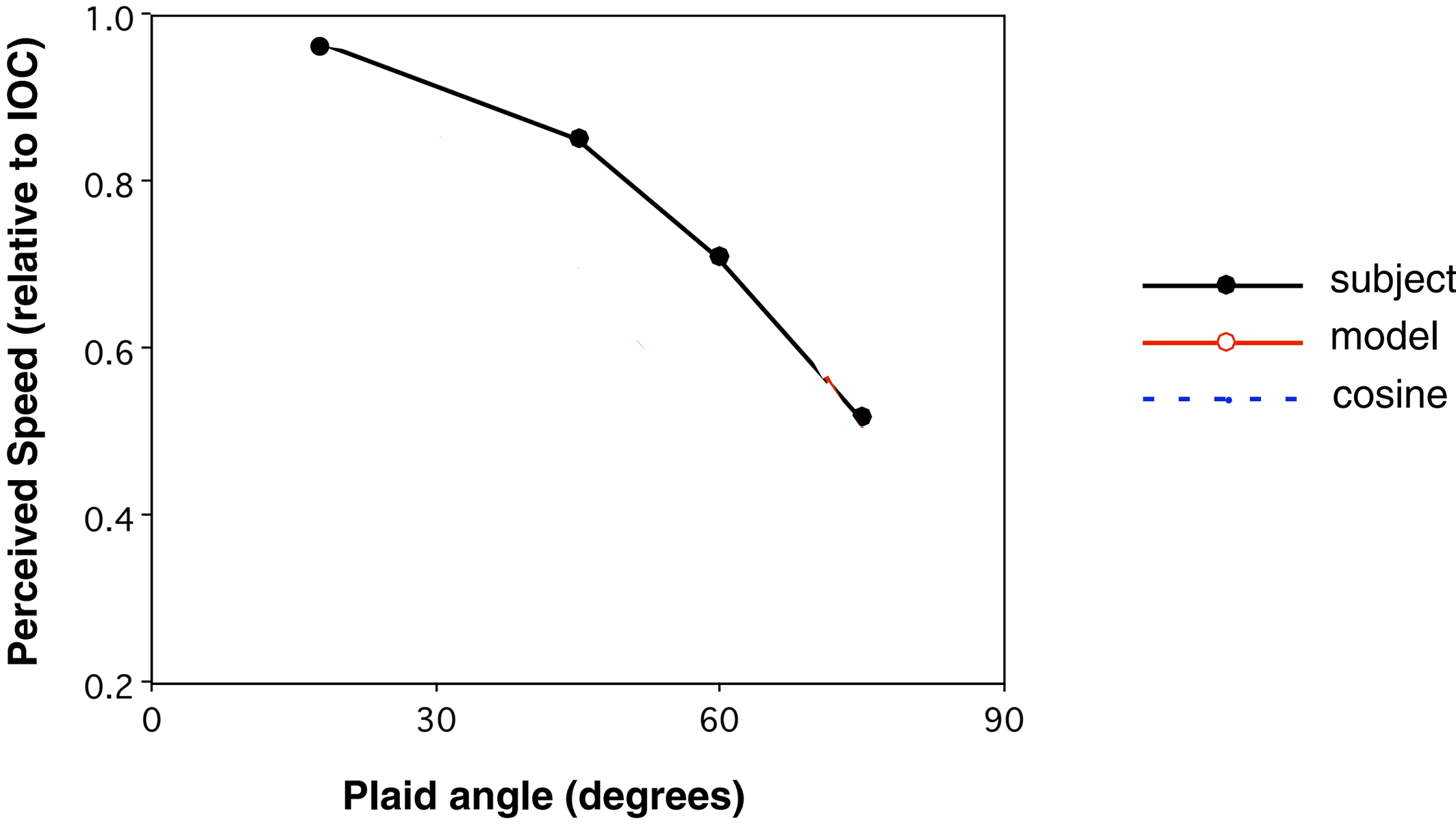


[Stone etal 1990]

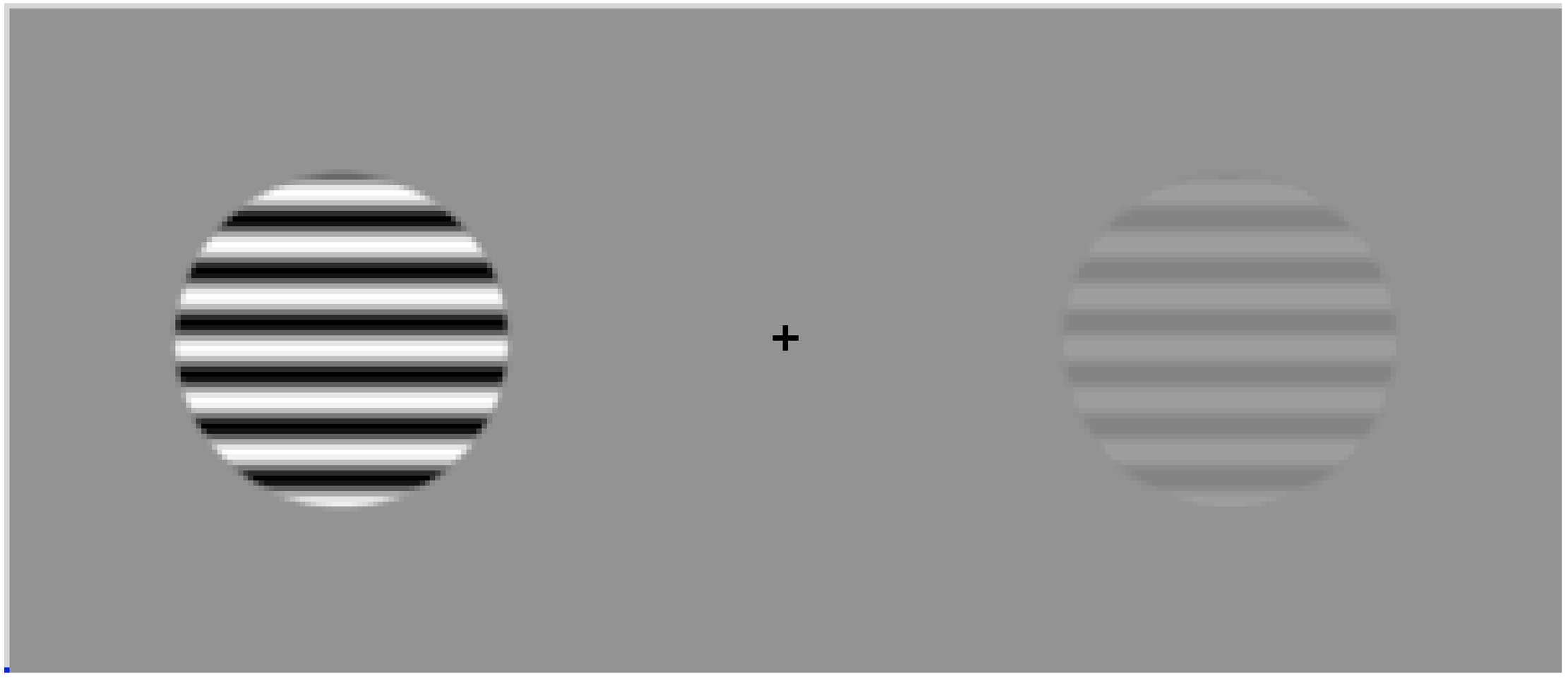
Stone, Watson, Mulligan 1990



Ferrera & Wilson, 1991



The “Thompson effect”



Contrast affects perceived speed

[Thompson ‘82]

Helmholtz (1866)

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Perception is our best guess as to what is in the world, given our current sensory input and our prior experience

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=> Bayes

Some Bayesian perceptual models

- Shading/lighting [Kersten 90; Knill, Kersten, Yuille 96; Mamassian, Landy, Maloney 01]
- Motion [Simoncelli 93; Weiss etal. 02; Stocker & Simoncelli 06]
- Surface orientation [Bülthoff & Yuille 96; Saunders & Knill 01]
- Color constancy [Brainard & Freeman 97]
- Contours [Geisler, Perry, Super 01]
- Sensory-motor tasks [Körding & Wolpert 04]

Brightness Constancy

- Assume translational motion (locally)
- Differential approximation (Taylor series)

$$\vec{\nabla} I \cdot \vec{v} + I_t = 0, \qquad \vec{\nabla} I = [Ix, Iy]$$

- Insufficient constraint, so combine over a neighborhood (space and/or time):

$$min \sum (\vec{\nabla} I \cdot \vec{v} + I_t)^2$$

[Fennema & Thompson ‘79; Horn and Schunck ‘81]

With noise...

- Additive Gaussian noise in temporal derivative:

$$\vec{\nabla} I \cdot \vec{v} + I_t = n$$

- Likelihood (combined over neighborhood):

$$P(\vec{\nabla} I, I_t | \vec{v}) \propto \exp[-\sum (\vec{\nabla} I \cdot \vec{v} + I_t)^2 / 2\sigma^2]$$

[Simoncelli, Adelson, Heeger ‘91]

With prior...

- Simplest prior choice: Gaussian (preference for slow speeds)

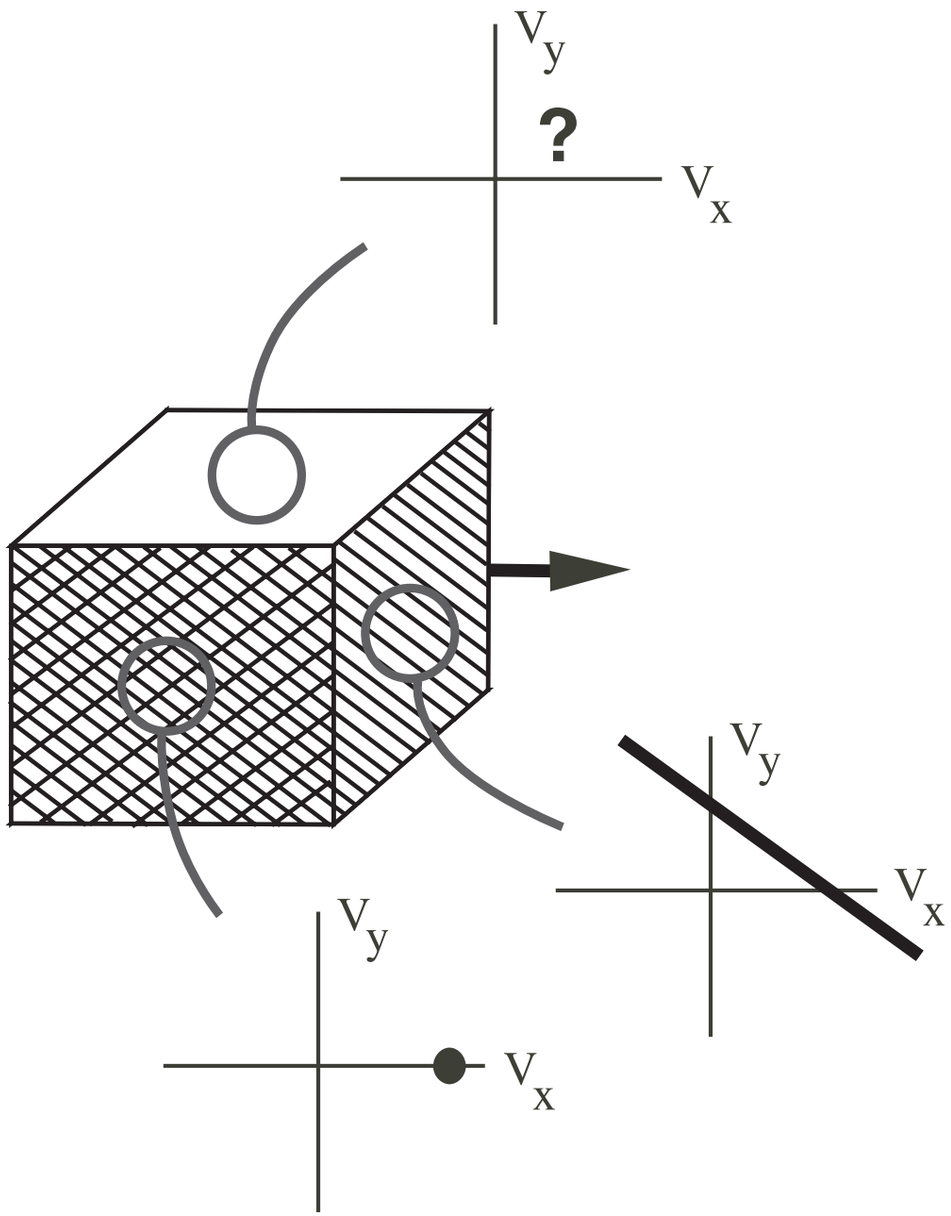
$$P(\vec{v}) \propto \exp[-||\vec{v}||/2\sigma_p^2]$$

- Posterior:

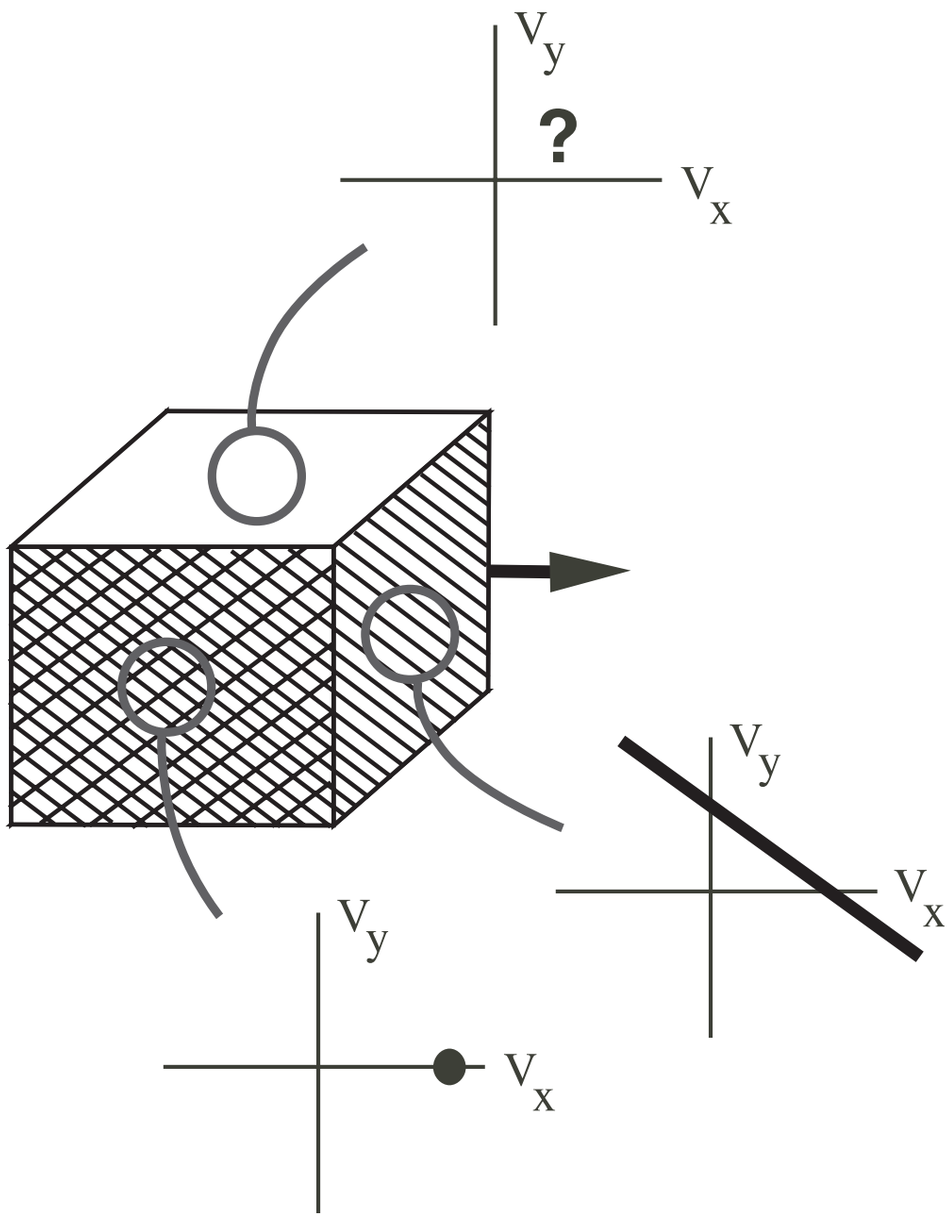
$$P(\vec{v}|\vec{\nabla} I, I_t) \propto$$

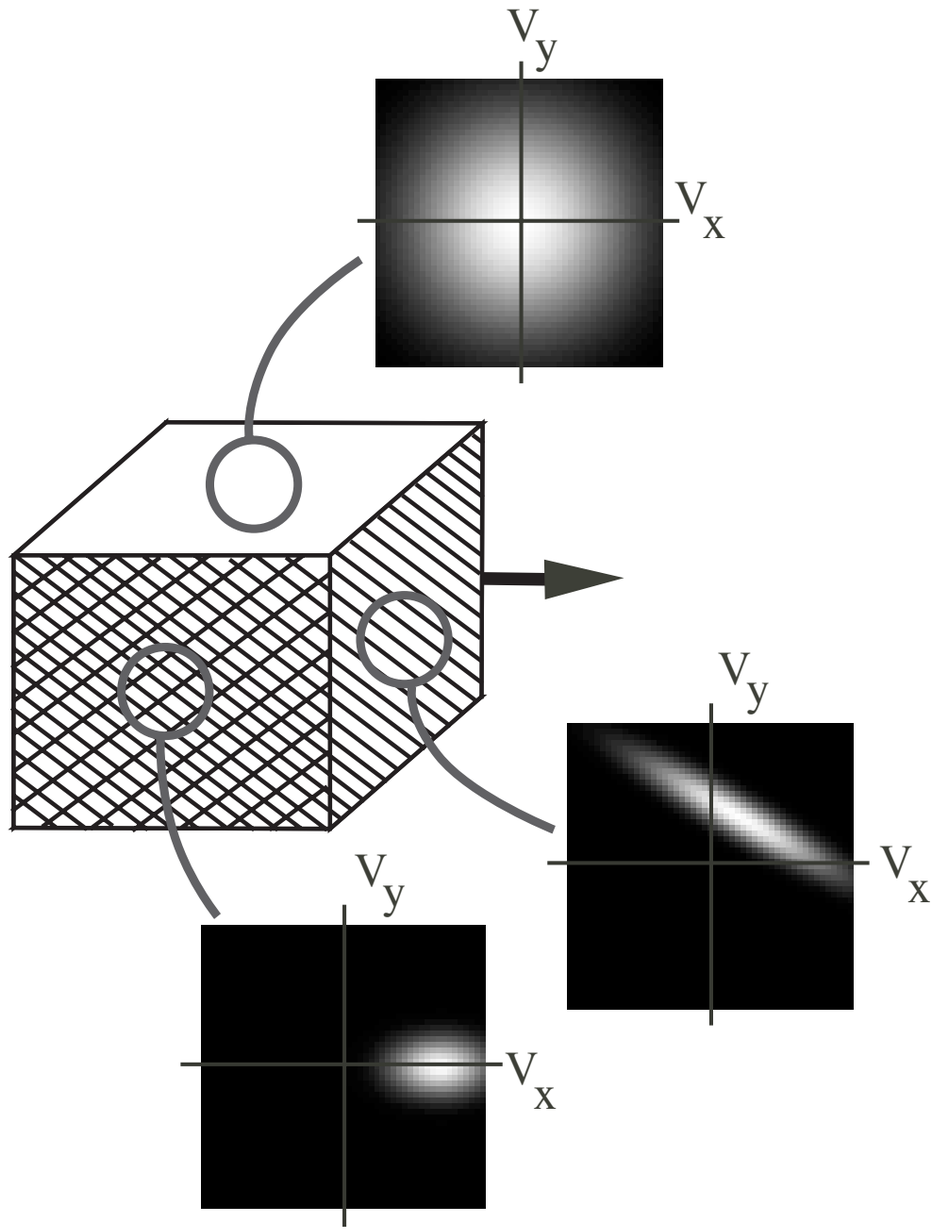
$$\exp[-||\vec{v}||/2\sigma_p^2 - \sum(\vec{\nabla} I \cdot \vec{v} + I_t)^2/2\sigma^2]$$

[Simoncelli, Adelson, Heeger ‘91]



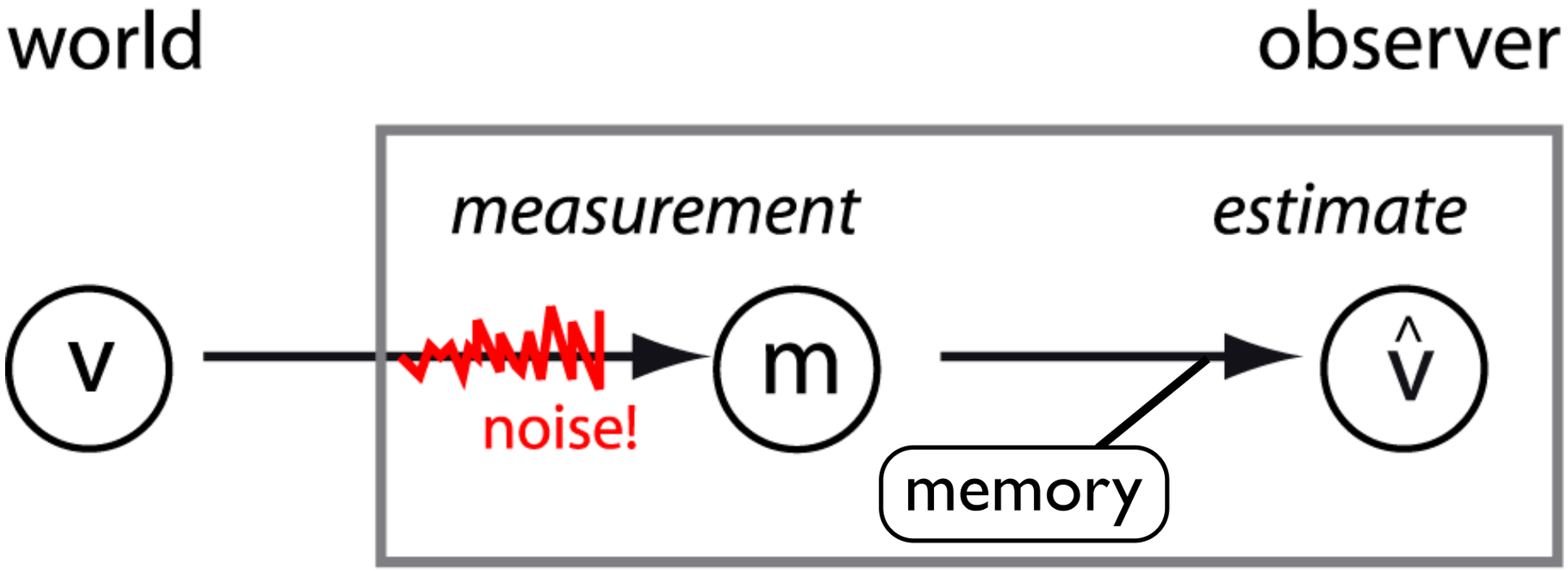
Bayesian posteriors



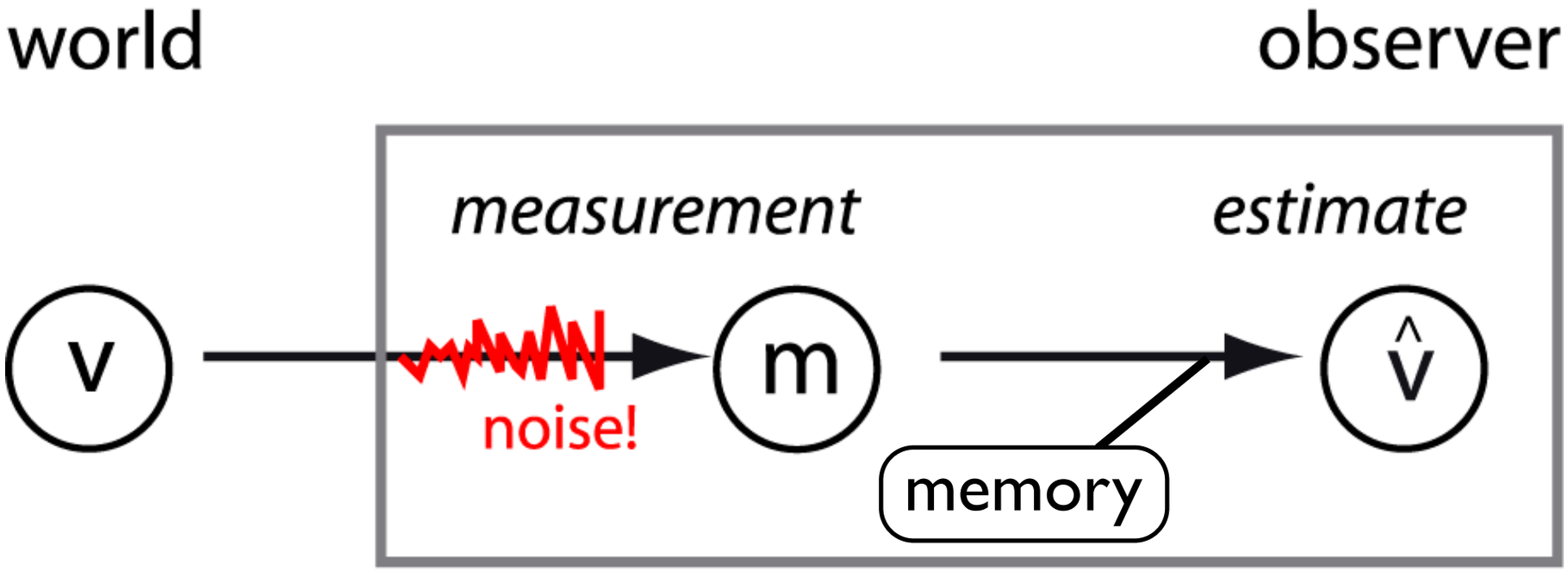


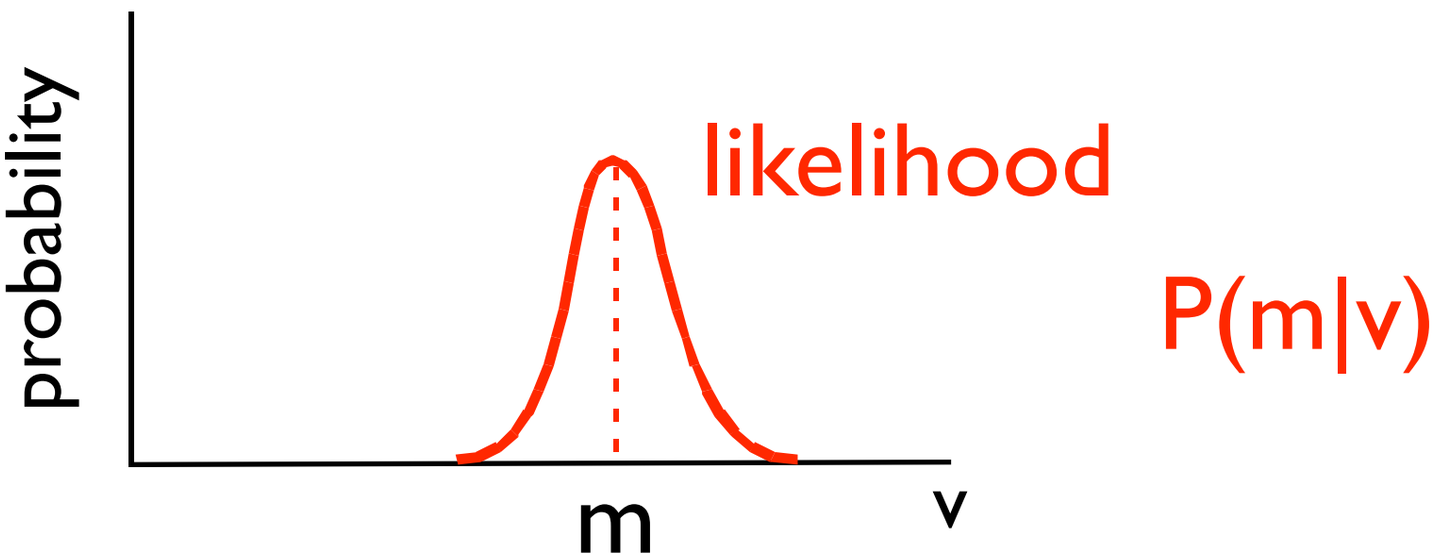
Bayesian posteriors

Bayesian perception

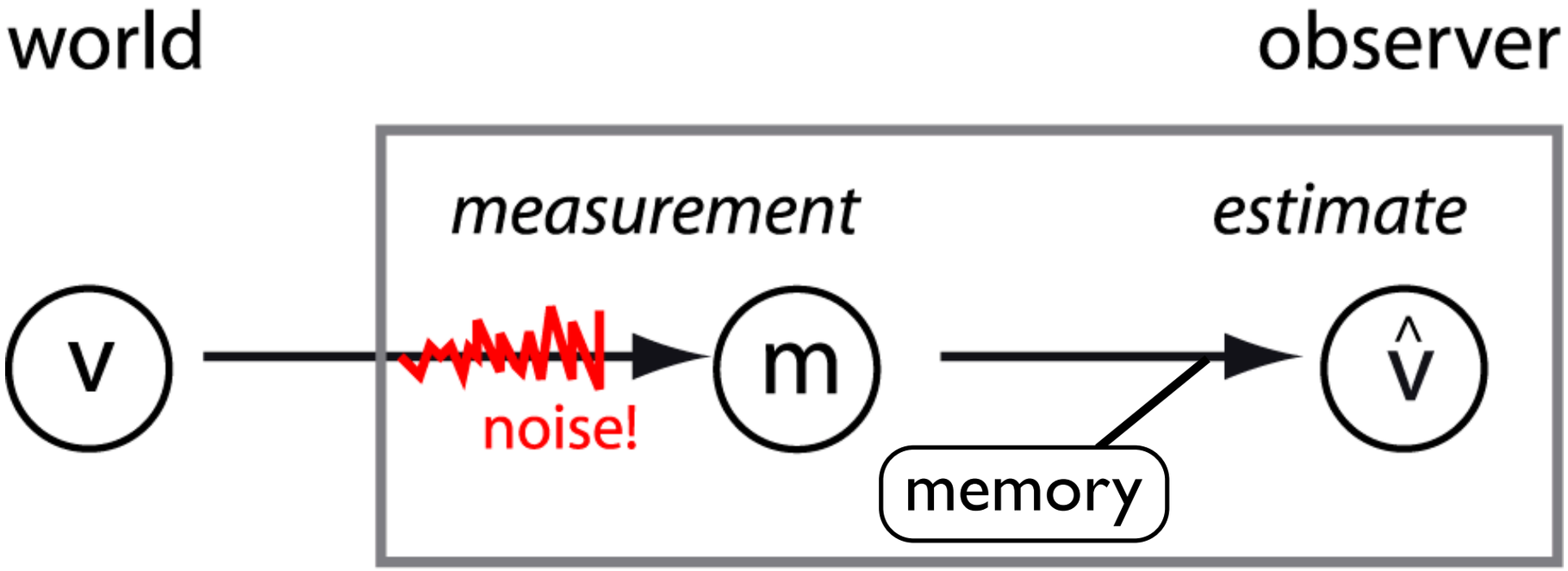


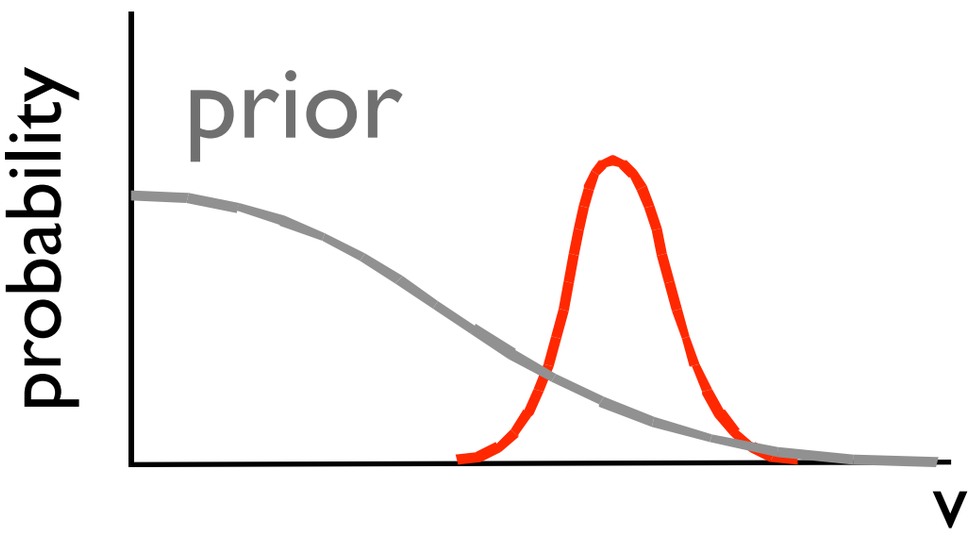
Bayesian perception





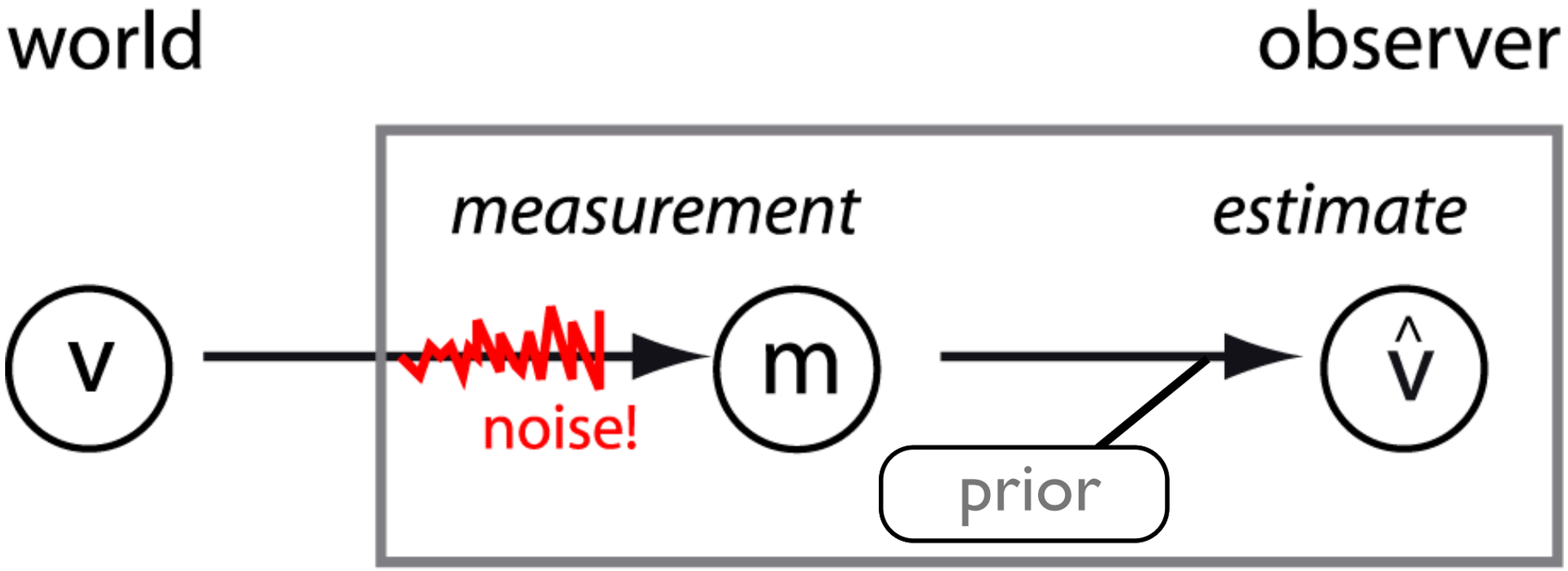
Bayesian perception





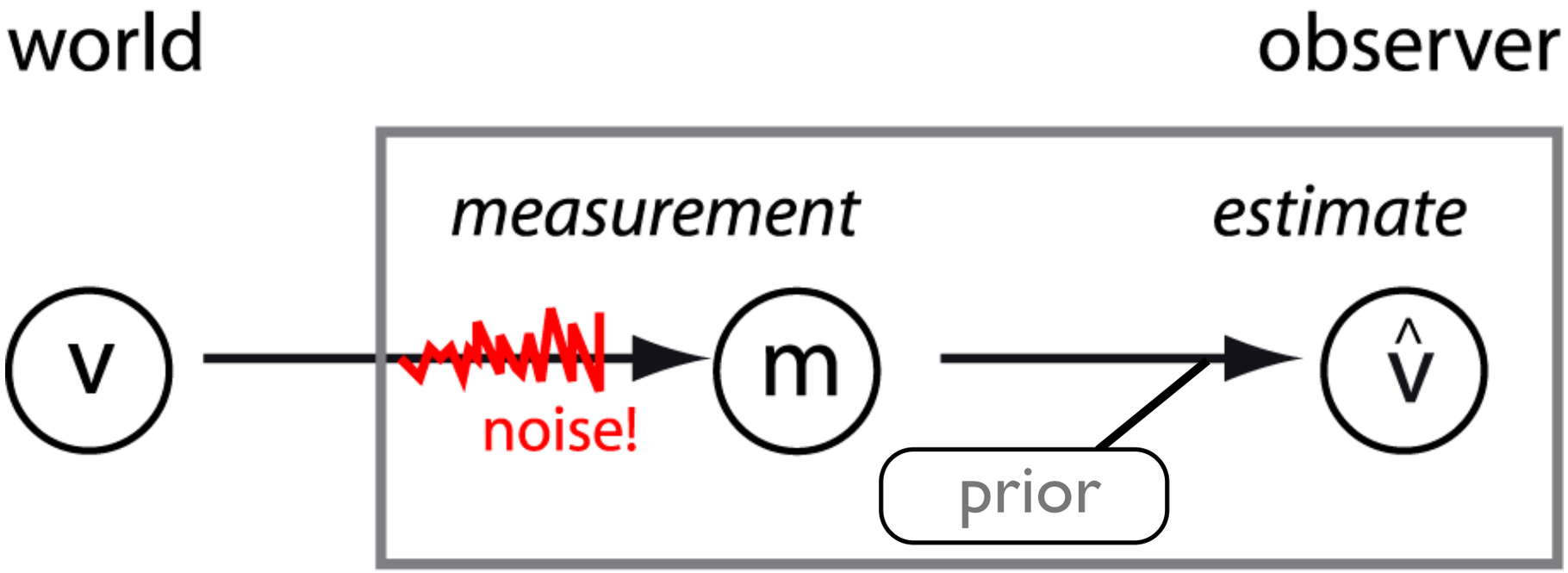
P(m|v) P(v)

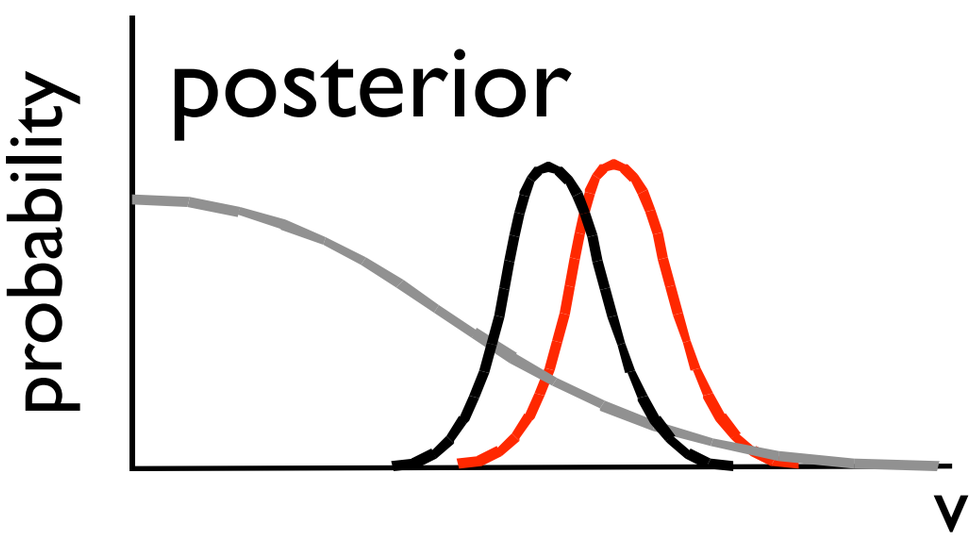
Bayesian perception



P(m|v) P(v)

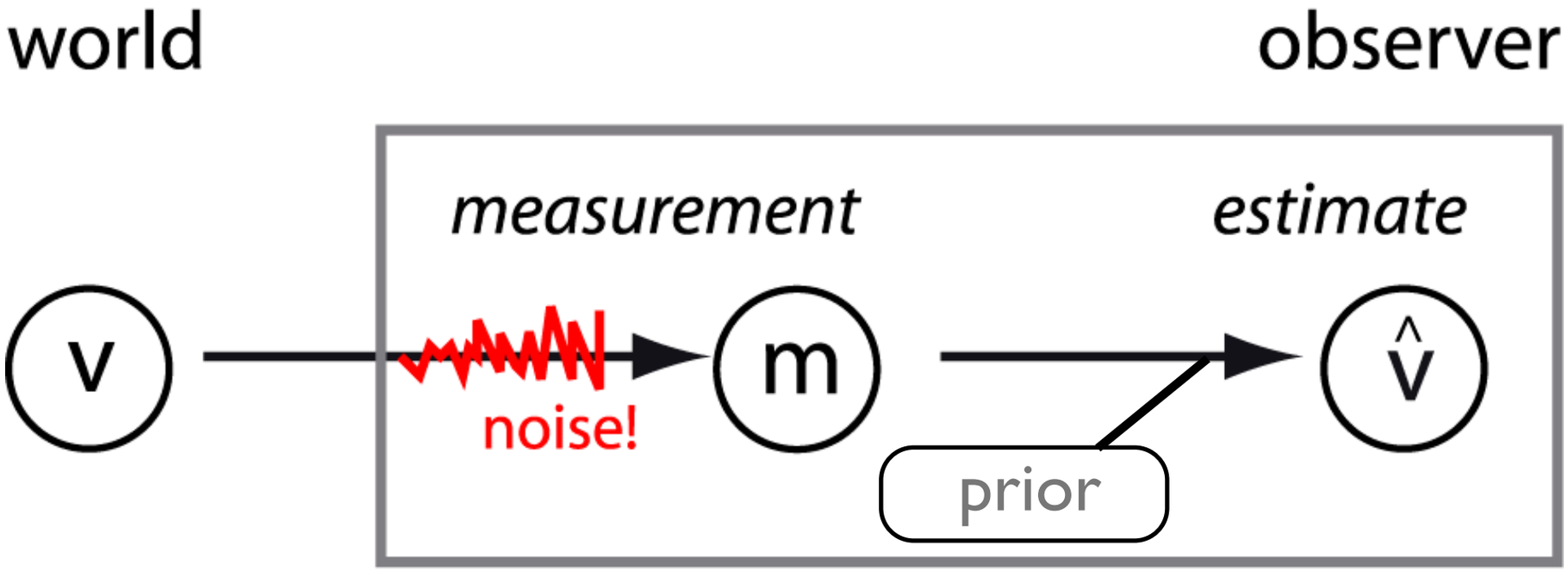
Bayesian perception

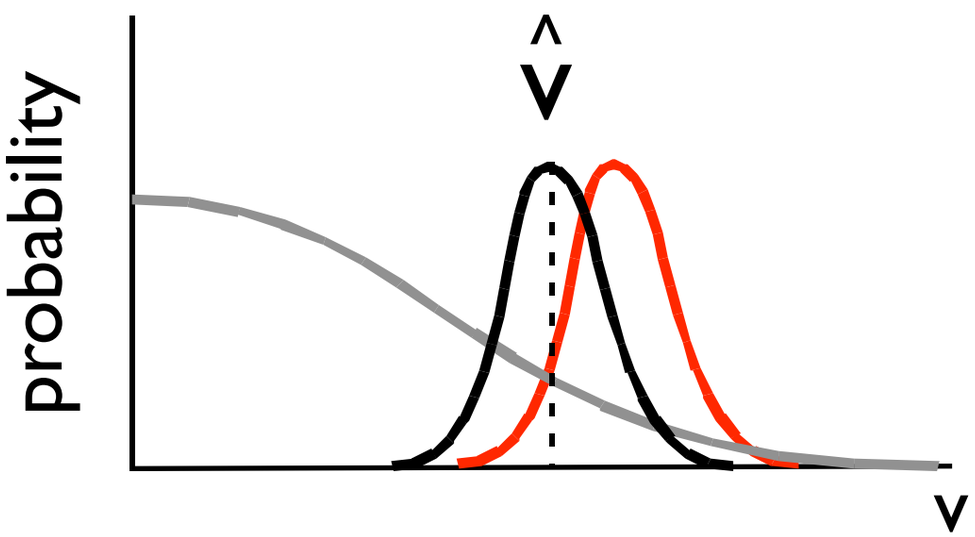




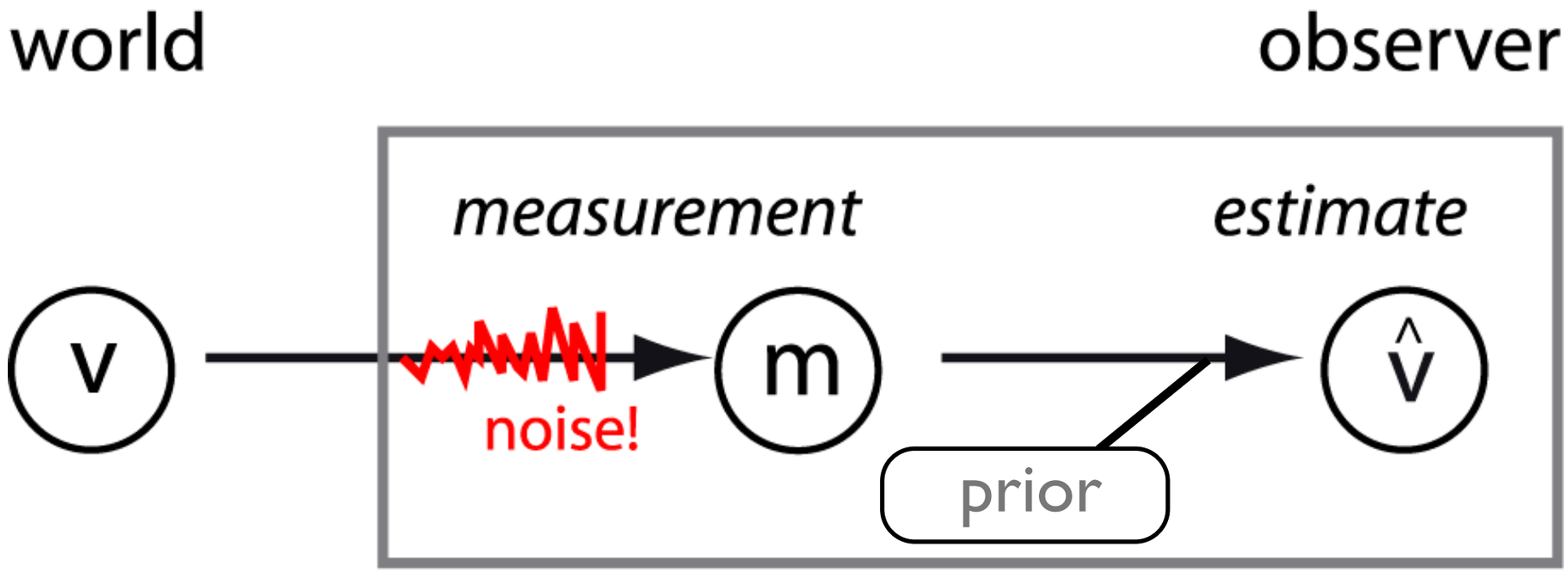
$$P(m|v) \times P(v) \sim P(v|m)$$

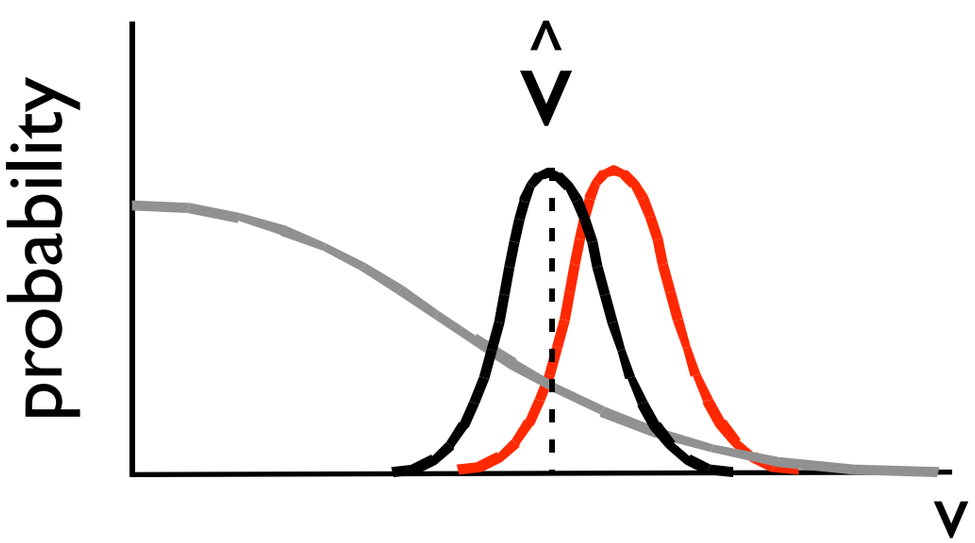
Bayesian perception

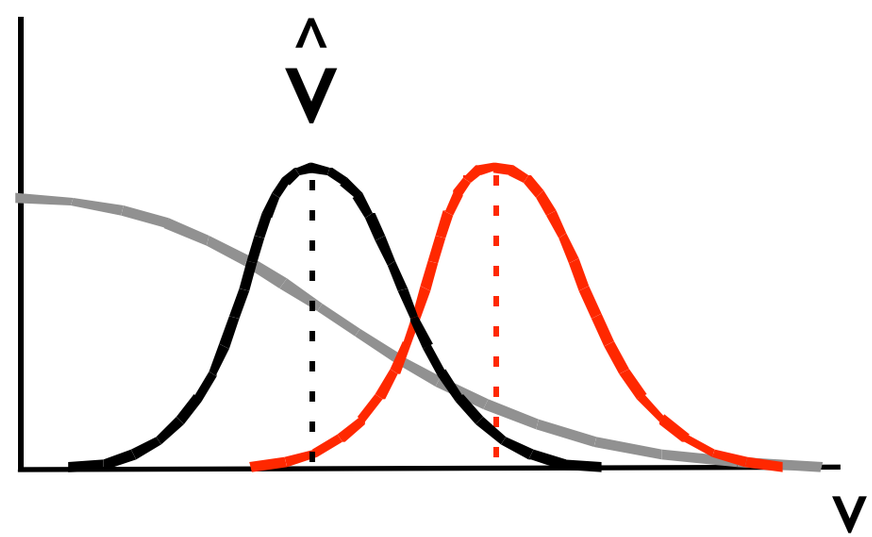




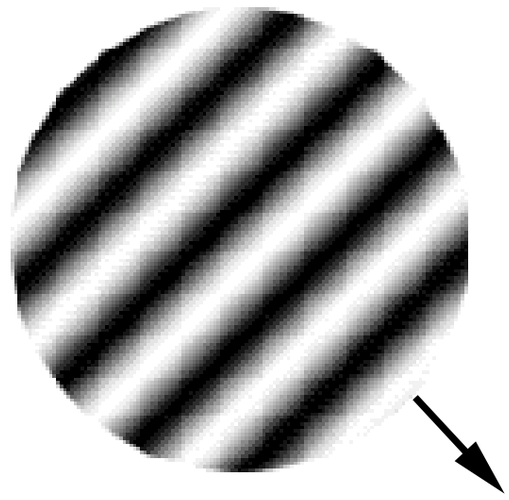
Bayesian perception

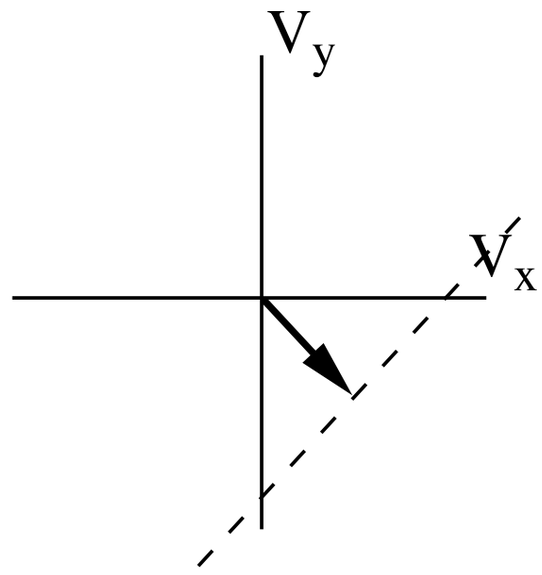


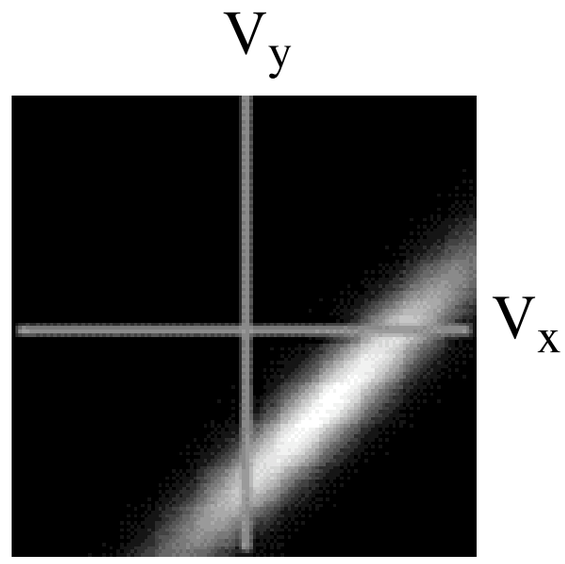


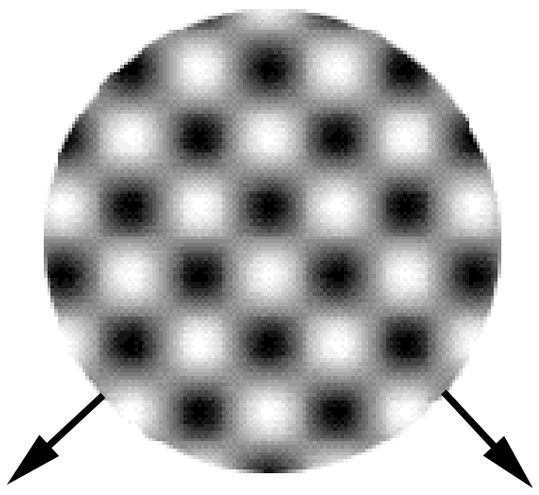


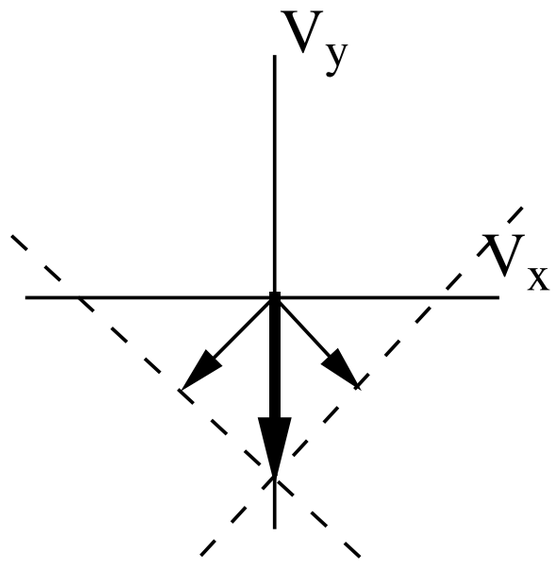
stimulus **idealization** **model**

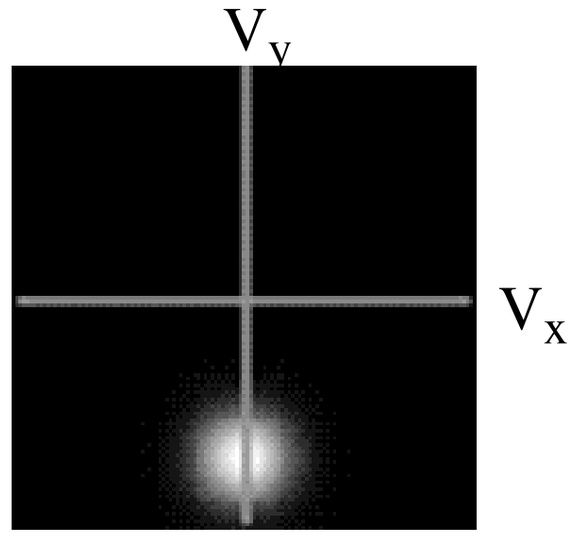






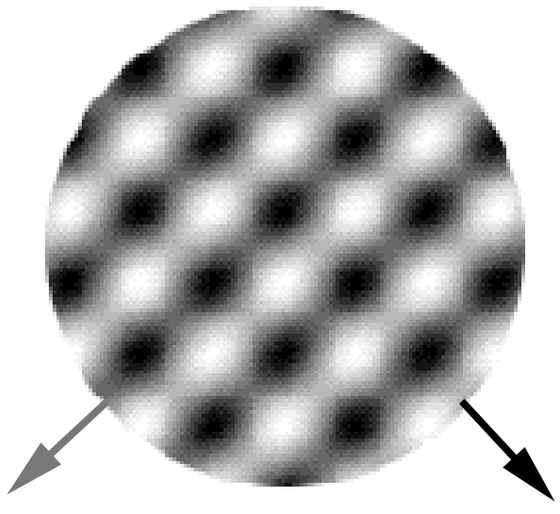


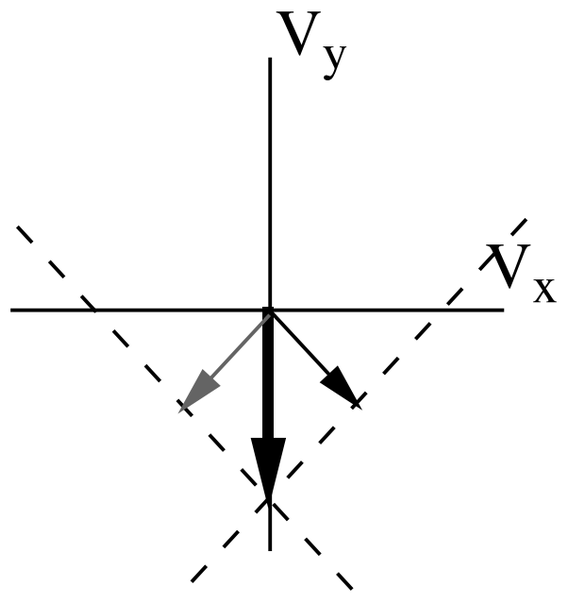


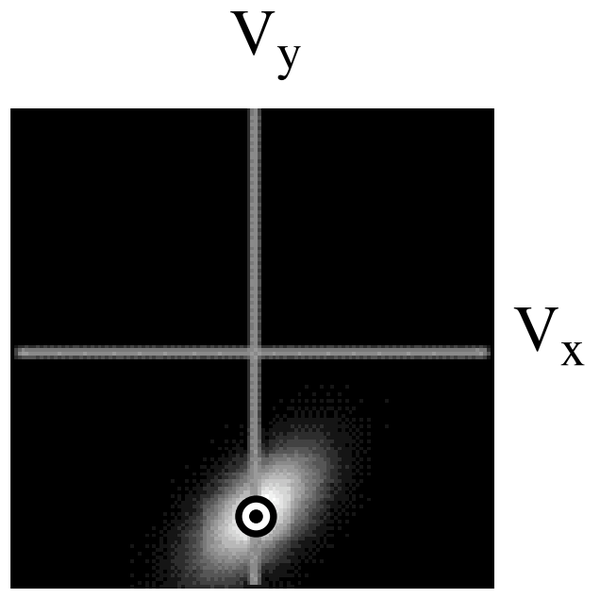


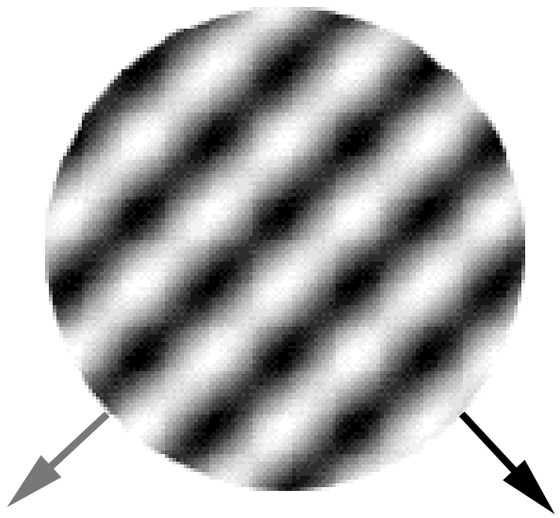
[Simoncelli & Heeger, ARVO ‘92]

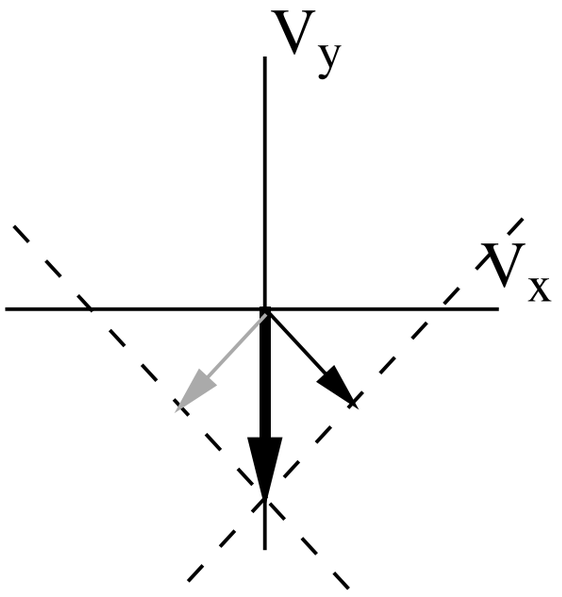
stimulus **idealization** **model**

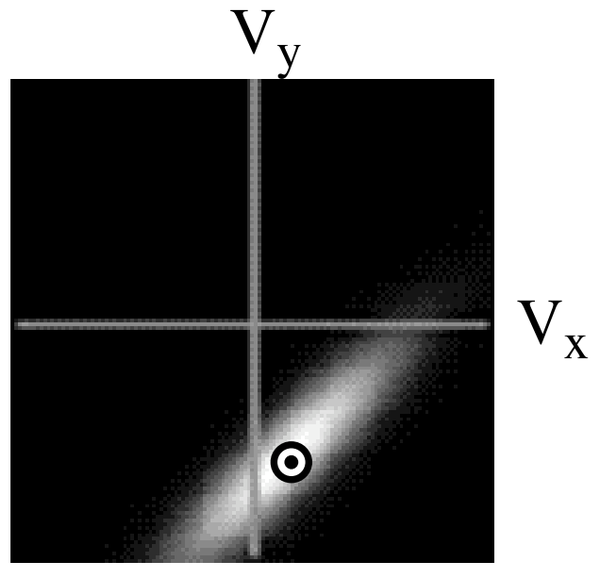




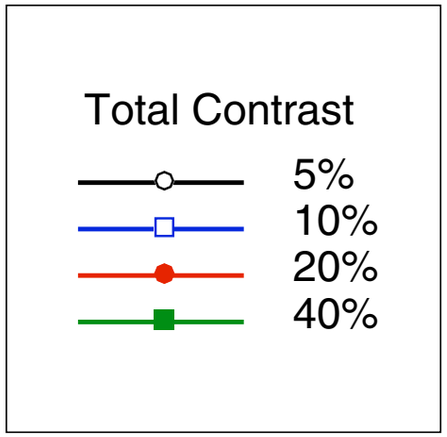




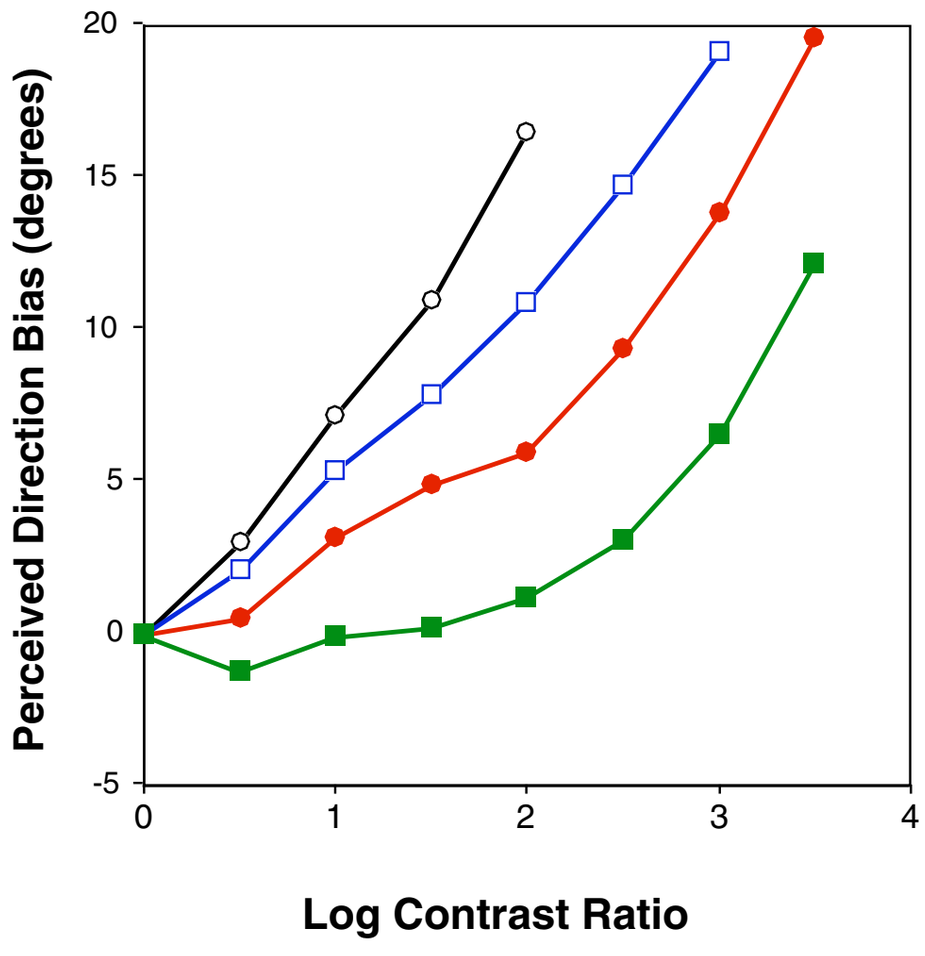




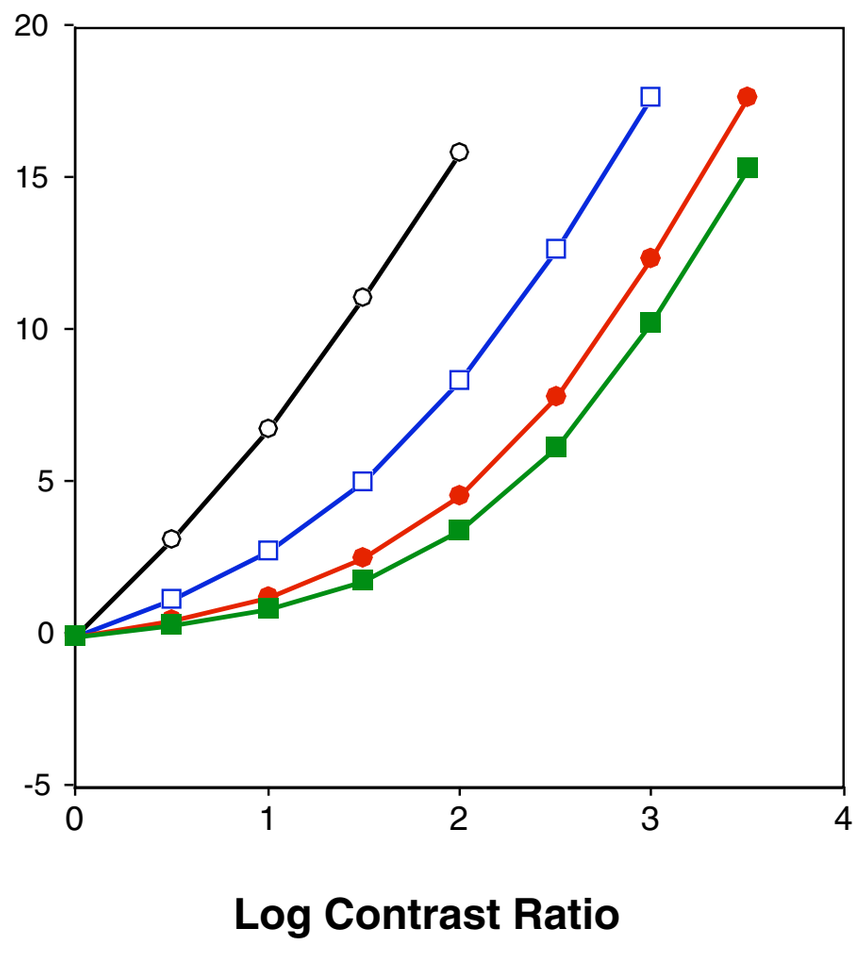
Stone et al. 1990



Subject

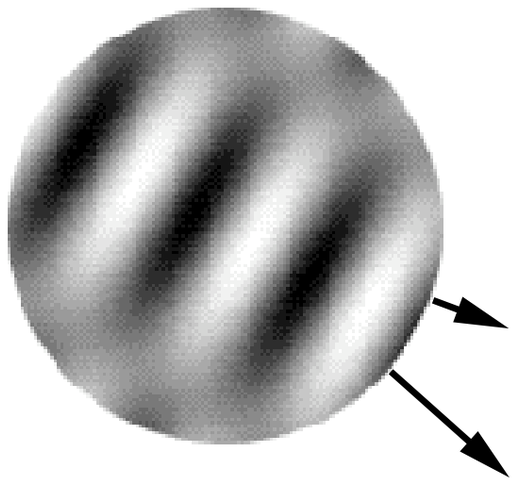


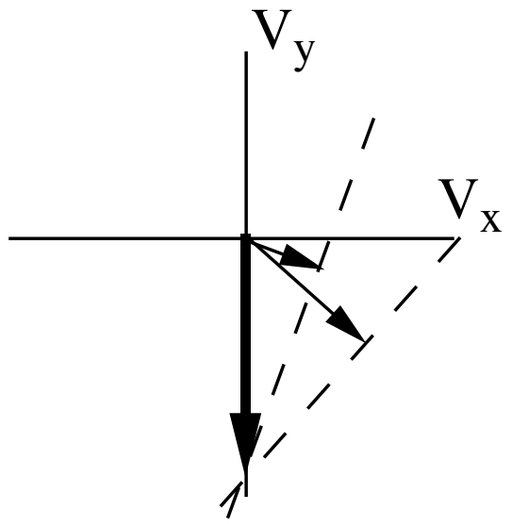
Model

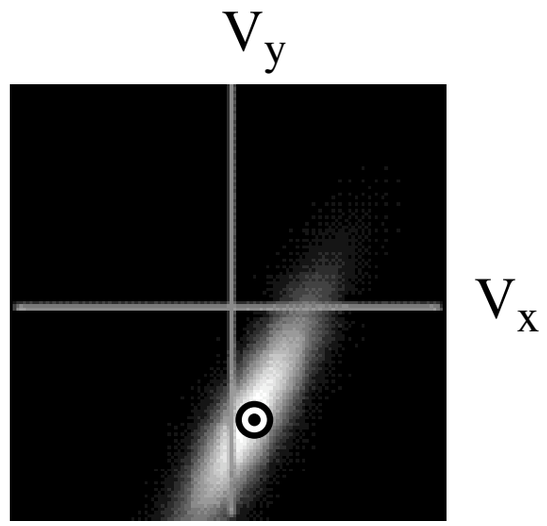


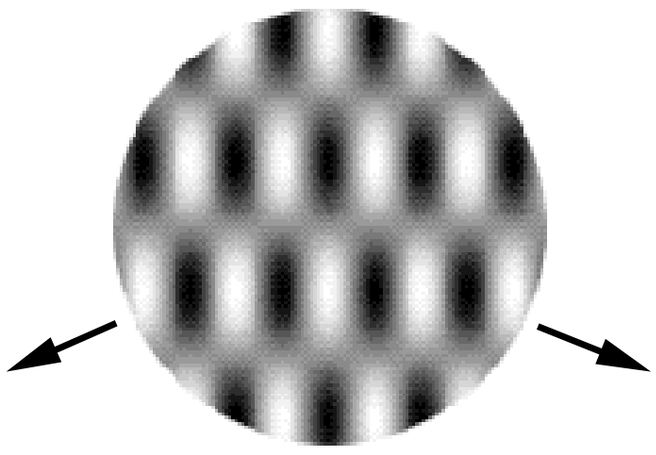
[Simoncelli & Heeger, ARVO ‘92]

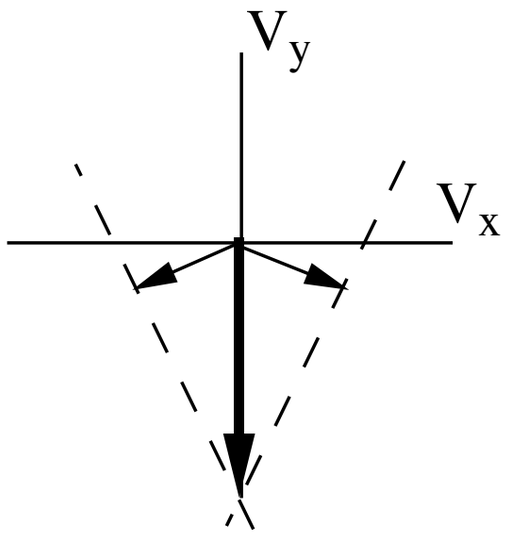
stimulus **idealization** **model**

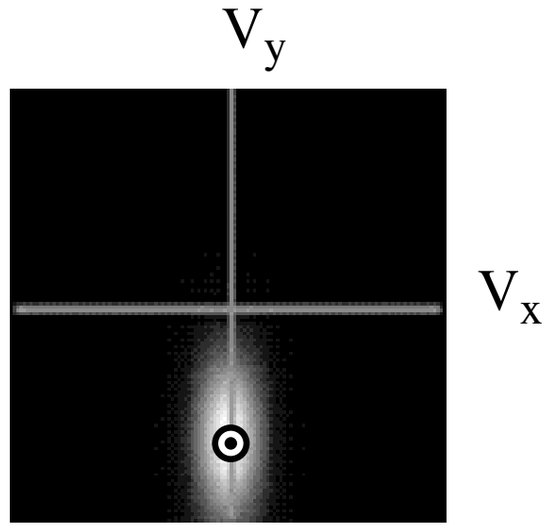


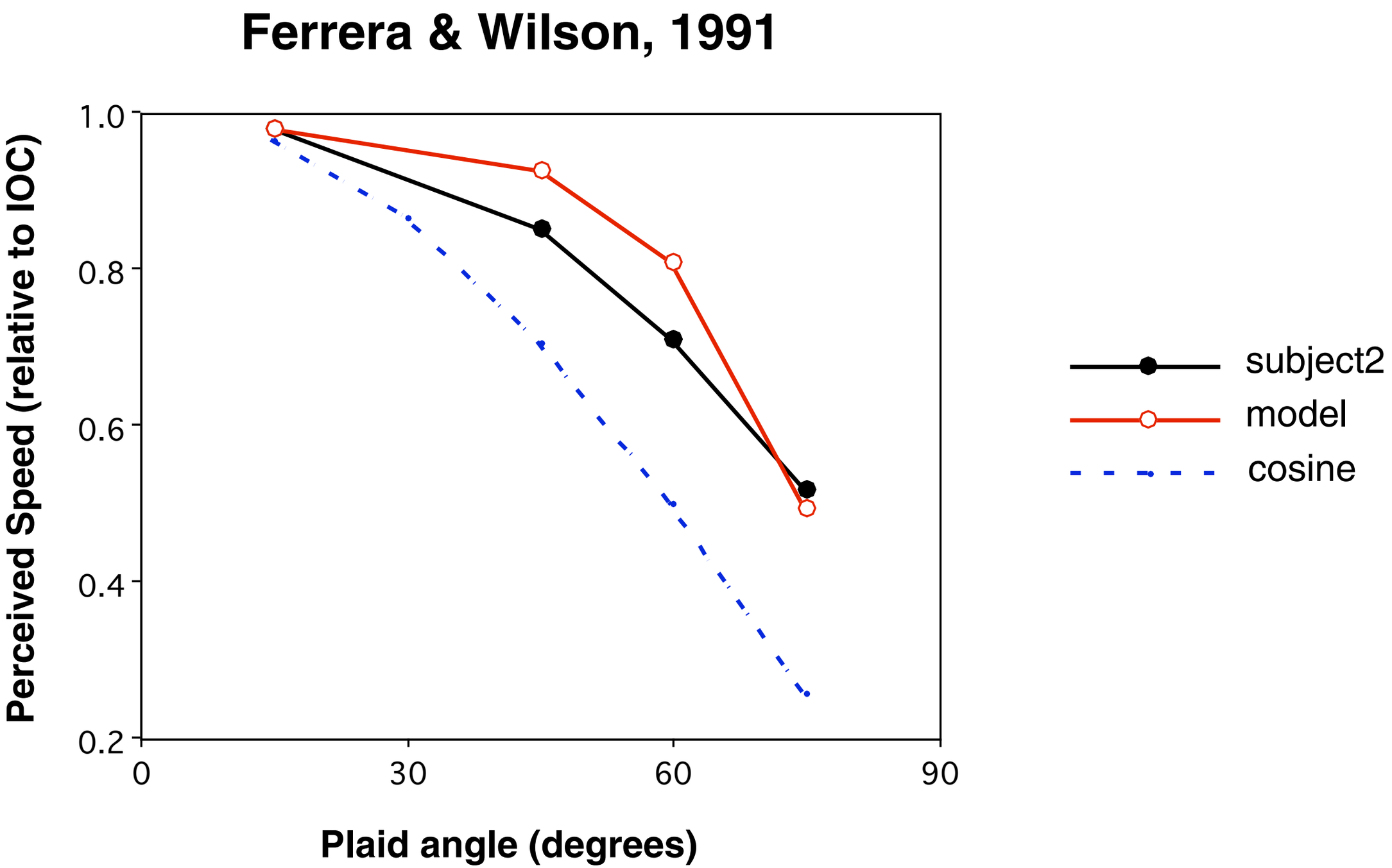






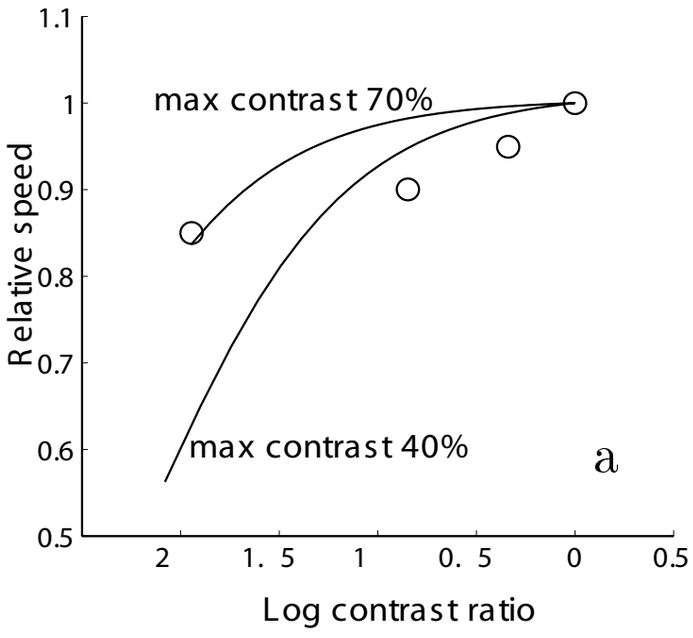




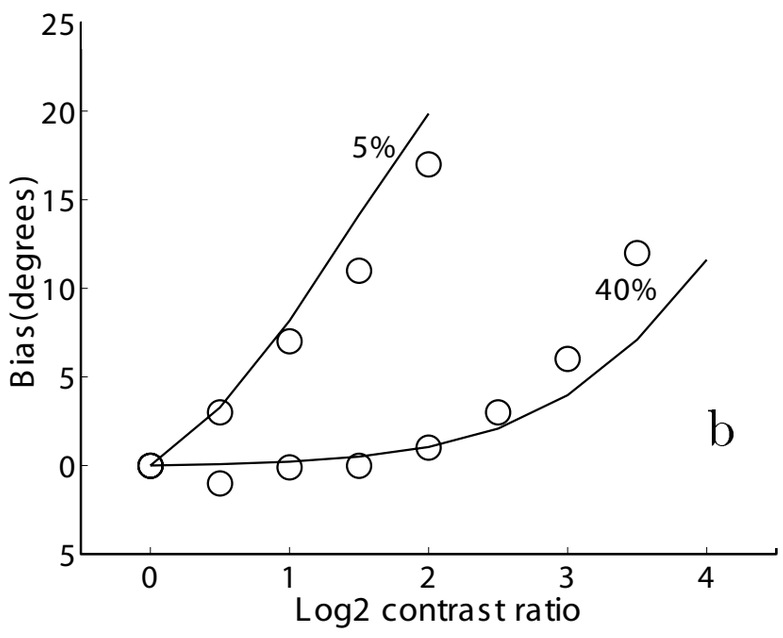


[Simoncelli & Heeger, ARVO ‘92]

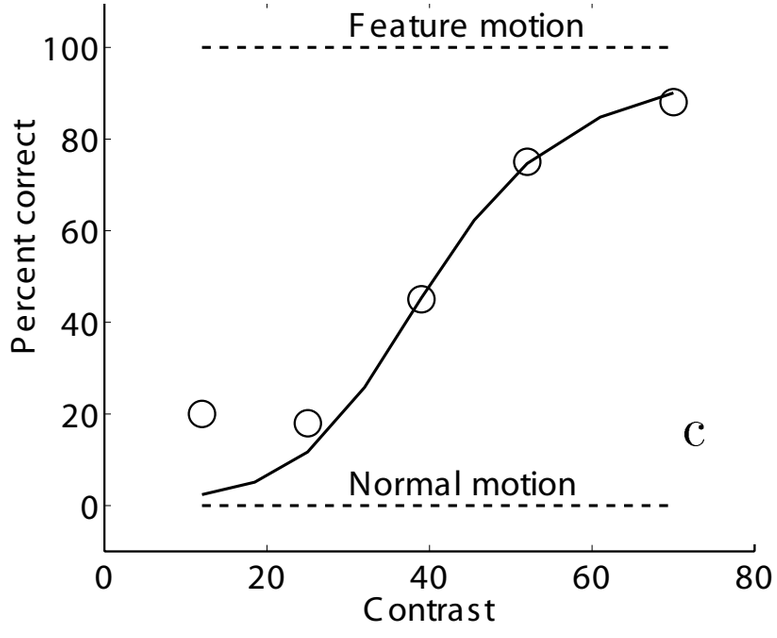
Stone & Thompson, ‘90



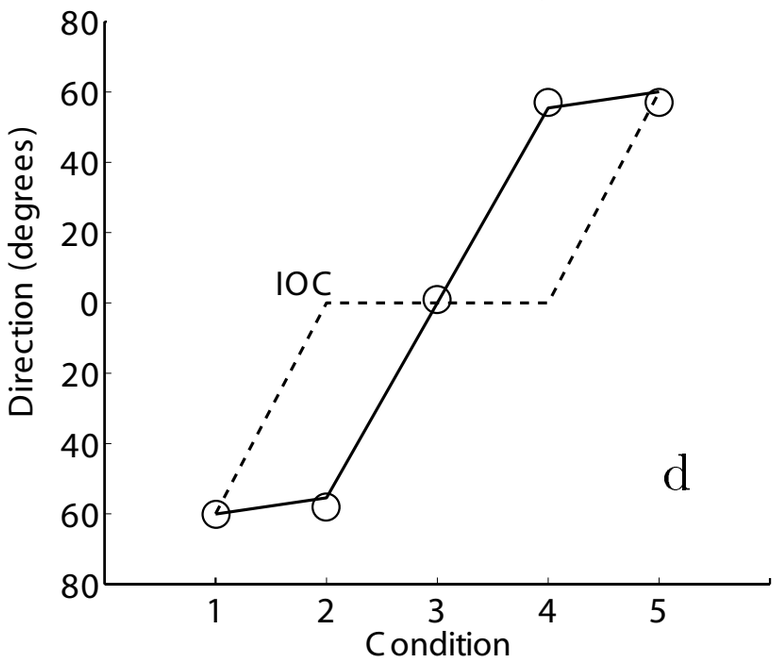
Stone etal, ‘90



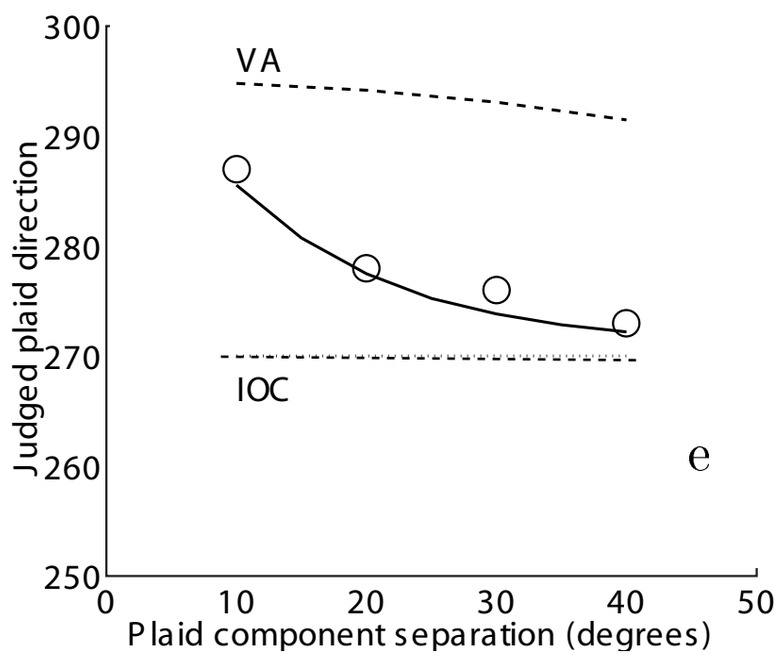
Lorenceau etal, ‘92



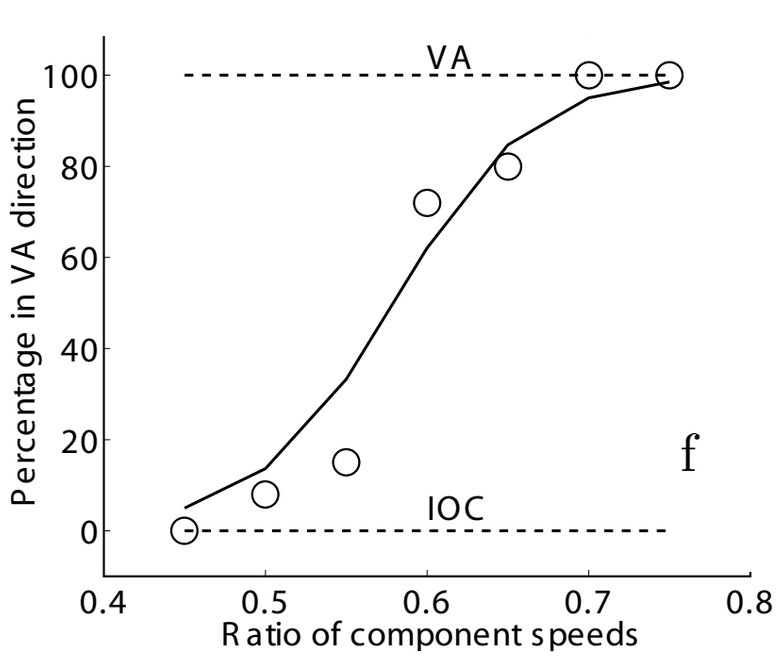
Yo & Wilson, ‘92



Burke & Wenderoth, ‘93



Bowns, ‘96



[Weiss, Simoncelli, Adelson, ‘02]

Bayesian motion model

Bayesian motion model

+ Theory: Optimal solution
  - unknown likelihood
  - unknown prior

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  - but mechanism unspecified and non-unique

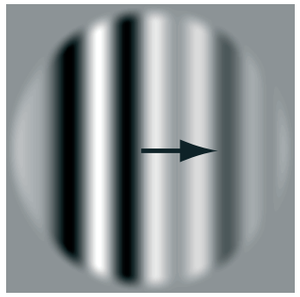
[Stocker & Simoncelli, NIPS*04 / Nature Neurosci 06]

Prior/likelihood from psychophysics

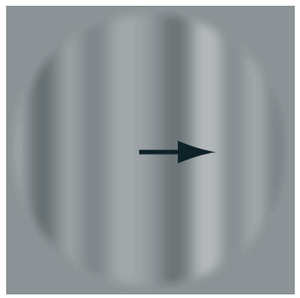
- Assume Gaussian likelihood, with contrast-dependent width
- Assume prior is smooth
- Assume MAP estimates (max posterior)
- Speed-matching and speed-discrimination data are sufficient to determine prior and

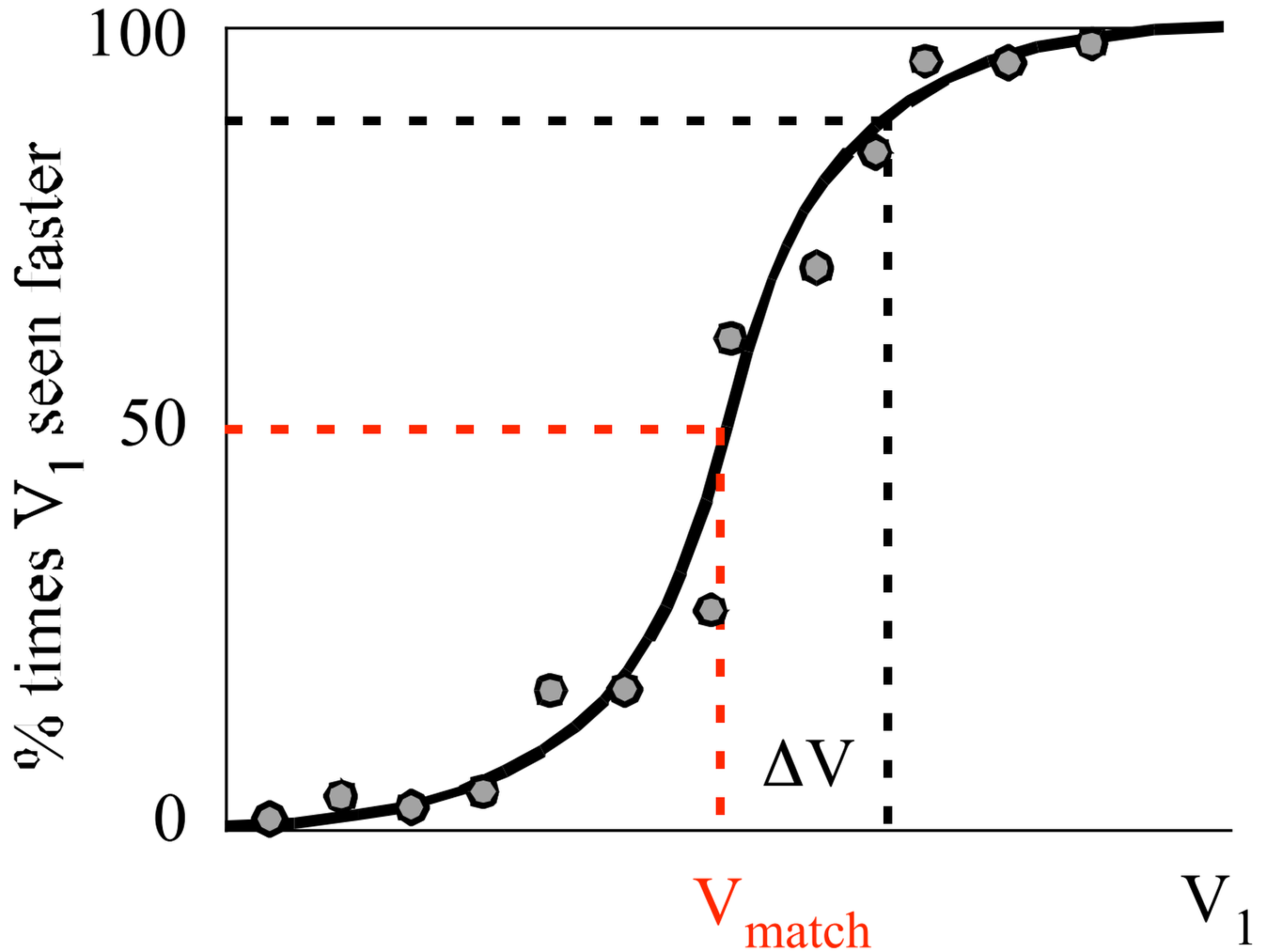
Which is faster?

v_1

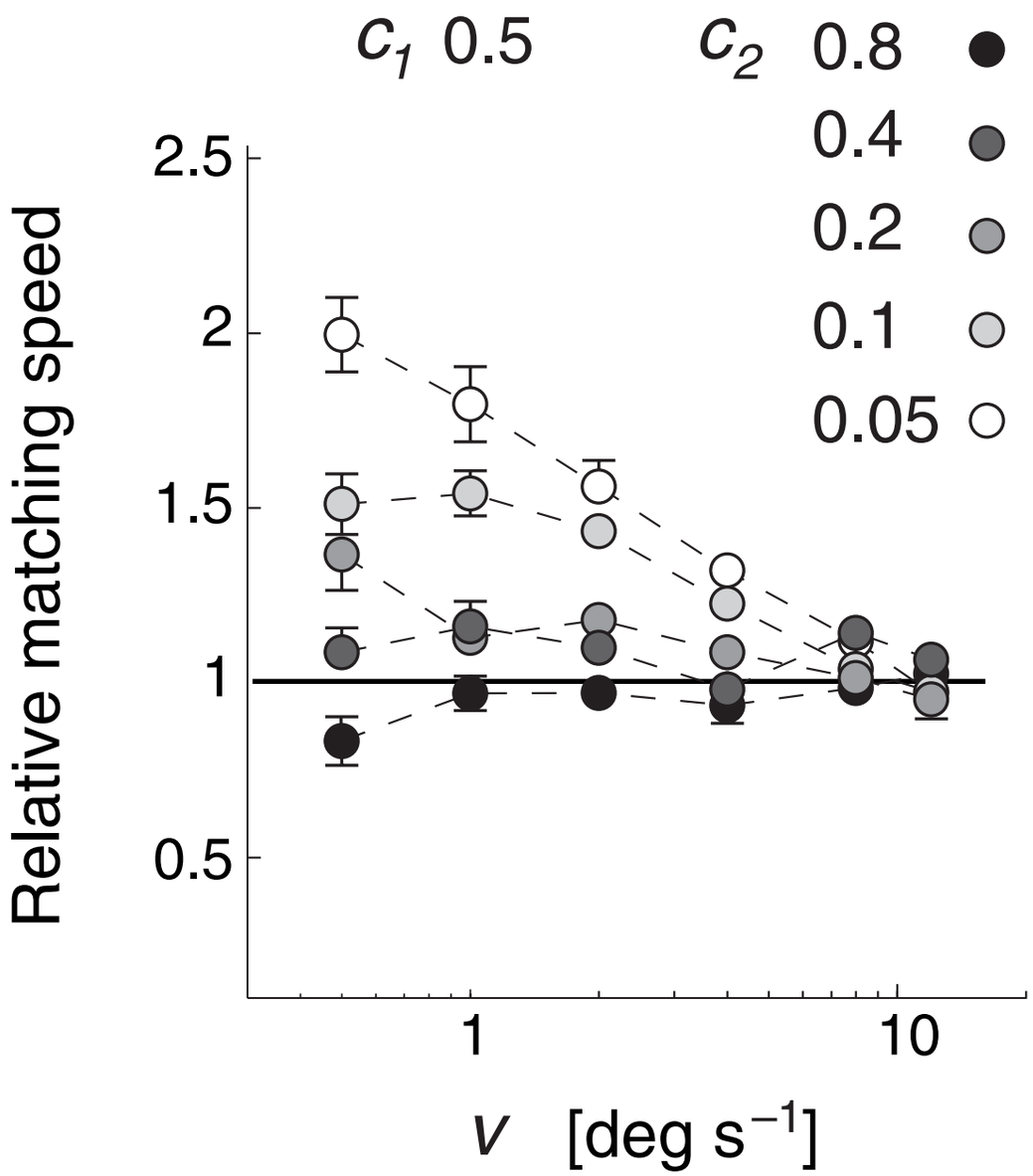


v_2



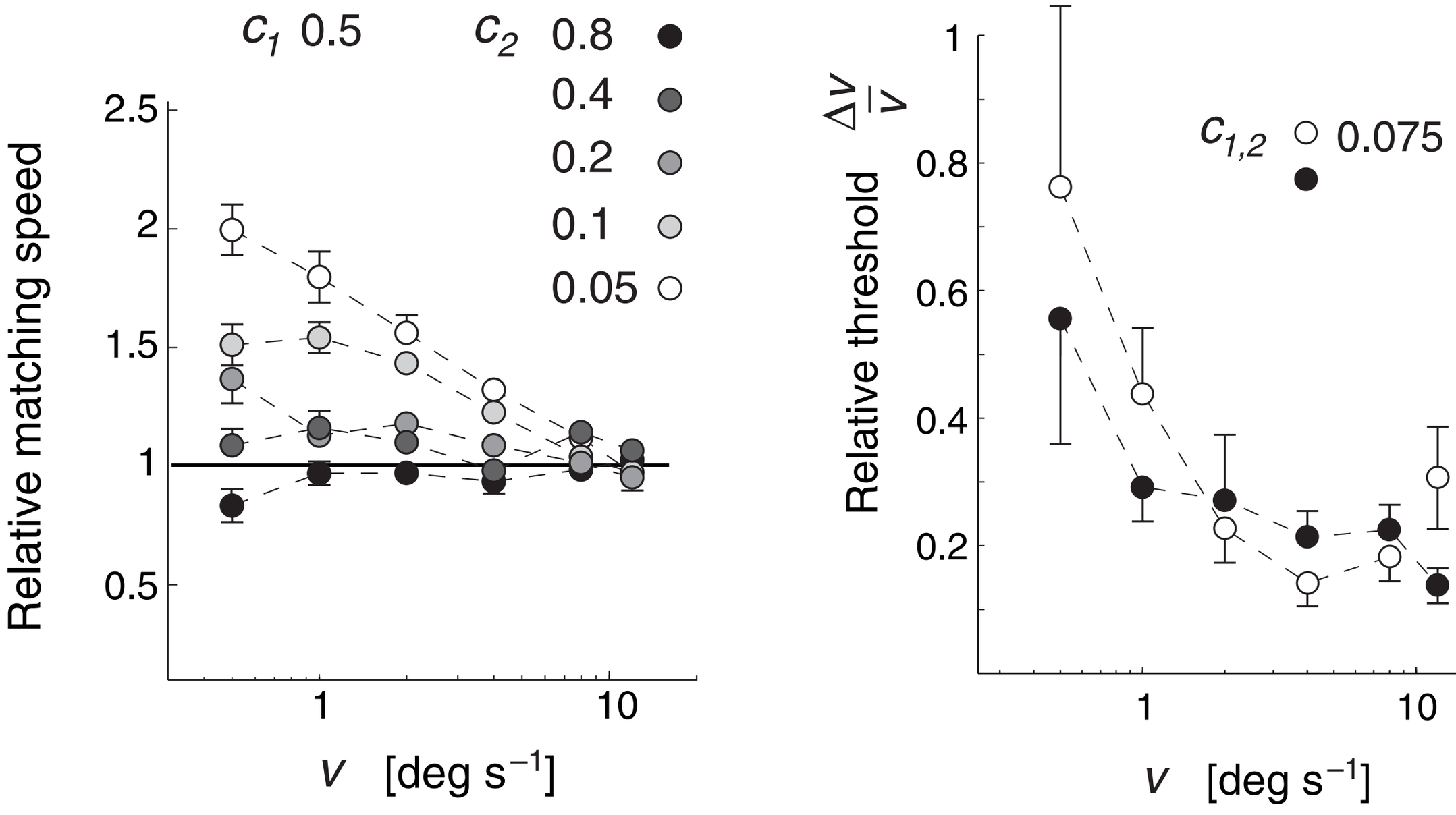


Effect increases with contrast ratio, decreases with speed



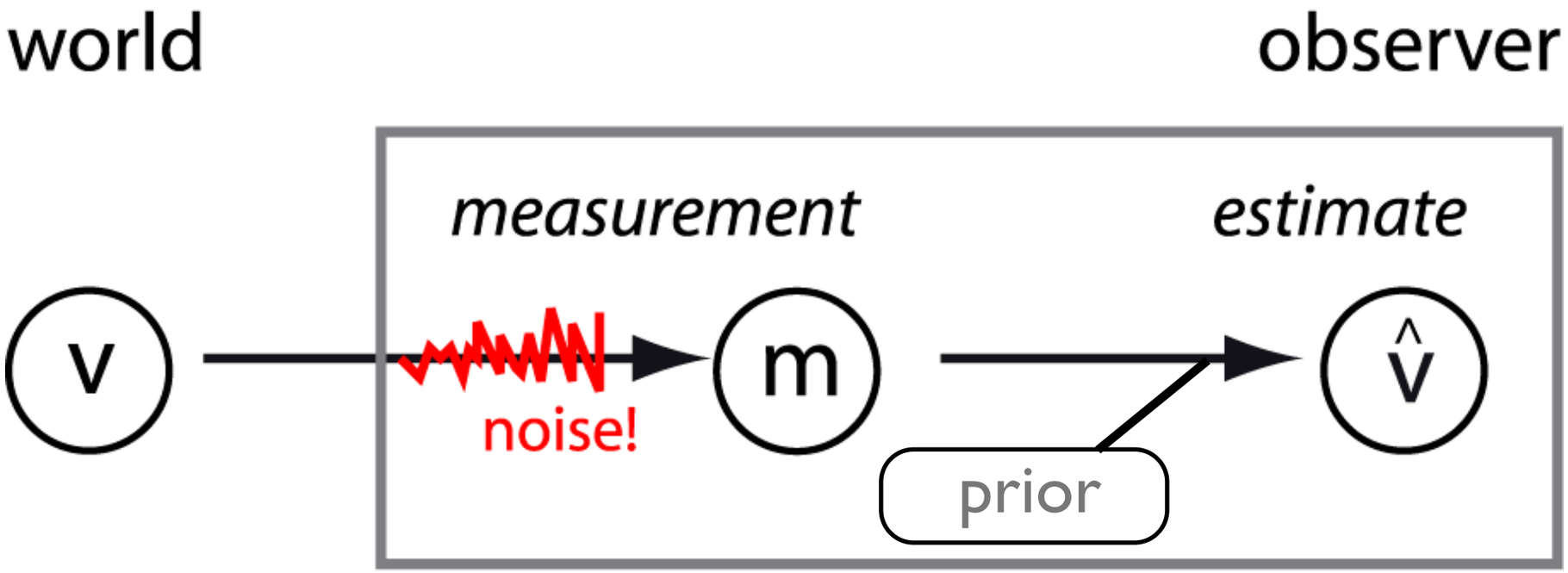
[Stocker & Simoncelli, ‘06]

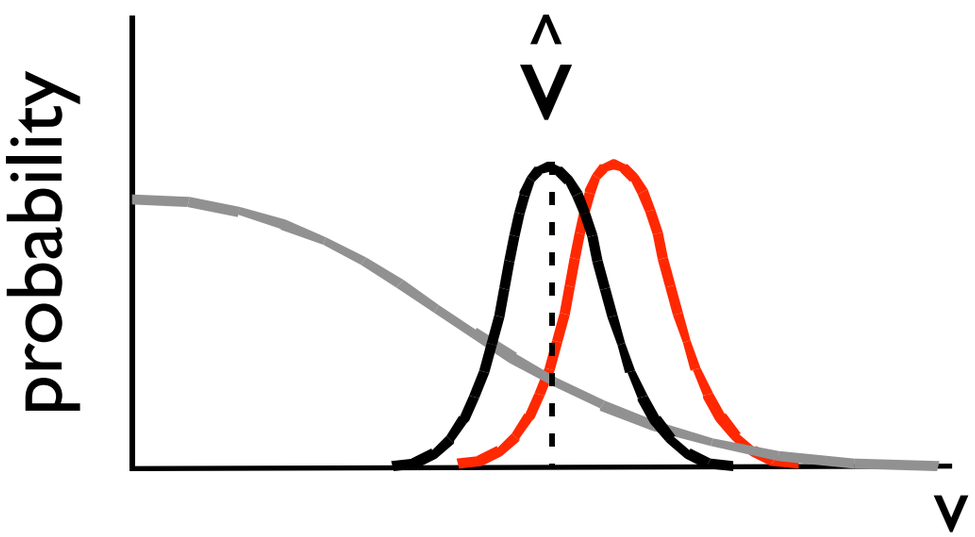
Effect increases with contrast ratio, decreases with speed



[Stocker & Simoncelli, ‘06]

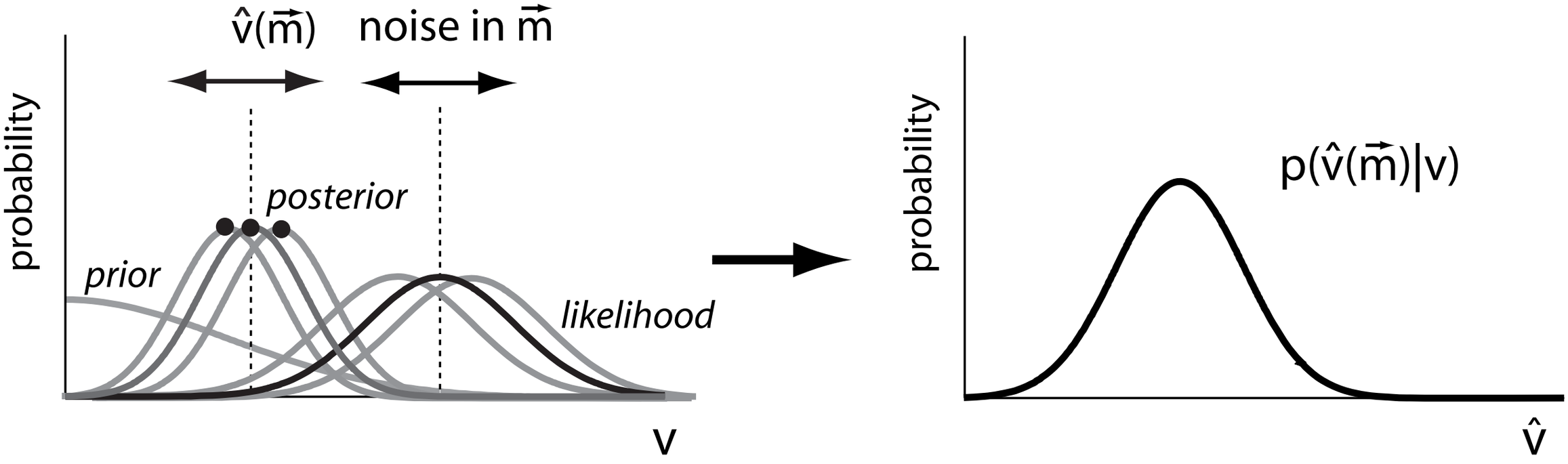
Bayesian perception





$$P(m|v) \times P(v) \sim P(v|m)$$

Trial-to-trial variability

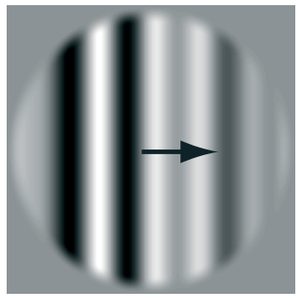


stimulus

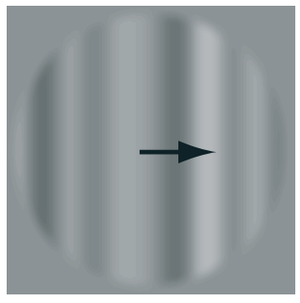
observer model

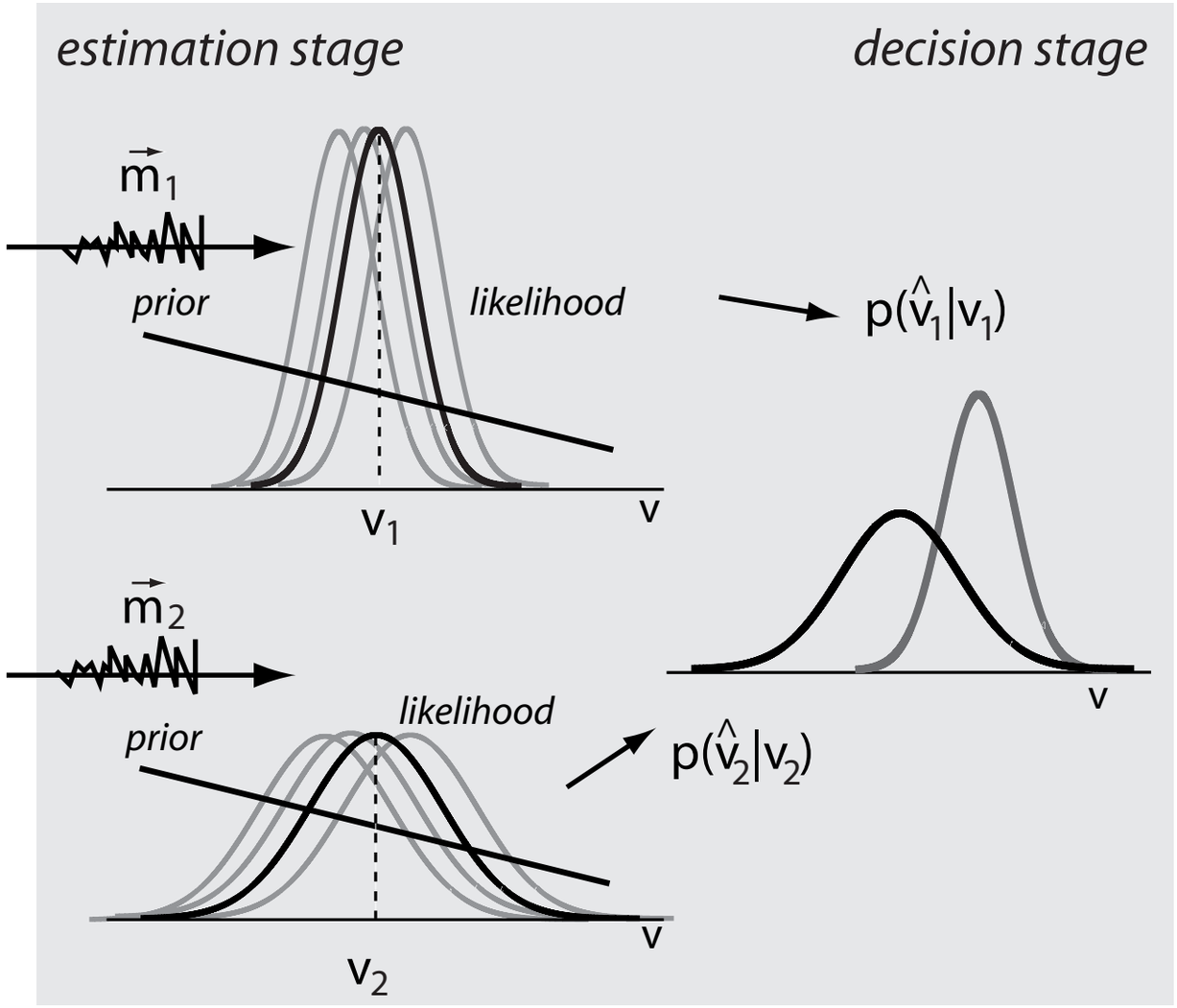
subject response

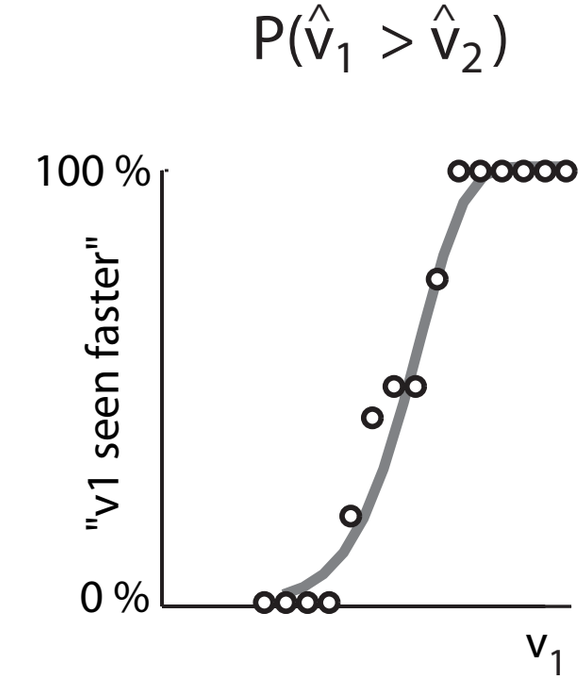
v_1



v_2

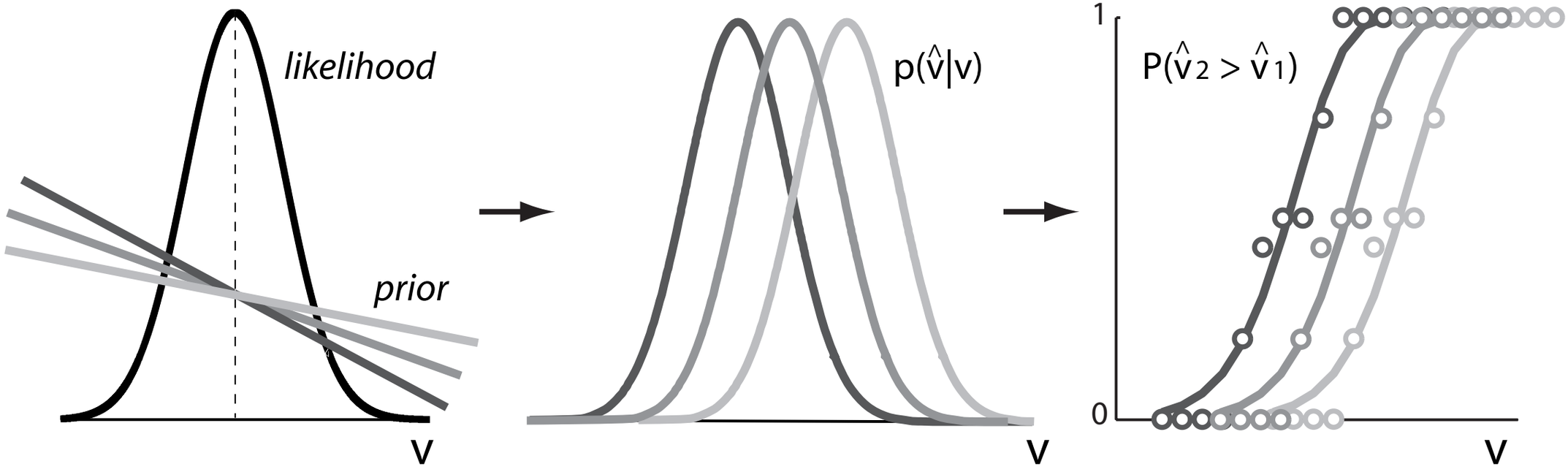




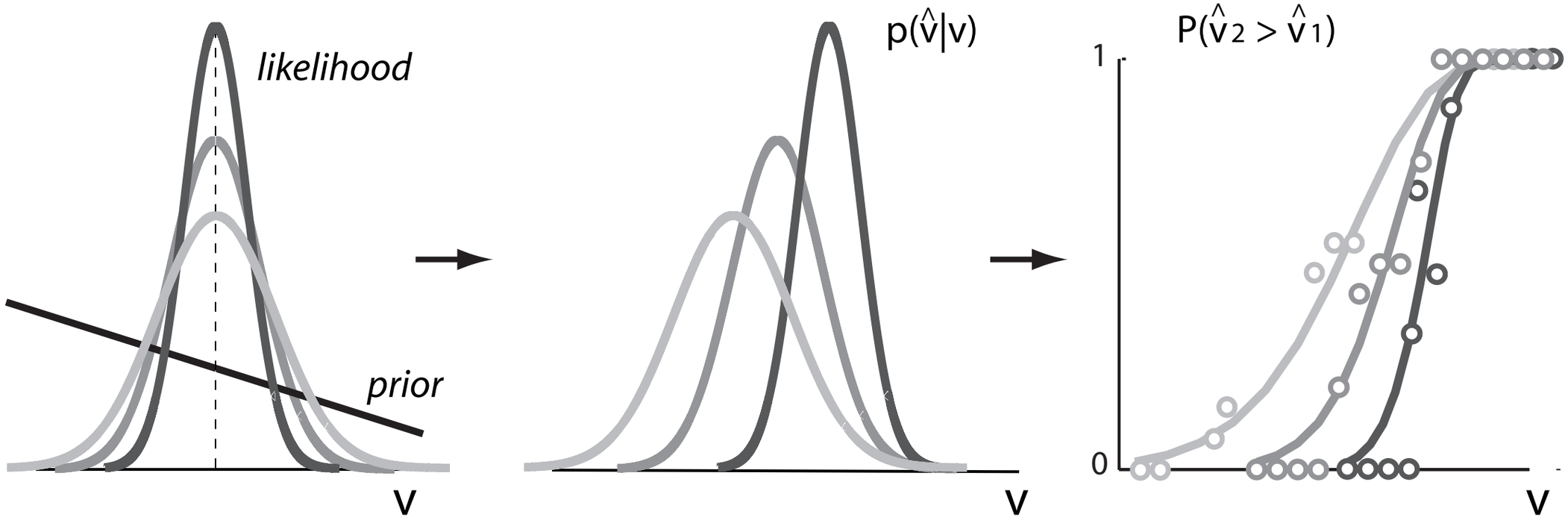


psychometric function

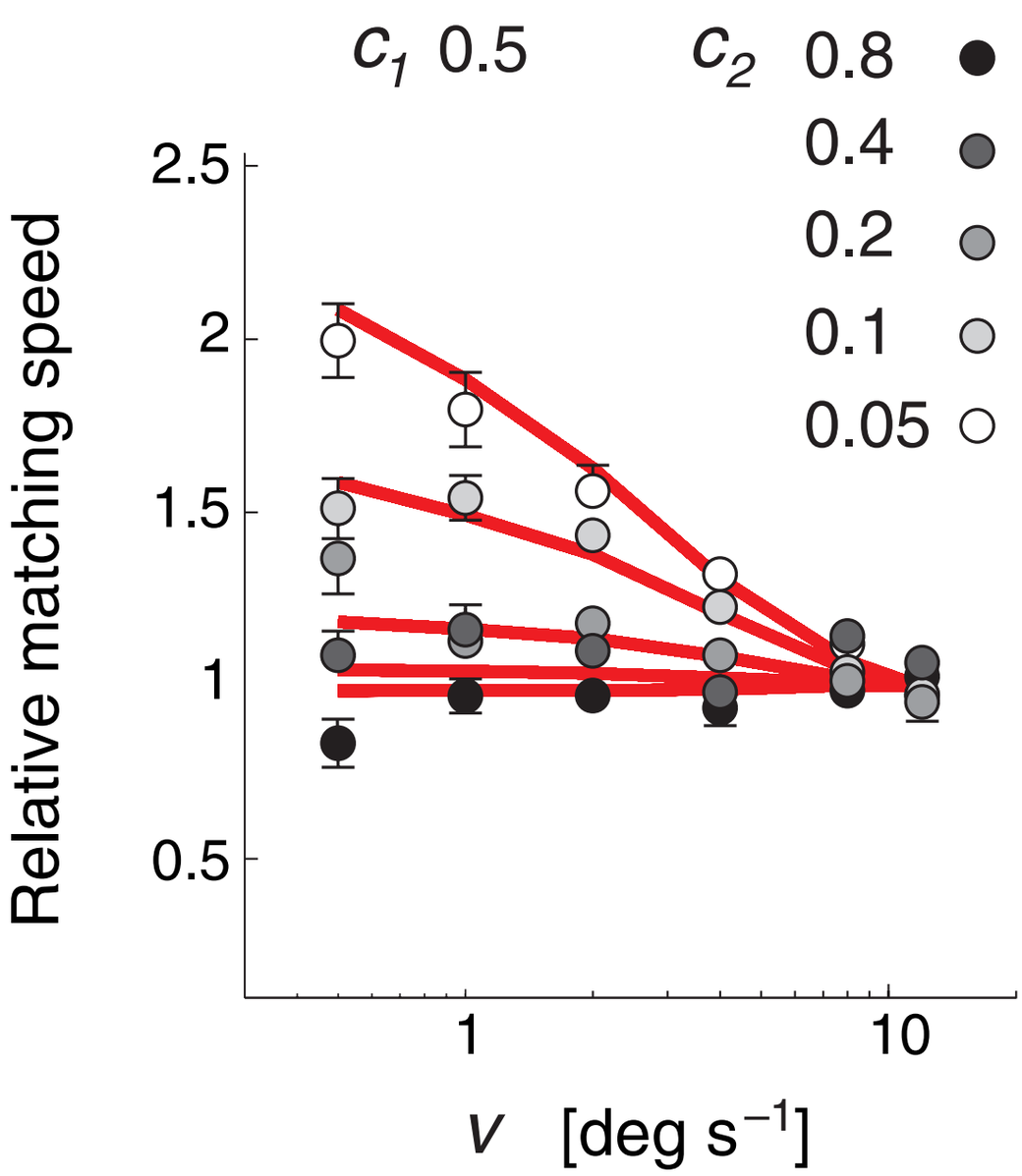
slope of prior

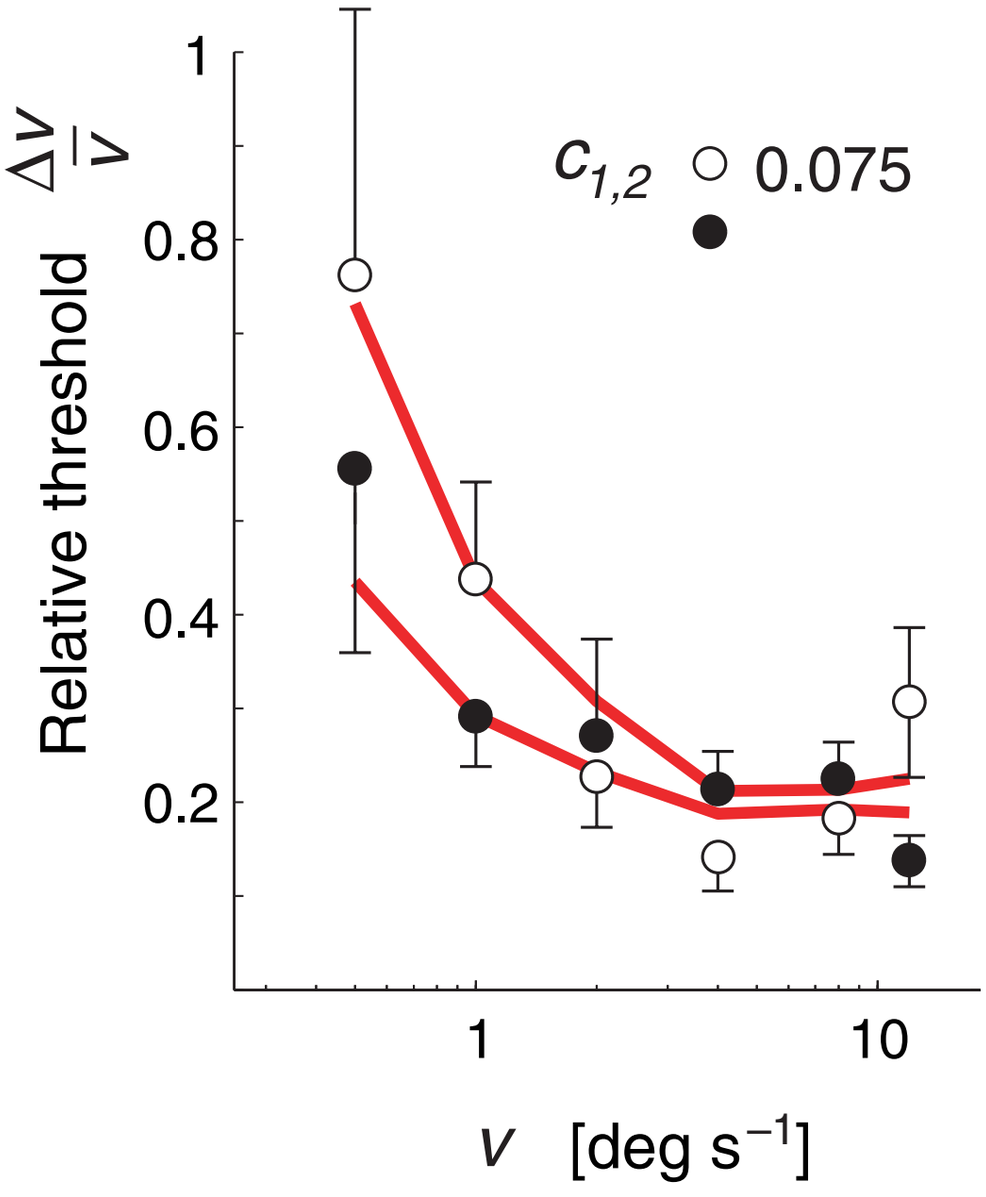


width of likelihood

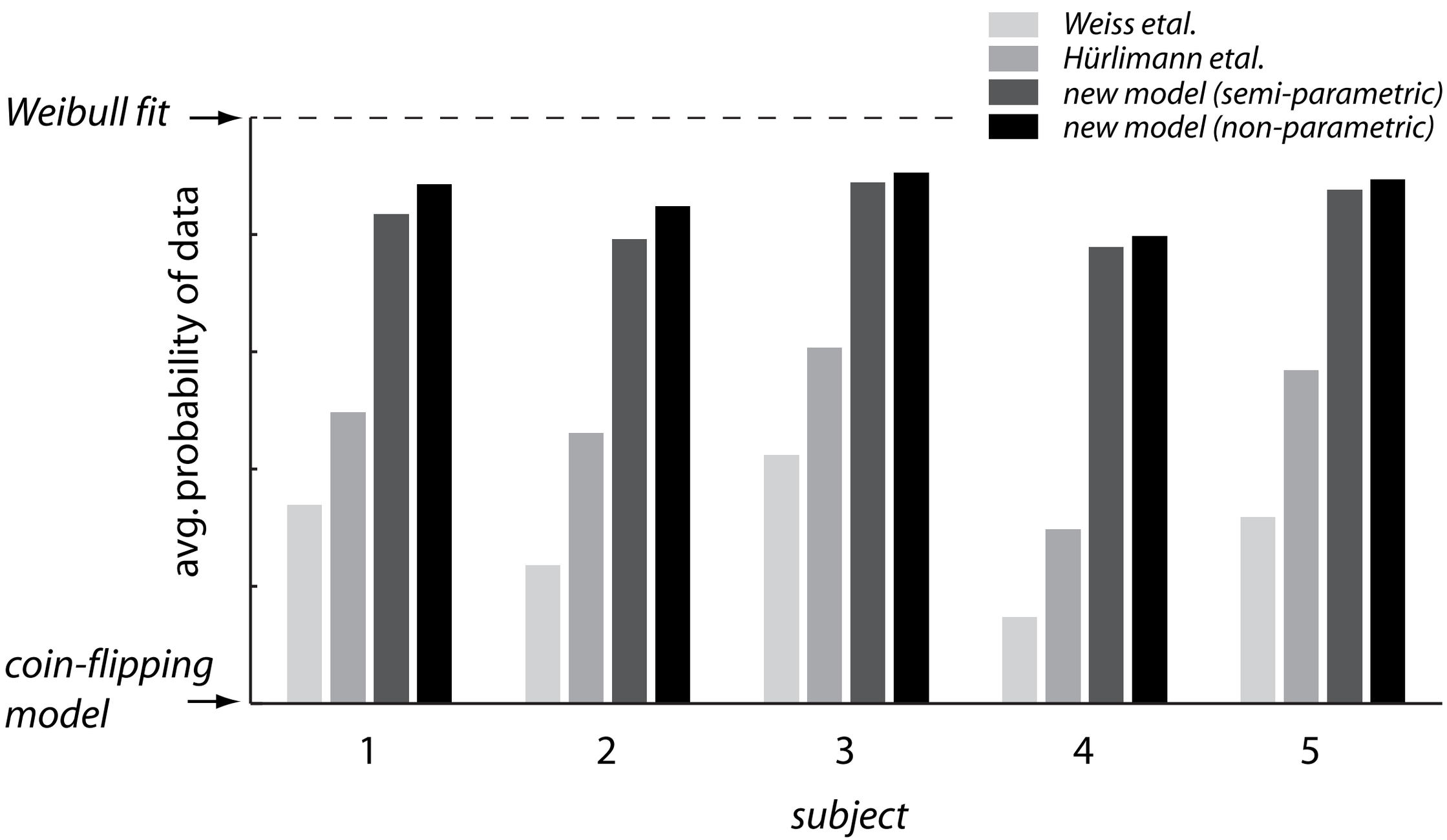


Model accounts for perceptual data





Model comparison



Prior

Likelihood width

Probability

1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1
10

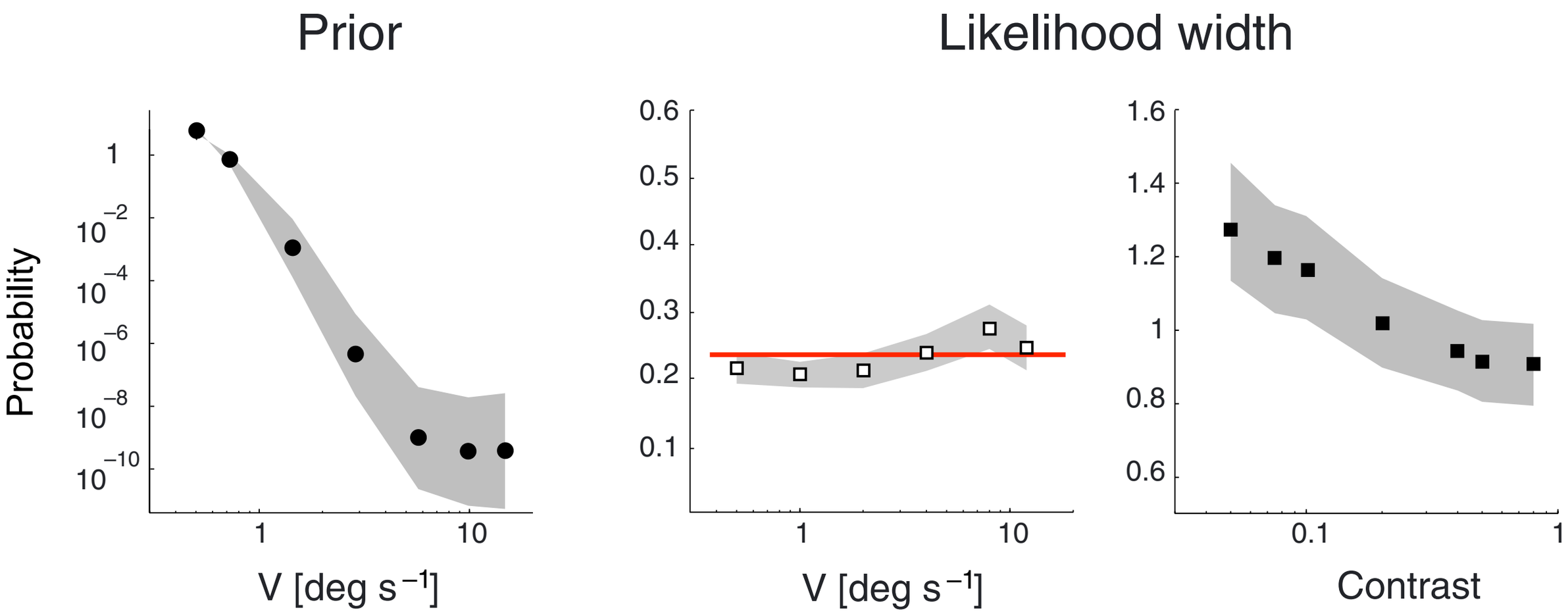
0.6
0.5
0.4
0.3
0.2
0.1
1
10

1.6
1.4
1.2
1
0.8
0.6
0.1
1

V [deg s^{-1}]

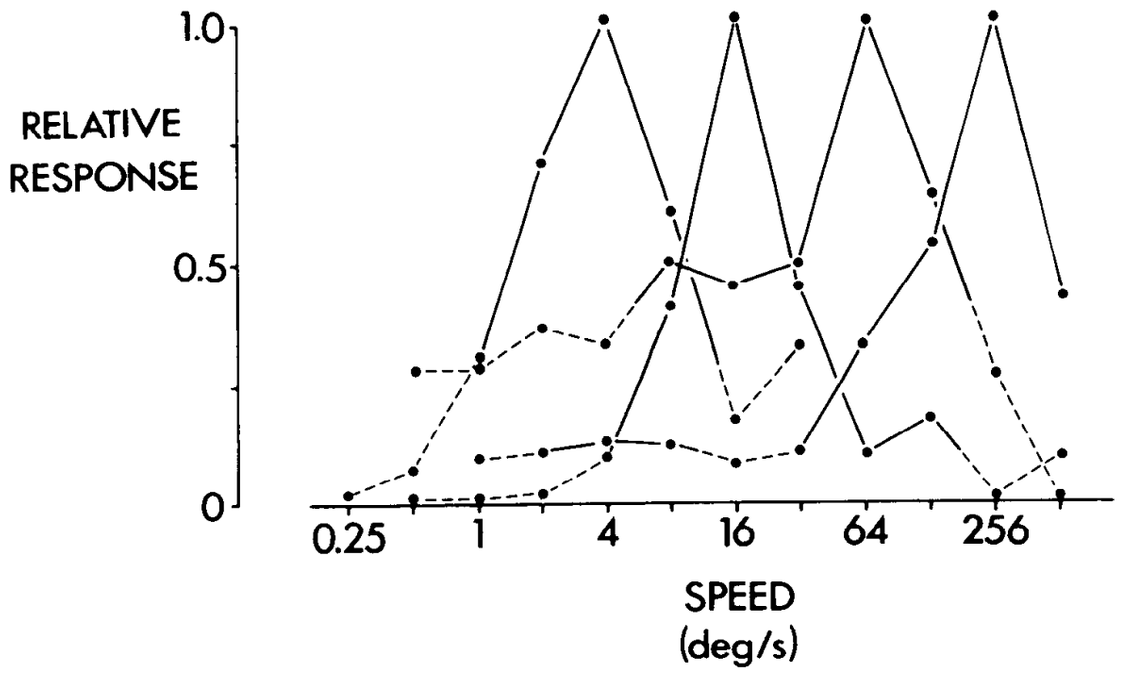
V [deg s^{-1}]

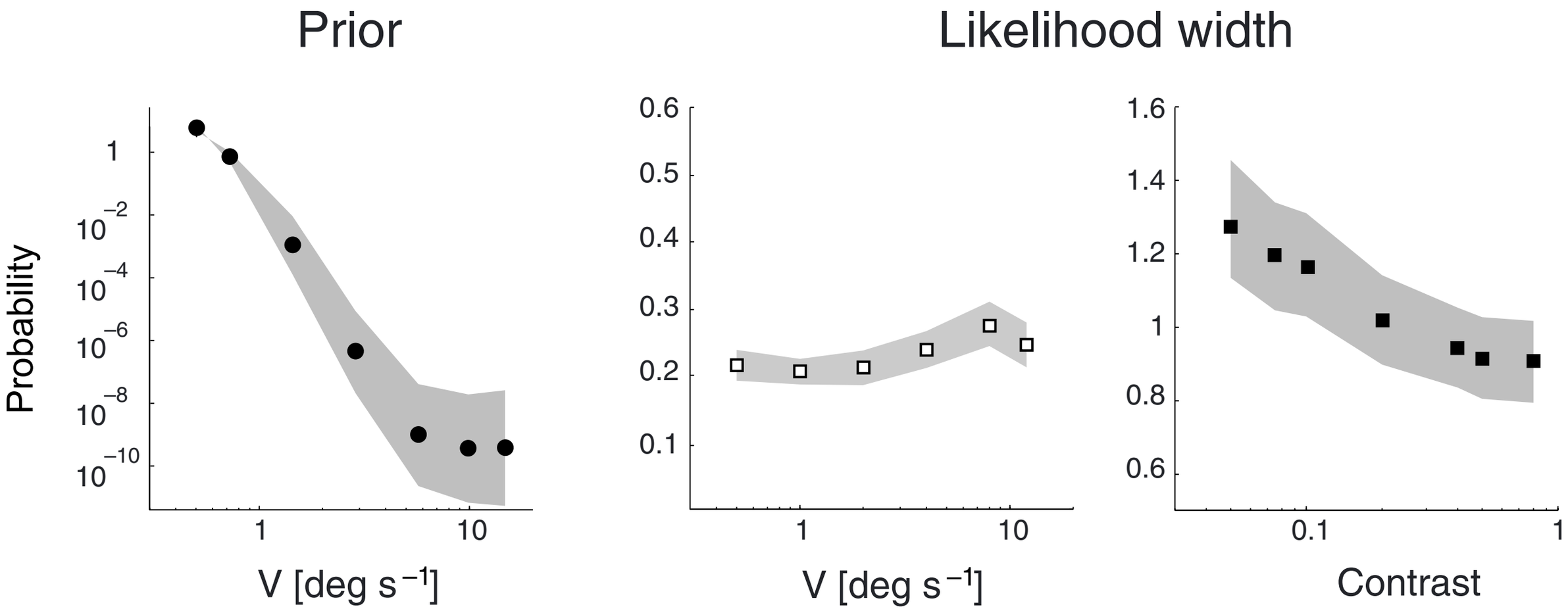
Contrast



Speed tuning in area MT is approximately constant in log(v)

- Maunsell & Van Essen 83
- also Nover et. al. 05

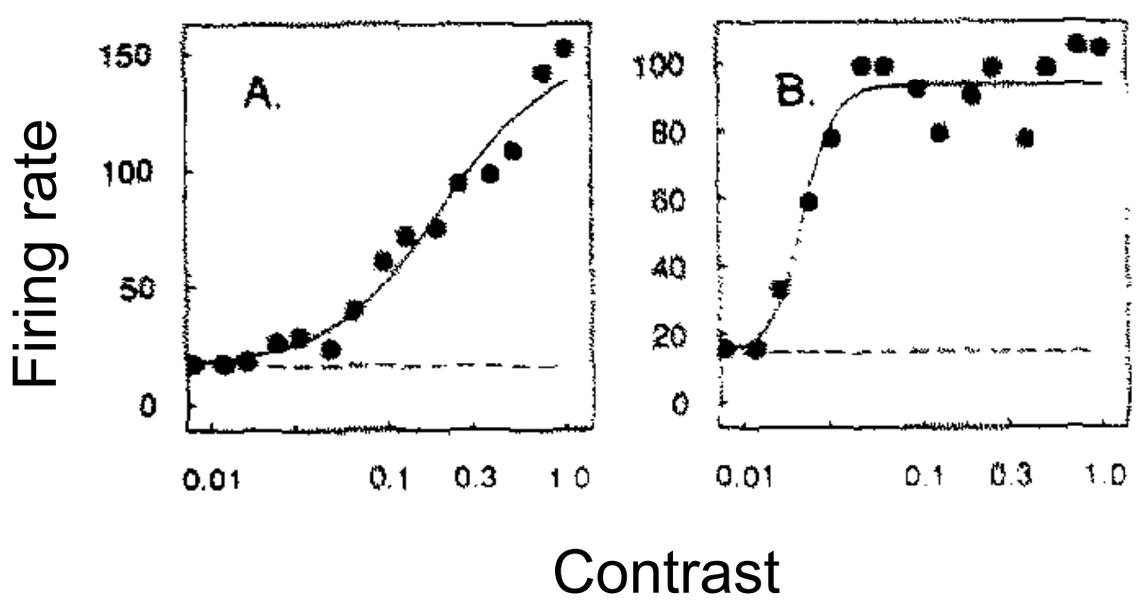


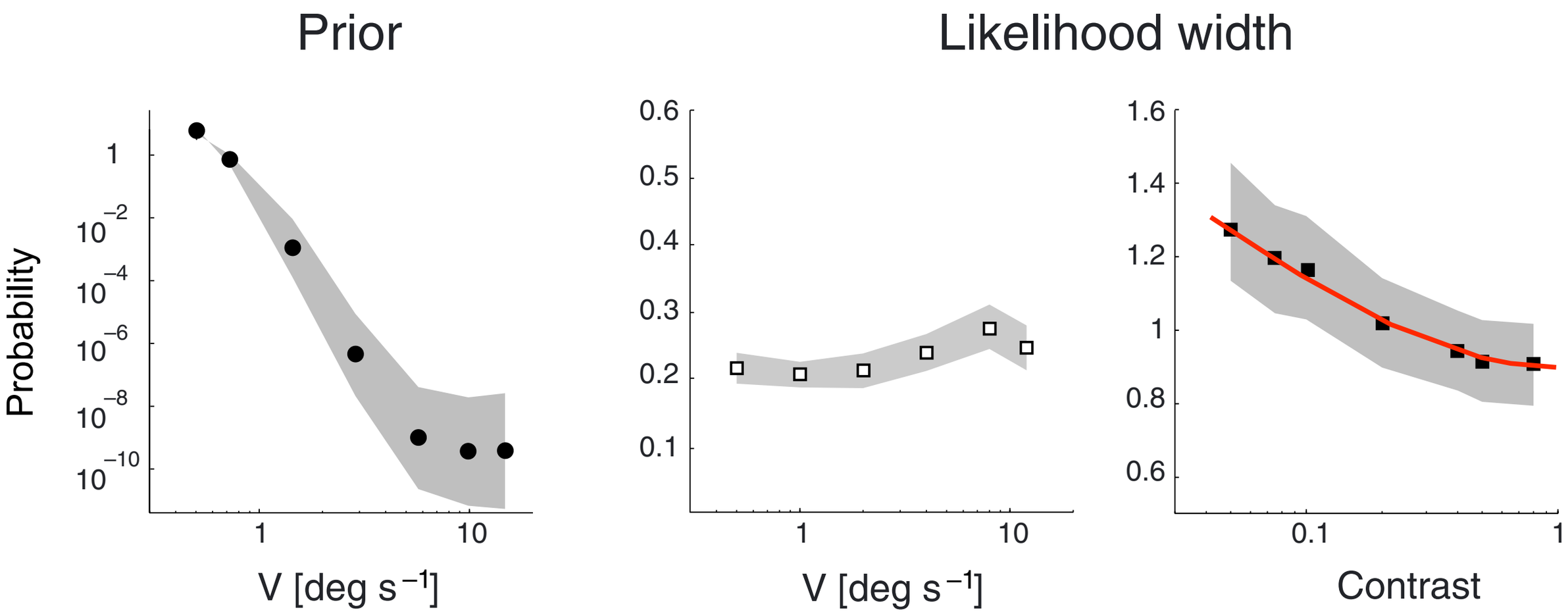


Area MT contrast-response function:

$$r(c) = \alpha \frac{c^k}{c^k + c_{50}^k} + \beta$$

- Sclar et. al. 90





Area MT contrast-response function:

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- Sclar et. al. 90

Likelihood width under Poisson variability:

$$w(c) \propto \left(\frac{1}{r(c)} \right)^2$$

Prior

Likelihood width

Probability

1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}

1
10

Speed [deg s^{-1}]

0.6
0.5
0.4
0.3
0.2
0.1

1
10

Speed [deg s^{-1}]

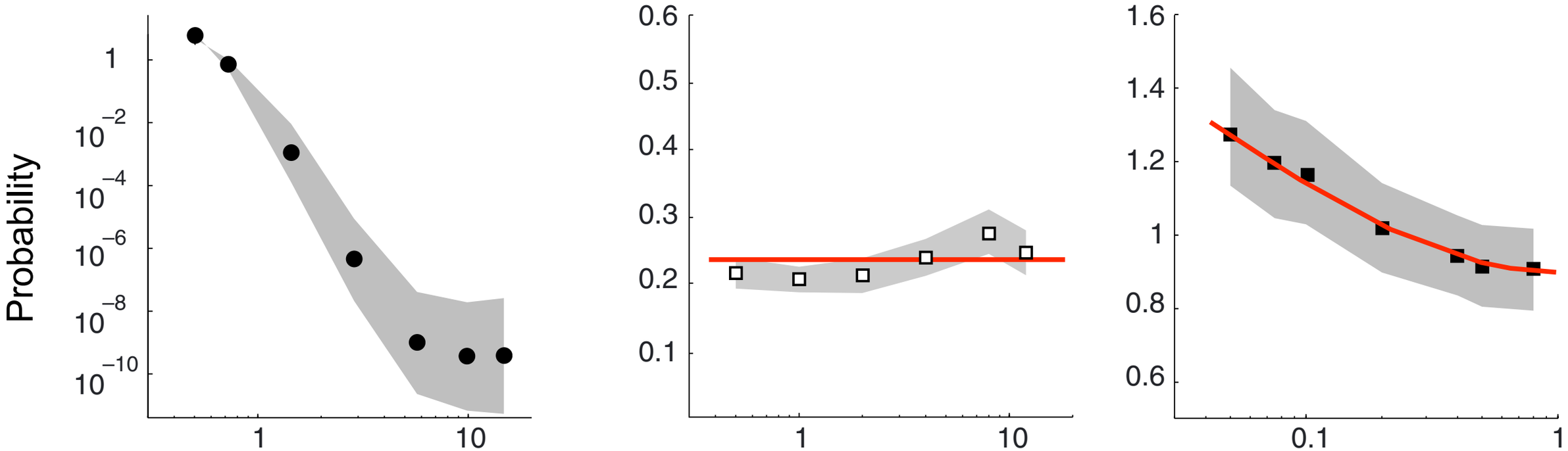
1.6
1.4
1.2
1
0.8
0.6

0.1
1

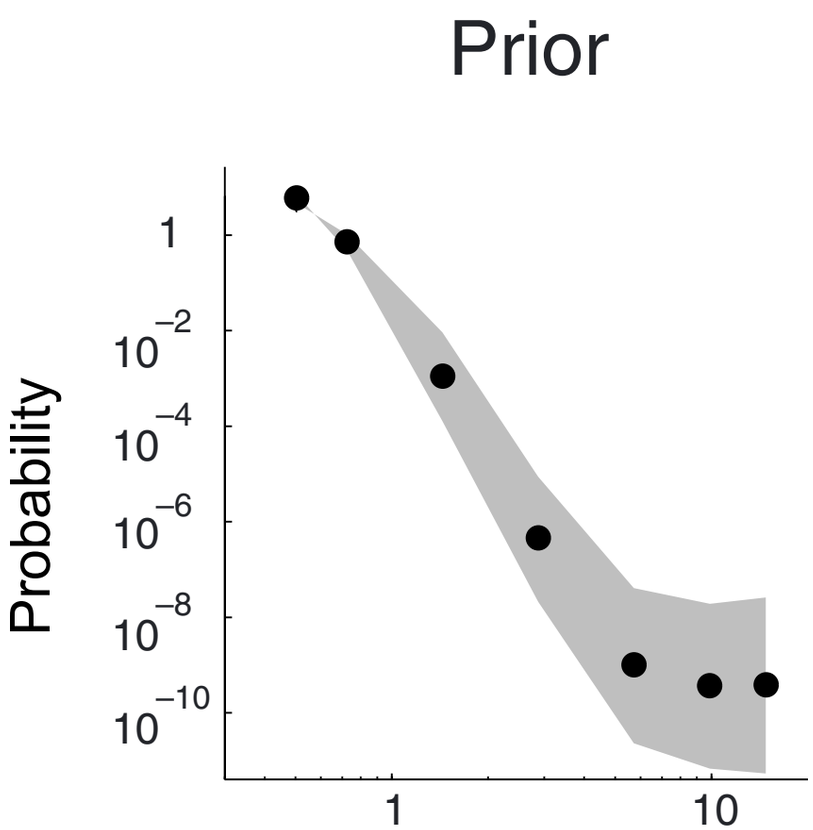
Contrast

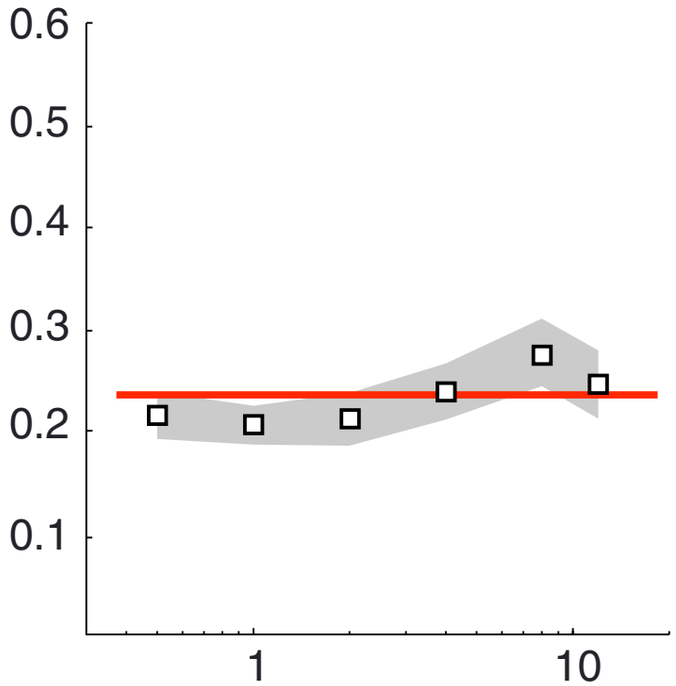
Prior

Likelihood width

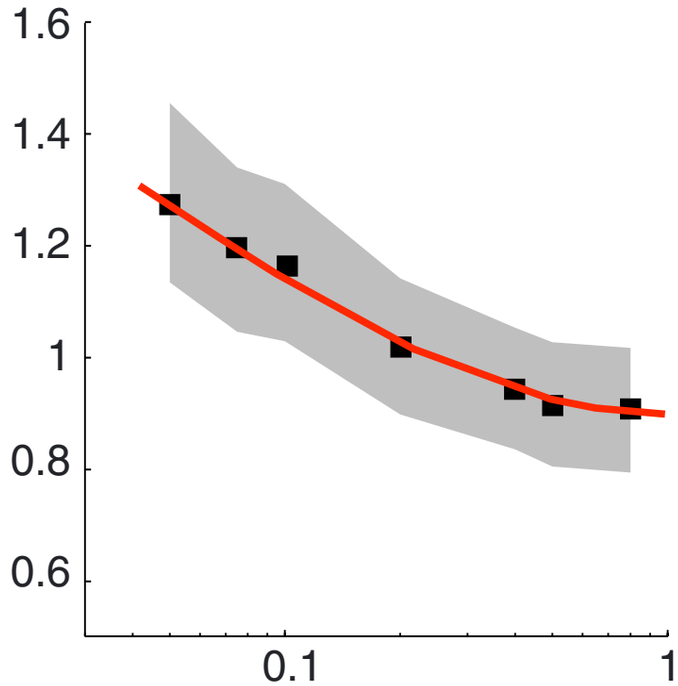


Log-spaced
tuning curves





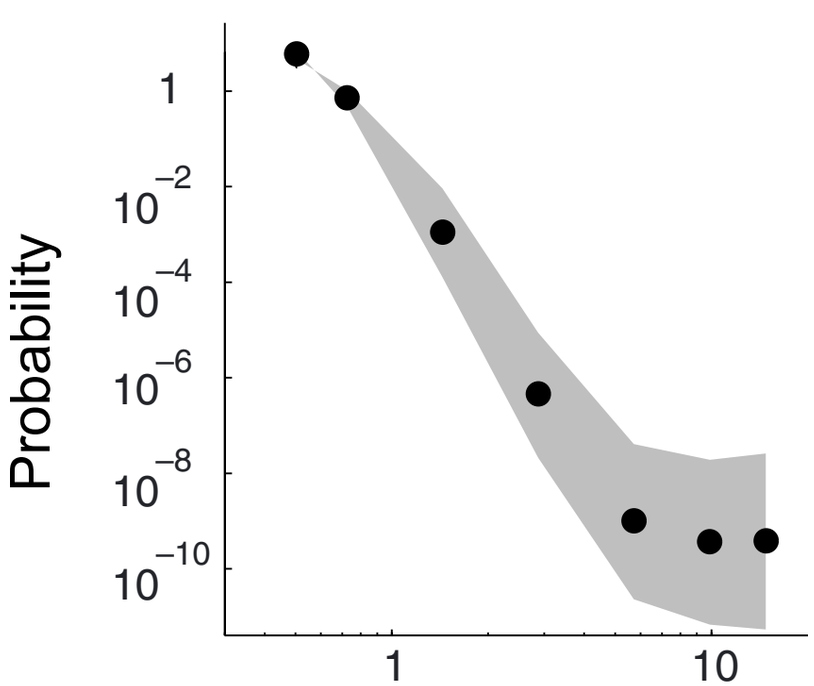
Log-spaced
tuning curves



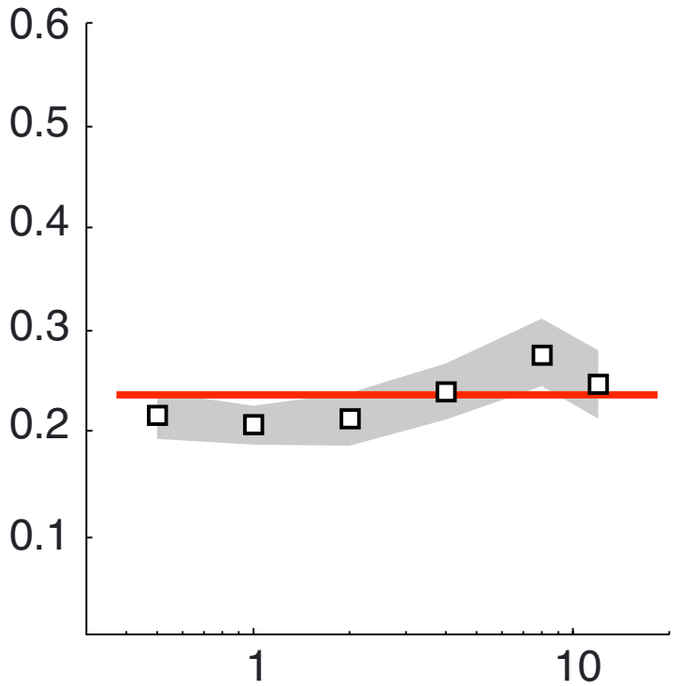
Contrast-response
+
Poisson variability

Prior

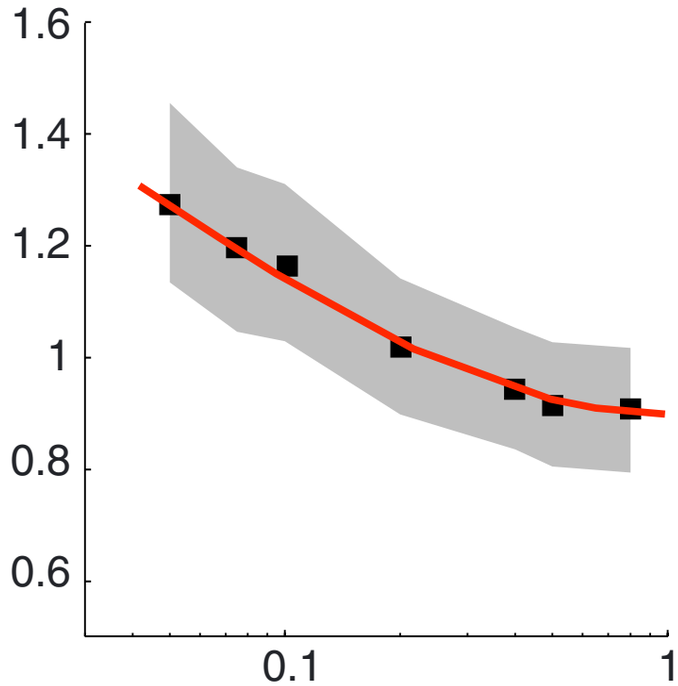
Likelihood width



?

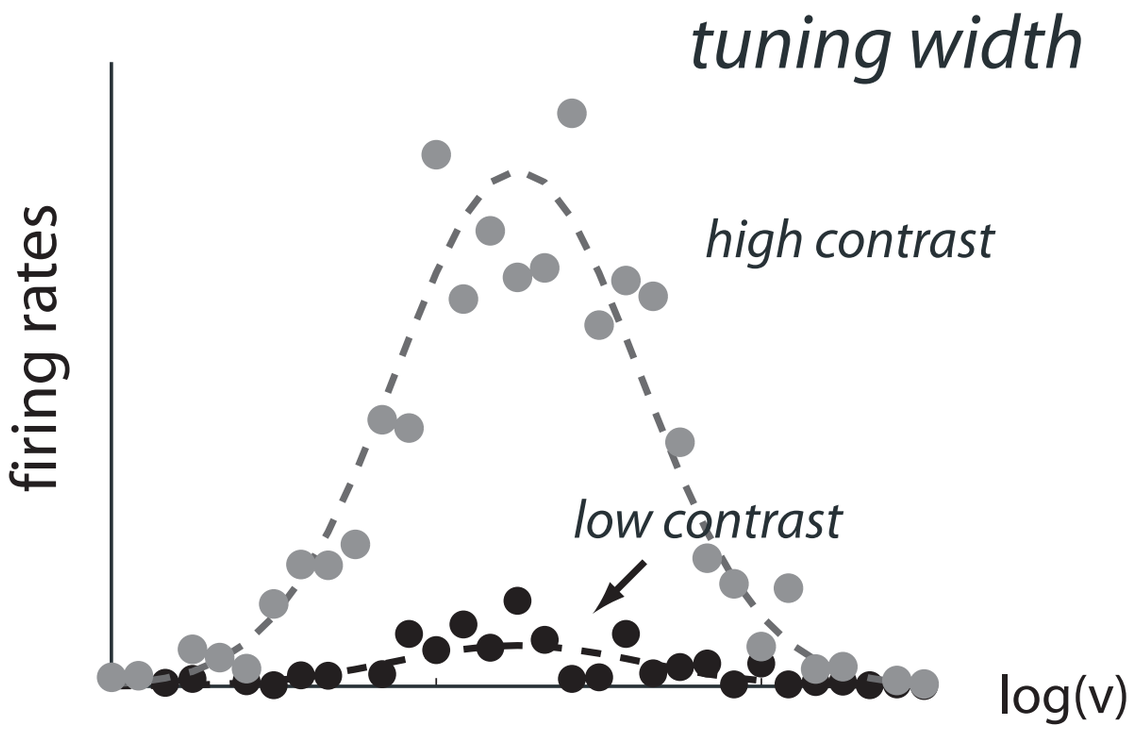


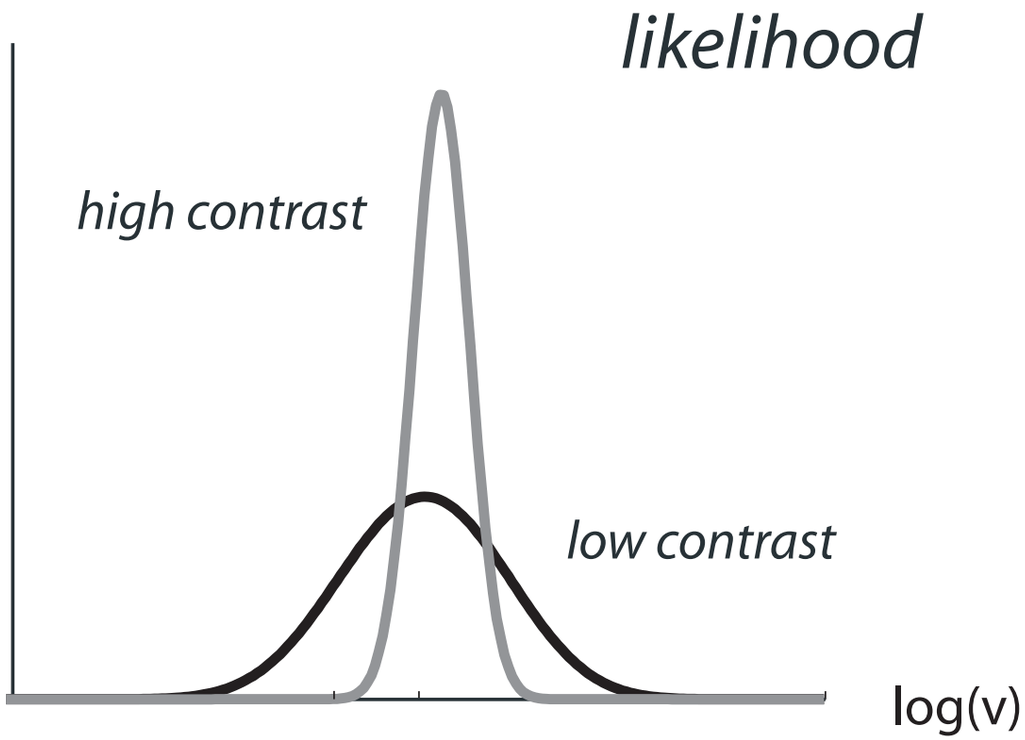
Log-spaced
tuning curves



Contrast-response
+
Poisson variability

Hypothesis 1: MT encodes likelihood

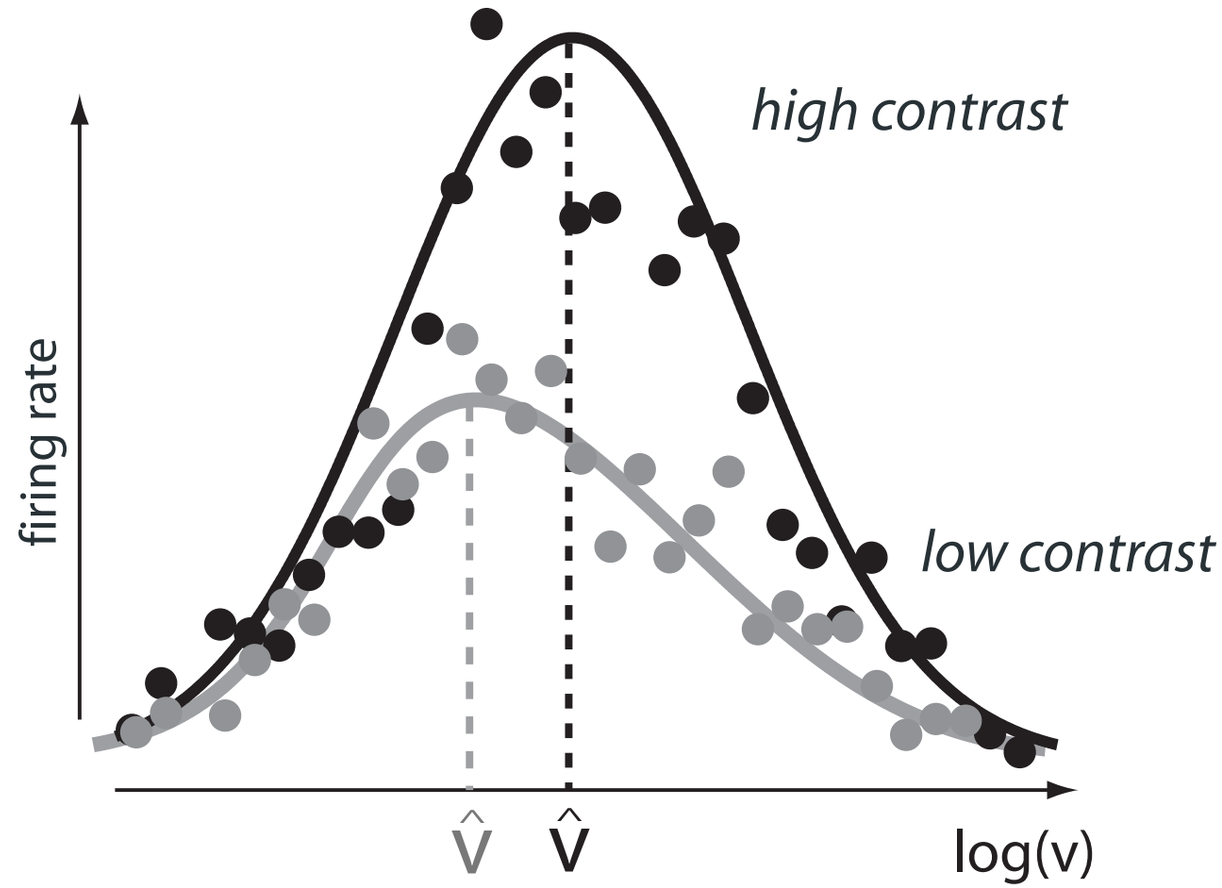




Responses are separable in speed and contrast

Prior is imposed on readout

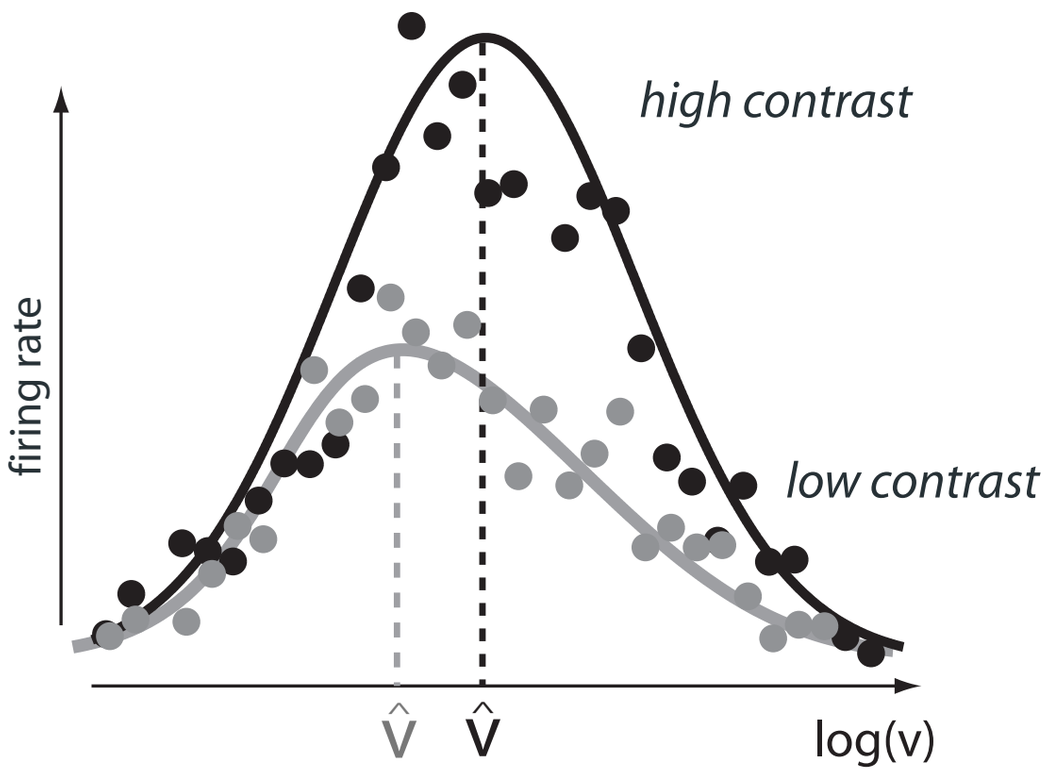
Hypothesis 2: MT population encodes posterior

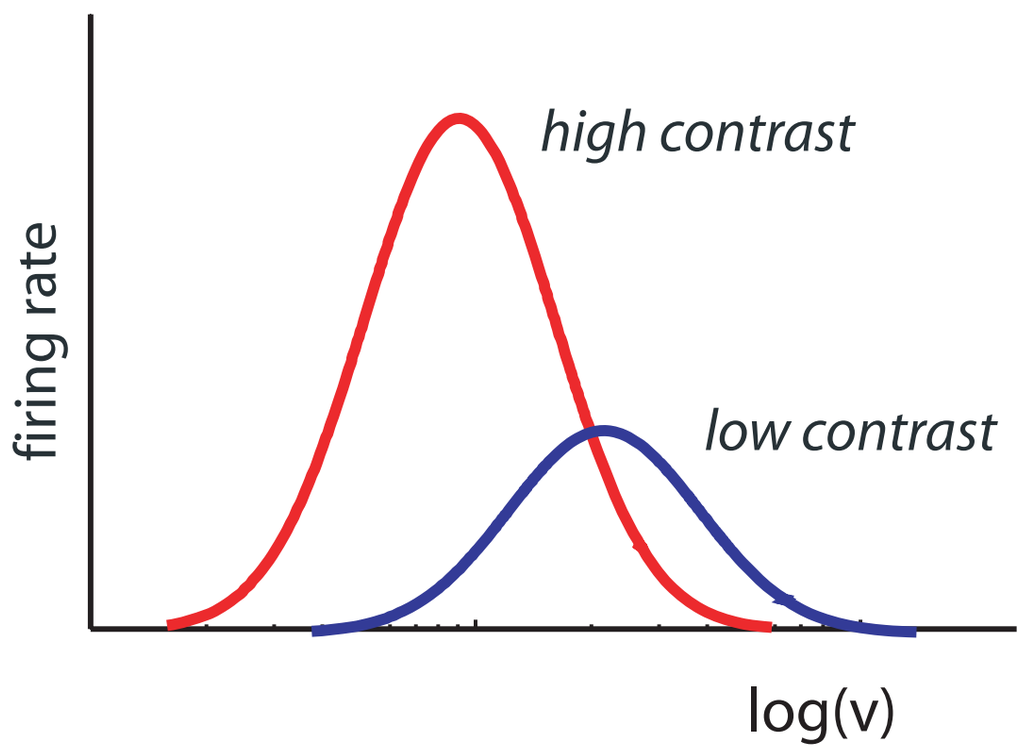


Each MT cell provides a “labelled line” for posterior at a particular velocity [Simoncelli, ‘03]

=> Speed and contrast are linked

Hypothesis 2a





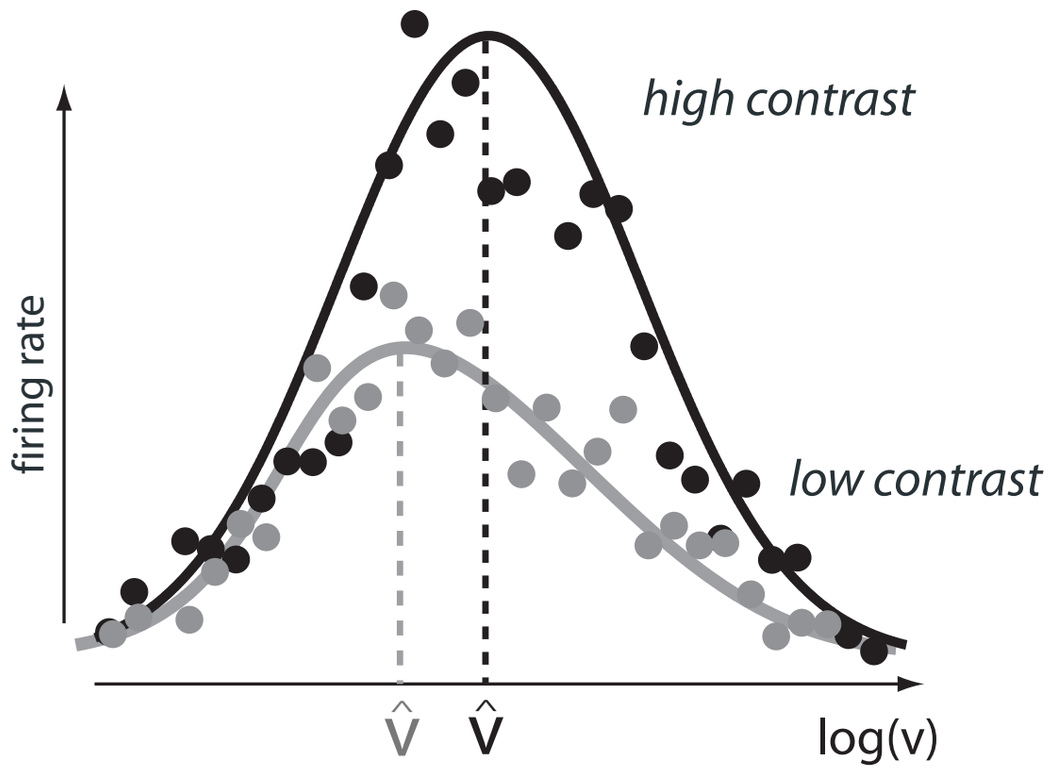
Cell speed tuning depends on contrast

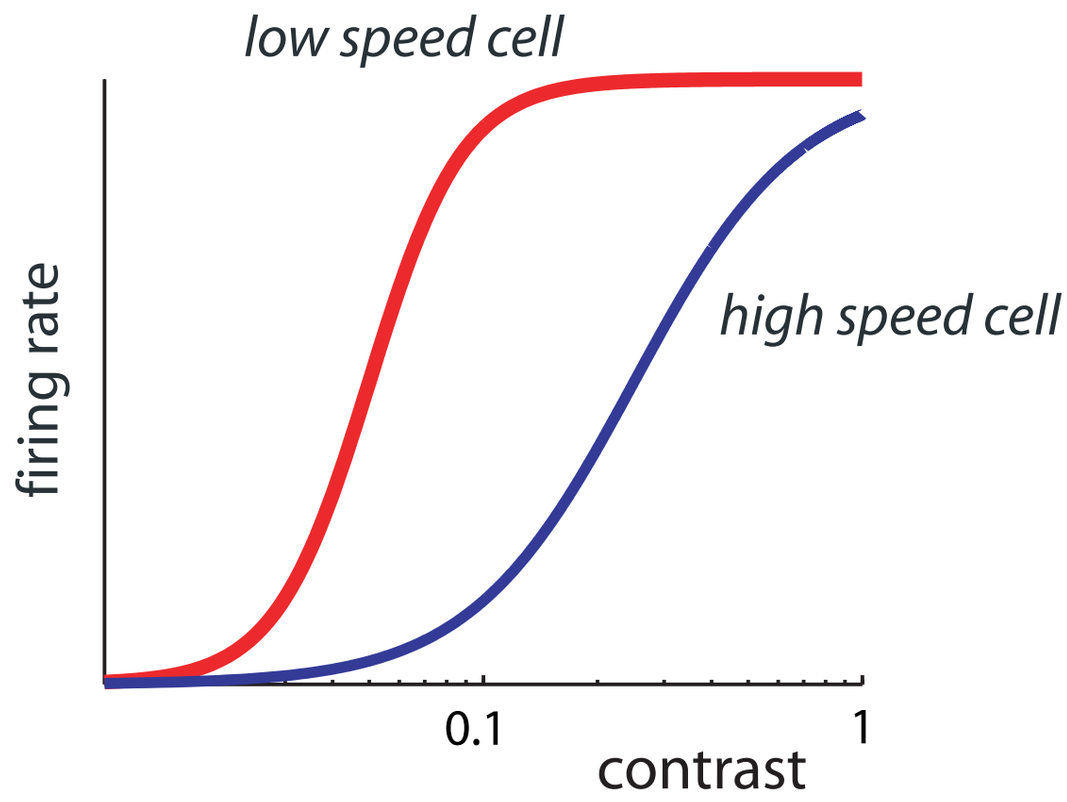
=> Should prefer higher speeds at lower contrast

Recent physiological evidence suggests not

[Priebe & Lisberger ‘05; Pack & Born ‘05; Krekelberg & Albright (unpublished)]

Hypothesis 2b





Responses are separable in speed and contrast

Contrast-response functions linked to speed tuning

Credits

- Reverse-engineered prior/likelihood: Alan Stocker
- Plaid motion modeling: Edward Adelson, David Heeger, Yair Weiss
- Physiological model: David Heeger