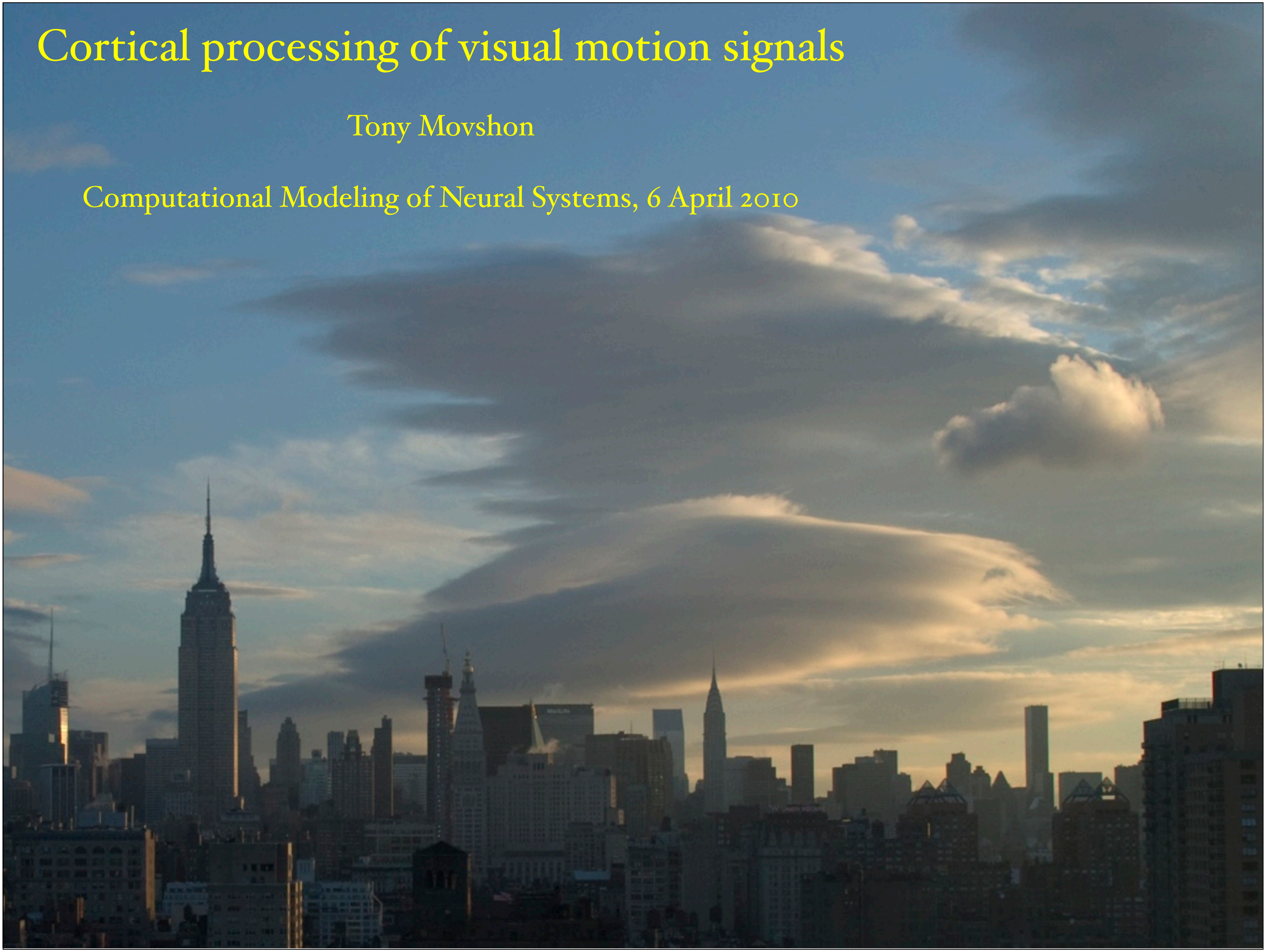
Cortical processing of visual motion signals

Tony Movshon

Computational Modeling of Neural Systems, 6 April 2010



Korbinian Brodmann
(1868-1918)

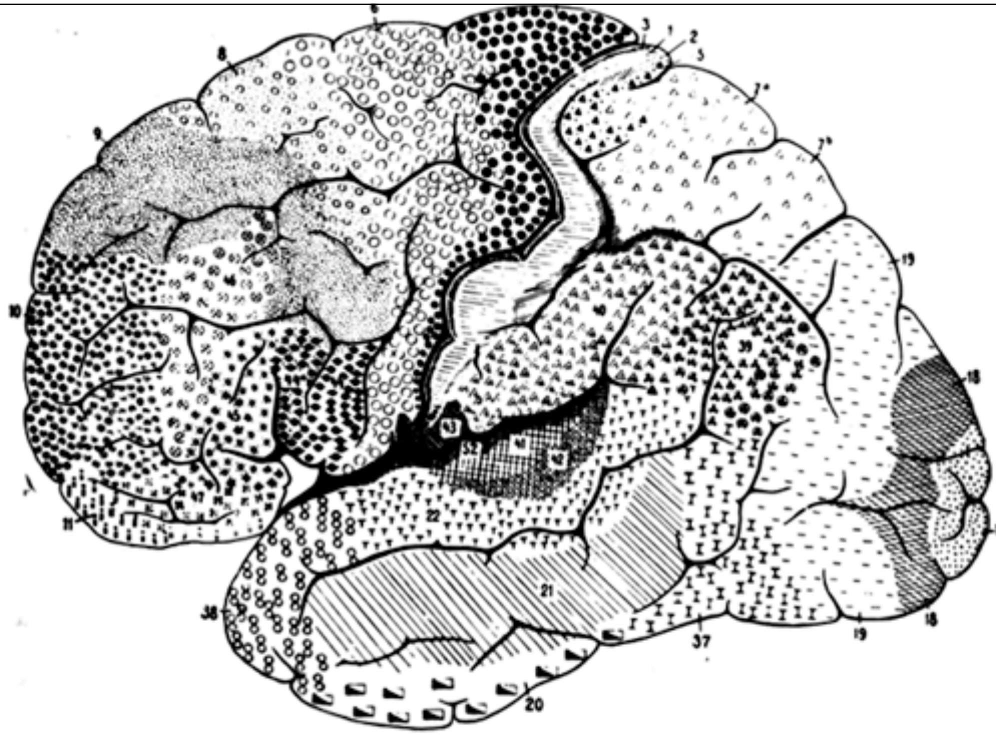


Abb. 6.

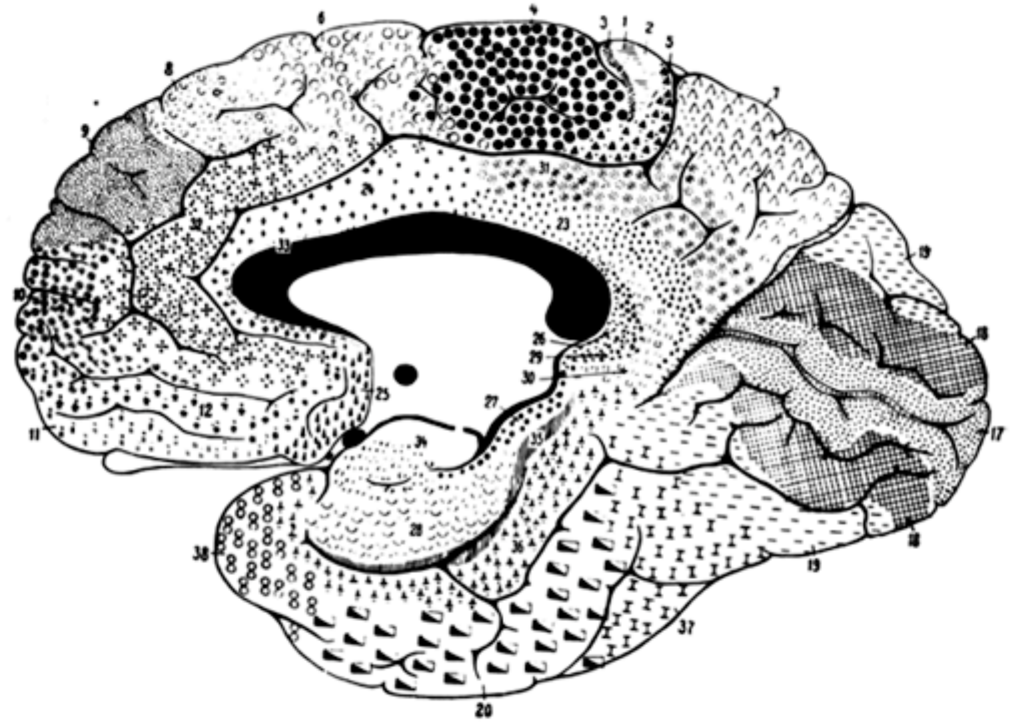
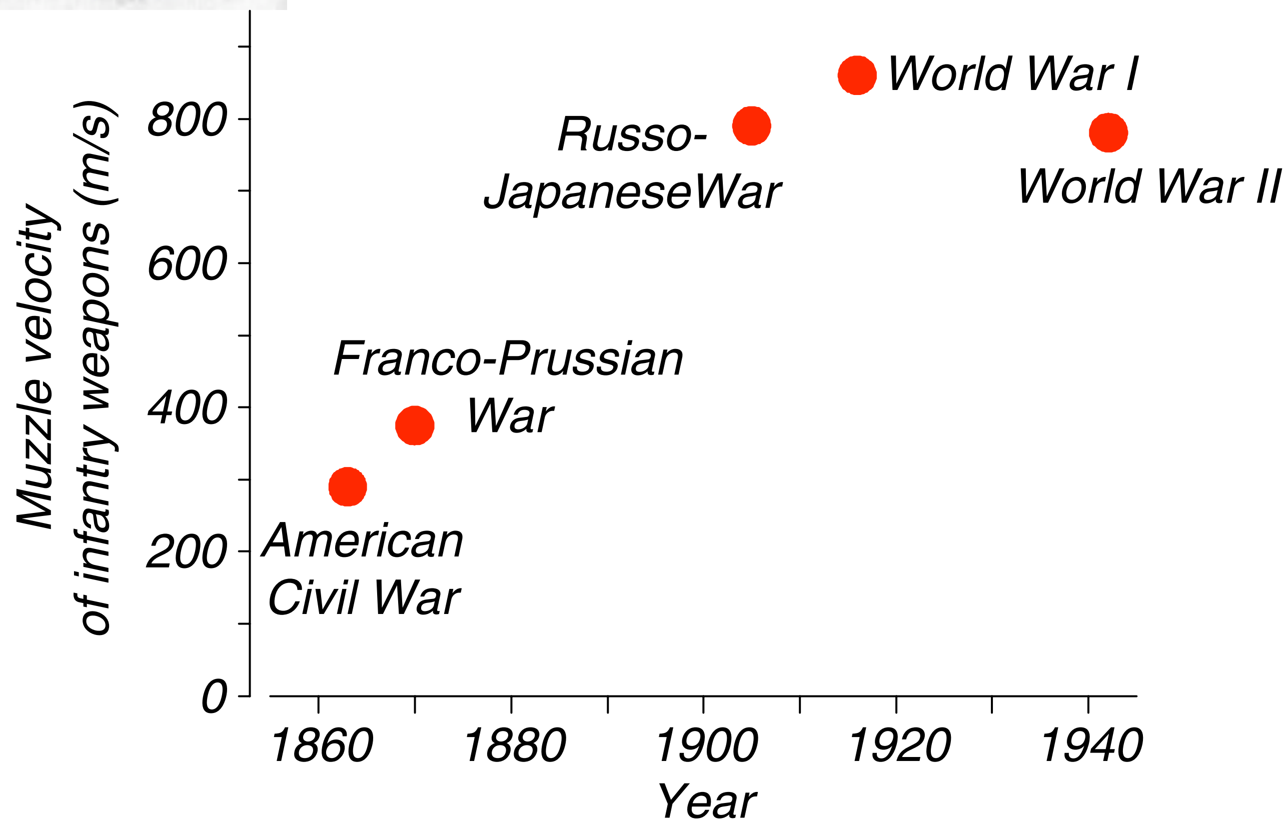


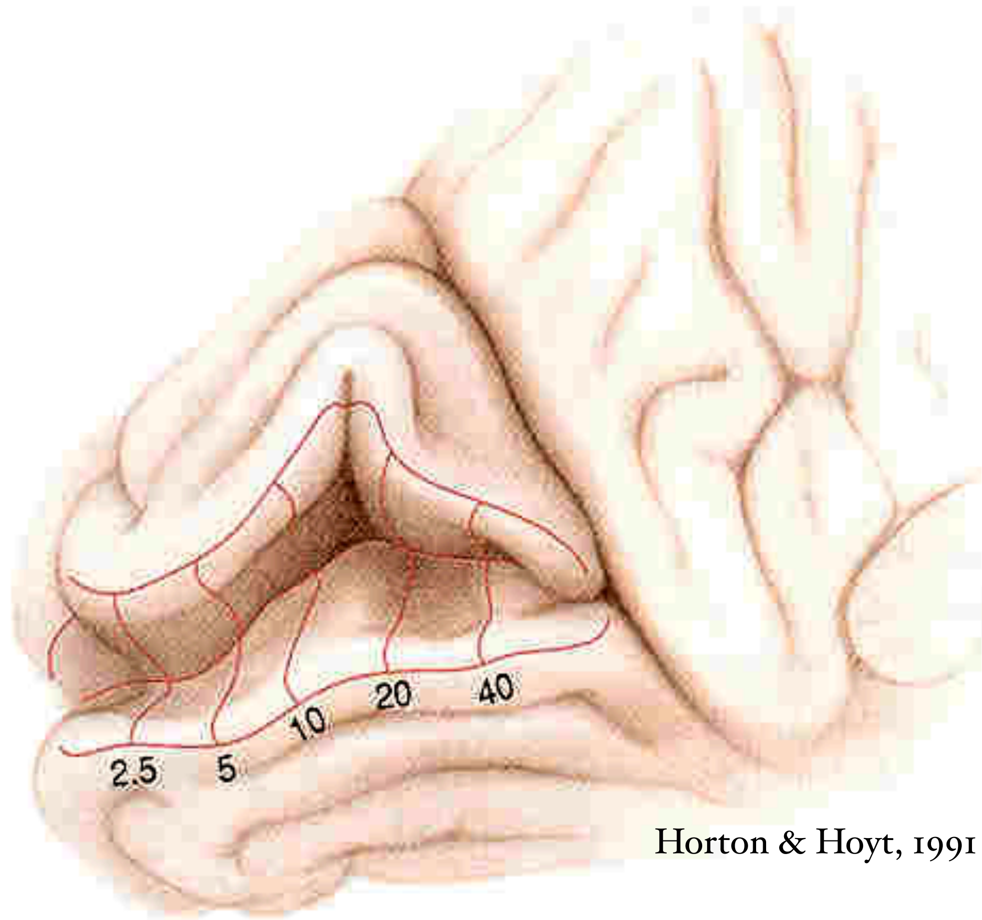
Abb. 7.


World War I
Russo-
JapaneseWar
World War II
Franco-Prussian
War
American
Civil War
Muzzle velocity
of infantry weapons (m/s)
0
200
400
600
800
1860
1880
1900
1920
1940
Year

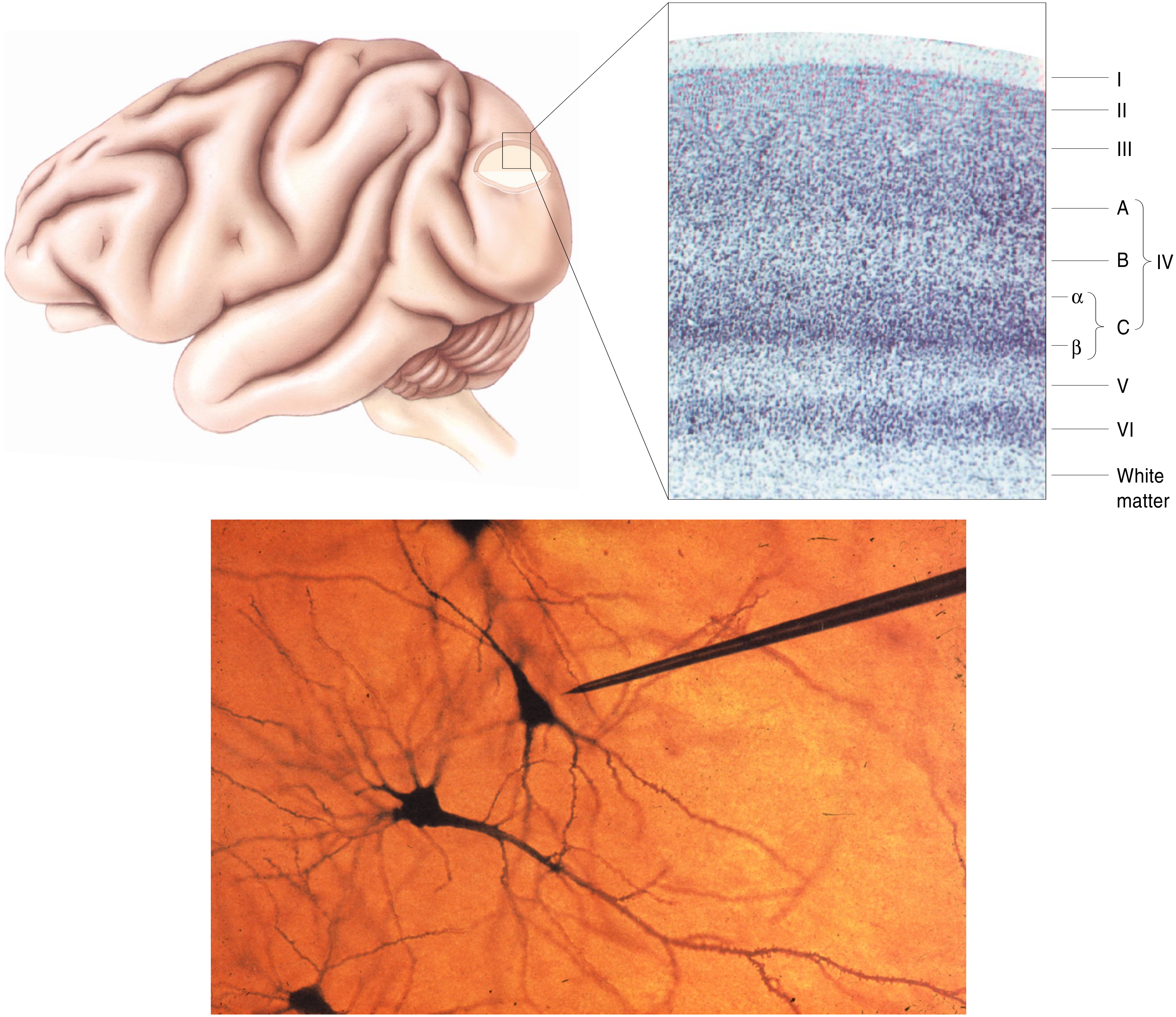
Tatsuji Inouye (1880-1976)

Visual Disturbances Following Gunshot Wounds of the Cortical Visual Area

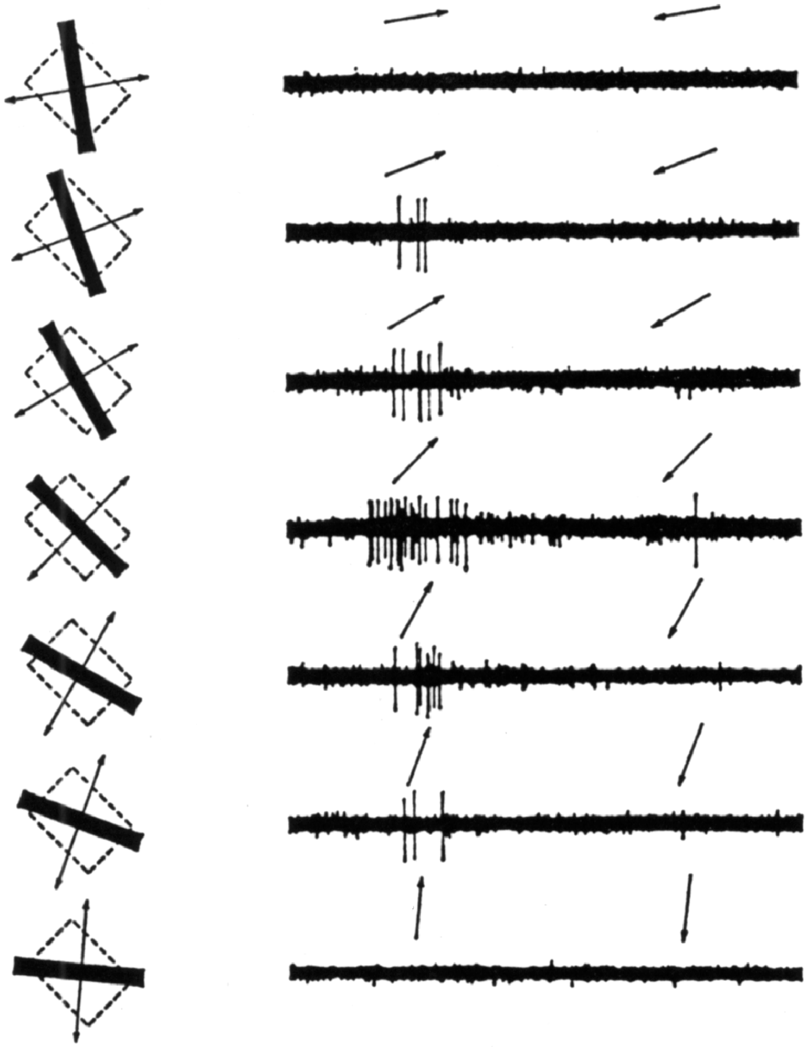
Based on observations of the wounded in the recent Japanese Wars

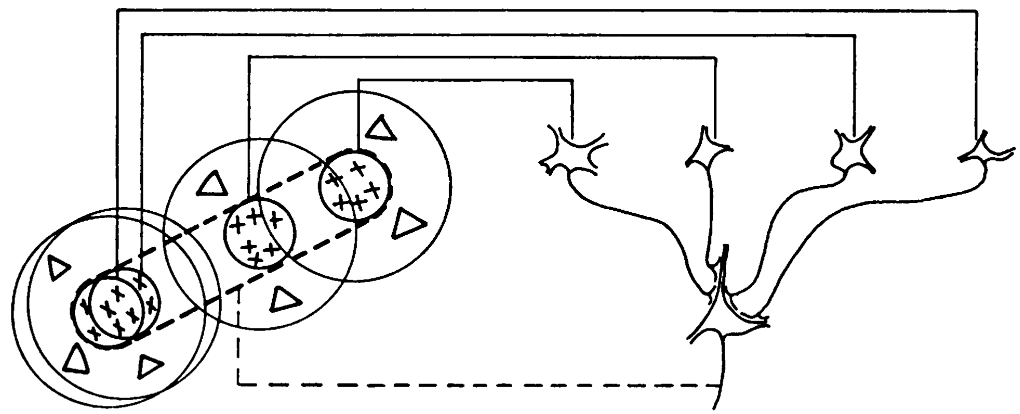


Horton & Hoyt, 1991



I
II
III
A
B
IV
α
C
β
V
VI
White matter



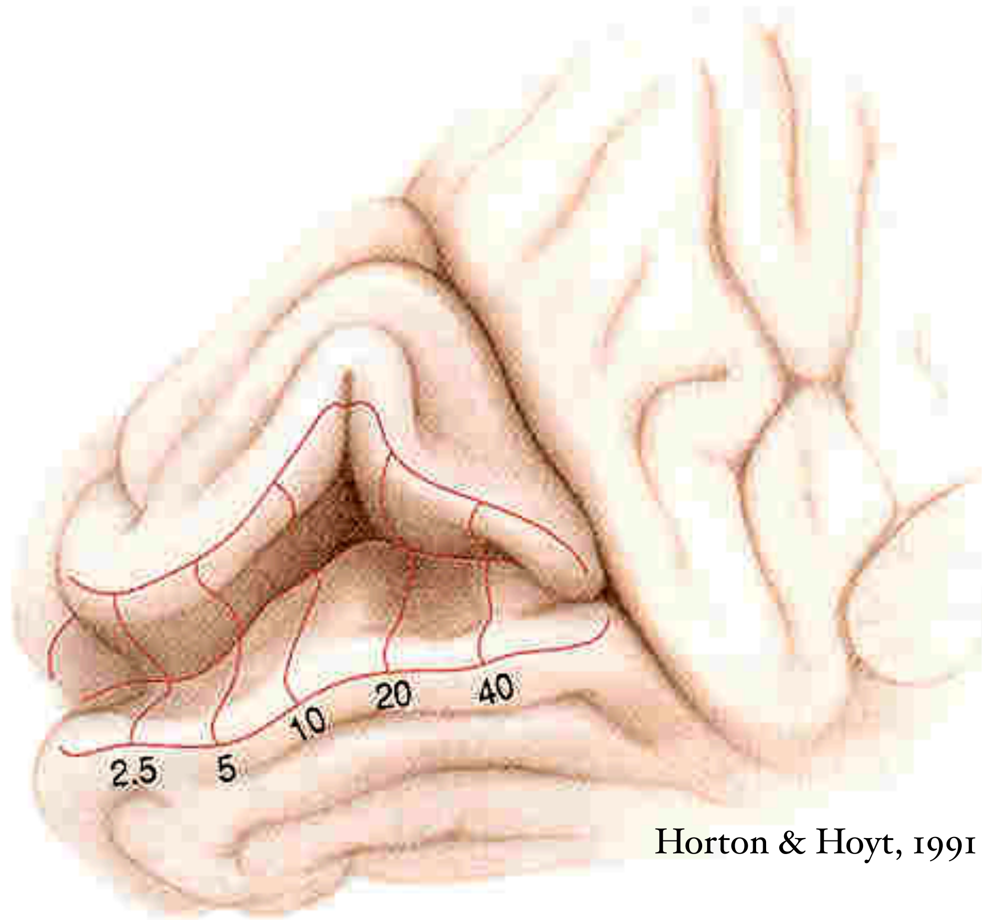


Hubel & Wiesel, 1962, 1968

Tatsuji Inouye (1880-1976)

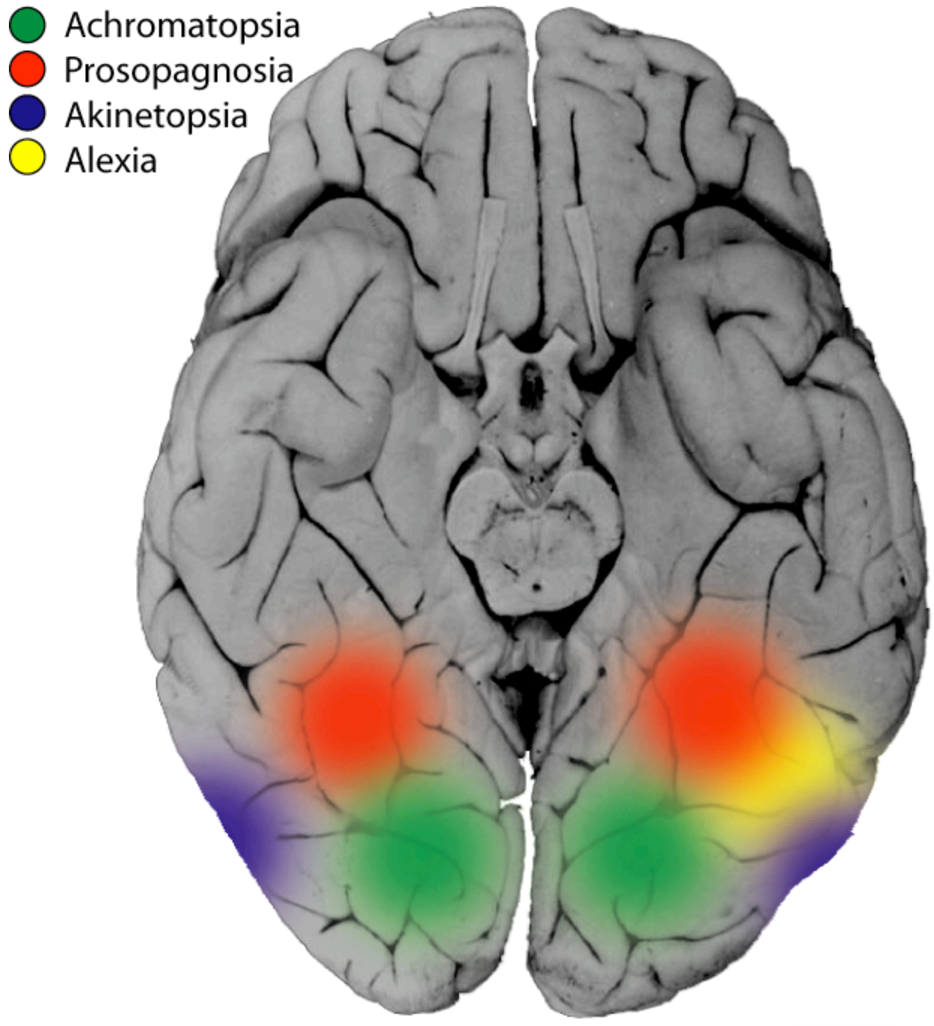
Visual Disturbances Following Gunshot Wounds of the Cortical Visual Area

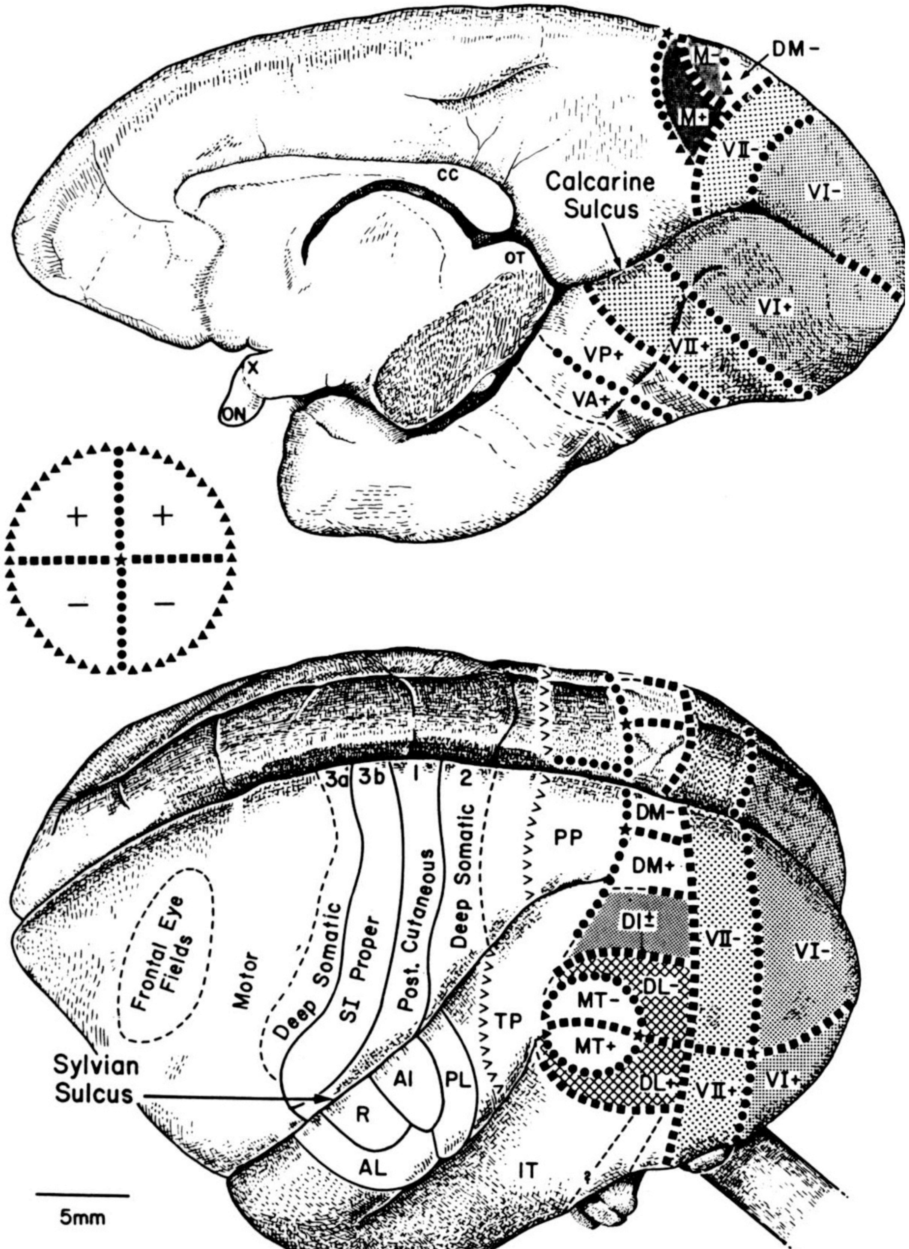
Based on observations of the wounded in the recent Japanese Wars



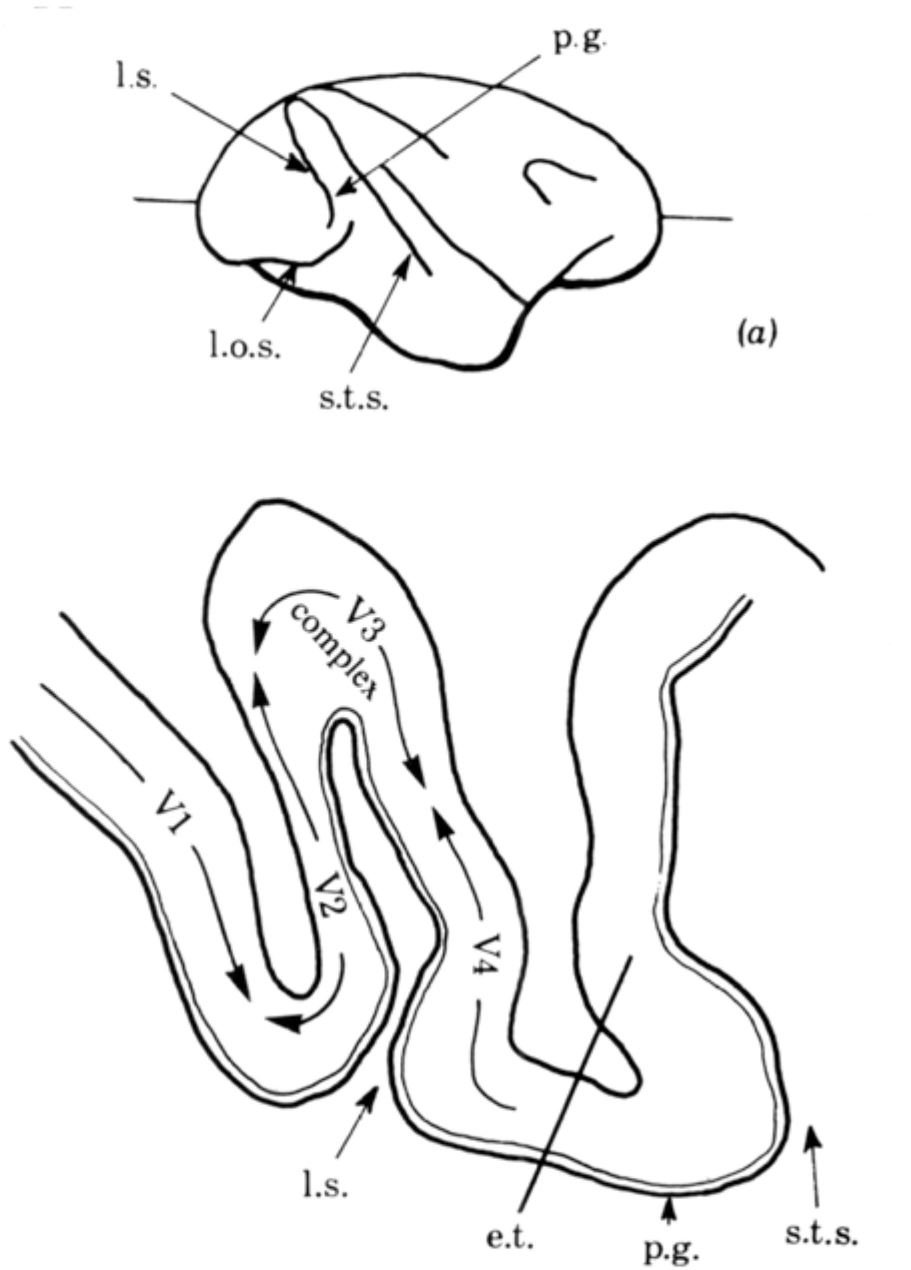
Horton & Hoyt, 1991

Functional specialization in human extrastriate visual cortex

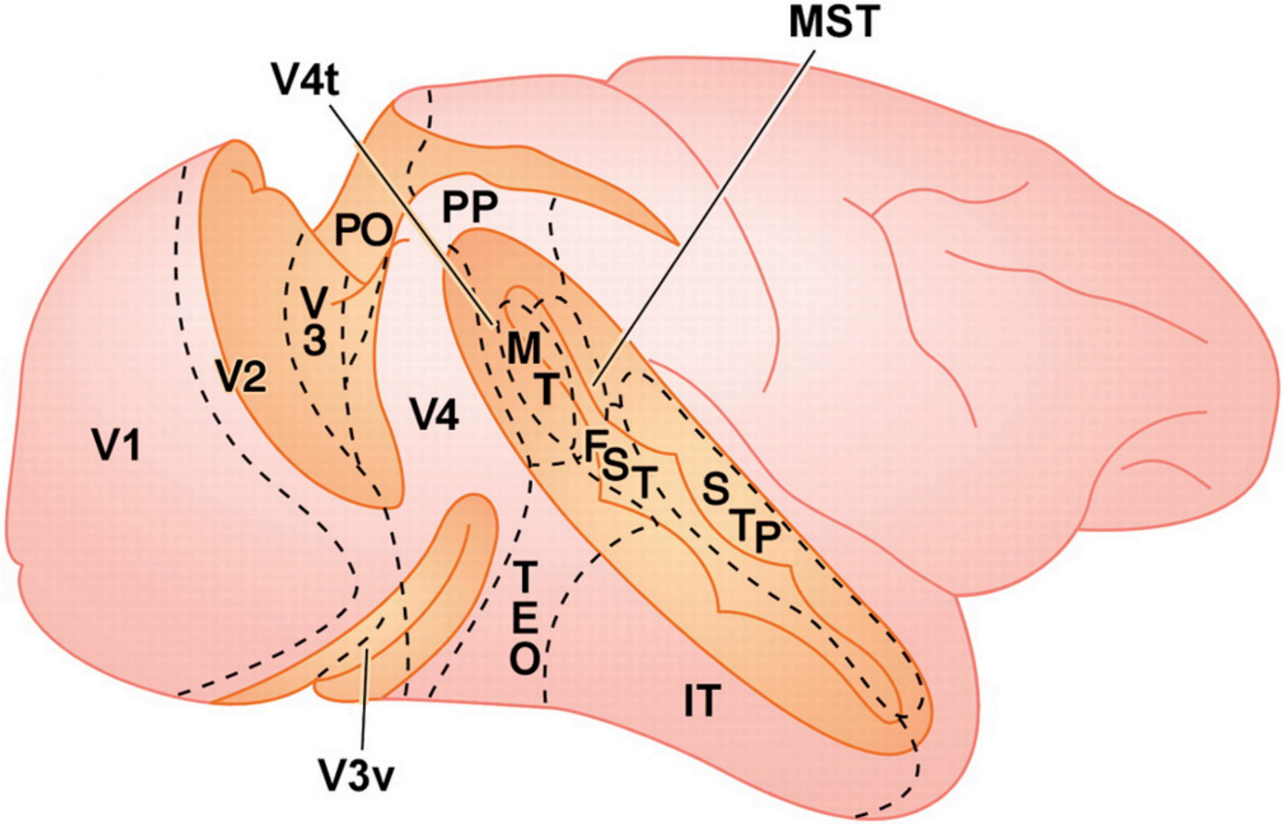




Allman & Kaas, 1981



Zeki, 1978



Dorsal pathway
Space, motion, action

Ventral pathway
Form, recognition, memory

Ungerleider & Mishkin, 1982

Parallel visual pathways in macaque

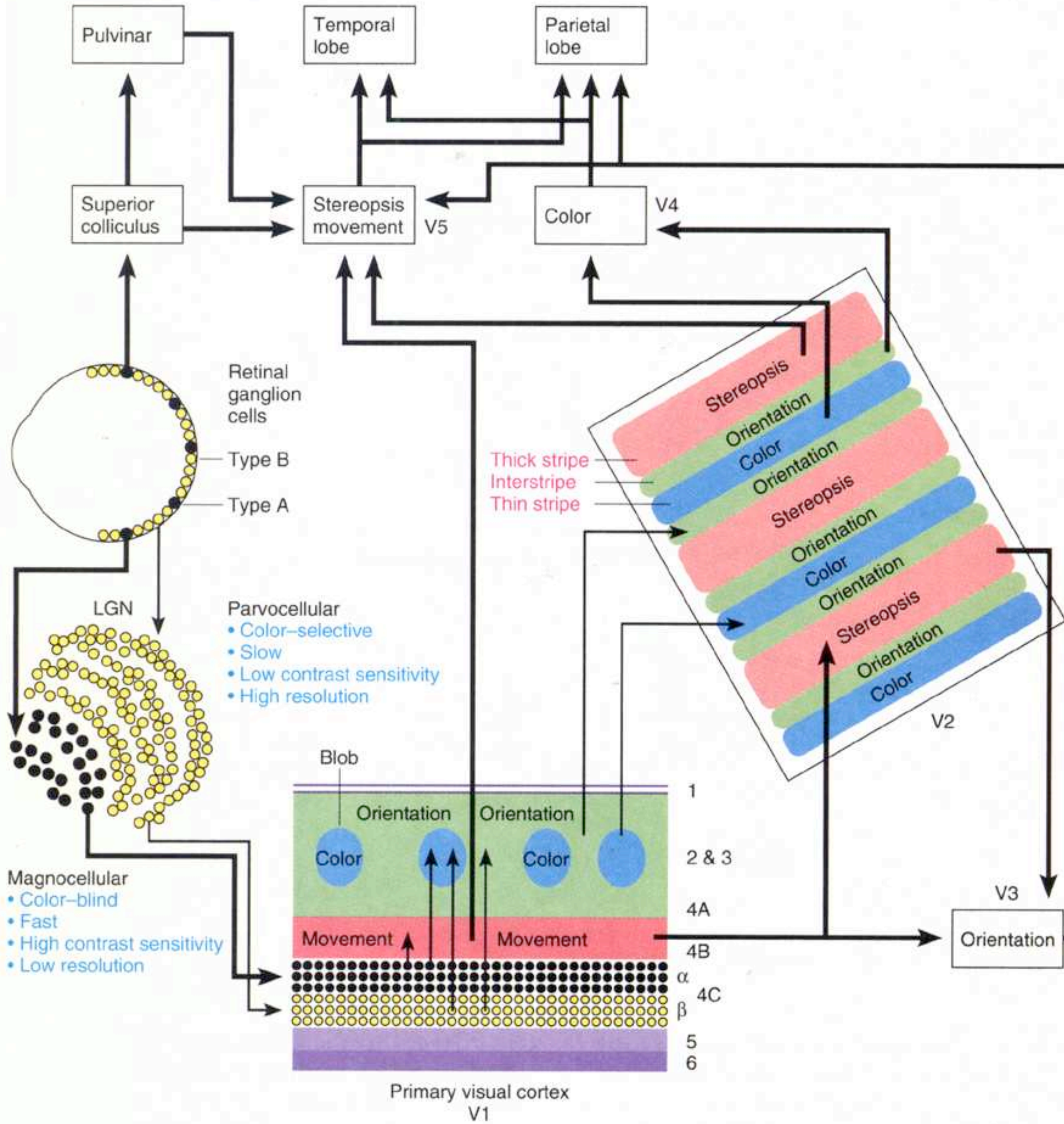
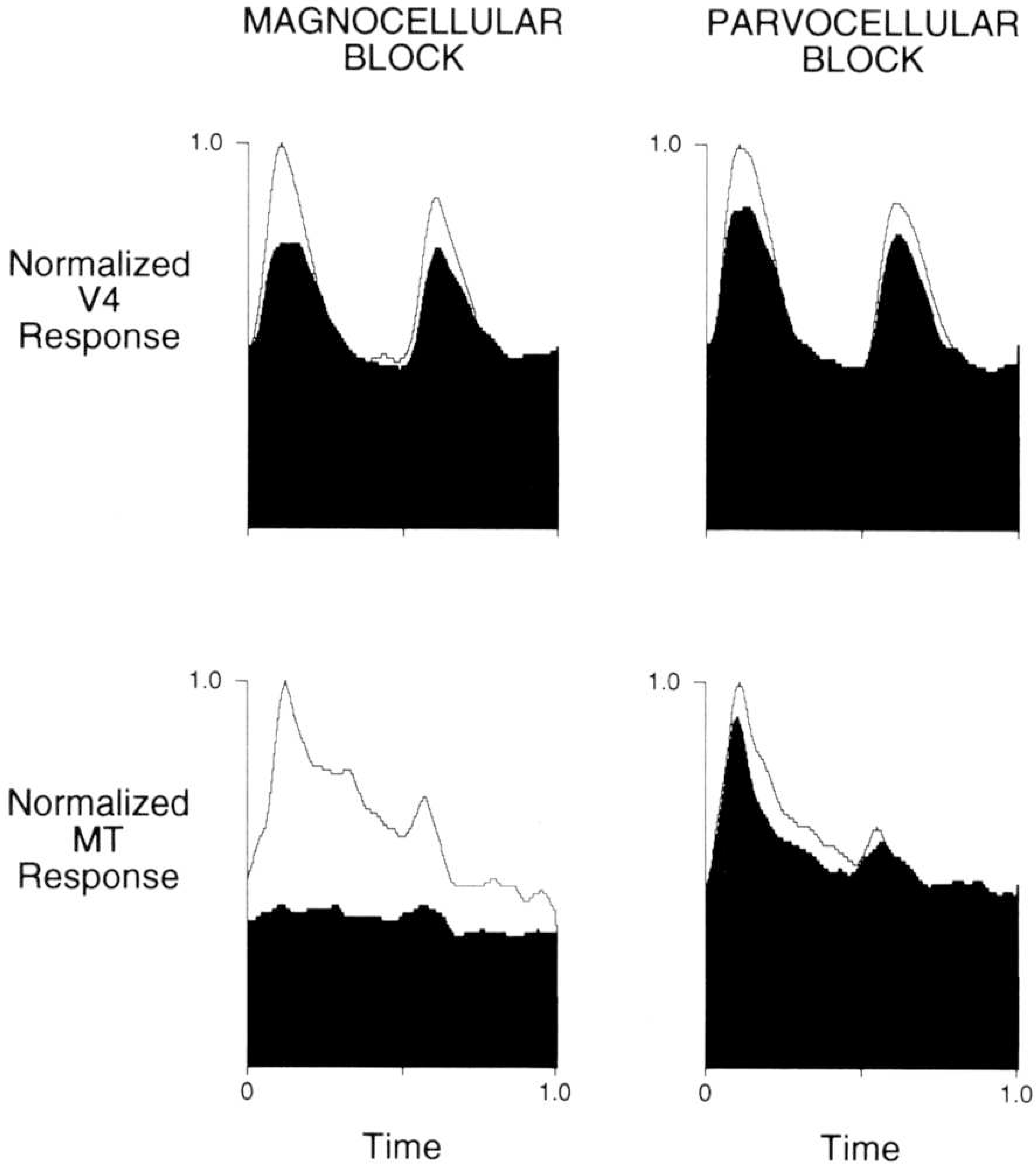


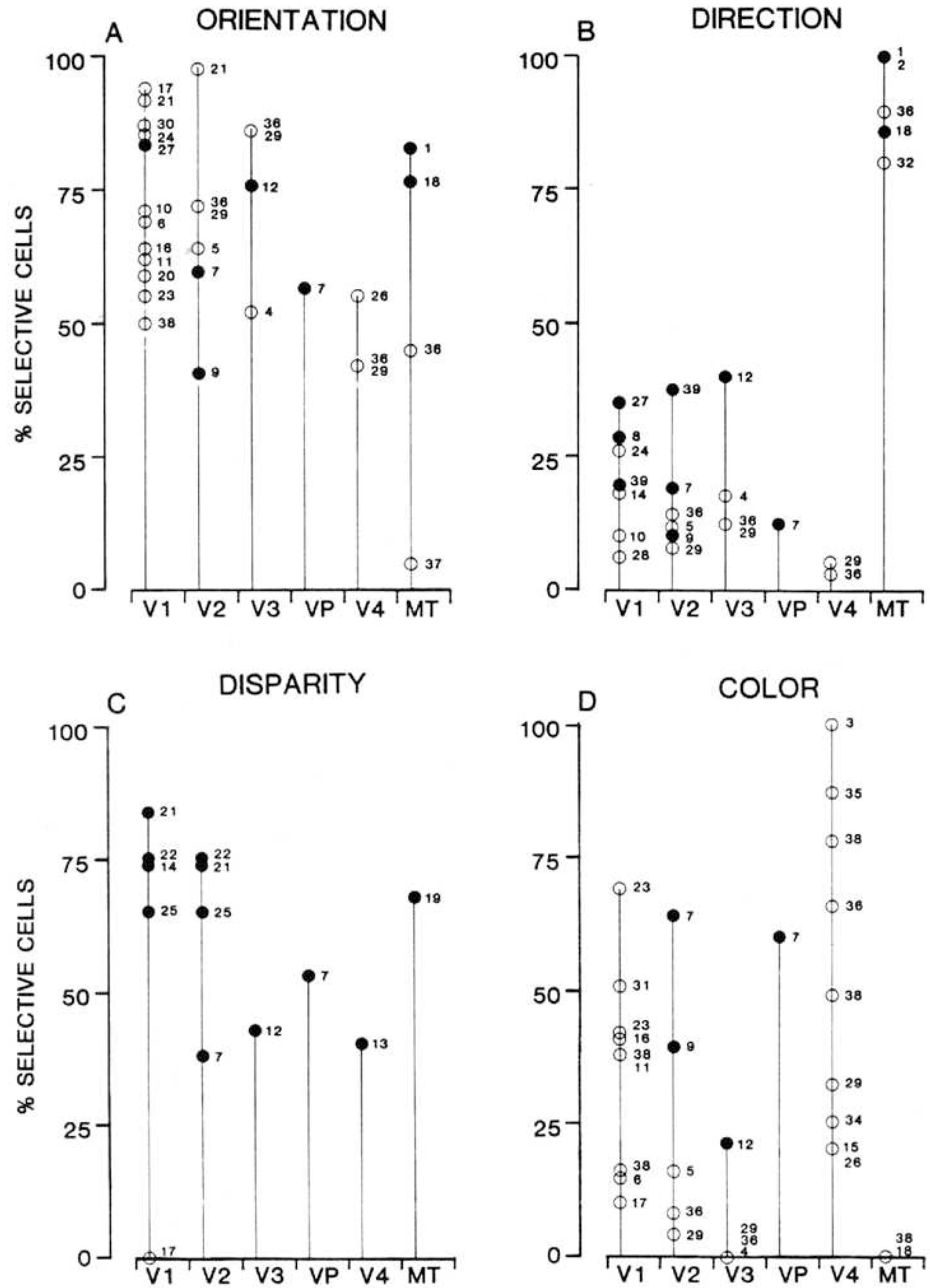
FIGURE 6.36

A summary of the parvocellular and magnocellular visual systems. (Adapted from Livingstone, M., and Hubel, D. *Science*, 1988, *240*, 740–749.)

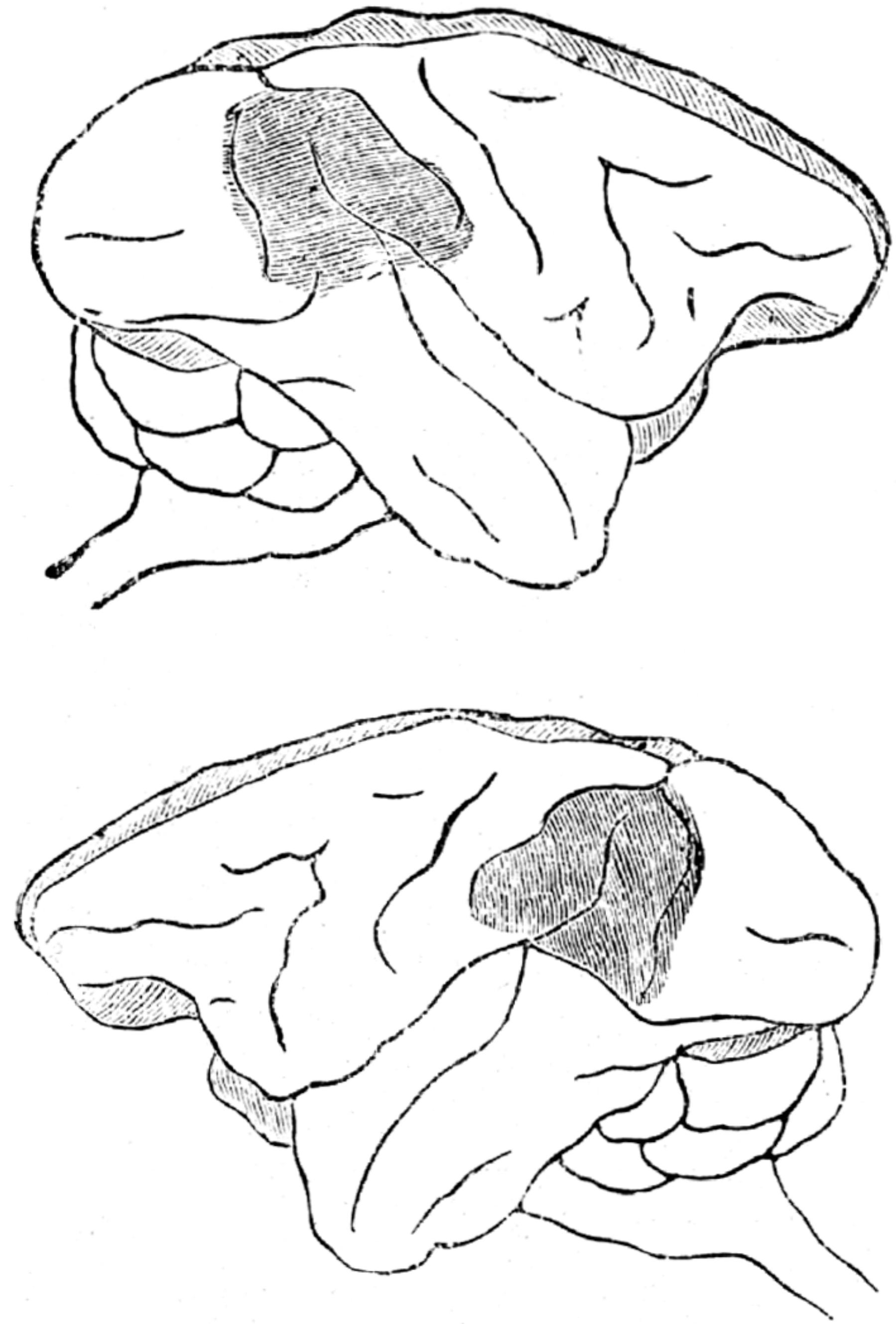
Geniculate inputs to parallel visual pathways studied with laminar blockade
(John Maunsell)



Physiological evidence for parallel cortical pathways? (Felleman and Van Essen, 1987)



Sir David Ferrier
(1843-1928)



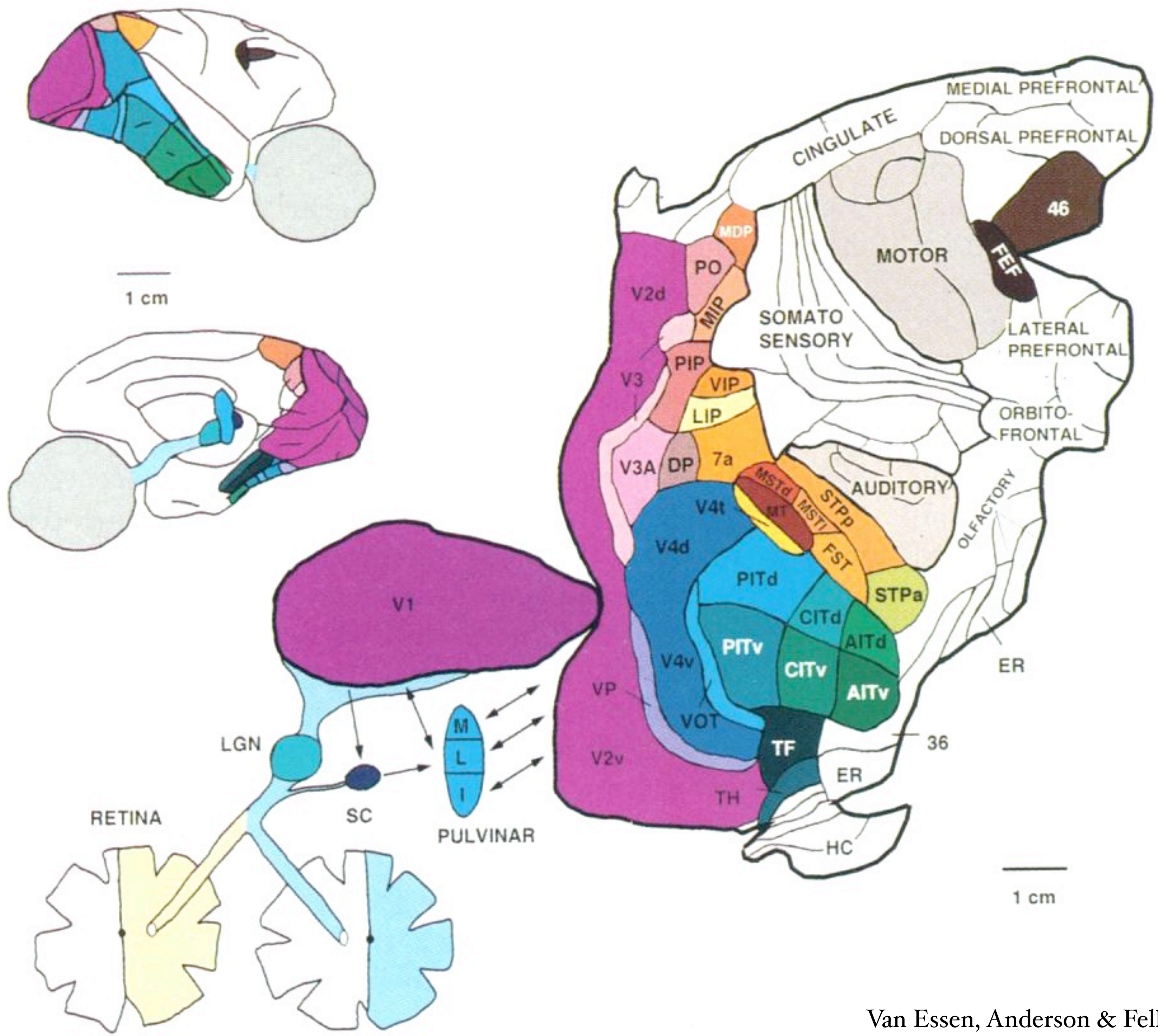
Lesions that caused blindness in monkeys
(The Functions of the Brain, 1876)

Physically flattening the macaque brain

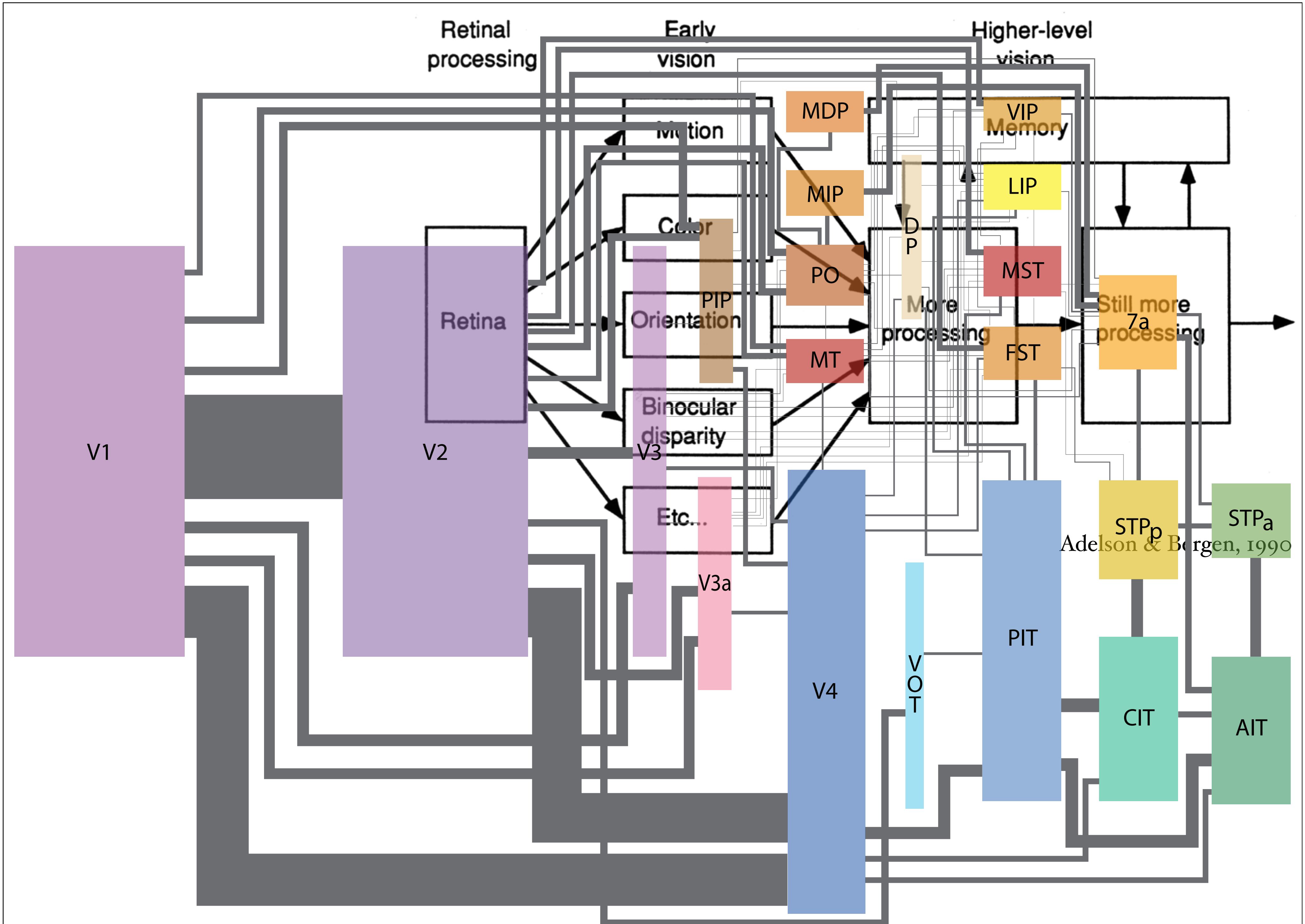
Sincich, Adams & Horton (2003)

Computationally flattening the human brain

David Van Essen



Van Essen, Anderson & Felleman, 1992

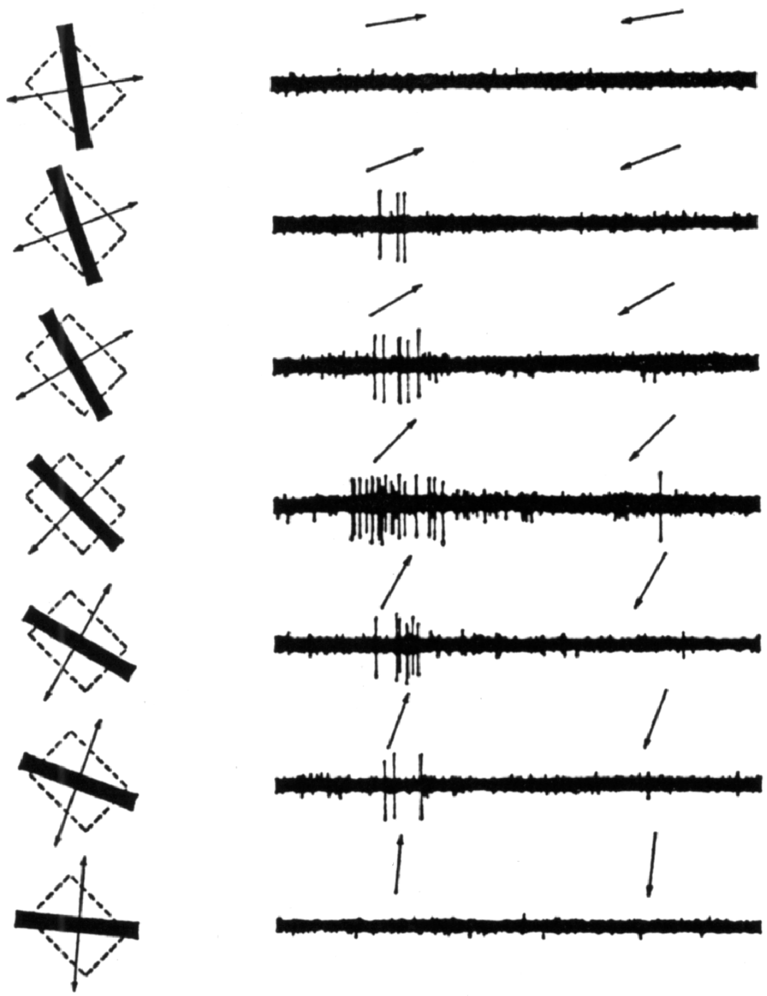


Wallisch & Movshon, 2008

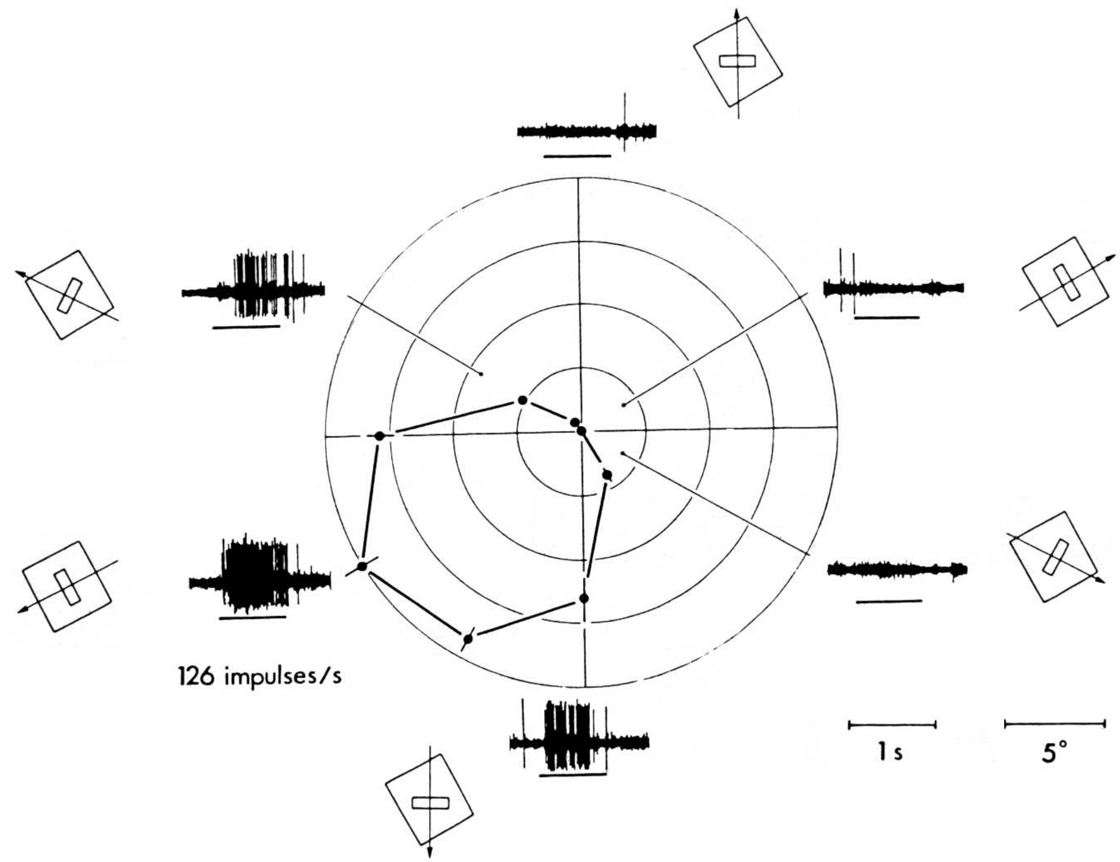
after Felleman & Van Essen, 1991


What MT does

V1

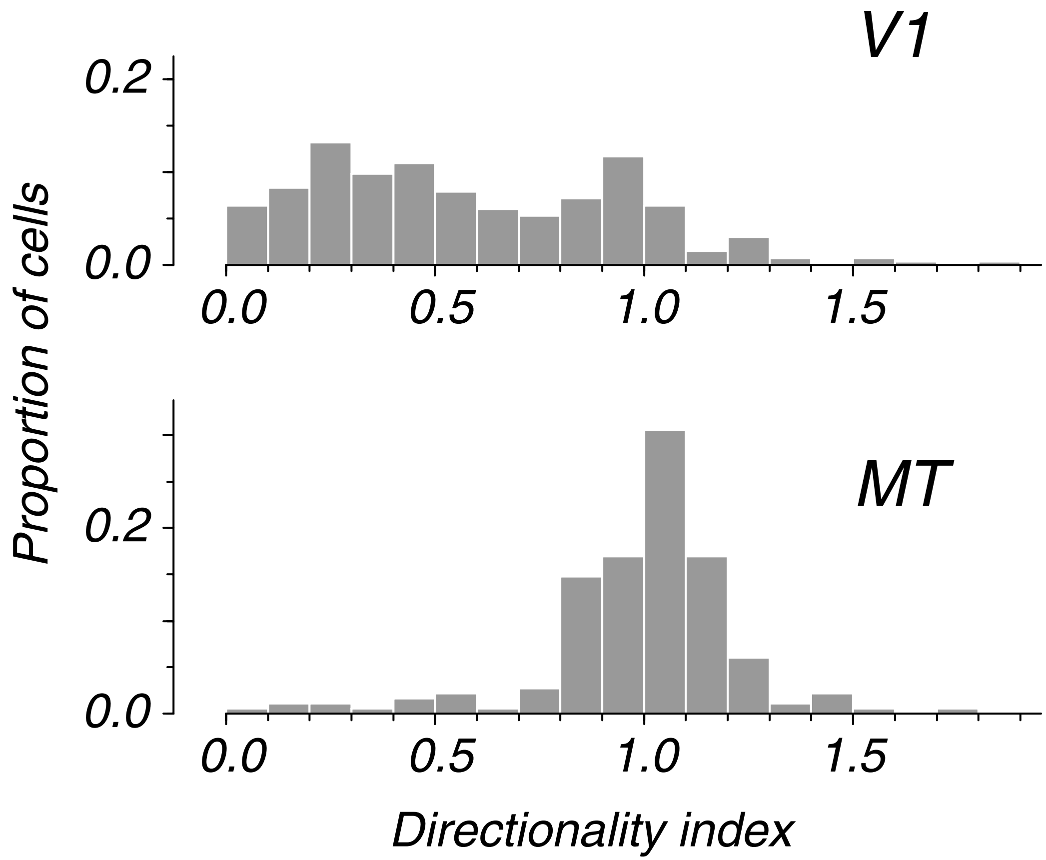


MT

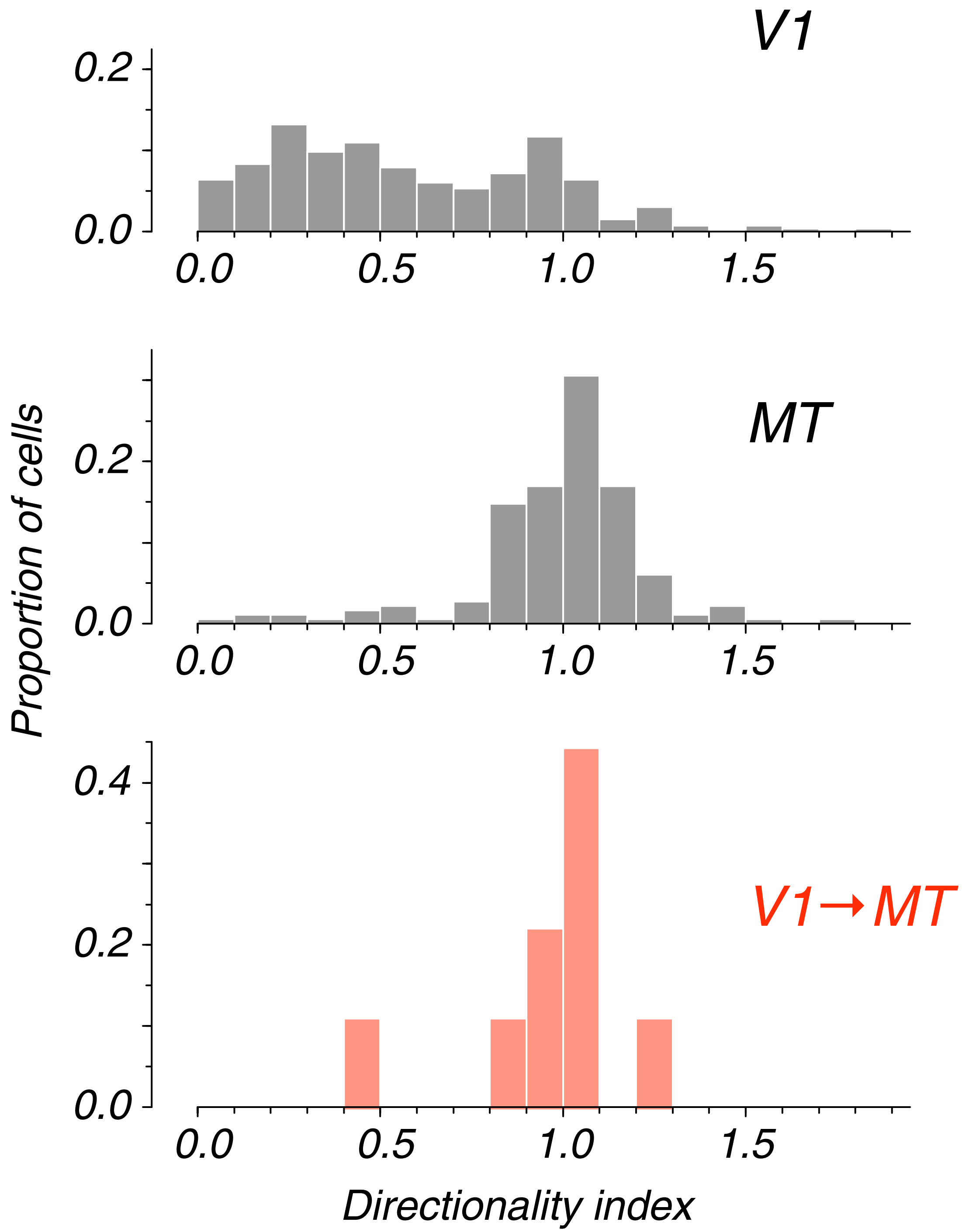


Hubel & Wiesel, 1968

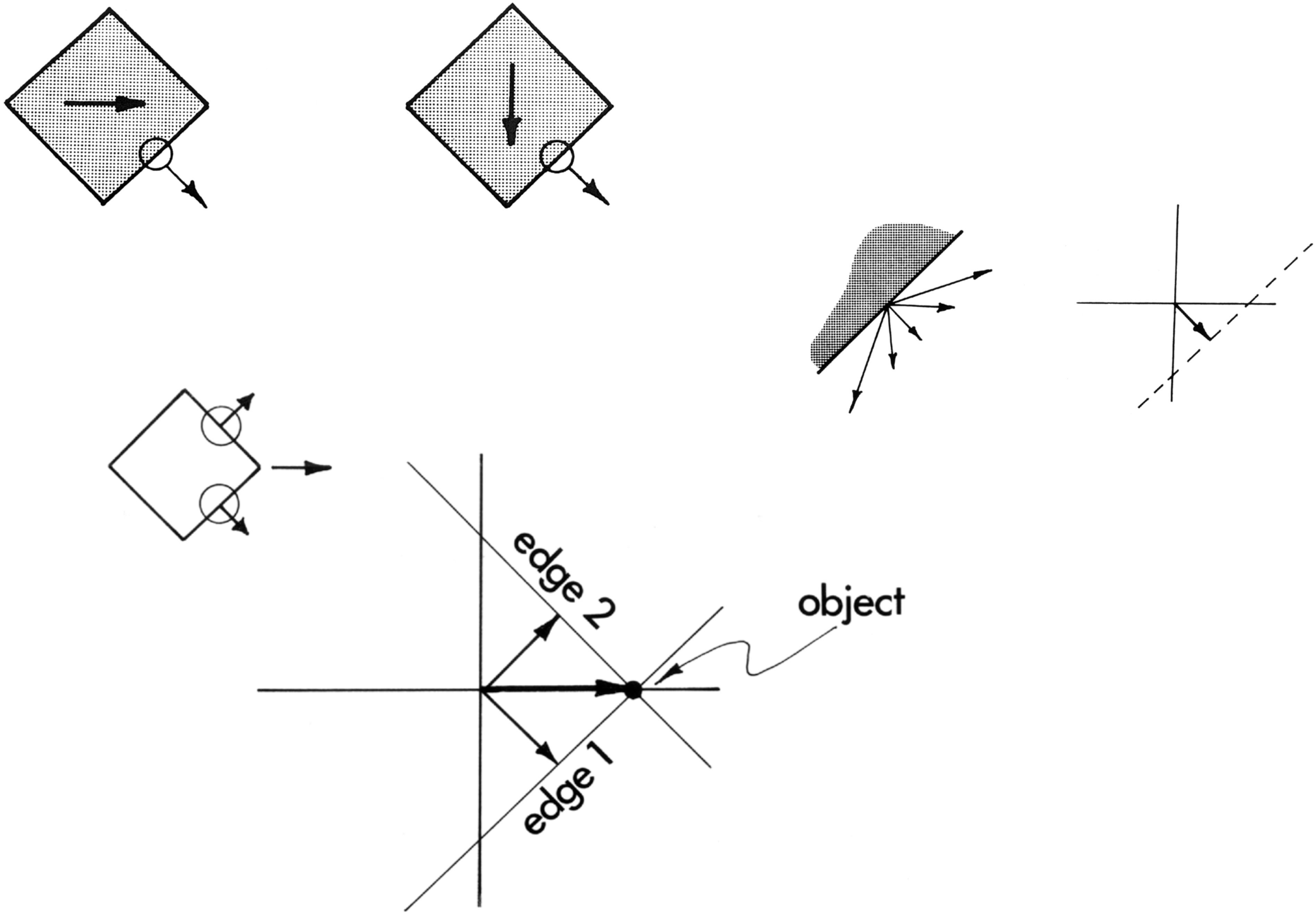
Maunsell & Van Essen, 1983



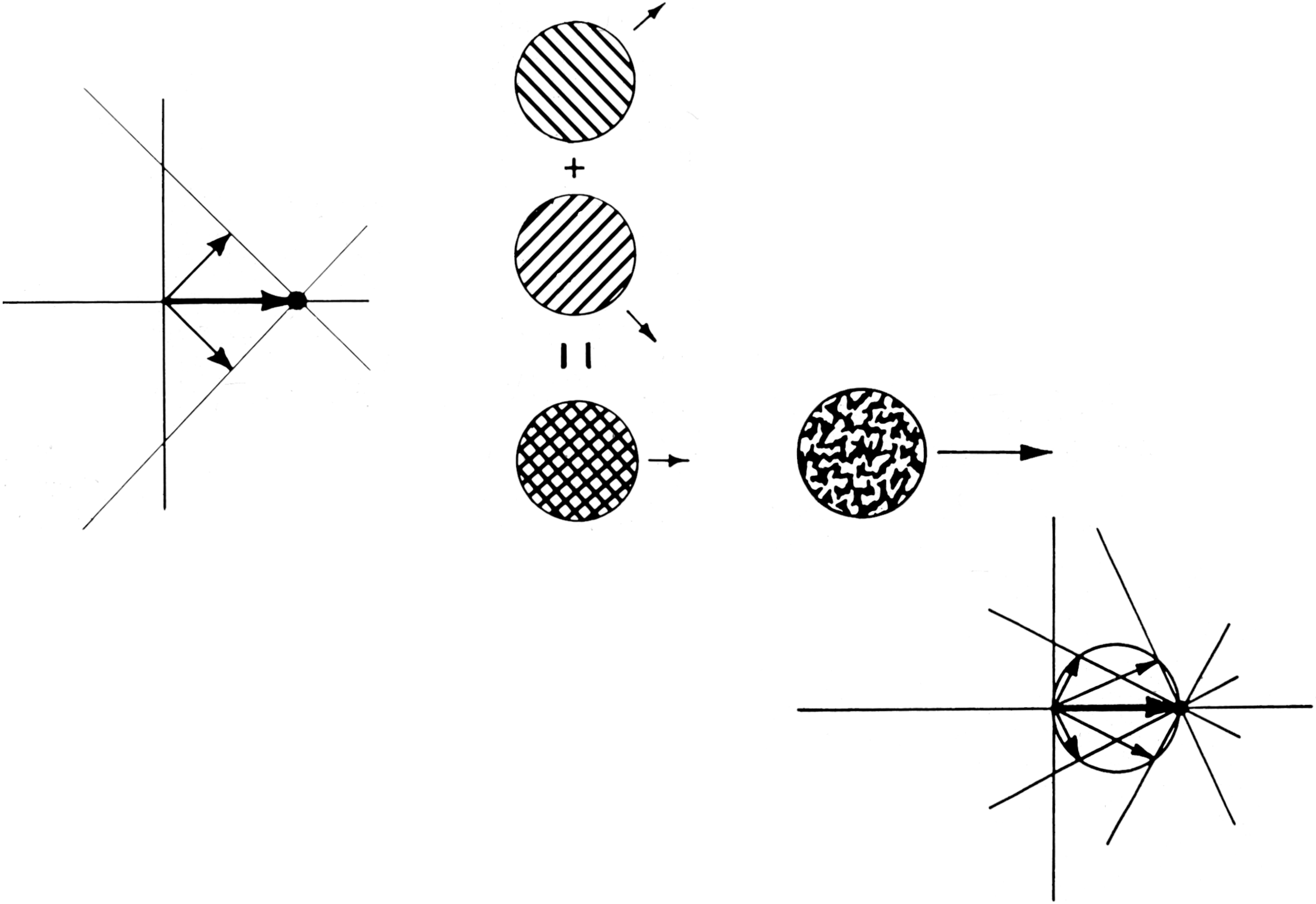
Movshon & Newsome, 1996



Movshon & Newsome, 1996

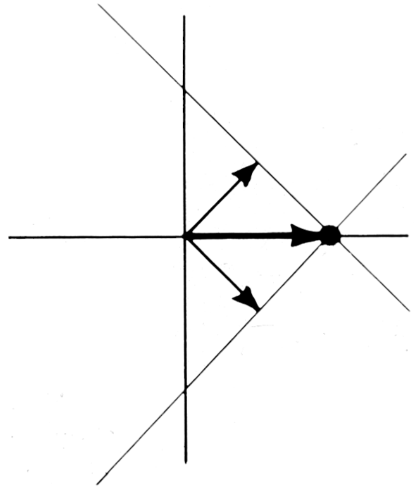


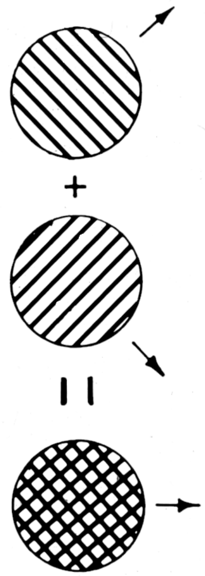
Movshon, Adelson, Gizzi & Newsome, 1985



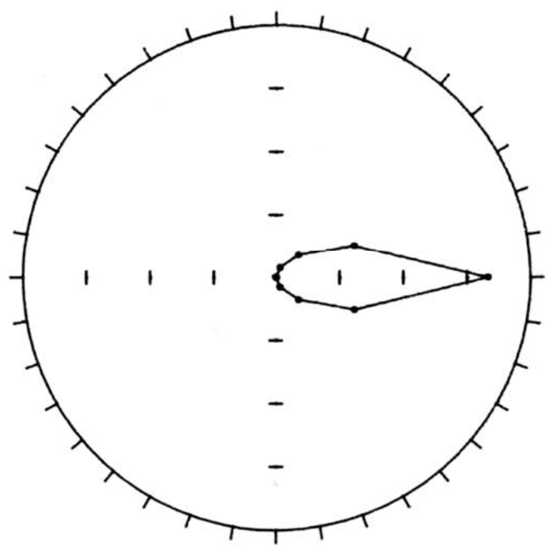
Movshon, Adelson, Gizzi & Newsome, 1985

Gratings, plaids, and coherent motion

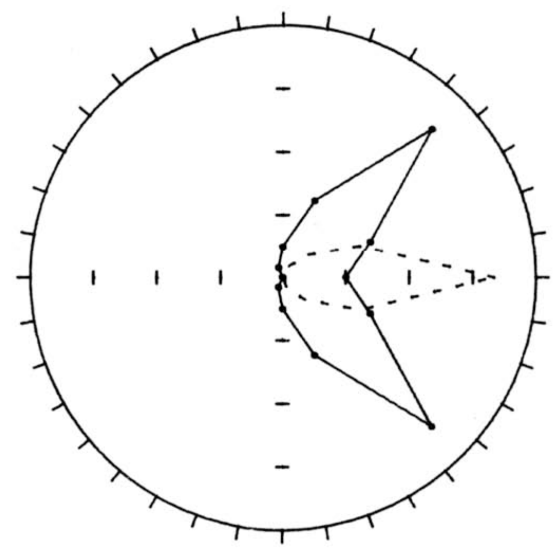




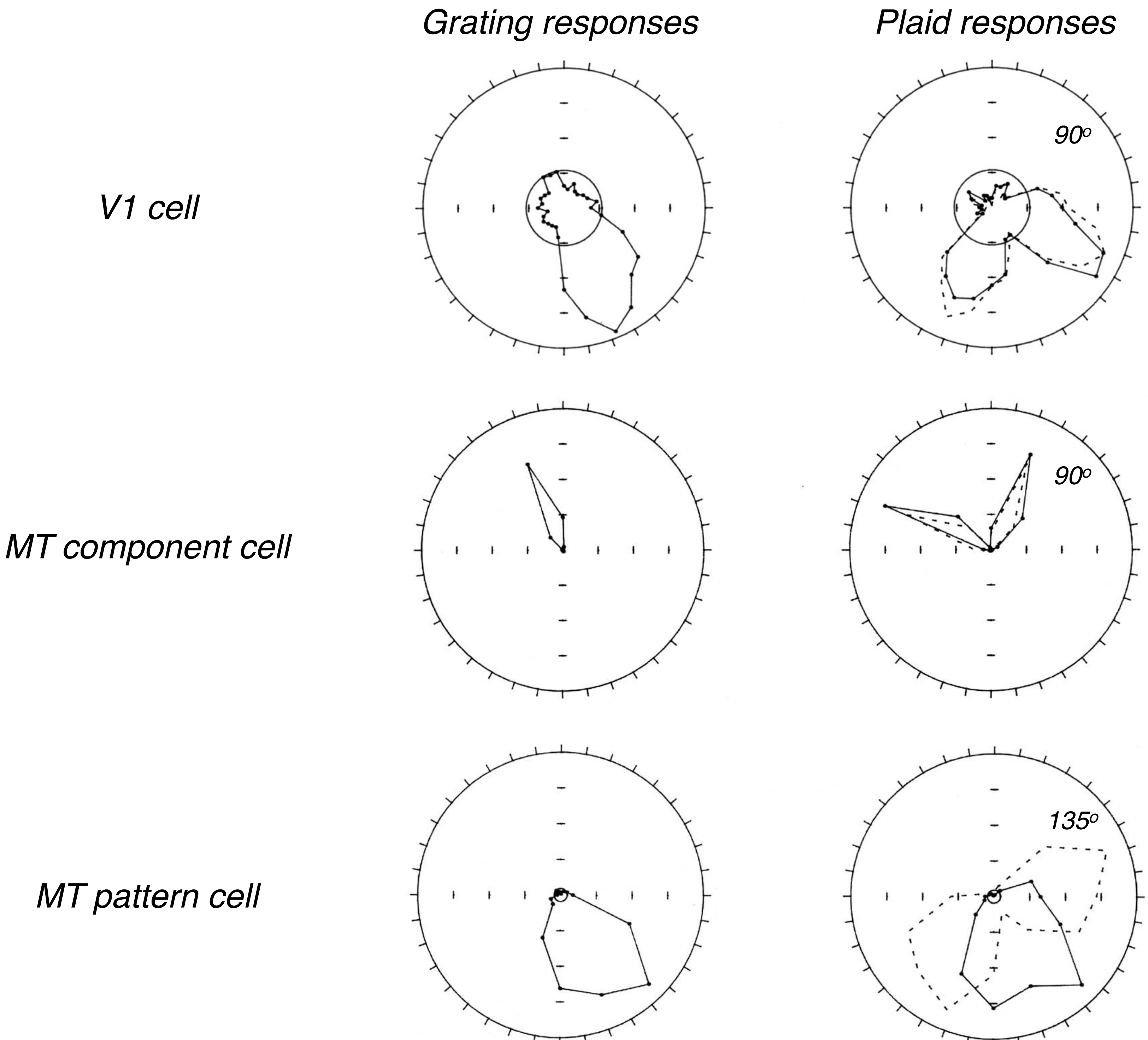
Grating response



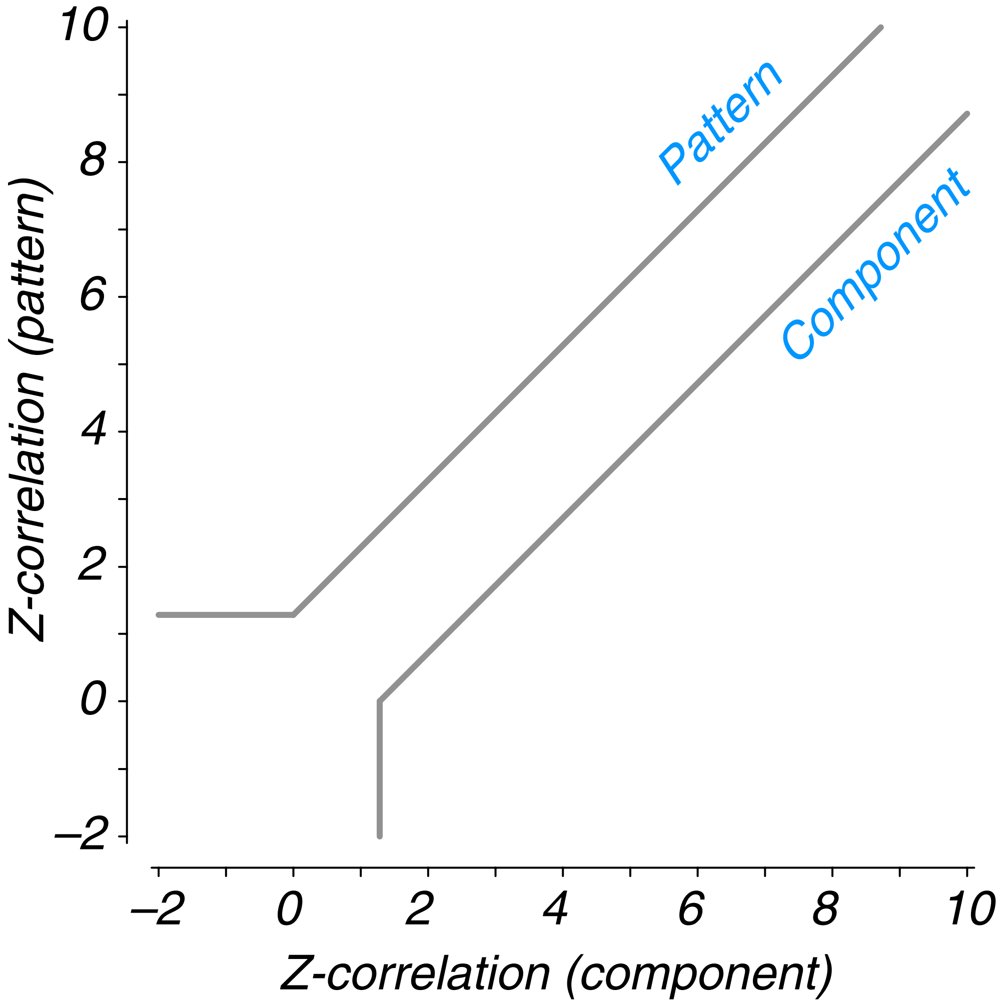
Predicted plaid response



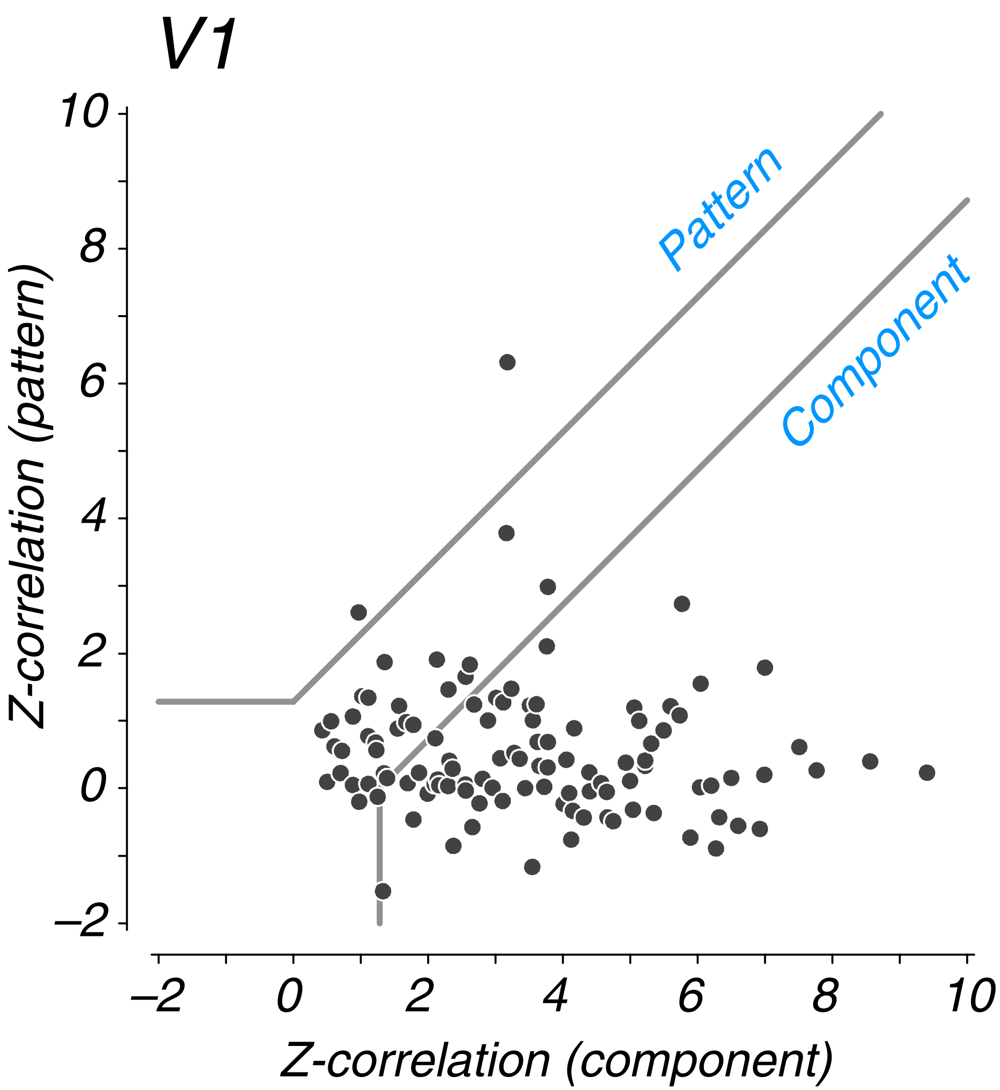
Movshon, Adelson, Gizzi & Newsome, 1985



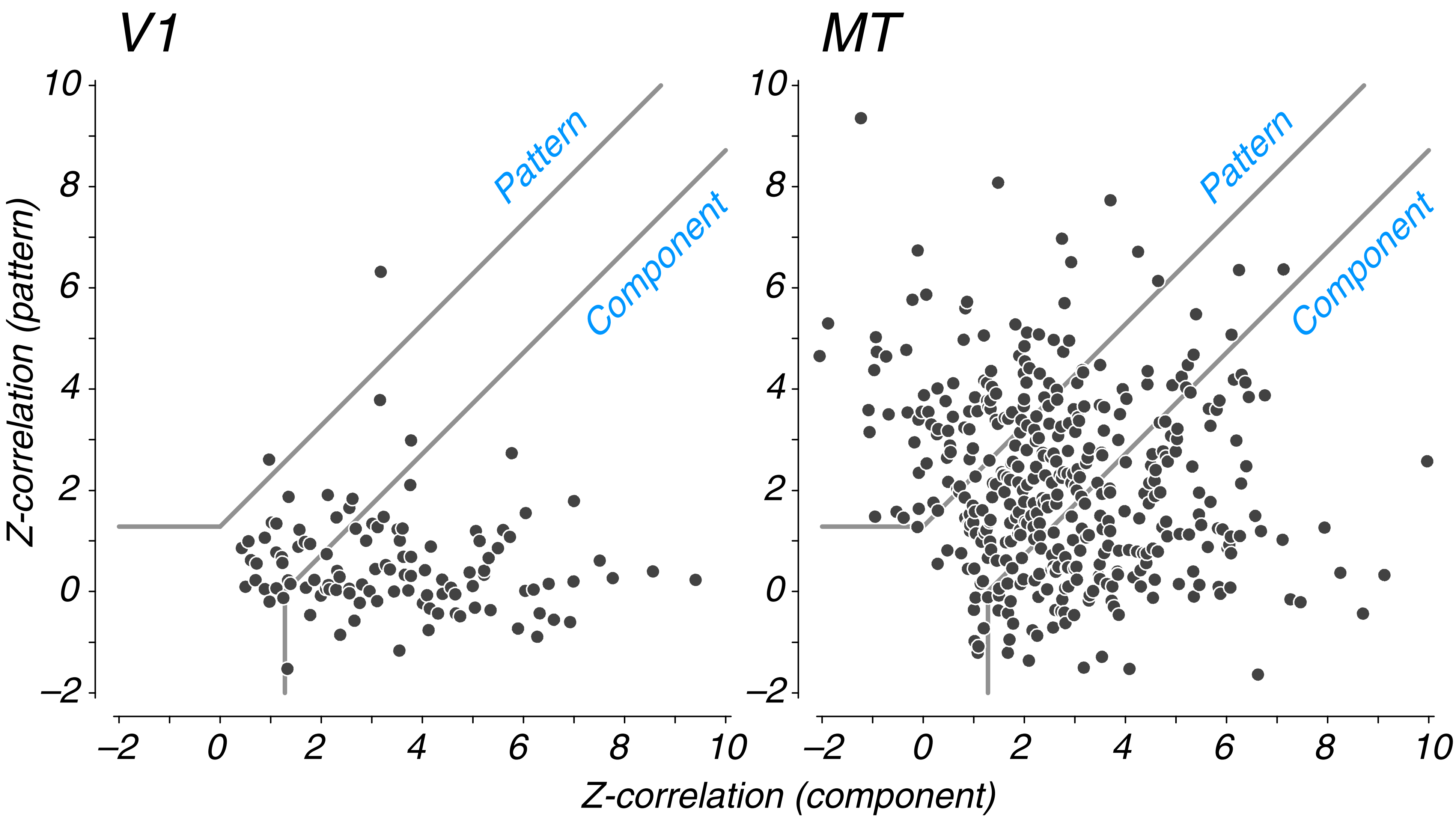
Movshon, Adelson, Gizzi & Newsome, 1985



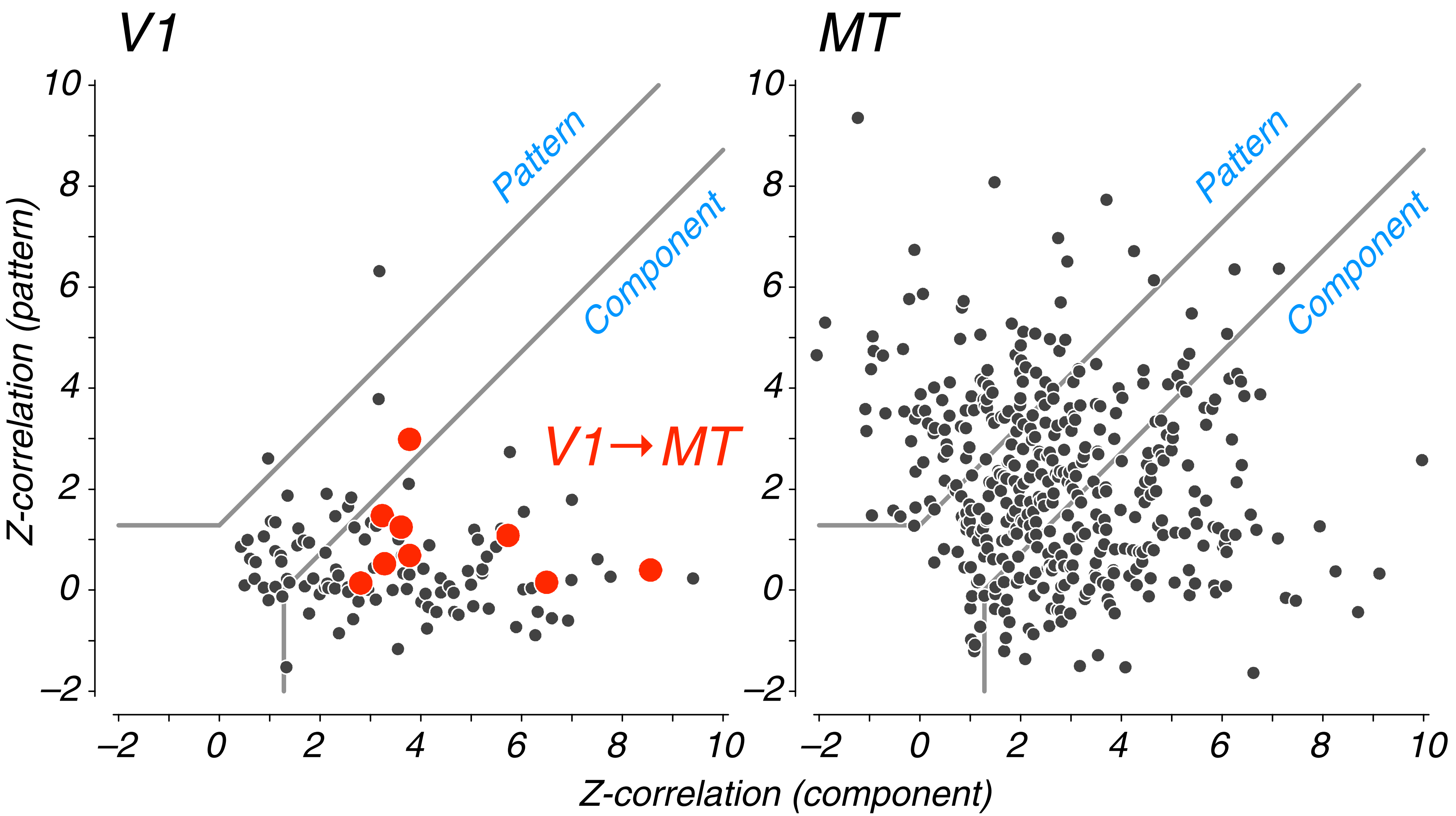
Pattern
Component
10
8
6
4
2
0
−2
−2
0
2
4
6
8
10
Z-correlation (pattern)
Z-correlation (component)



V1
Pattern
Component
Z-correlation (pattern)
Z-correlation (component)
10
8
6
4
2
0
–2
–2
0
2
4
6
8
10



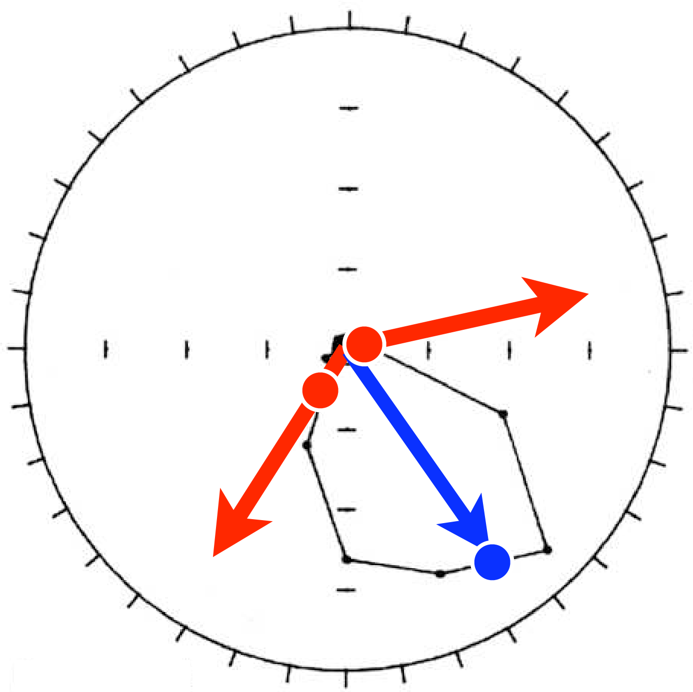
V1
MT
Pattern
Component
Pattern
Component
Z-correlation (pattern)
Z-correlation (component)
10
8
6
4
2
0
−2
−2
0
2
4
6
8
10



Movshon & Newsome, 1996

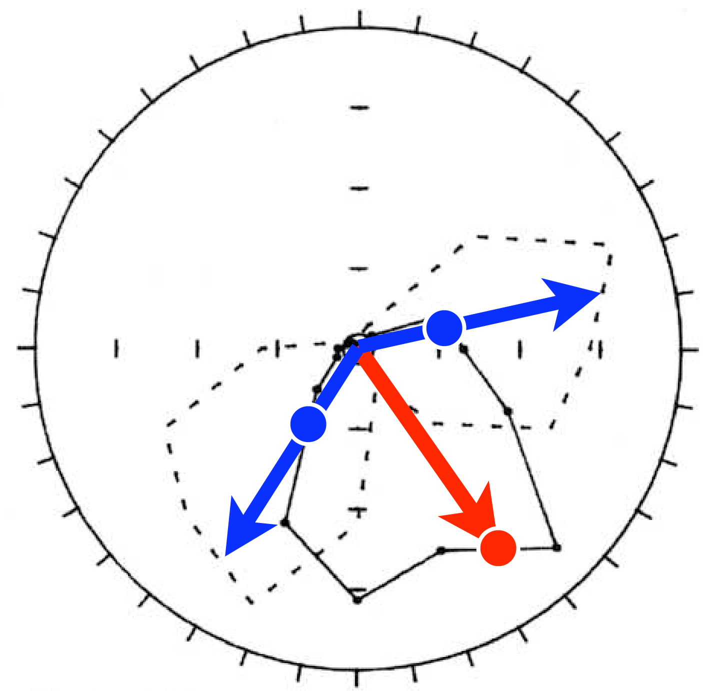
MT pattern cell

Grating responses



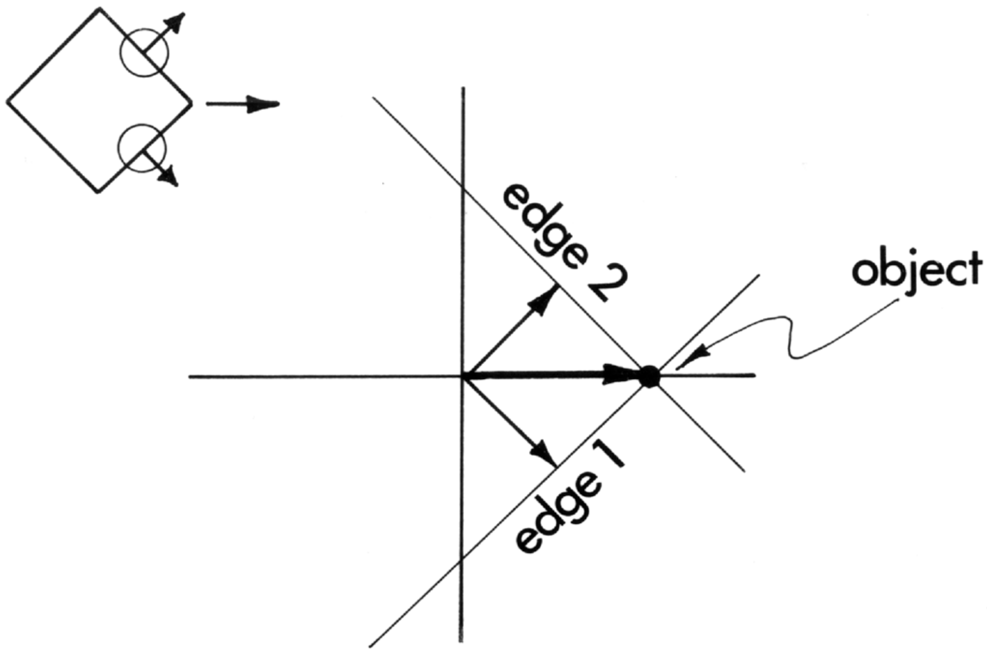
Components of the optimal plaid

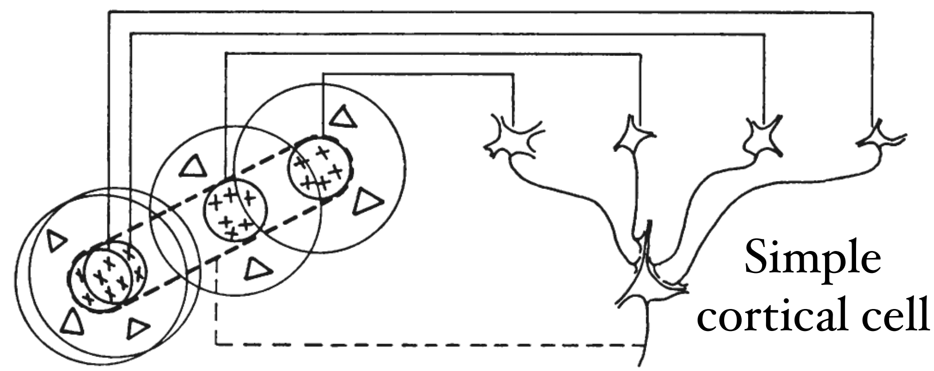
Plaid responses



Plaids containing the optimal grating

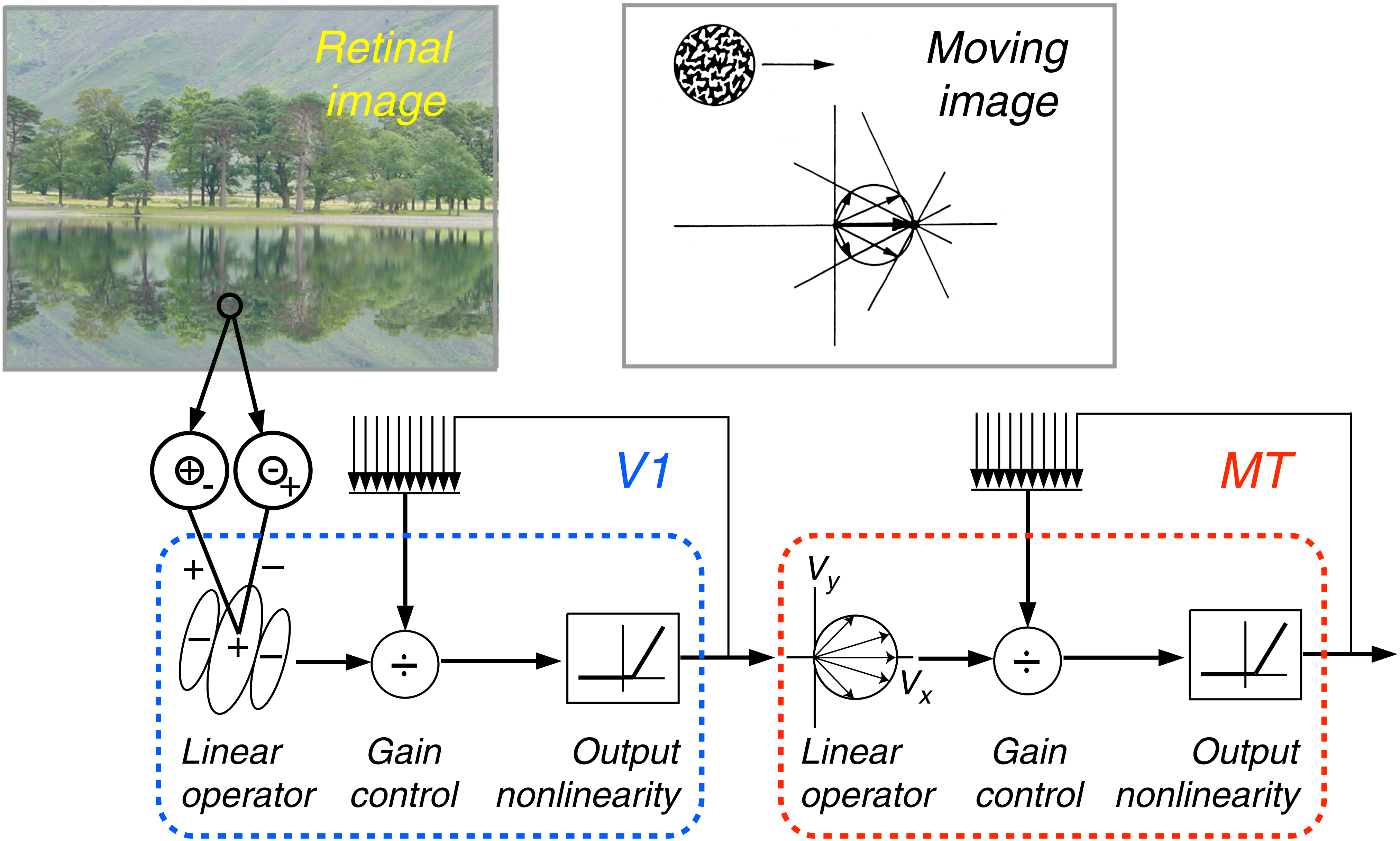
Movshon, Adelson, Gizzi & Newsome, 1985



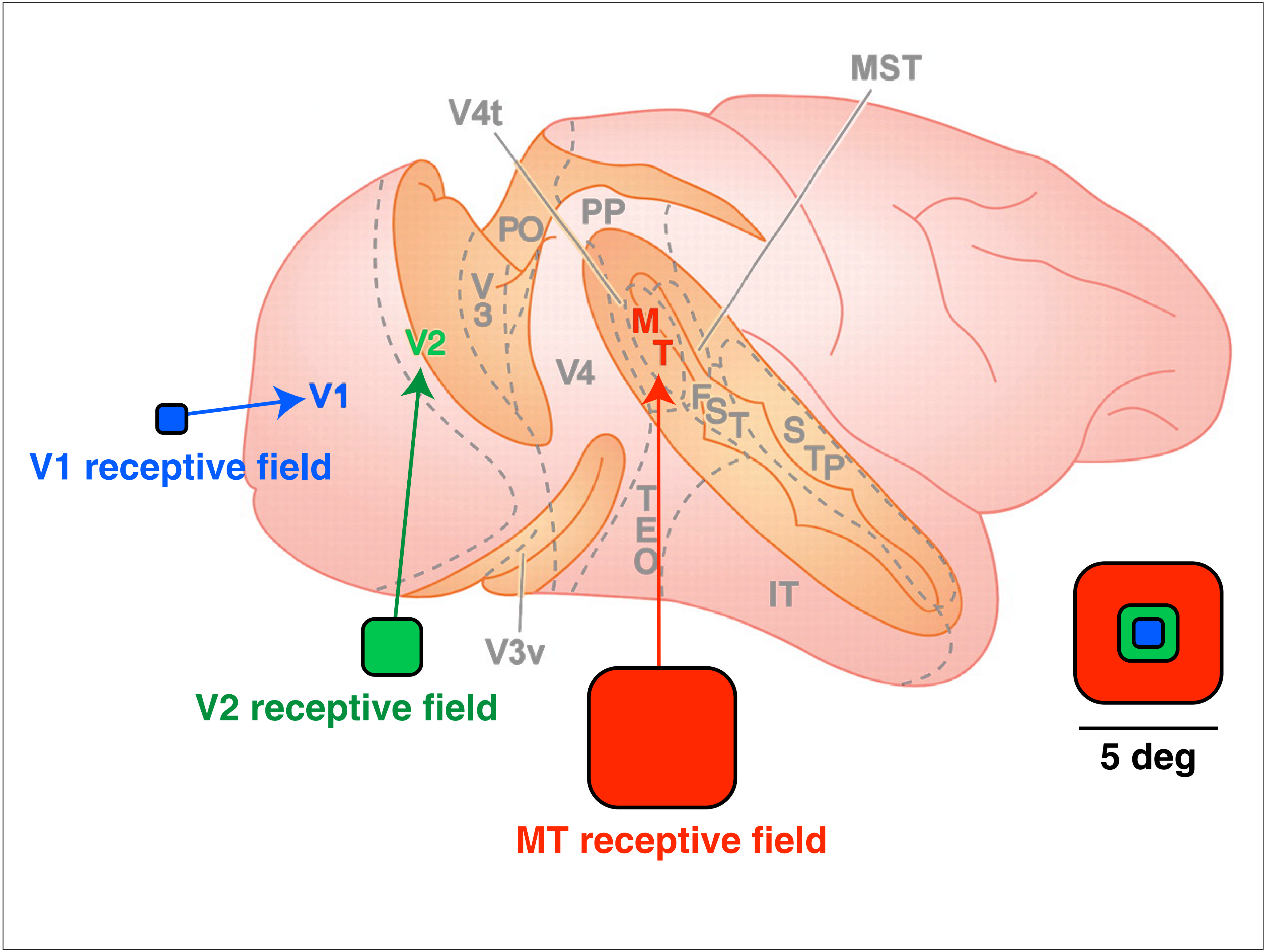


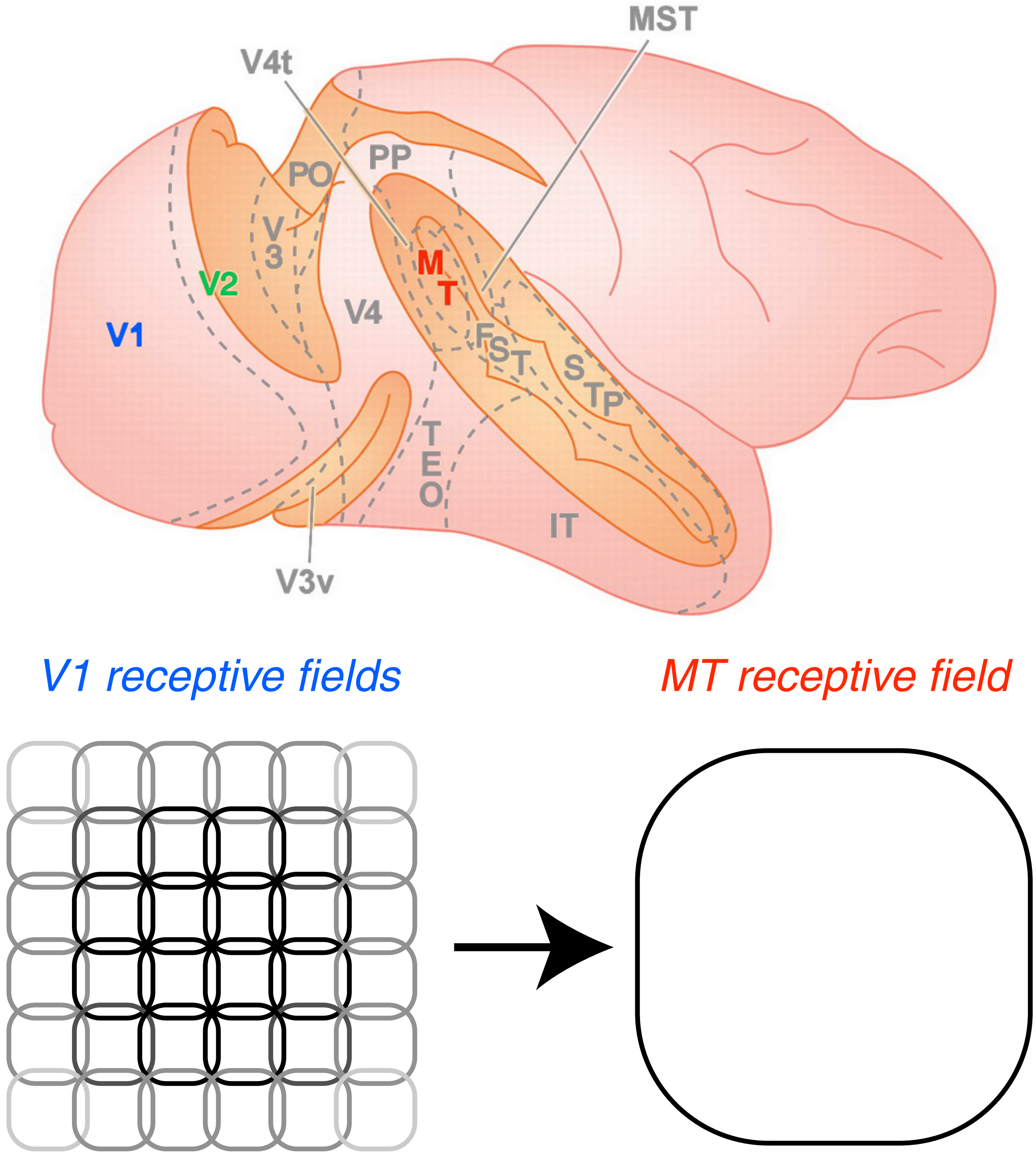
Movshon, Adelson, Gizzi & Newsome, 1985

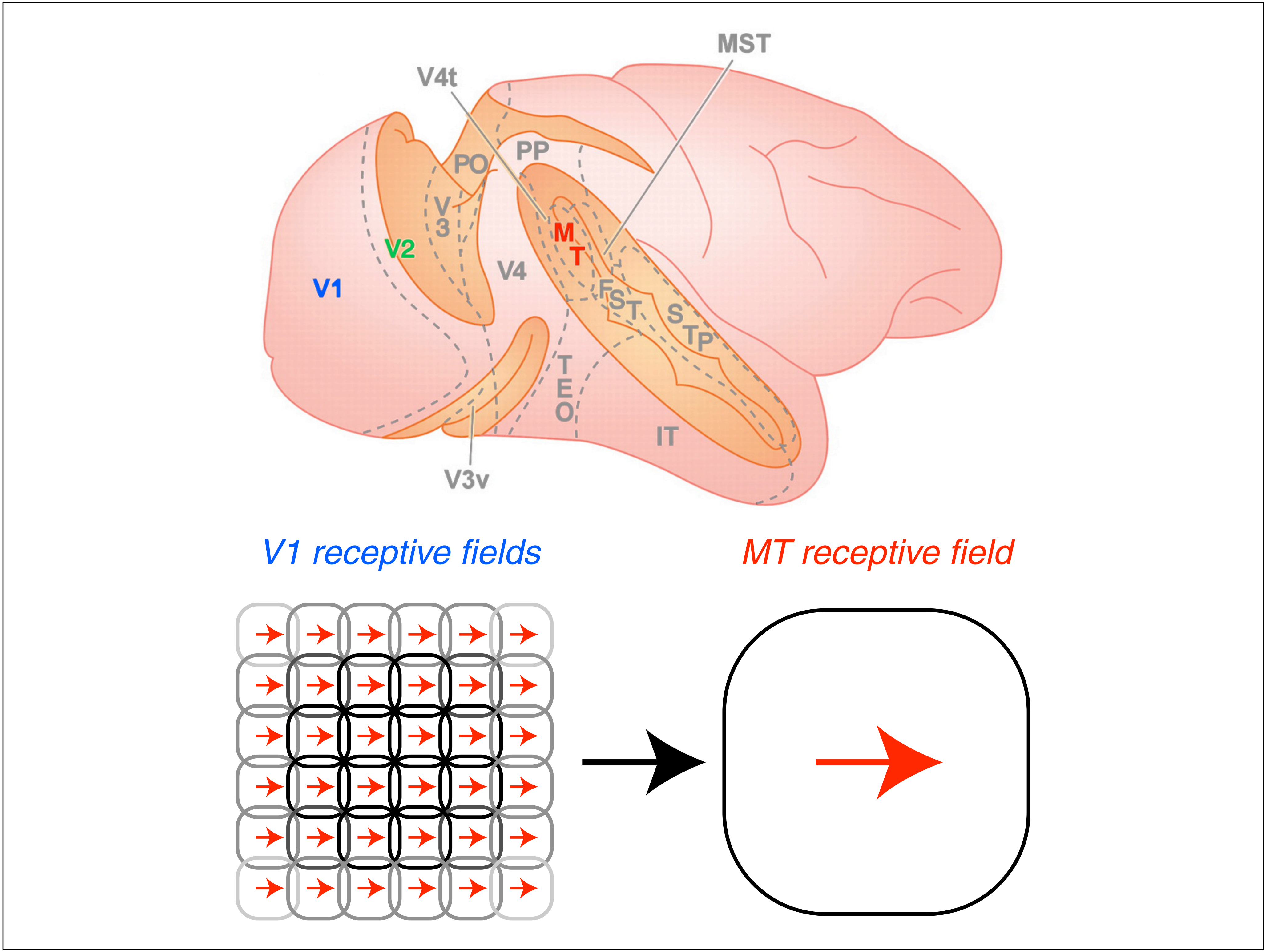
Hubel & Wiesel, 1962



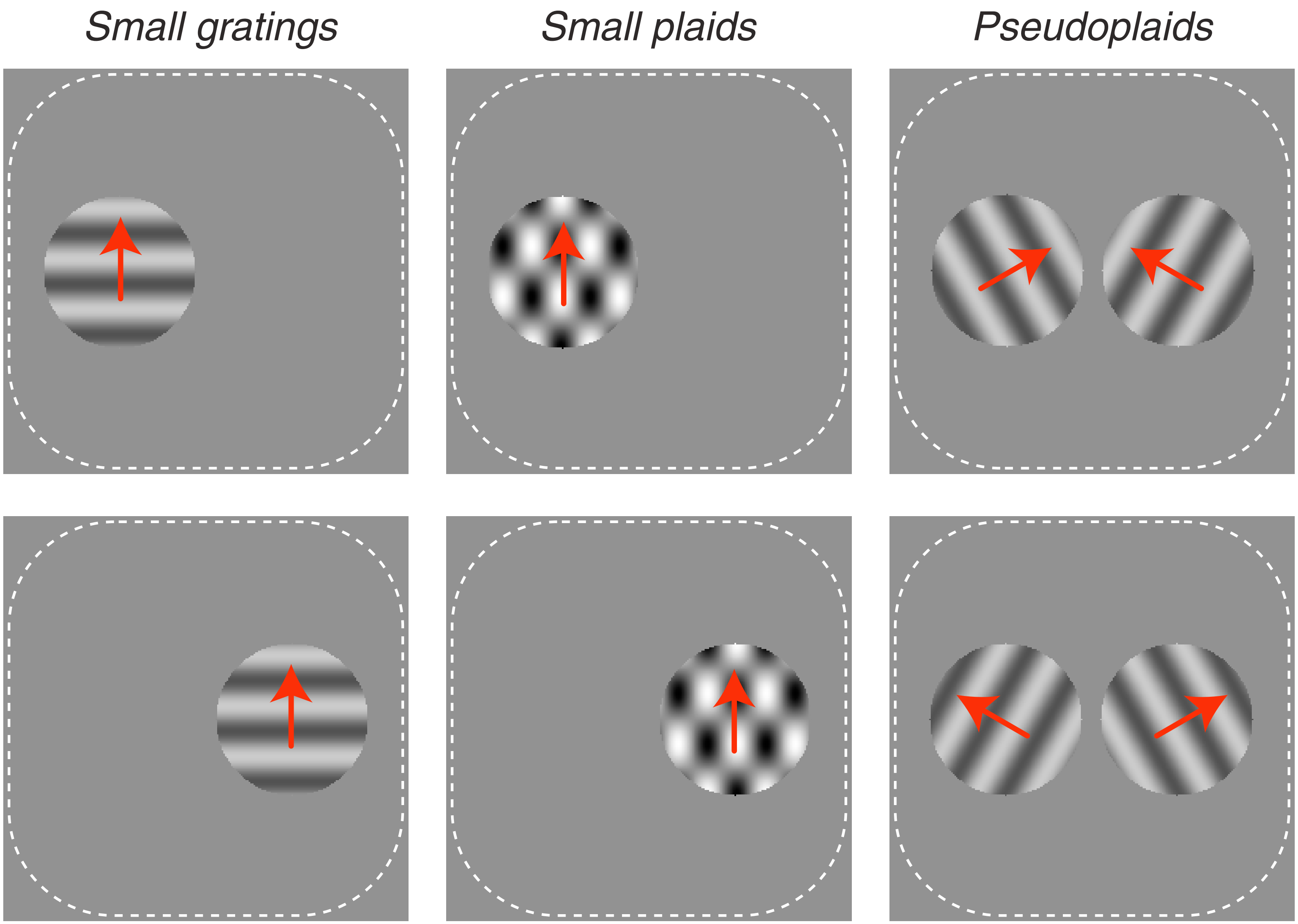
Simoncelli & Heeger, 1998


MST
V4t
PP
PO
V3
V2
V4
MT
FST
STP
V1
V1 receptive field
TEO
IT
V3v
V2 receptive field
MT receptive field
5 deg

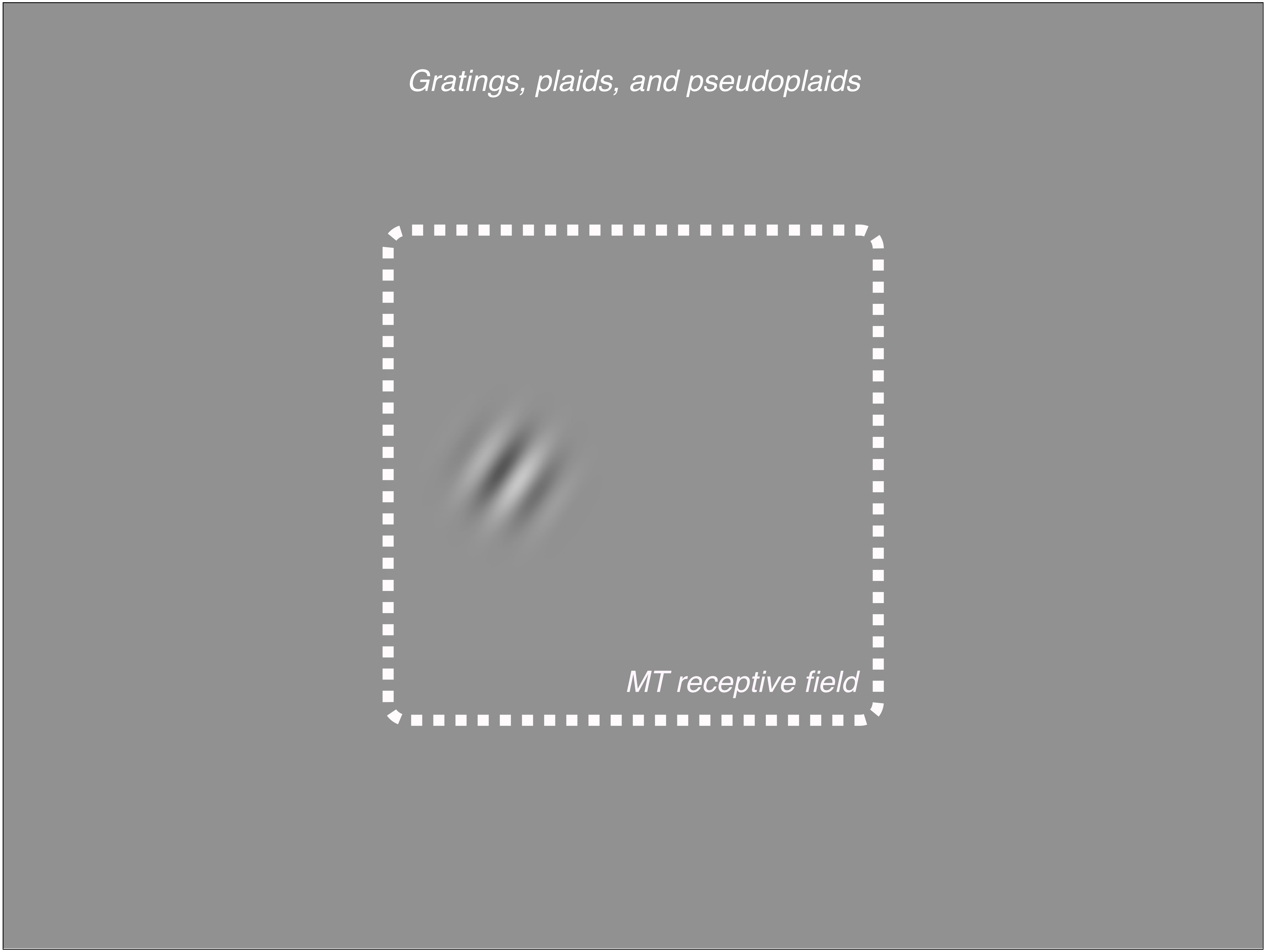

MST
V4t
PP
PO
V3
V2
V1
V4
MT
FST
STP
TEO
IT
V3v
V1 receptive fields
MT receptive field


MST
V4t
PP
PO
V3
V2
V1
MT
V4
FST
STP
TEO
IT
V3v
V1 receptive fields
MT receptive field

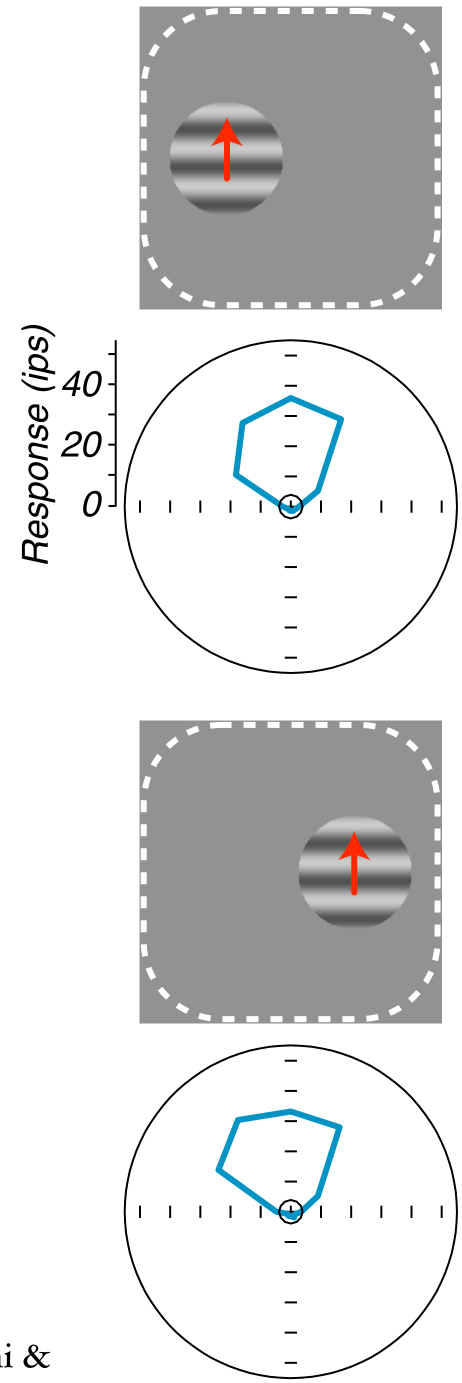
Is pattern motion computed globally?



Majaj, Carandini & Movshon, 2007

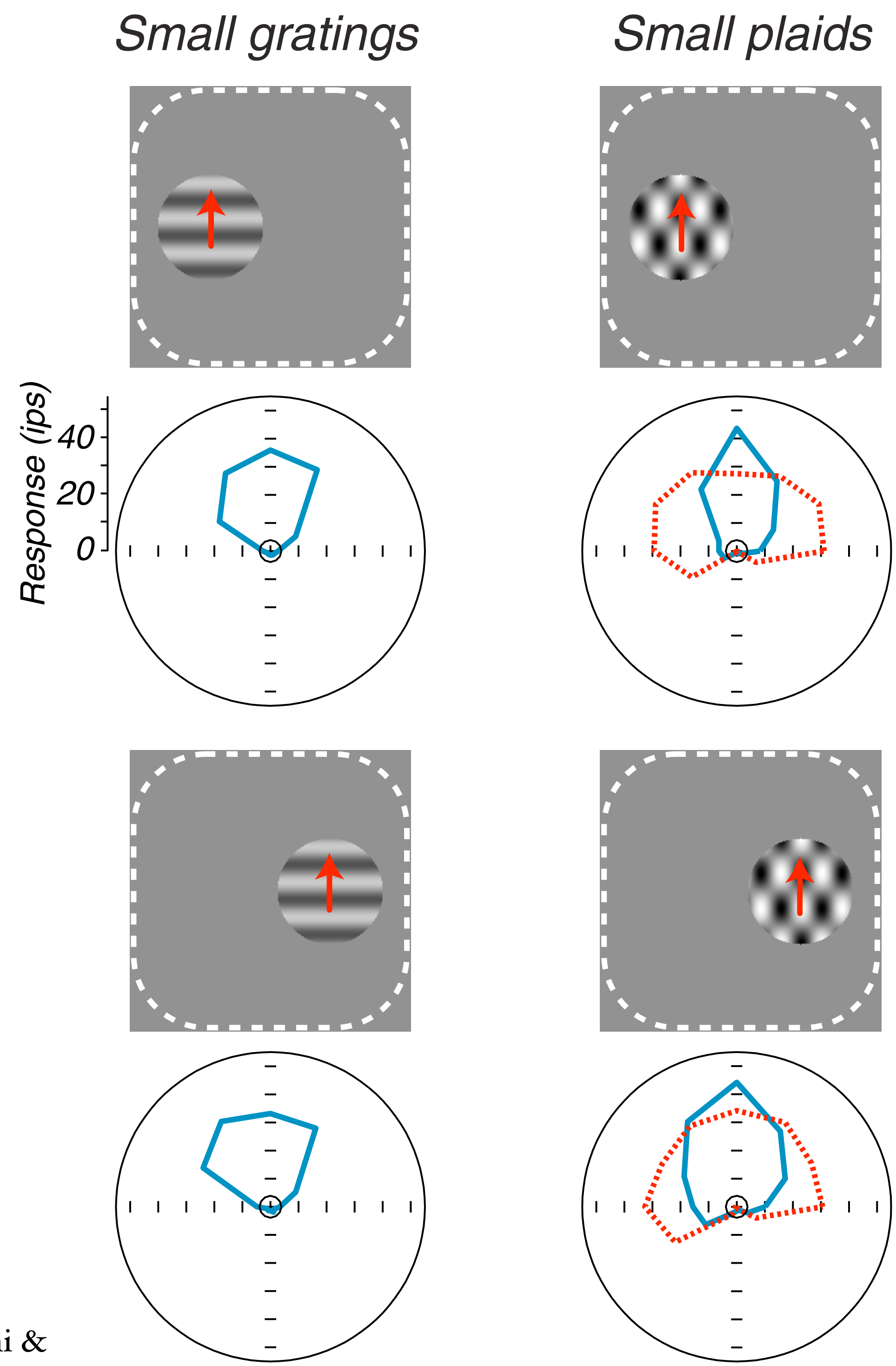

Gratings, plaids, and pseudoplaids
MT receptive field

Small gratings

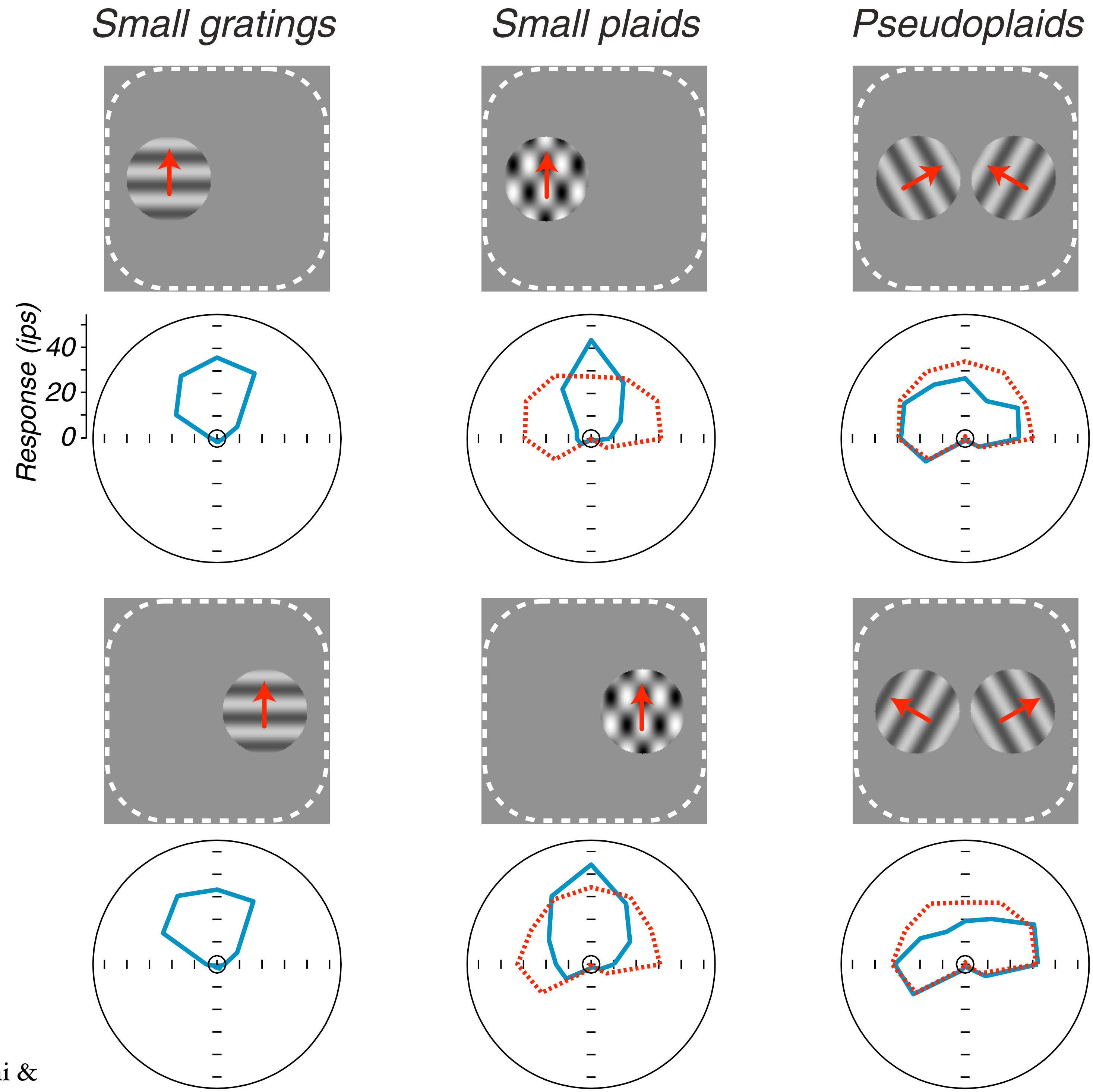


Majaj, Carandini &
Movshon, 2007

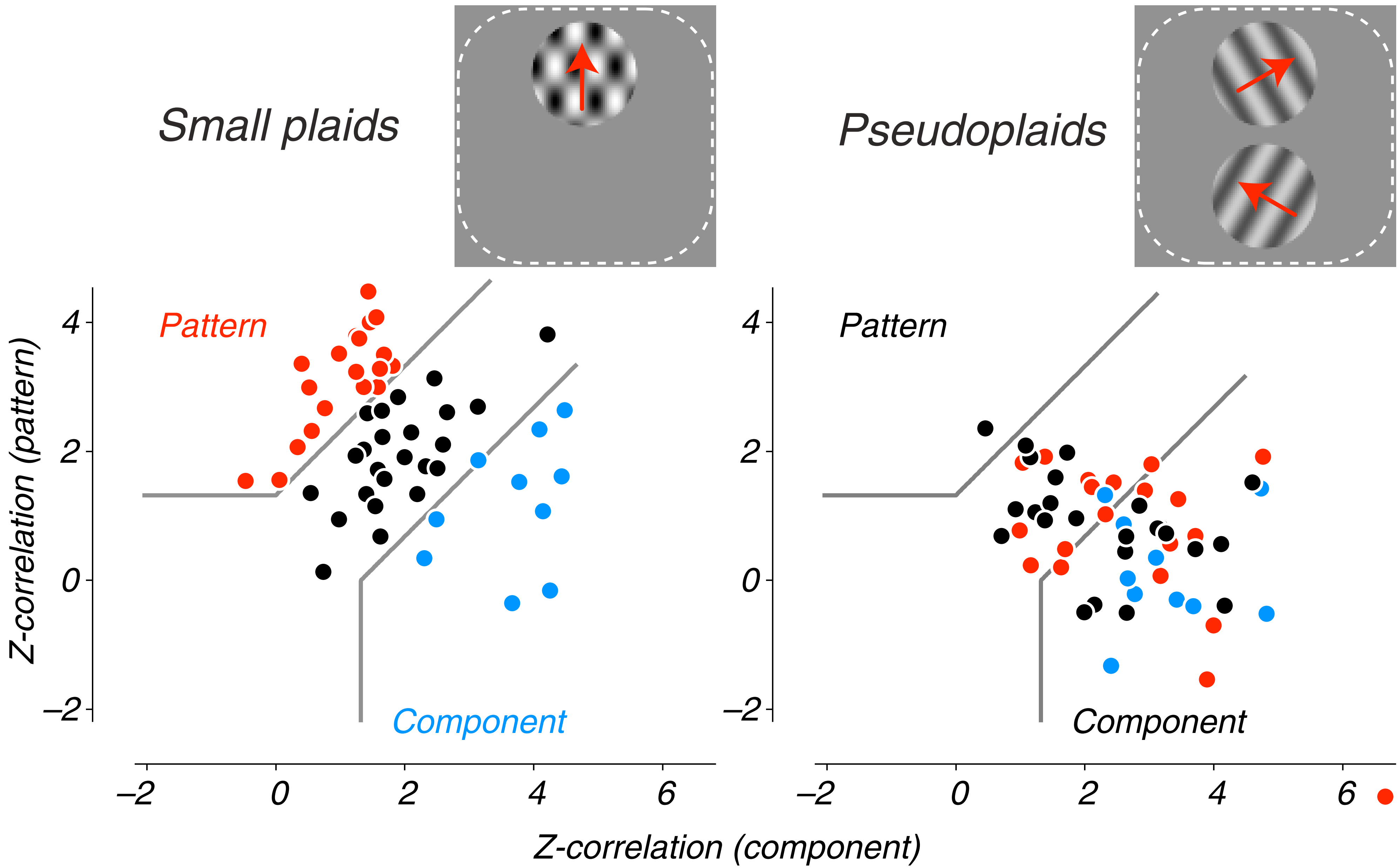
Small gratings | *Small plaids*



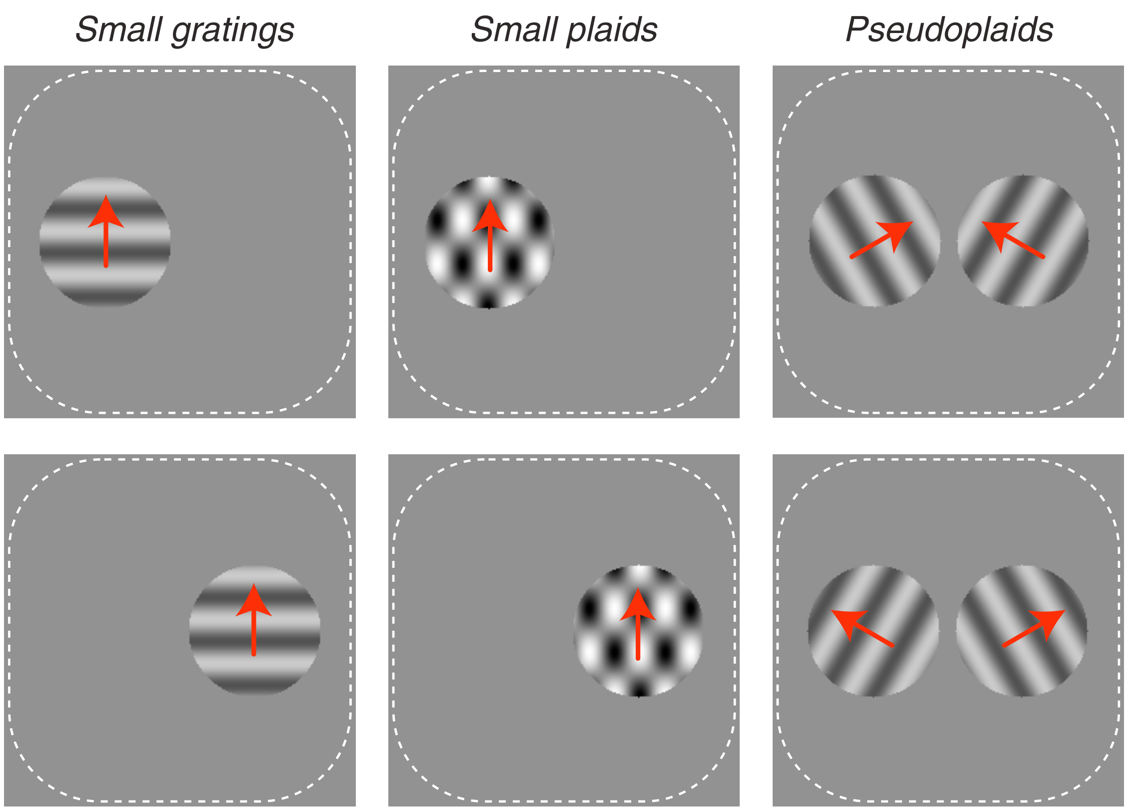
Majaj, Carandini & Movshon, 2007



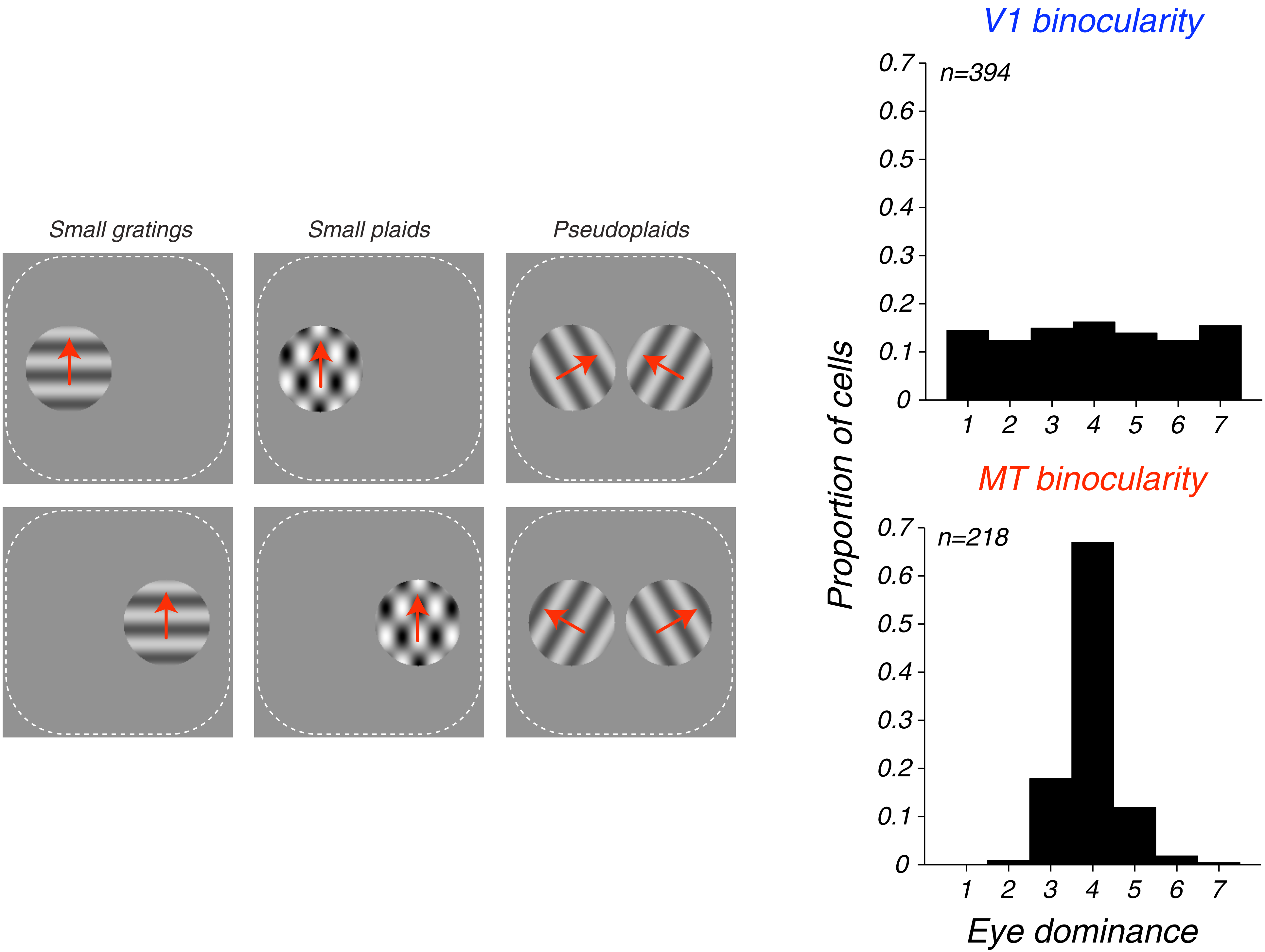
Majaj, Carandini &
Movshon, 2007



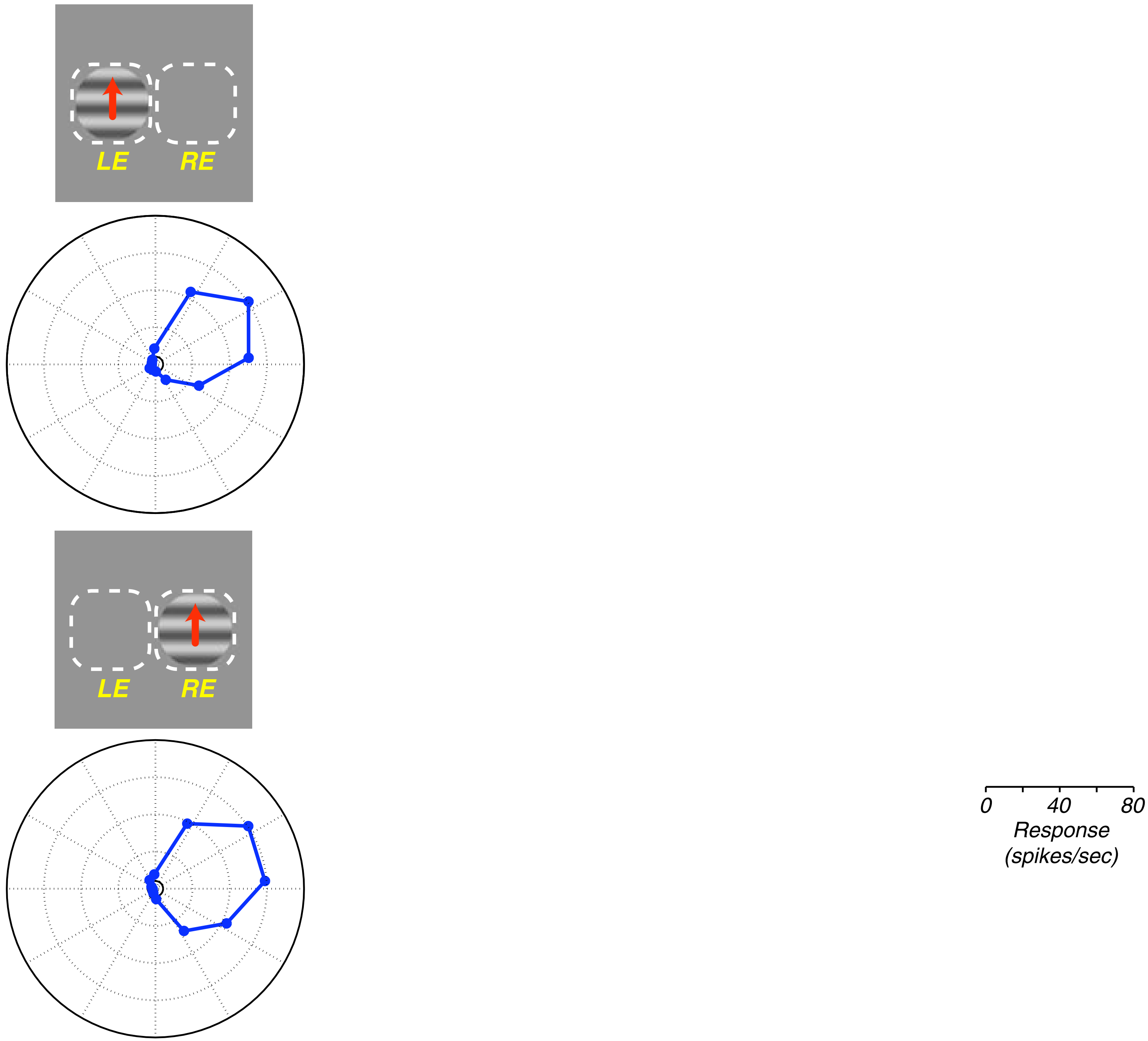
Majaj, Carandini & Movshon, 2007

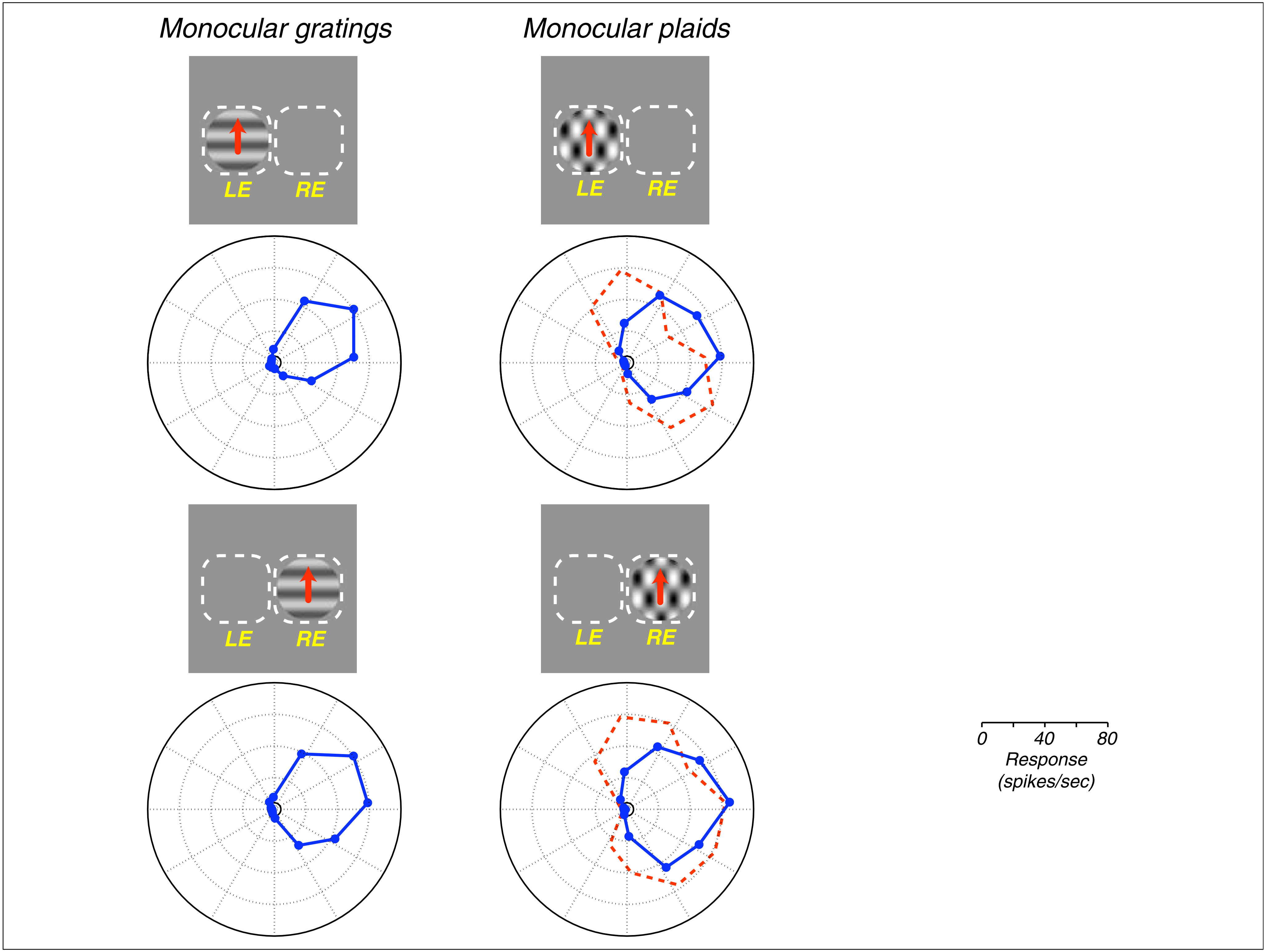


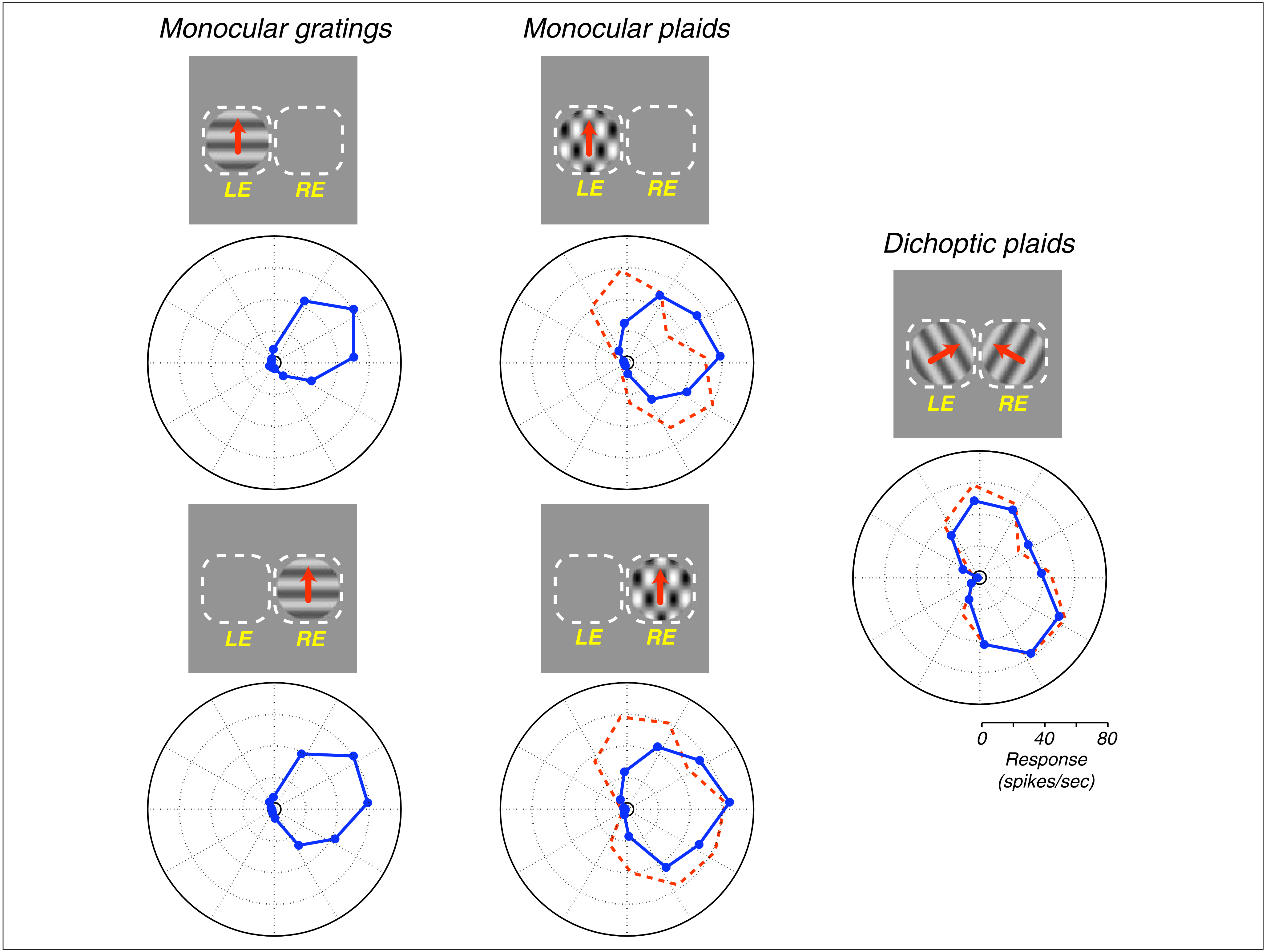
Pattern motion is computed locally


Small gratings
Small plaids
Pseudoplaids
V1 binocularity
n=394
MT binocularity
n=218
Proportion of cells
Eye dominance
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
1
2
3
4
5
6
7

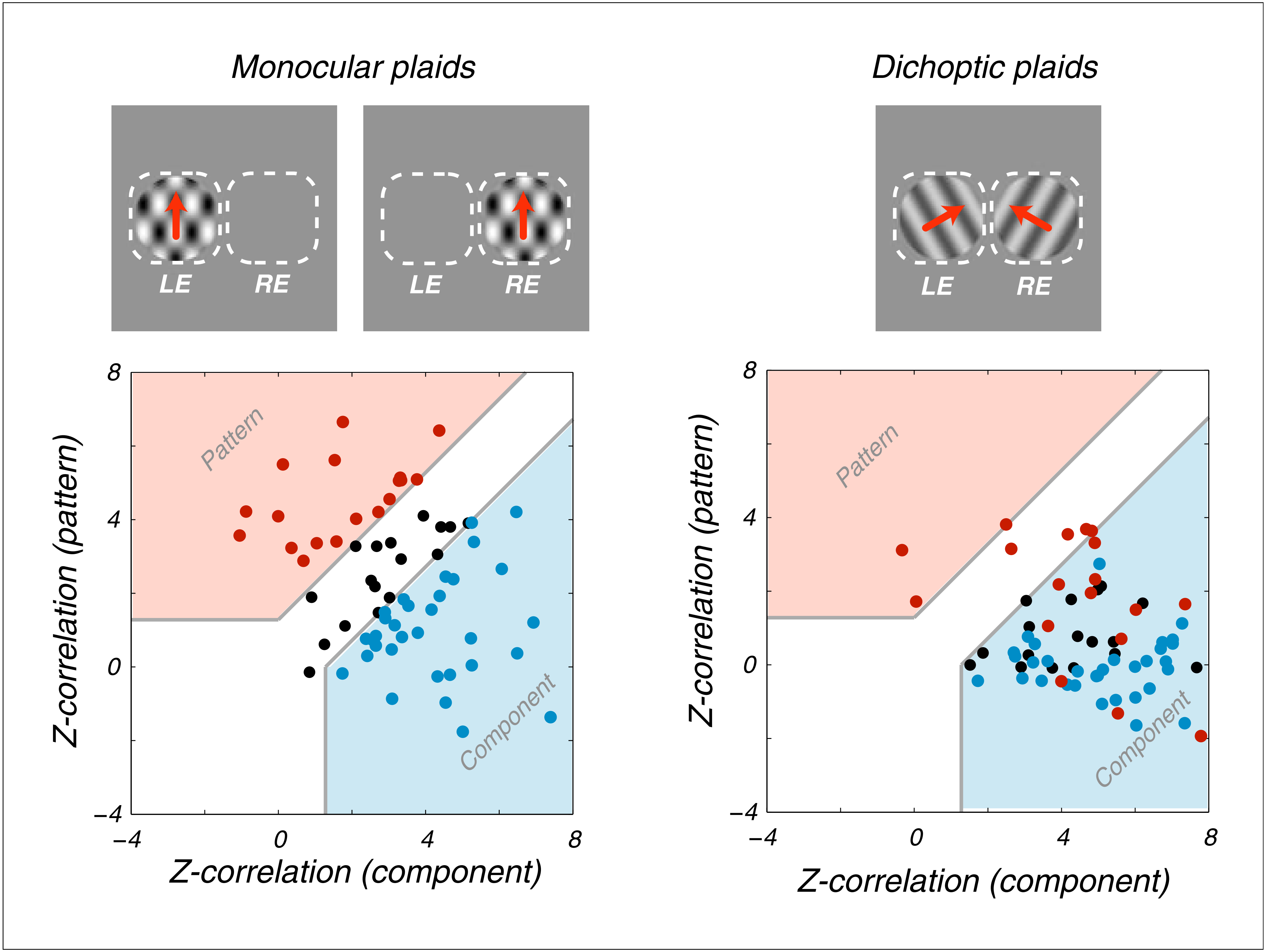
Monocular gratings



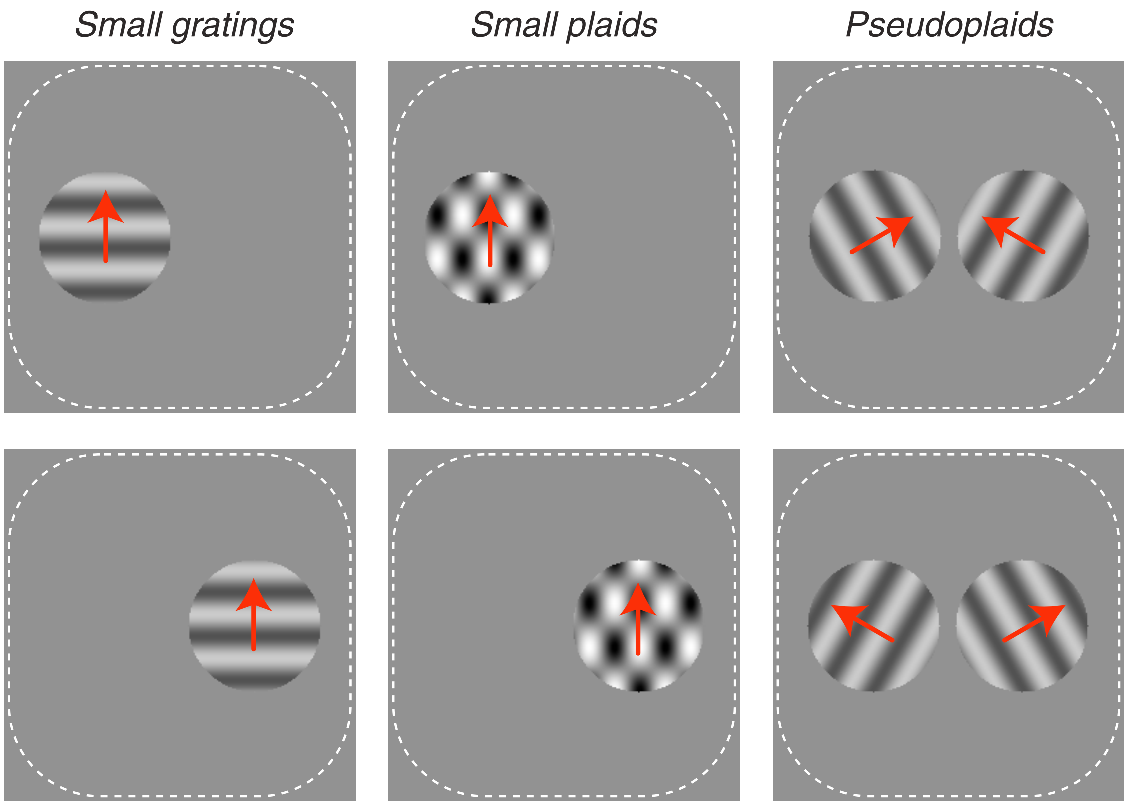

Monocular gratings
Monocular plaids
LE
RE
LE
RE
LE
RE
LE
RE
0
40
80
Response
(spikes/sec)



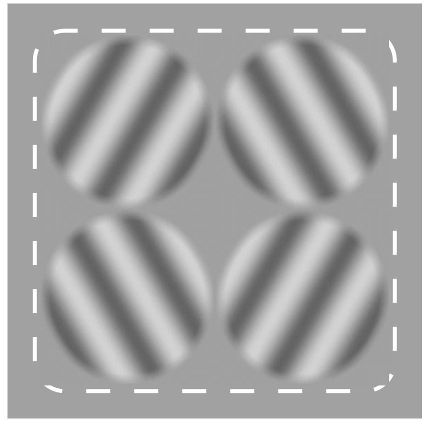
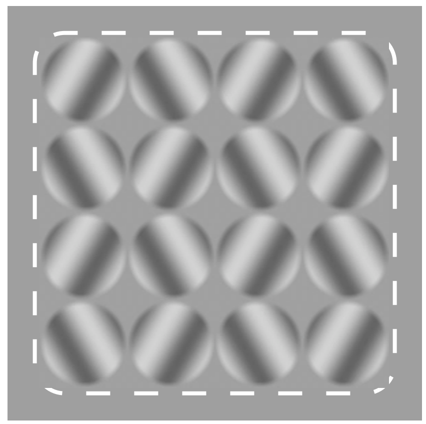
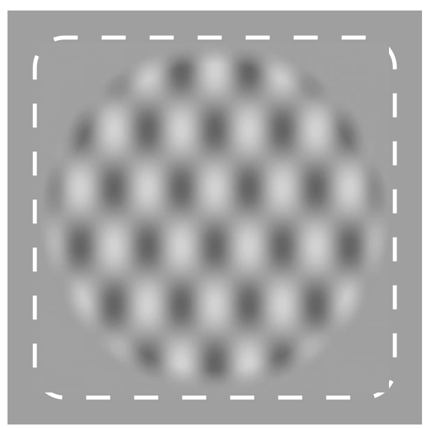
Monocular gratings
Monocular plaids
Dichoptic plaids
LE
RE
LE
RE
LE
RE
LE
RE
LE
RE
0
40
80
Response
(spikes/sec)

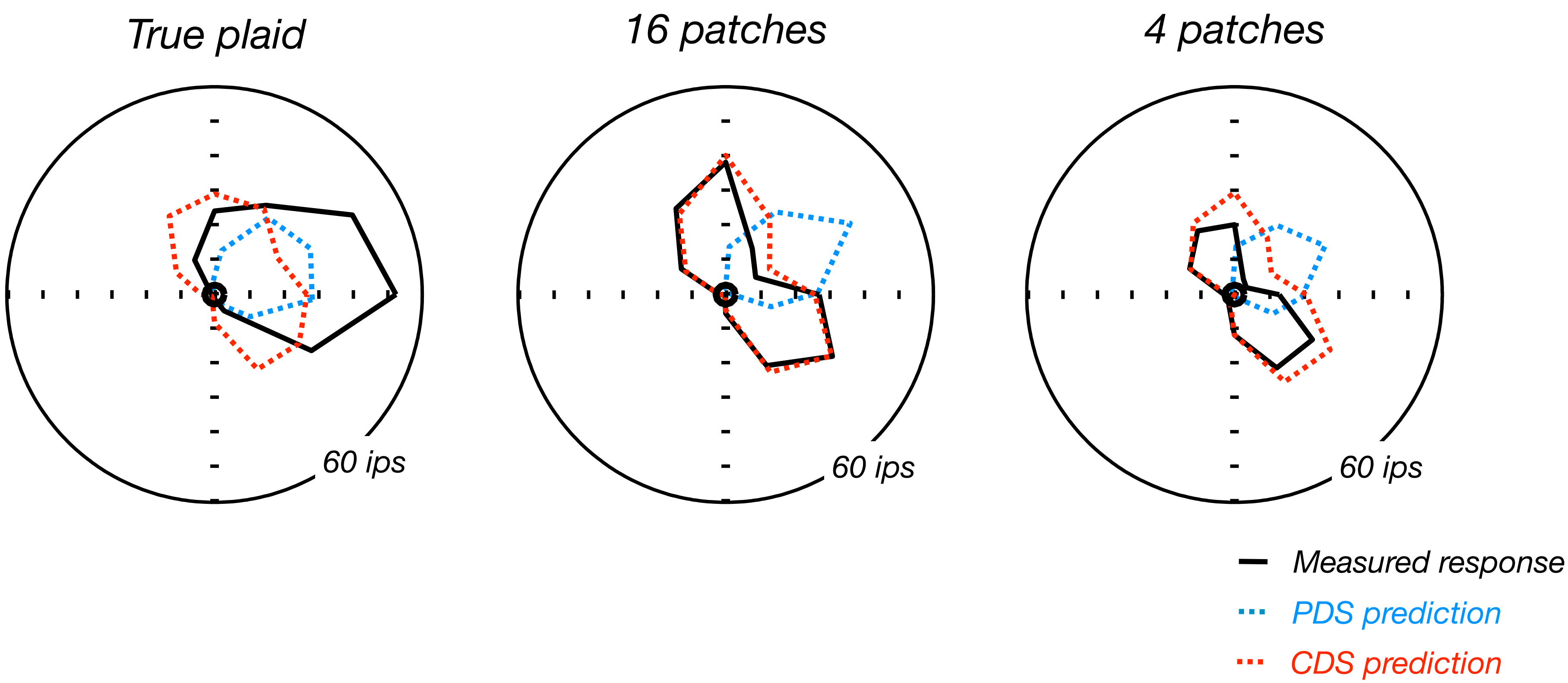


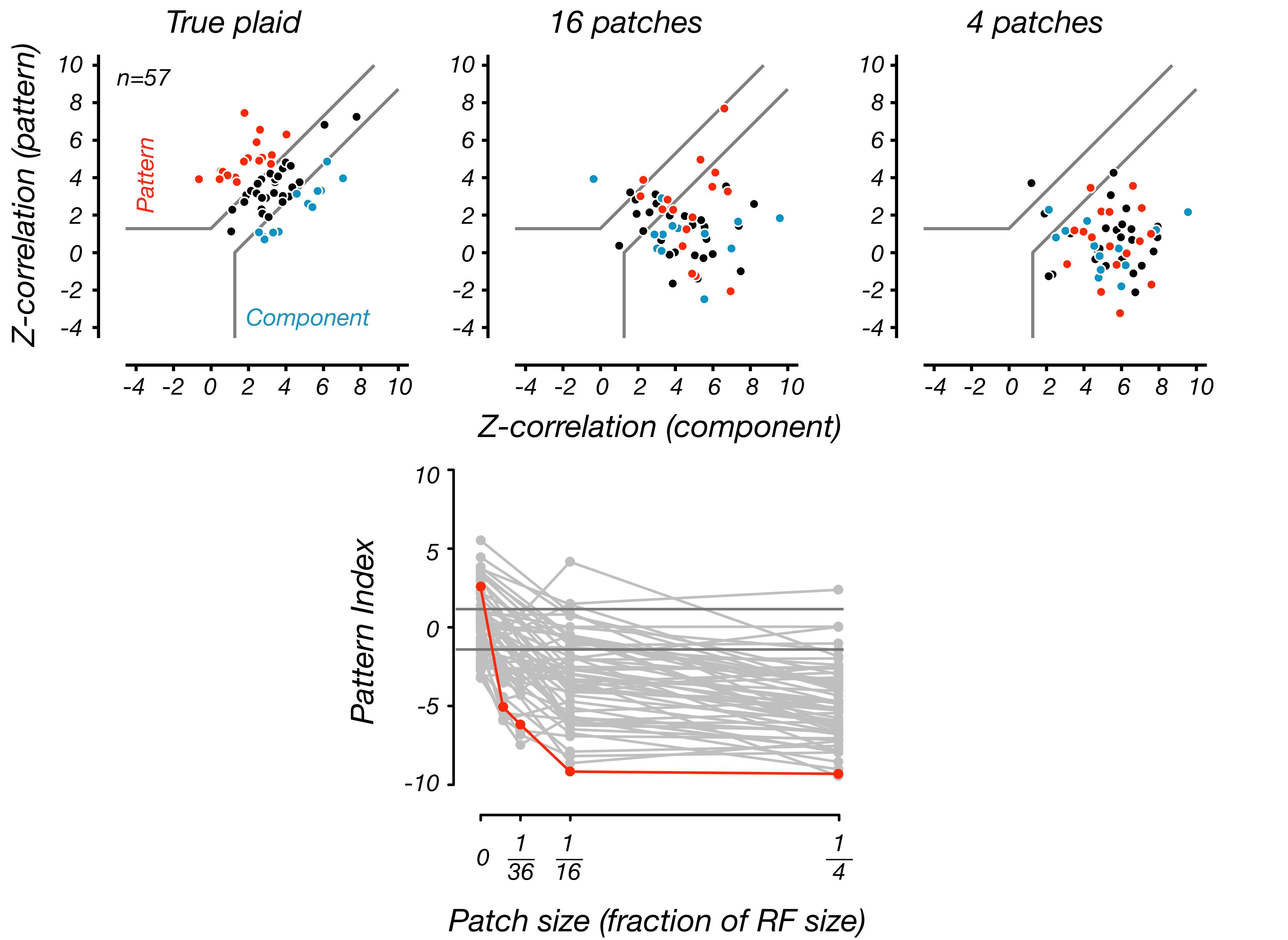
Monocular plaids
LE
RE
LE
RE
Dichoptic plaids
LE
RE
Pattern
Component
Z-correlation (pattern)
Z-correlation (component)
8
4
0
−4
Pattern
Component
Z-correlation (pattern)
Z-correlation (component)



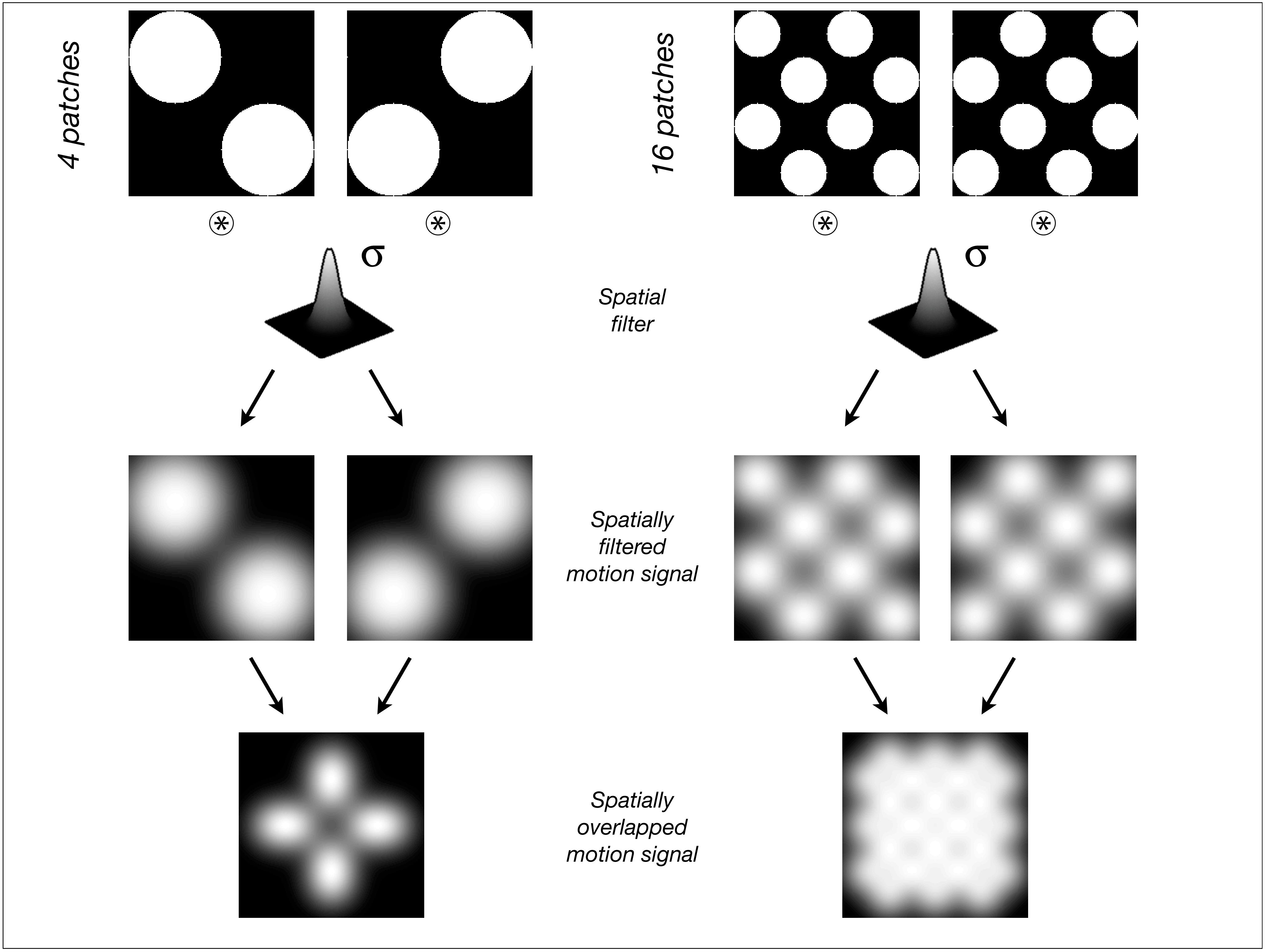
Pattern motion is computed locally and monocularly

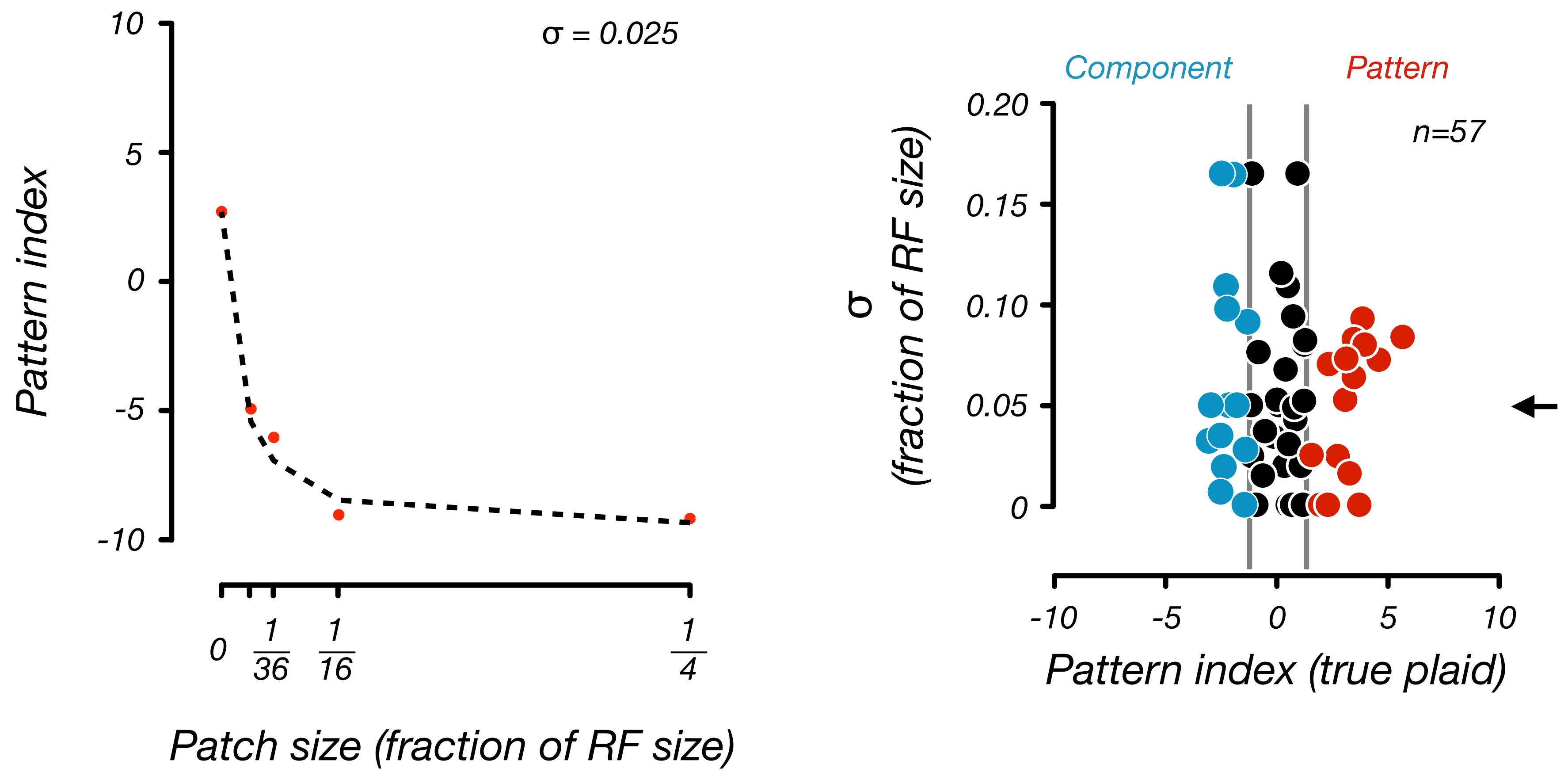
Number of patches	*Visual schematic*	*Patch size (fraction of RF size)*
4		*1/4*
16		*1/16*
∞		*0*

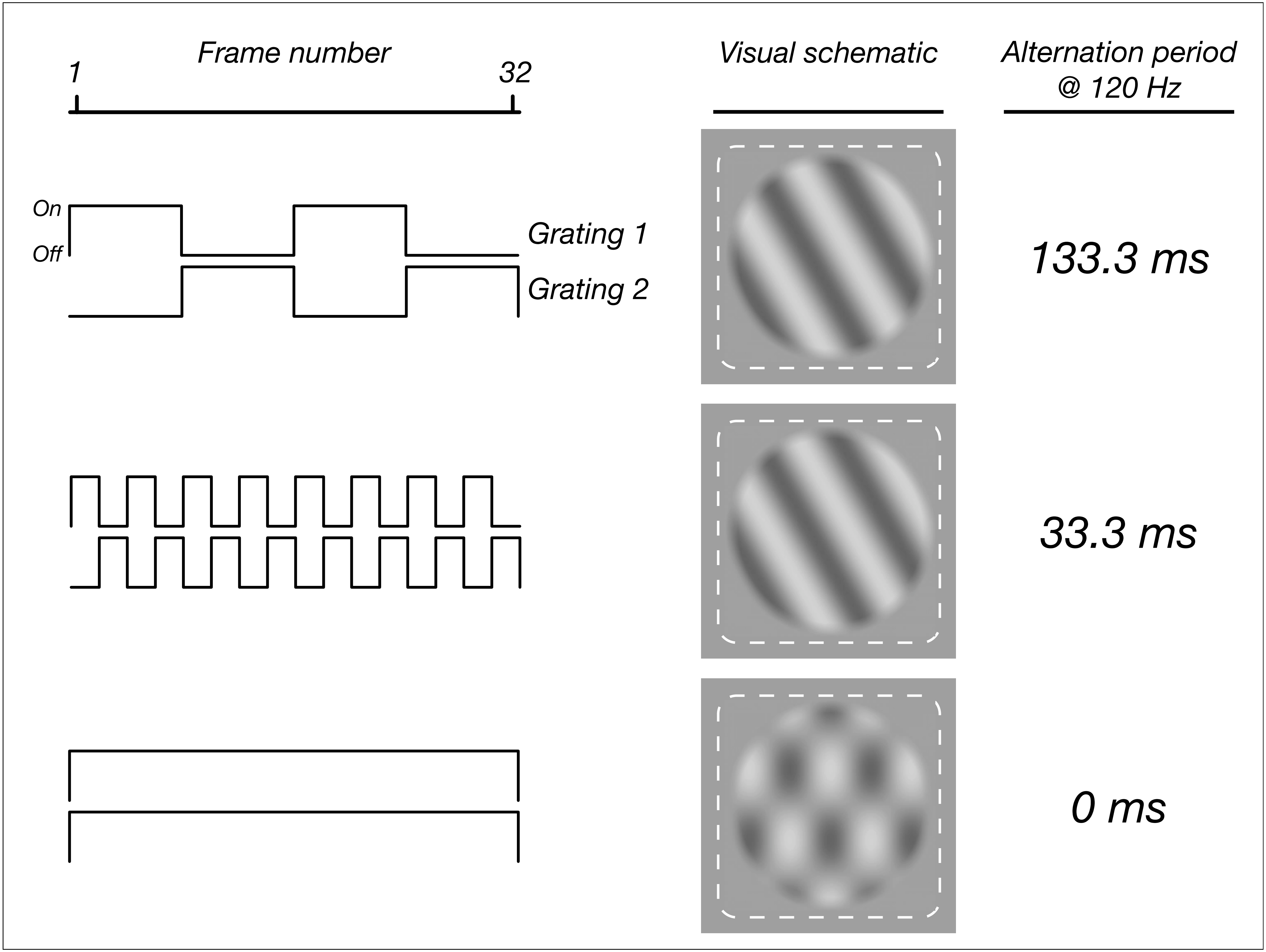

True plaid
16 patches
4 patches
60 ips
60 ips
60 ips
Measured response
PDS prediction
CDS prediction

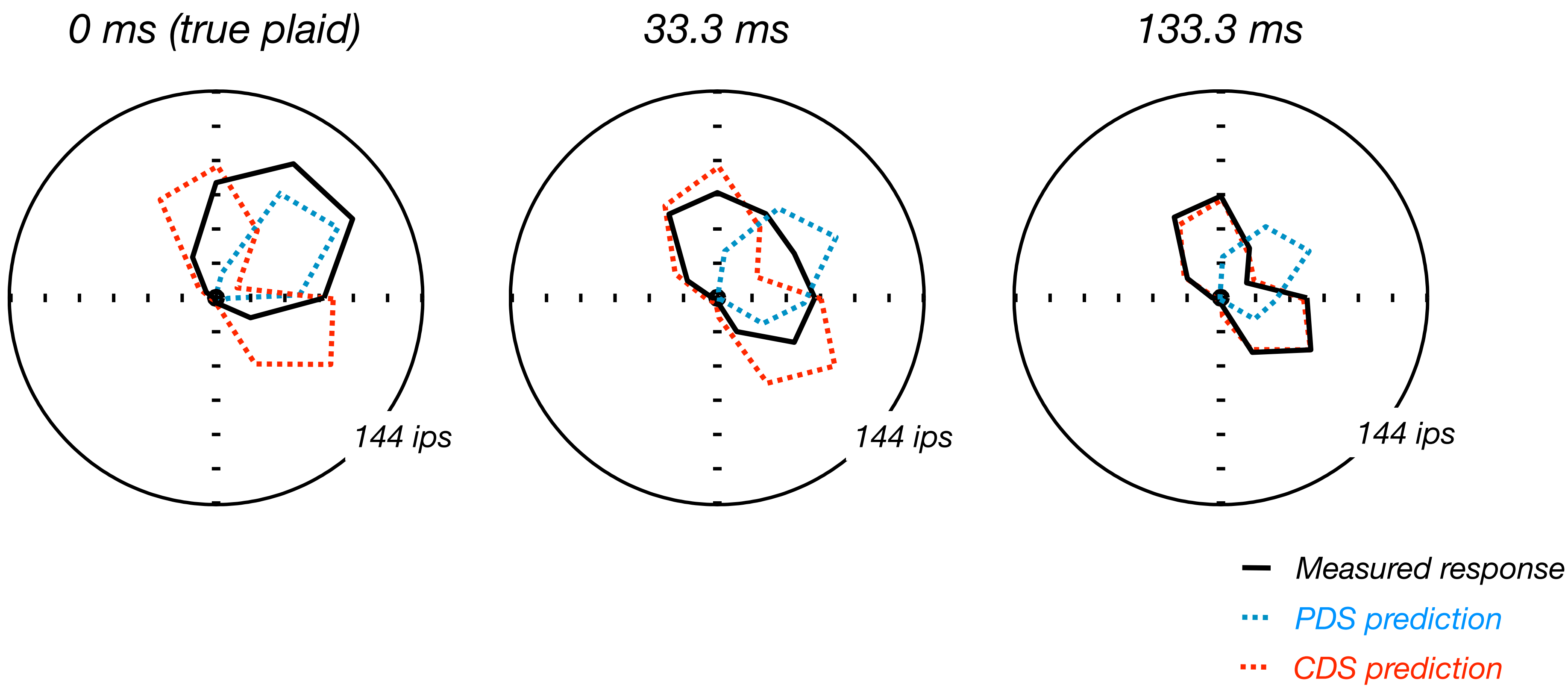


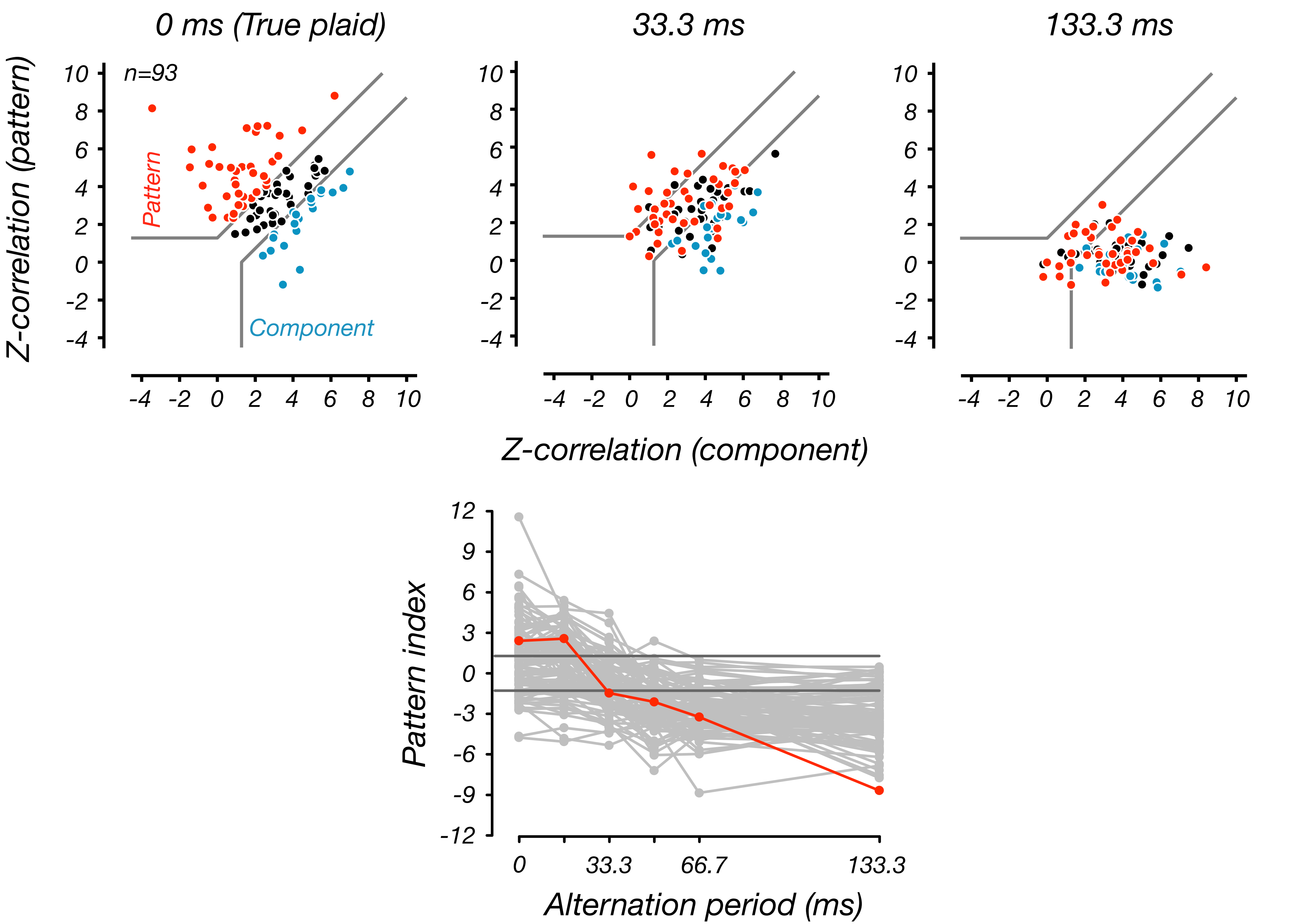
True plaid
16 patches
4 patches
n=57
Pattern
Component
Z-correlation (pattern)
Z-correlation (component)
10
8
6
4
2
0
-2
-4
Pattern Index
5
-5
-10
0
1/36
1/16
1/4
Patch size (fraction of RF size)


4 patches
16 patches
σ
σ
Spatial filter
Spatially filtered motion signal
Spatially overlapped motion signal

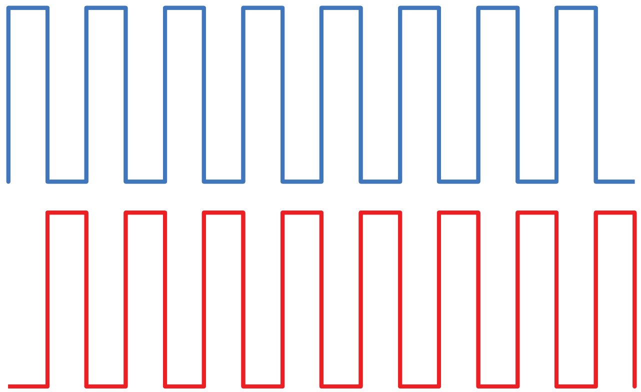

σ = 0.025
Pattern index
10
5
0
-5
-10
0
1/36
1/16
1/4
Patch size (fraction of RF size)
Component
Pattern
n=57
σ
(fraction of RF size)
0.20
0.15
0.10
0.05
0
-10
-5
0
5
10
Pattern index (true plaid)


Frame number
1
32
Visual schematic
Alternation period @ 120 Hz
On
Off
Grating 1
Grating 2
133.3 ms
33.3 ms
0 ms


0 ms (true plaid)
33.3 ms
133.3 ms
144 ips
144 ips
144 ips
Measured response
PDS prediction
CDS prediction

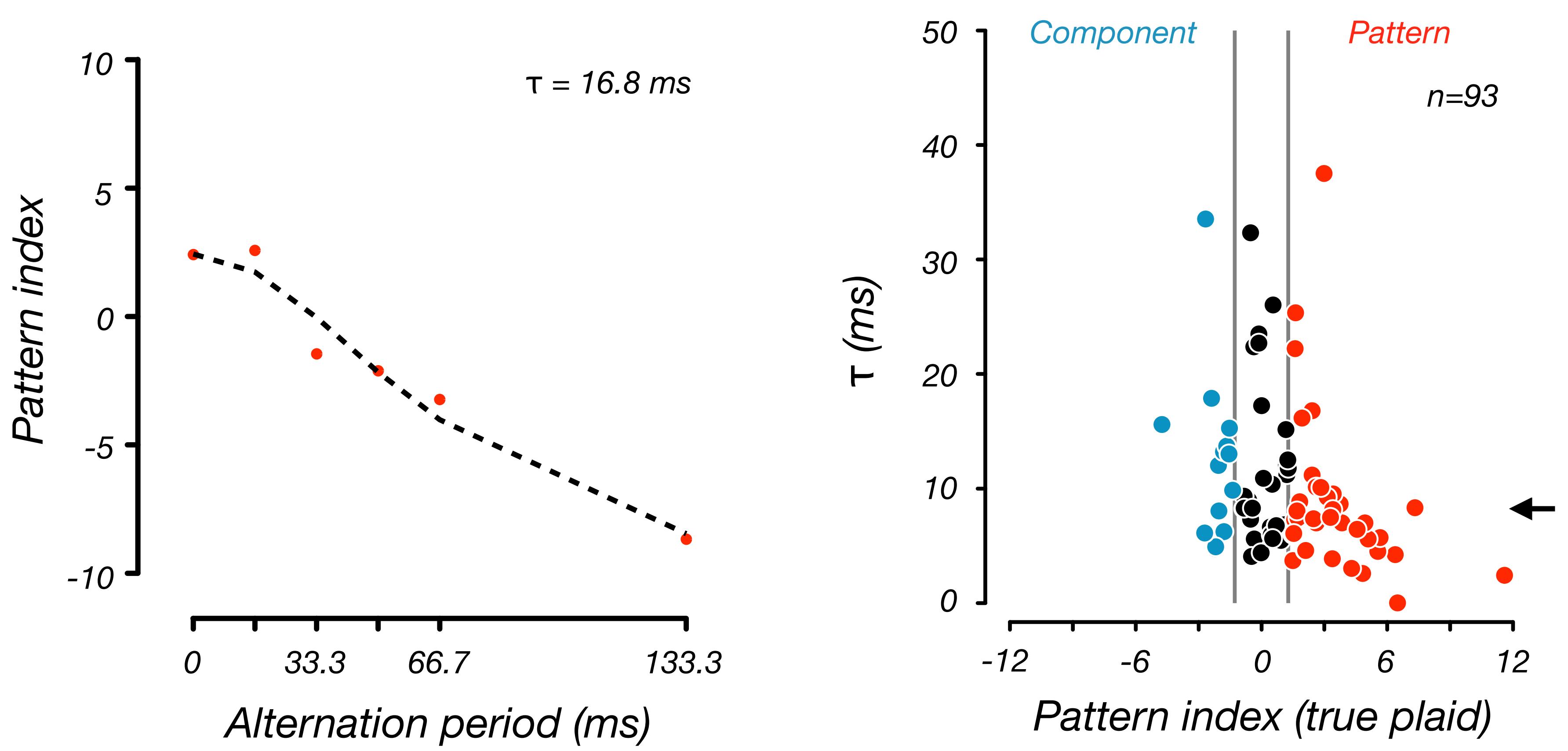

0 ms (True plaid)
33.3 ms
133.3 ms
n=93
Pattern
Component
Z-correlation (pattern)
Z-correlation (component)
Pattern index
Alternation period (ms)

Rapid alternation

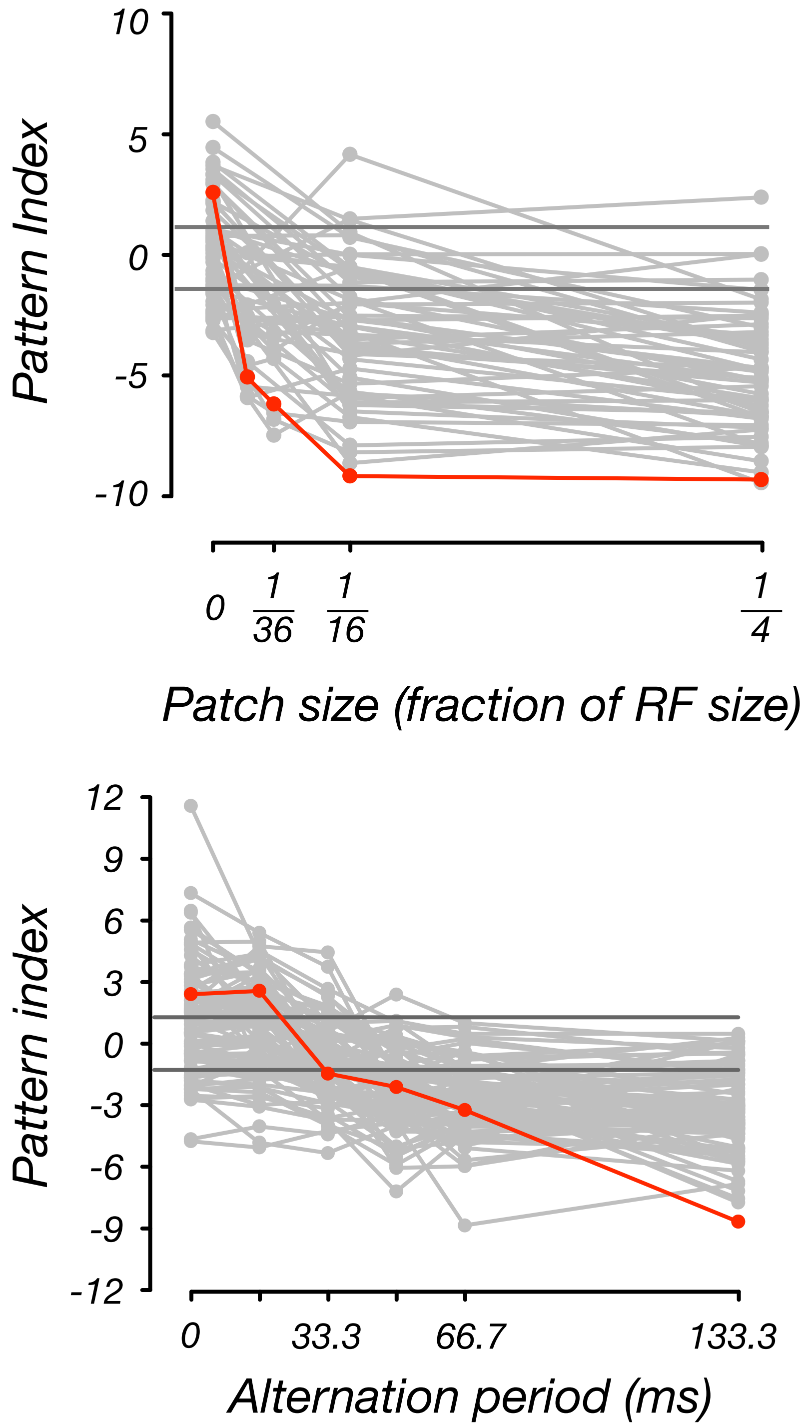


Grating 1

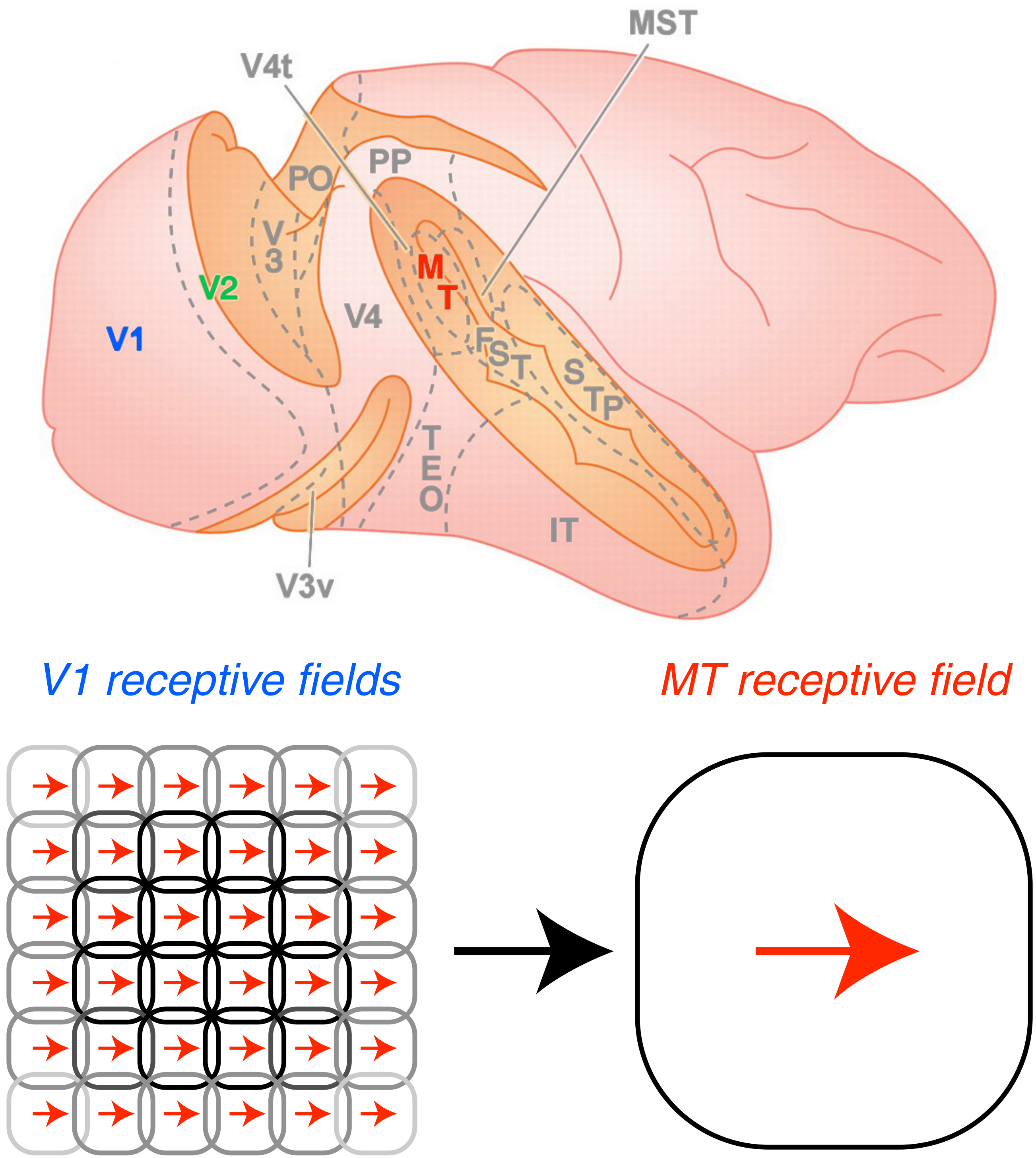
Grating 2



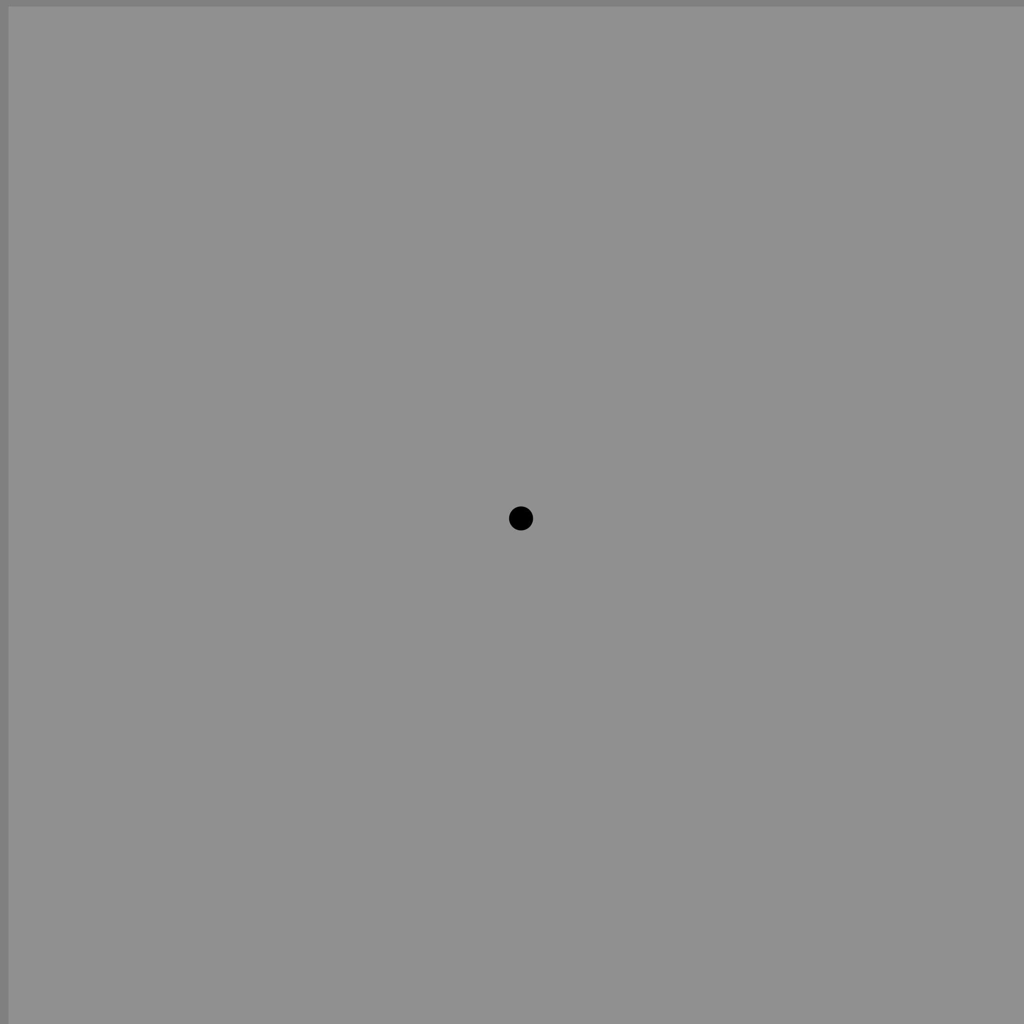
τ = 16.8 ms
Pattern index
10
5
0
-5
-10
0
33.3
66.7
133.3
Alternation period (ms)
Component
Pattern
n=93
τ (ms)
50
40
30
20
10
0
-12
-6
0
6
12
Pattern index (true plaid)



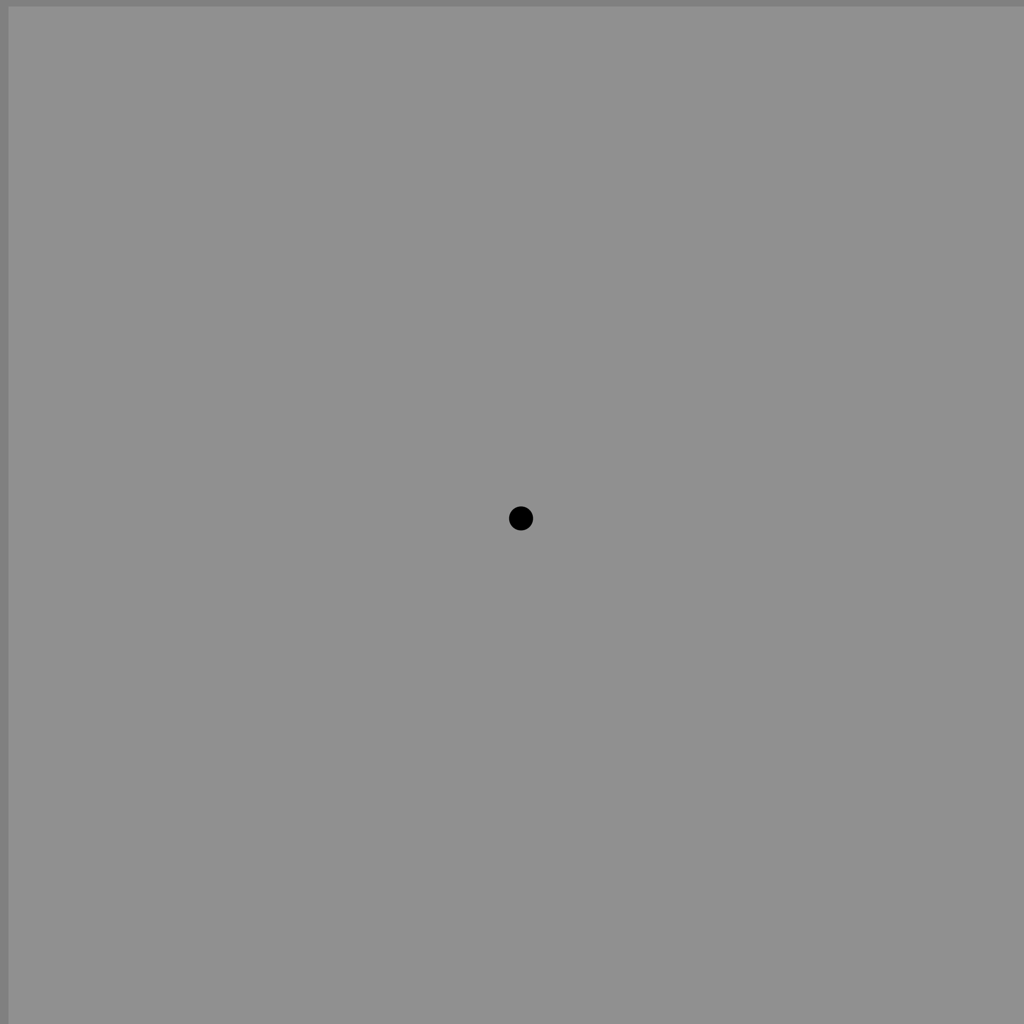
Spatio-temporal integration of pattern motion is sharply limited

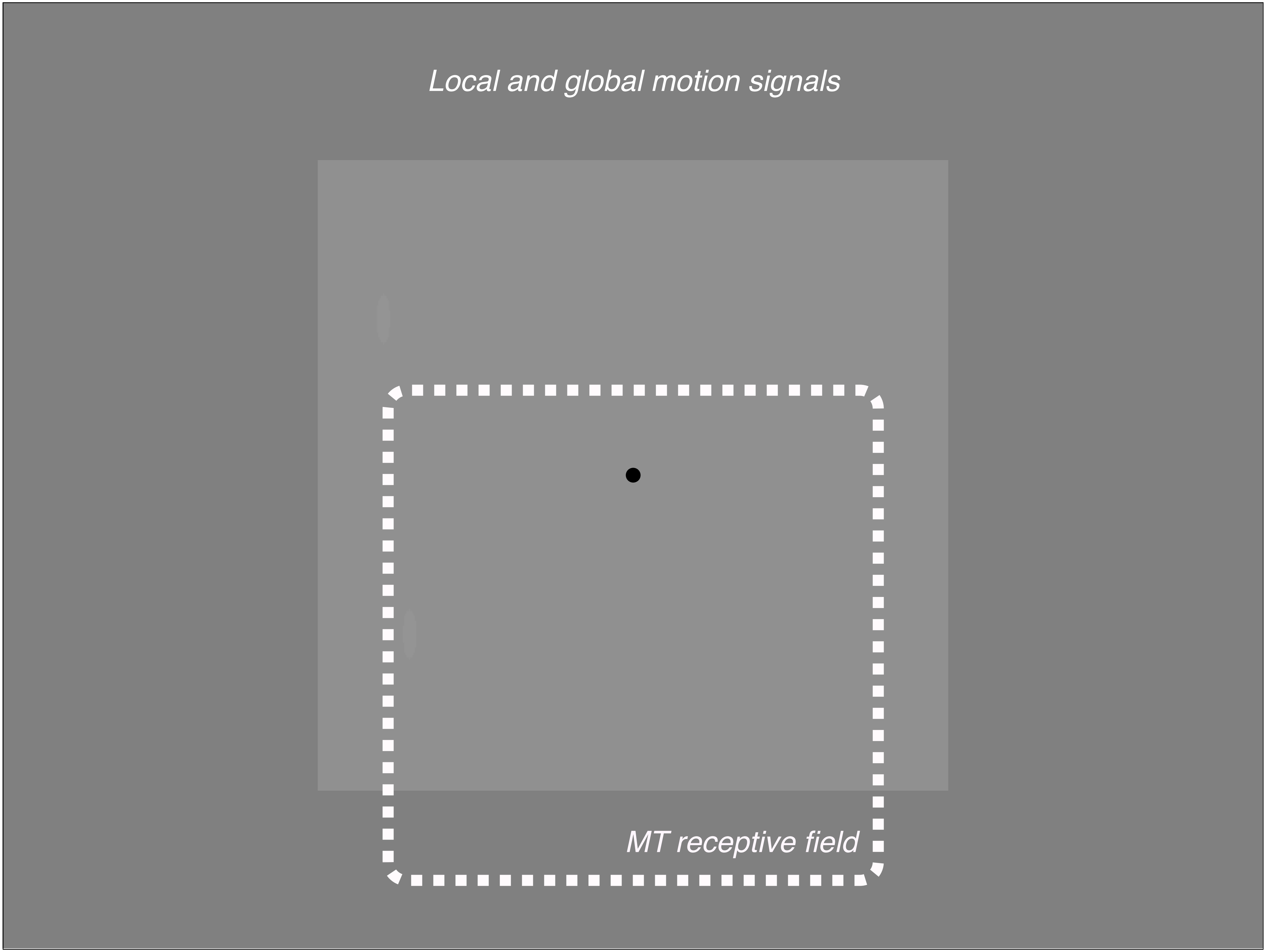

MST
V4t
PP
PO
V3
V2
V1
V4
MT
FST
STP
TEO
IT
V3v
V1 receptive fields
MT receptive field

Local and global motion signals



Local and global motion signals




Local and global motion signals
MT receptive field

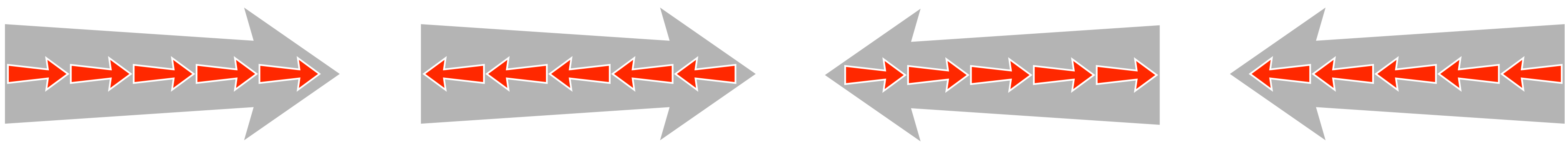
How do local and global motion signals interact?

Global preferred
Local preferred

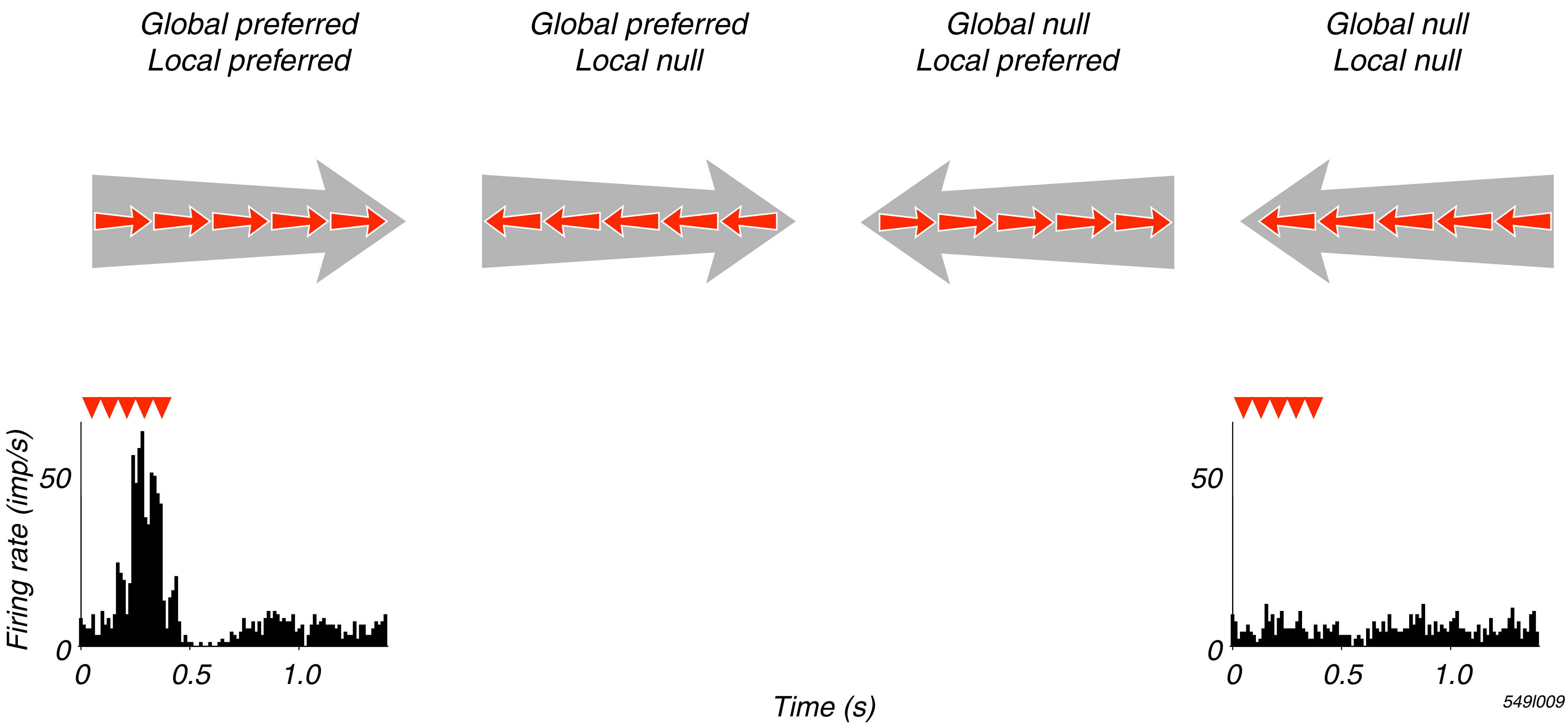
Global preferred
Local null

Global null
Local preferred

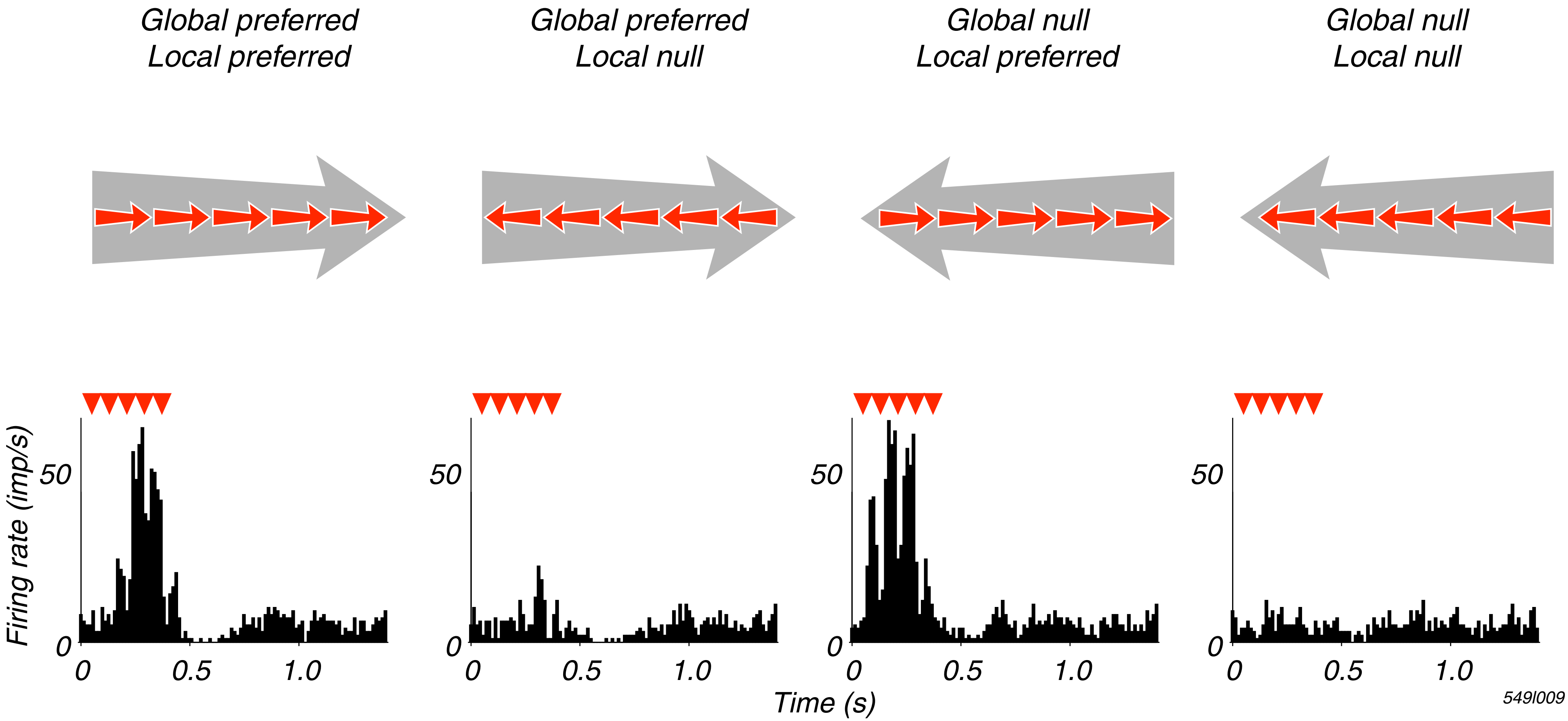
Global null
Local null

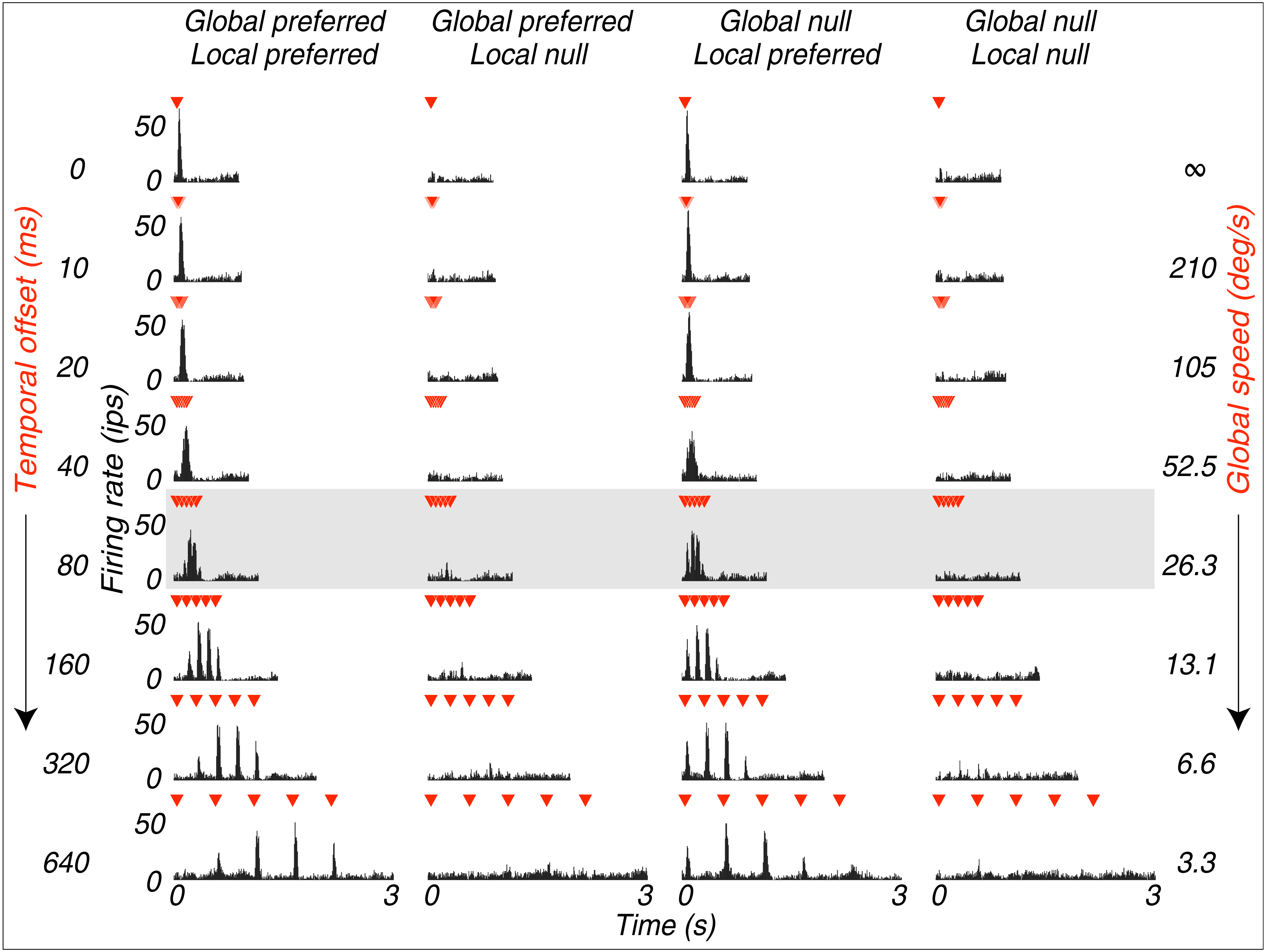


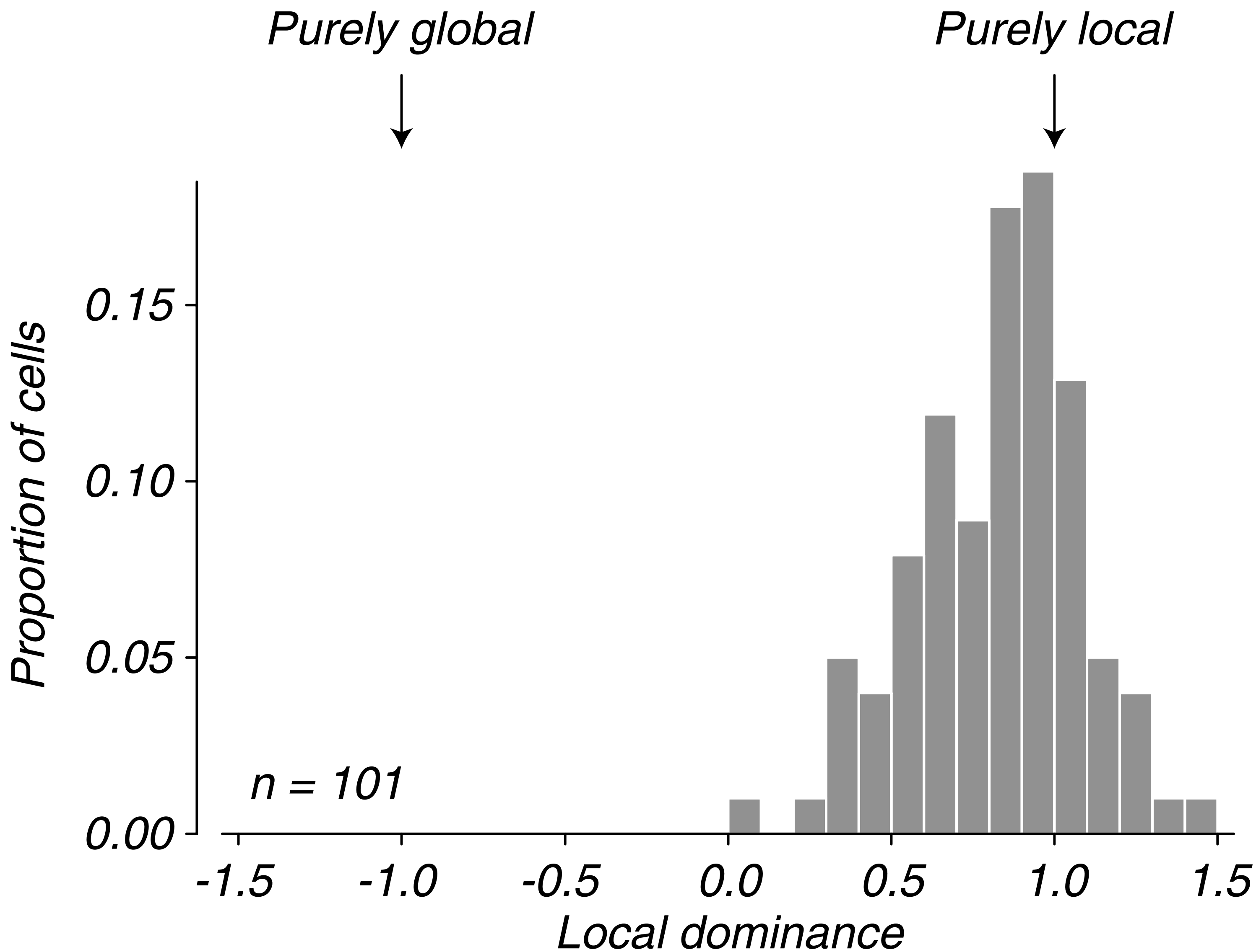
How do local and global motion signals interact?



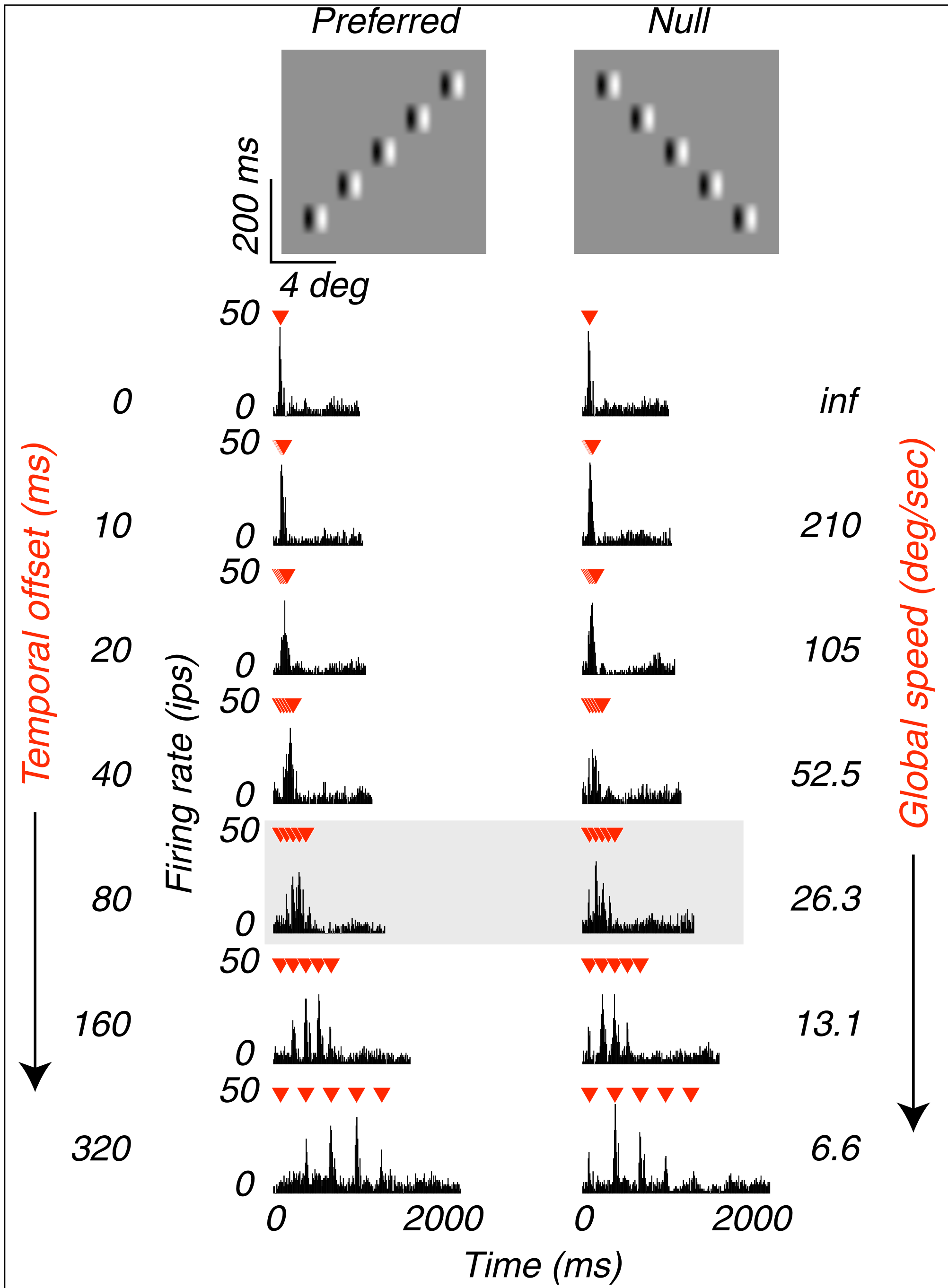
How do local and global motion signals interact?



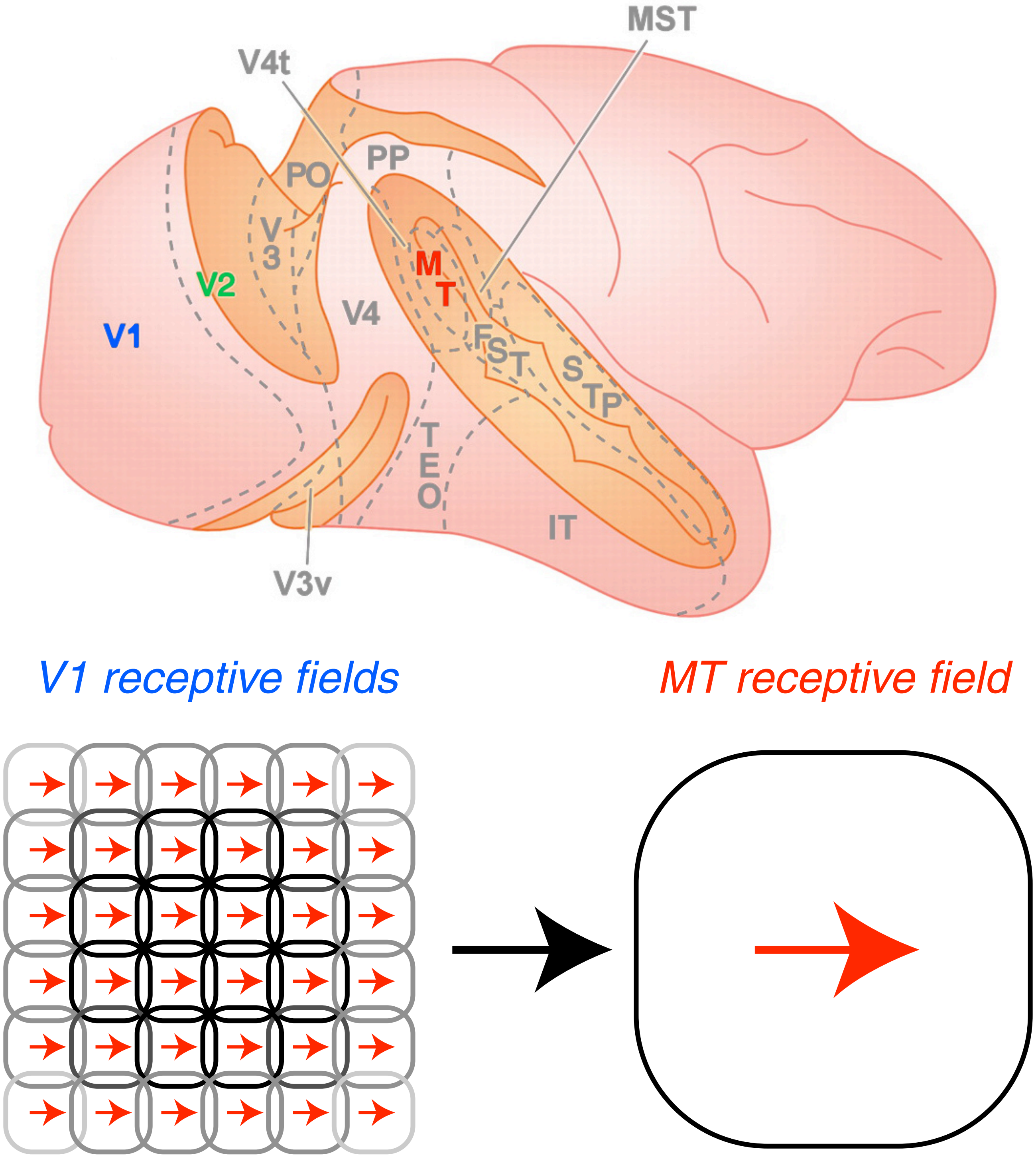

Global preferred
Local preferred
Global preferred
Local null
Global null
Local preferred
Global null
Local null
Temporal offset (ms)
0
10
20
40
80
160
320
640
Firing rate (ips)
50
0
Global speed (deg/s)
∞
210
105
52.5
26.3
13.1
6.6
3.3
0
3
Time (s)

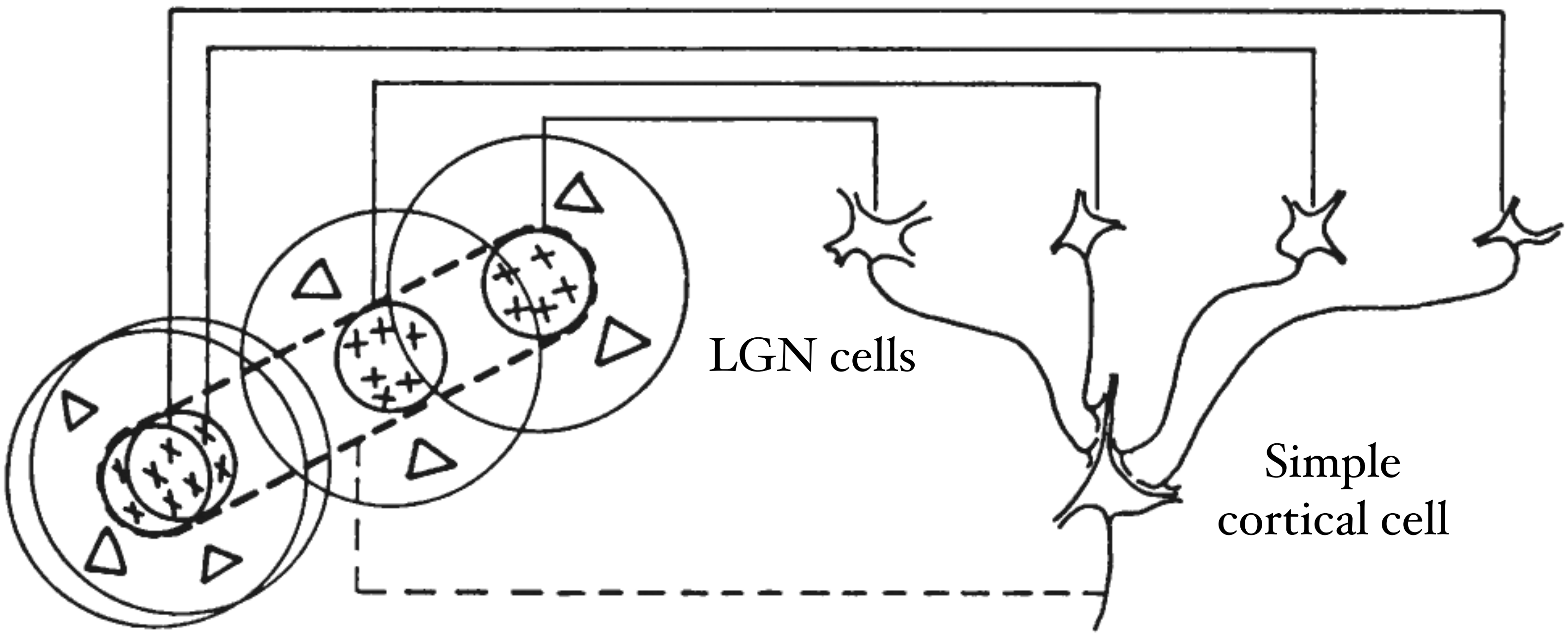


Purely global
Purely local
Proportion of cells
0.00
0.05
0.10
0.15
n = 101
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
Local dominance

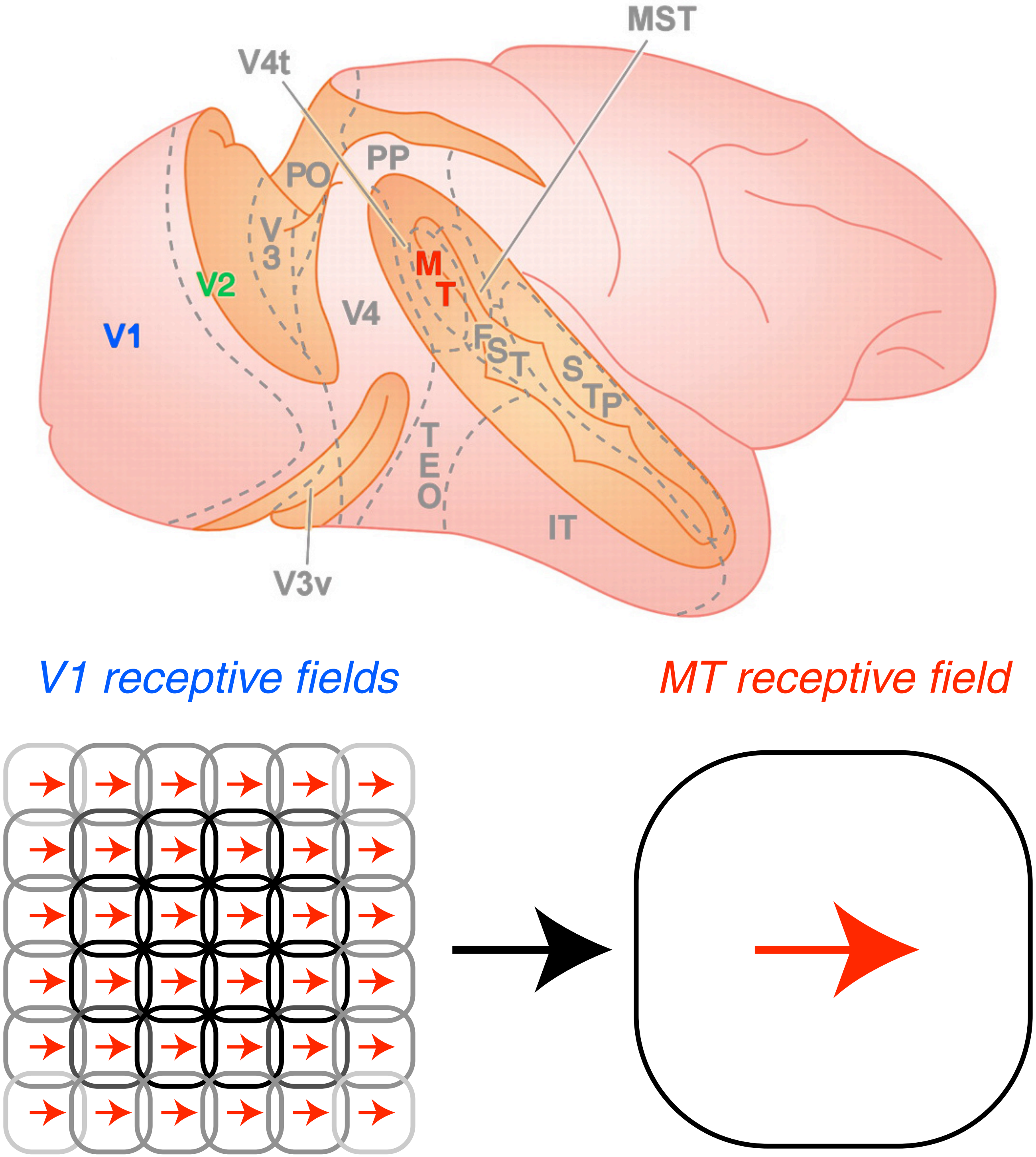


Preferred
Null
200 ms
4 deg
Temporal offset (ms)
0
10
20
40
80
160
320
Firing rate (ips)
50
0
inf
210
105
52.5
26.3
13.1
6.6
Global speed (deg/sec)
Time (ms)
2000


MST
V4t
PP
PO
V3
V2
V1
V4
MT
FST
STP
TEO
IT
V3v
V1 receptive fields
MT receptive field

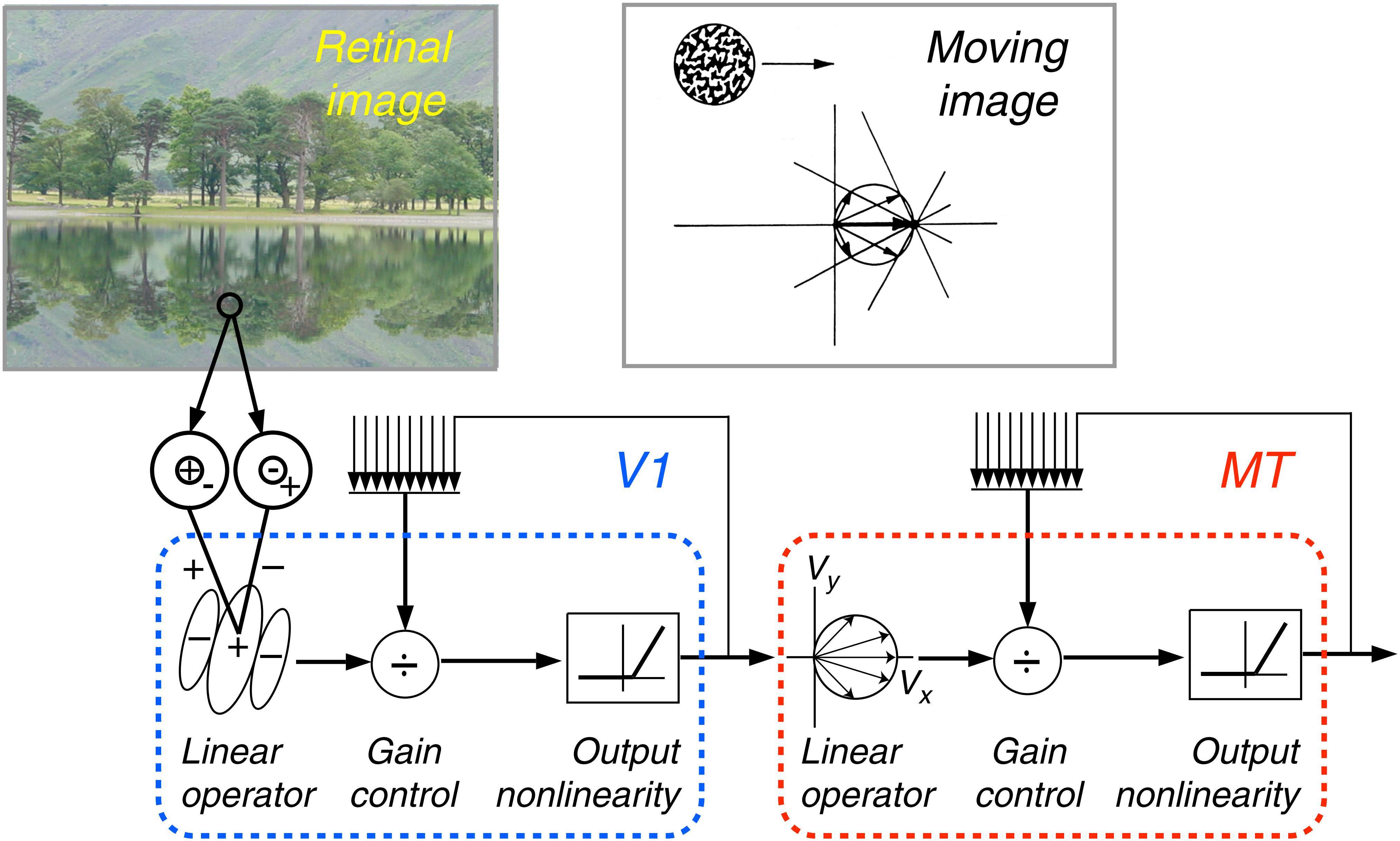


Hubel & Wiesel, 1962

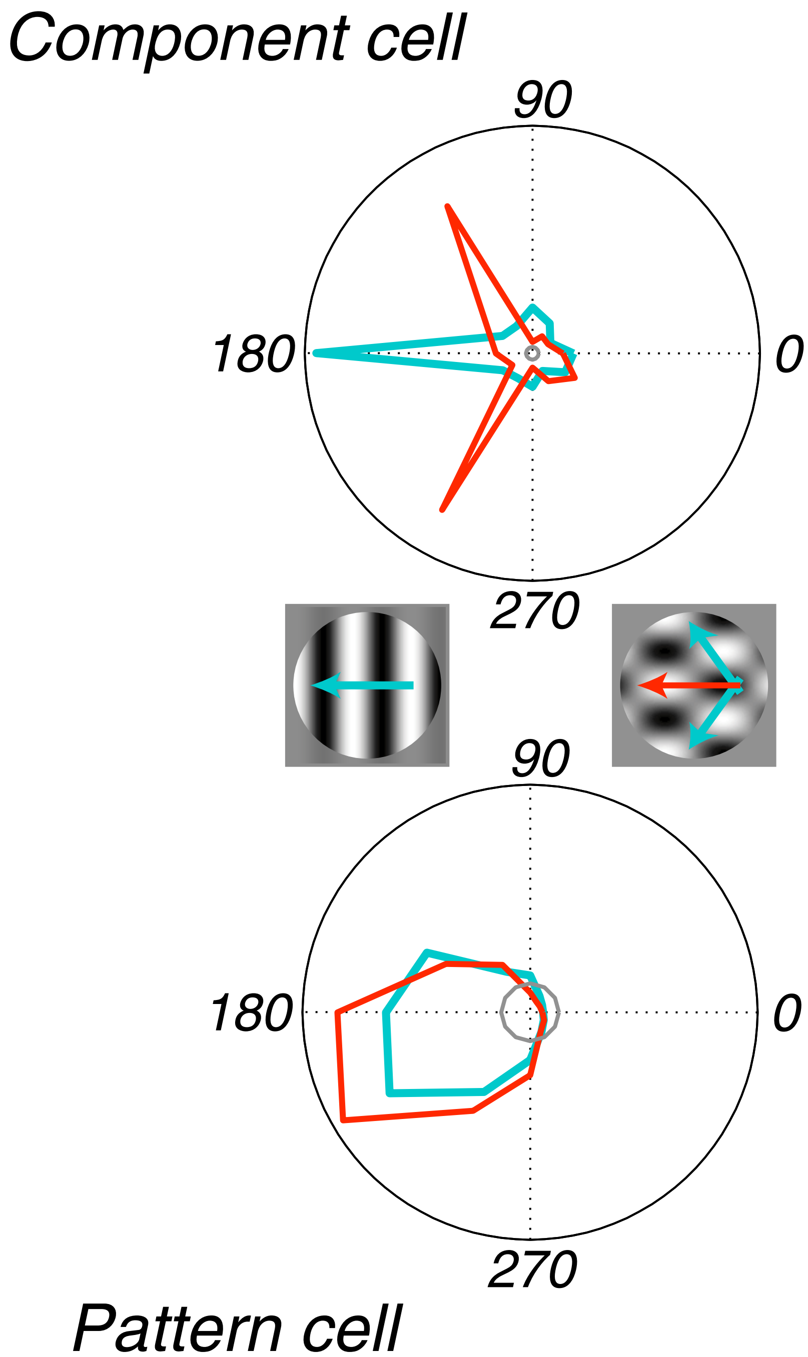


MST
V4t
PP
PO
V3
V2
V1
V4
MT
FST
STP
TEO
IT
V3v
V1 receptive fields
MT receptive field

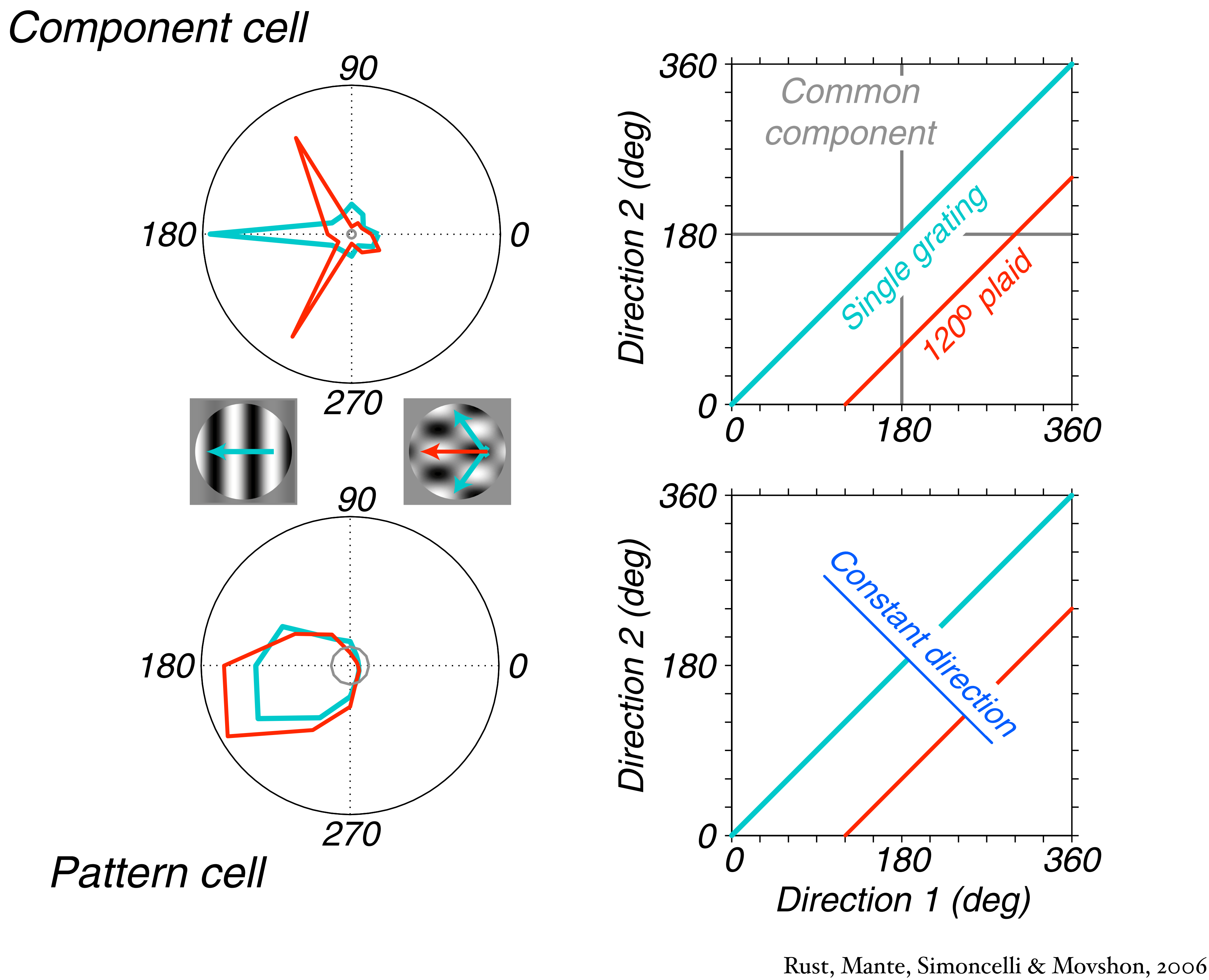
Recovering and validating the model:
1. A rich test set



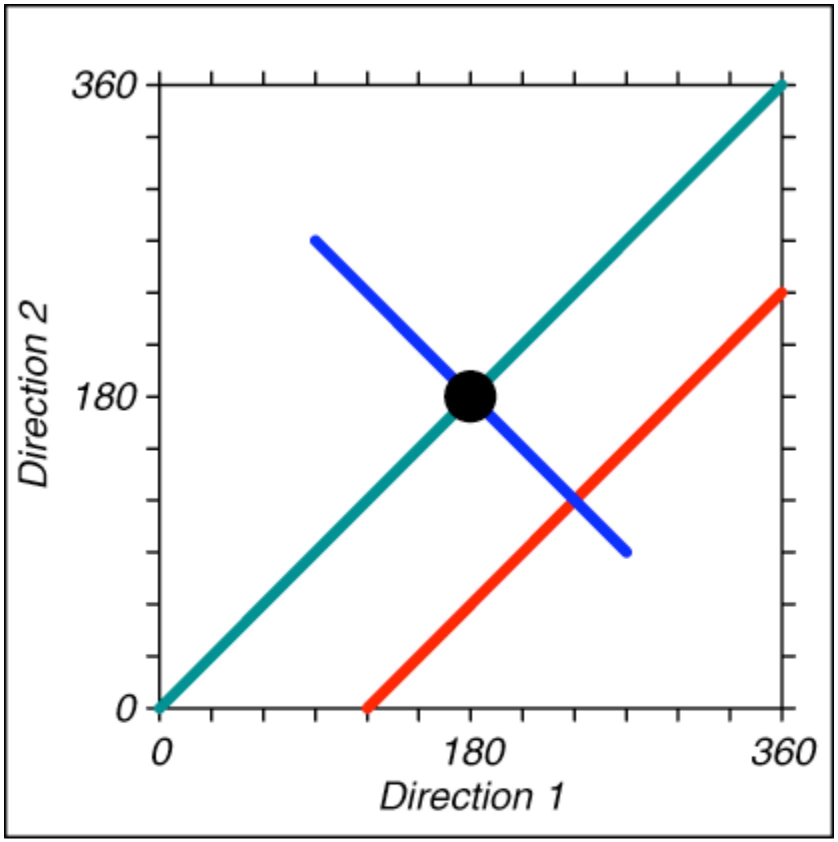
Simoncelli & Heeger, 1998

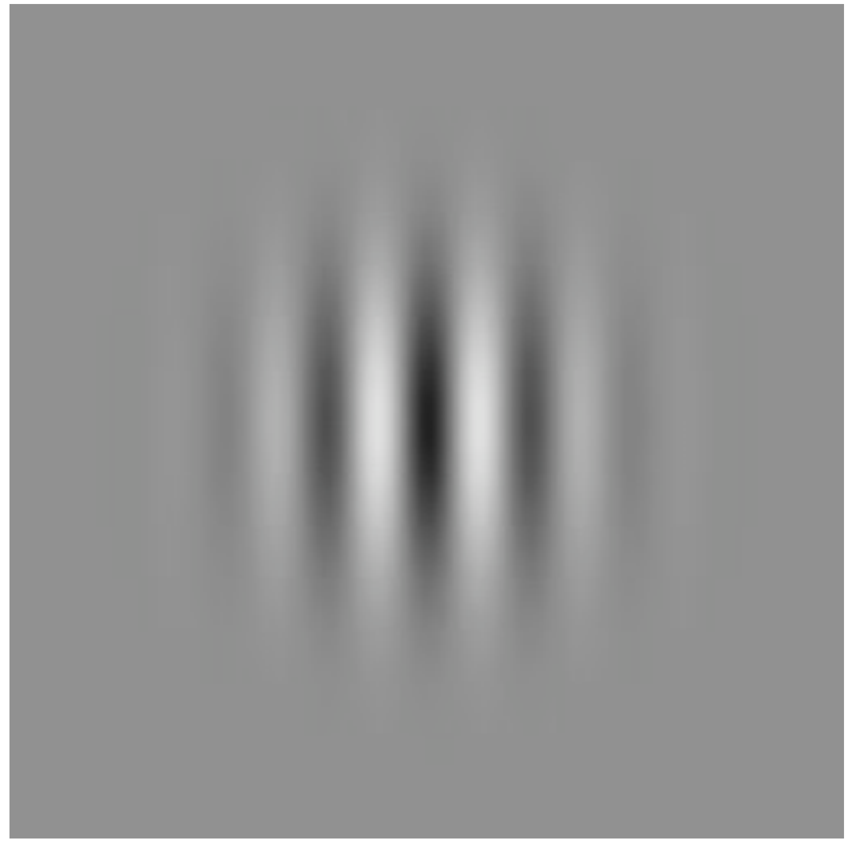


Rust, Mante, Simoncelli & Movshon, 2006

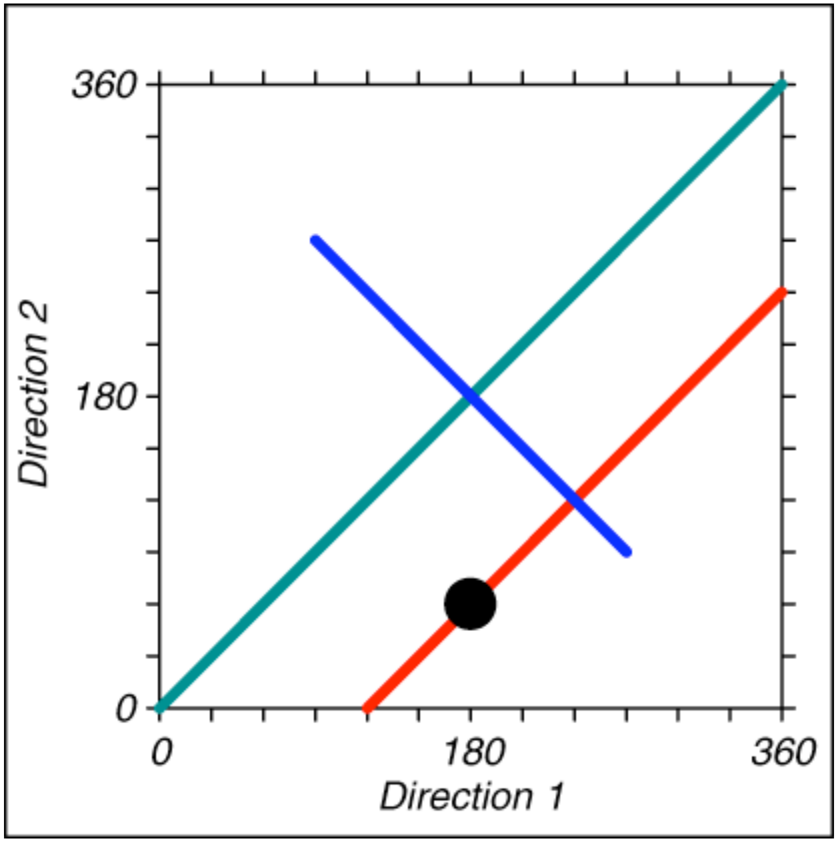

Component cell
90
180
0
270
360
Common
component
Single grating
120o plaid
Direction 2 (deg)
0
180
360
90
180
0
270
Pattern cell
Constant direction
Direction 1 (deg)
Rust, Mante, Simoncelli & Movshon, 2006

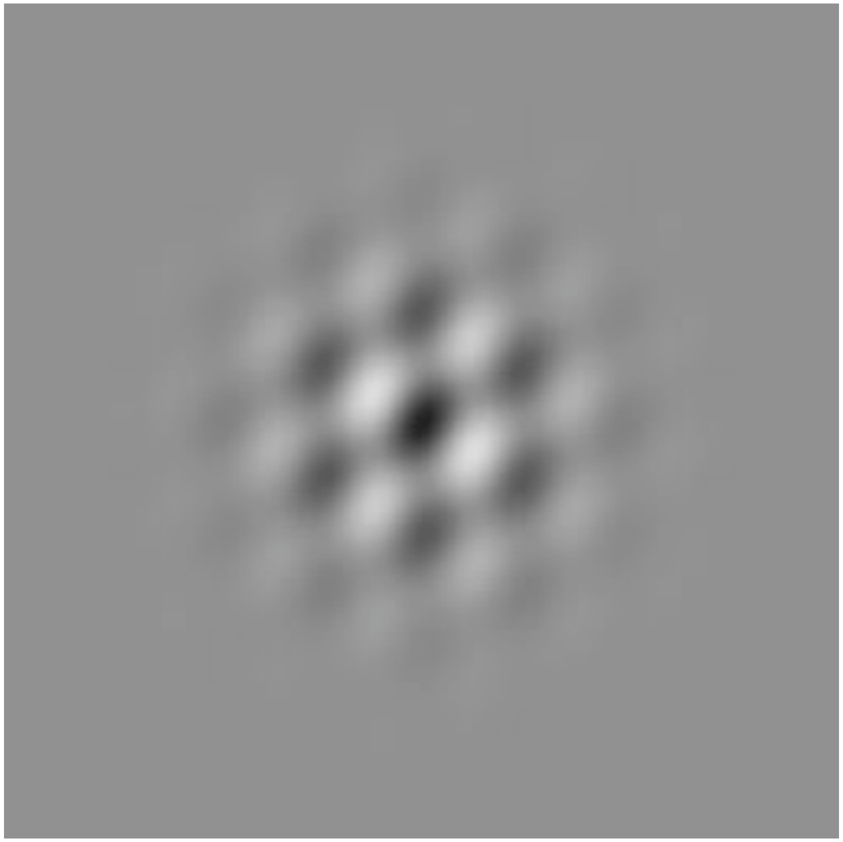
Direction-interaction: Gratings



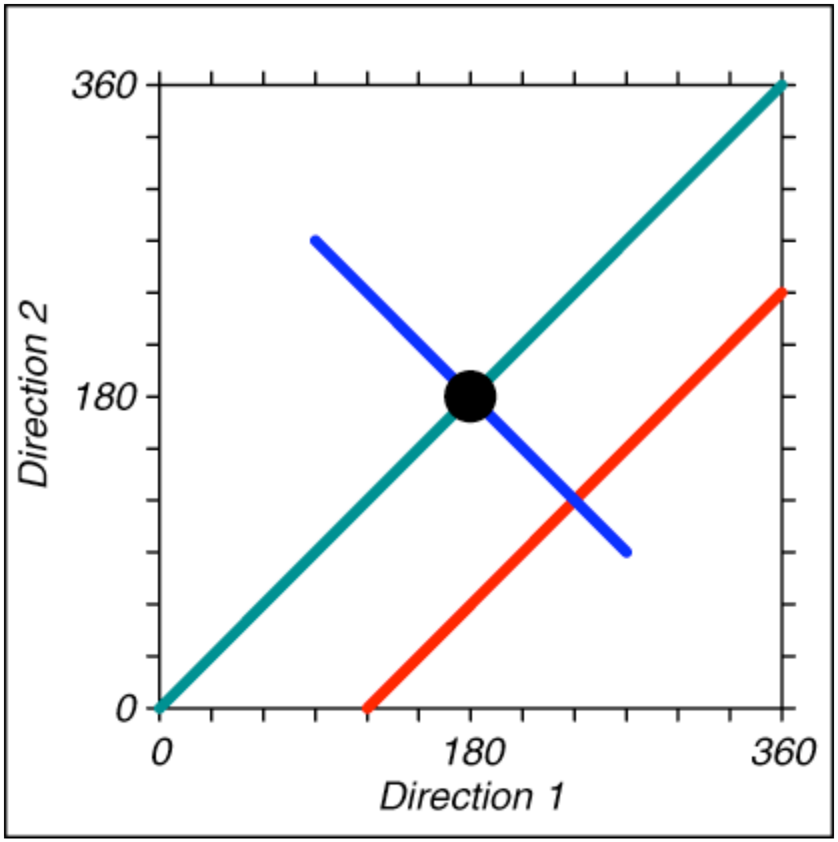


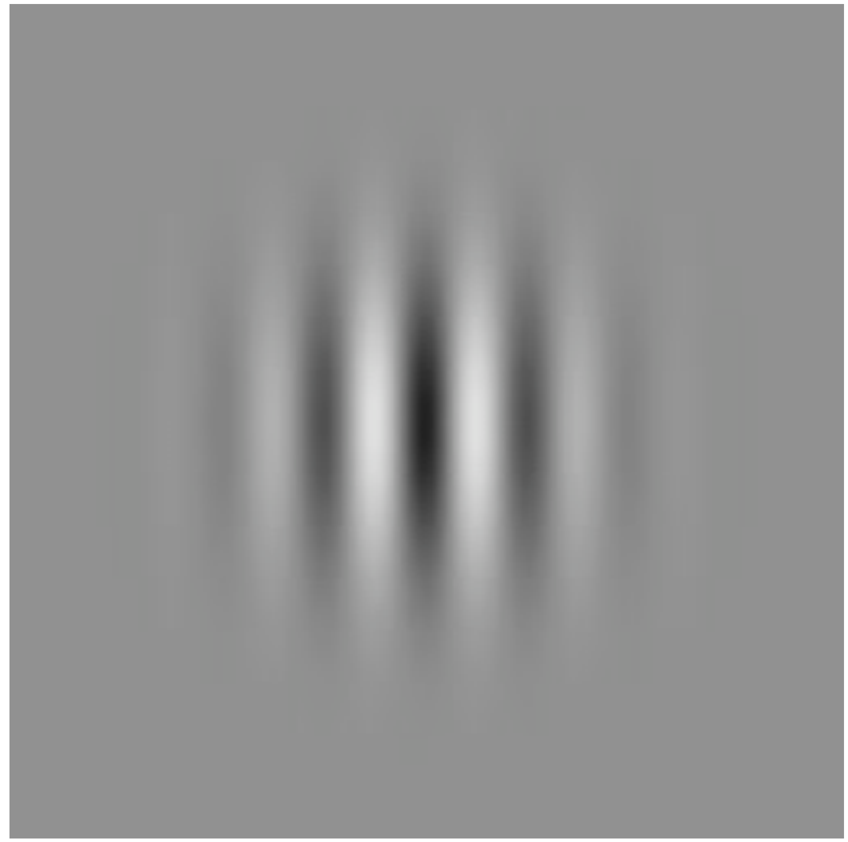
Direction-interaction: Plaids



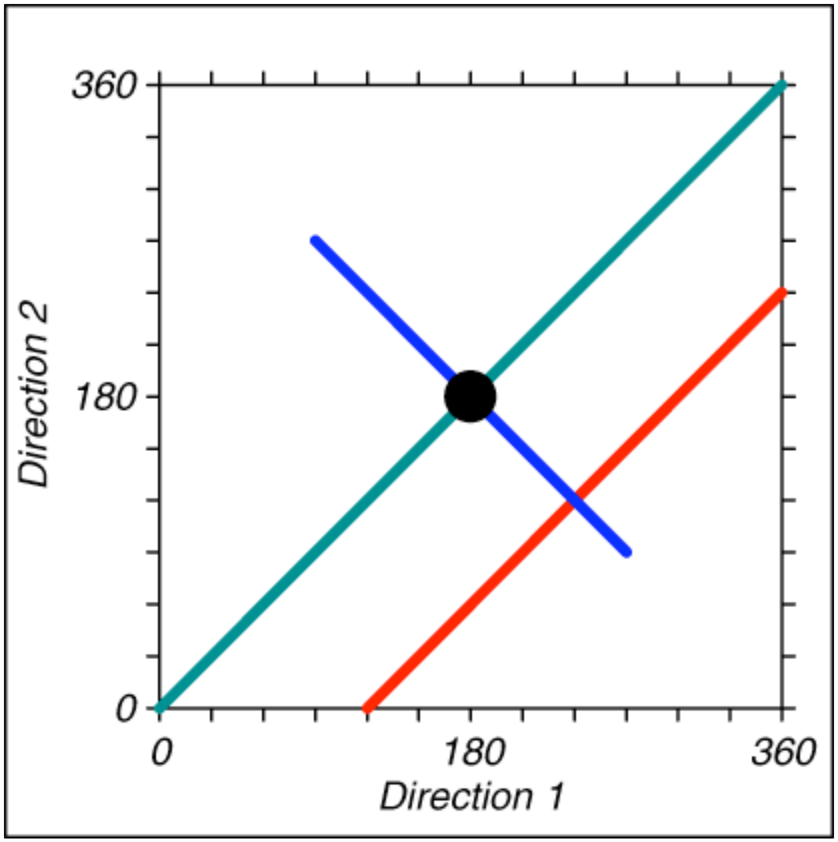


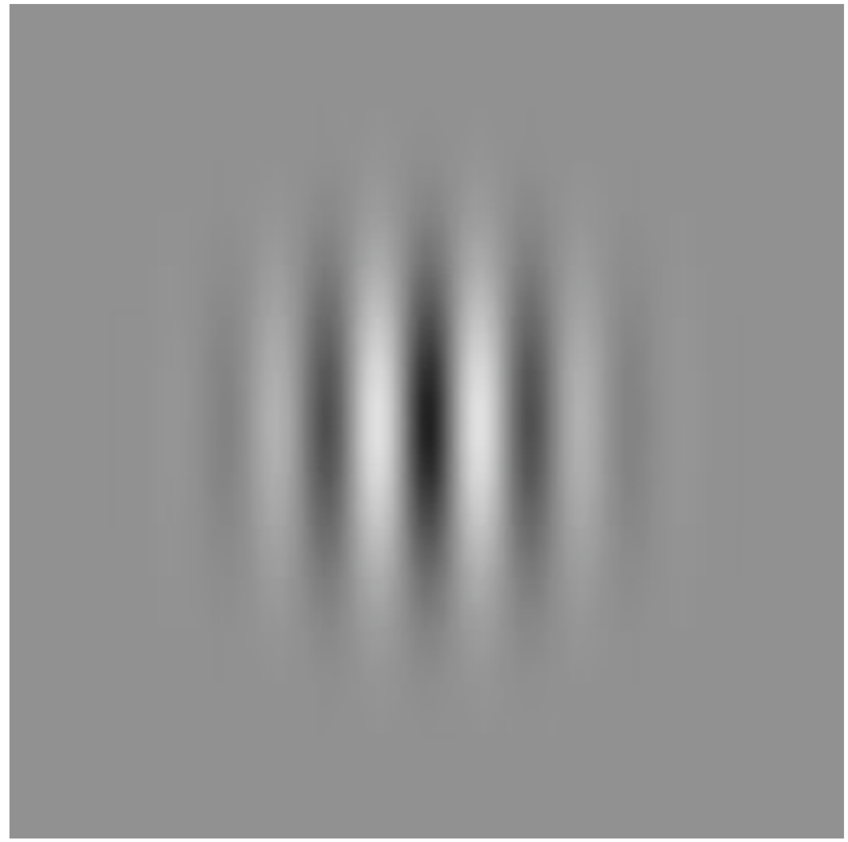
Direction-interaction:
One common component

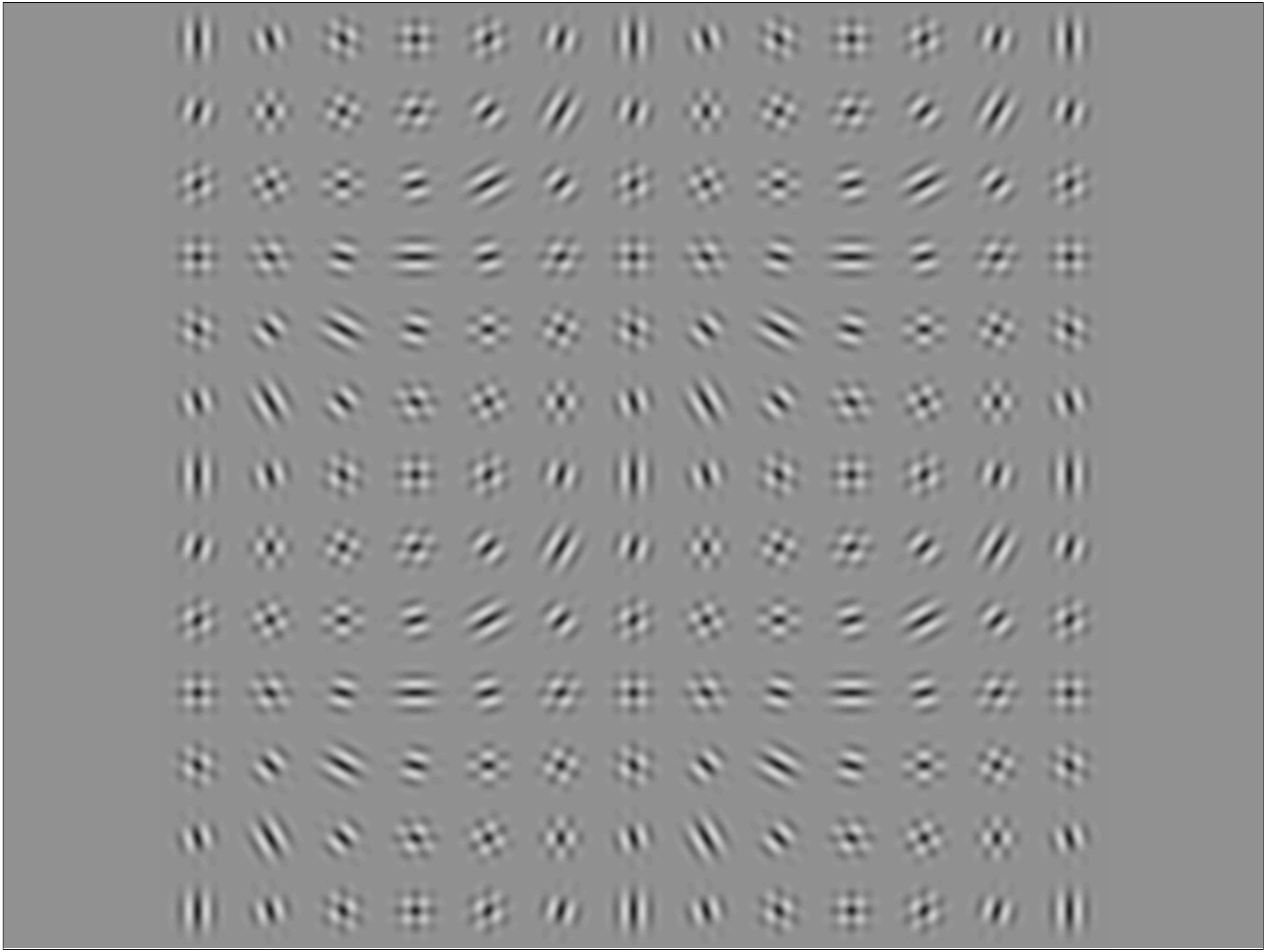


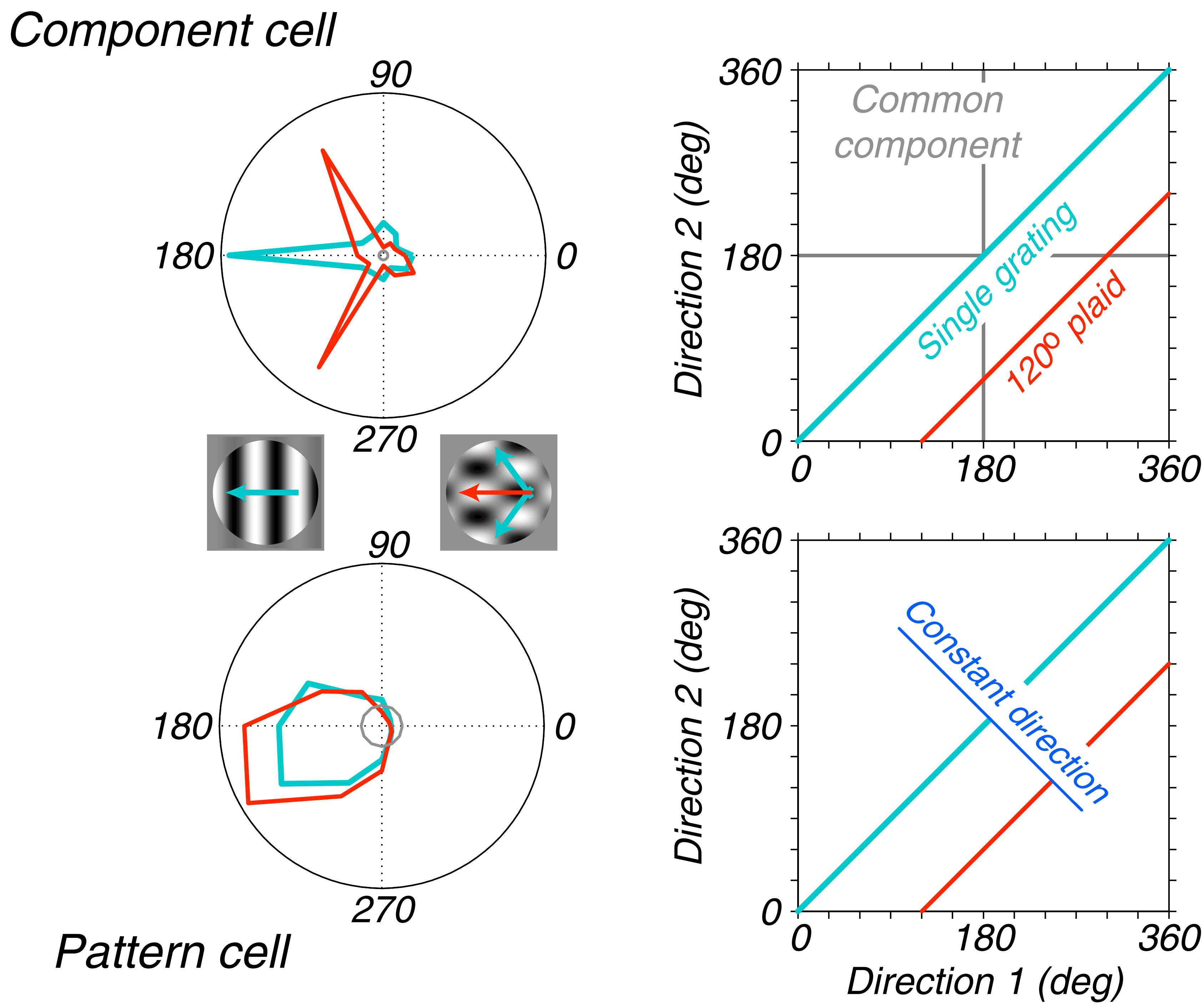


Direction-interaction:
Common axis

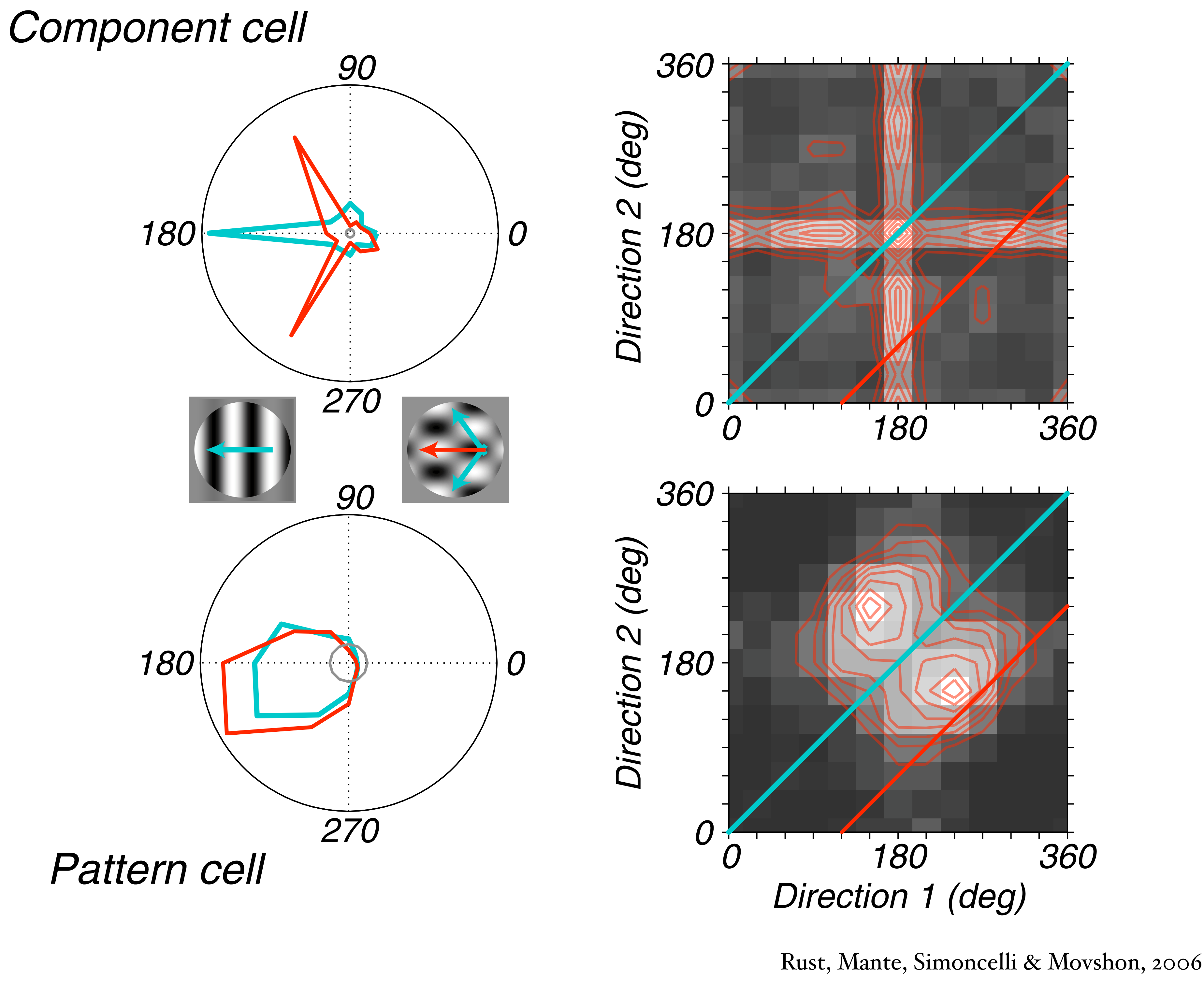








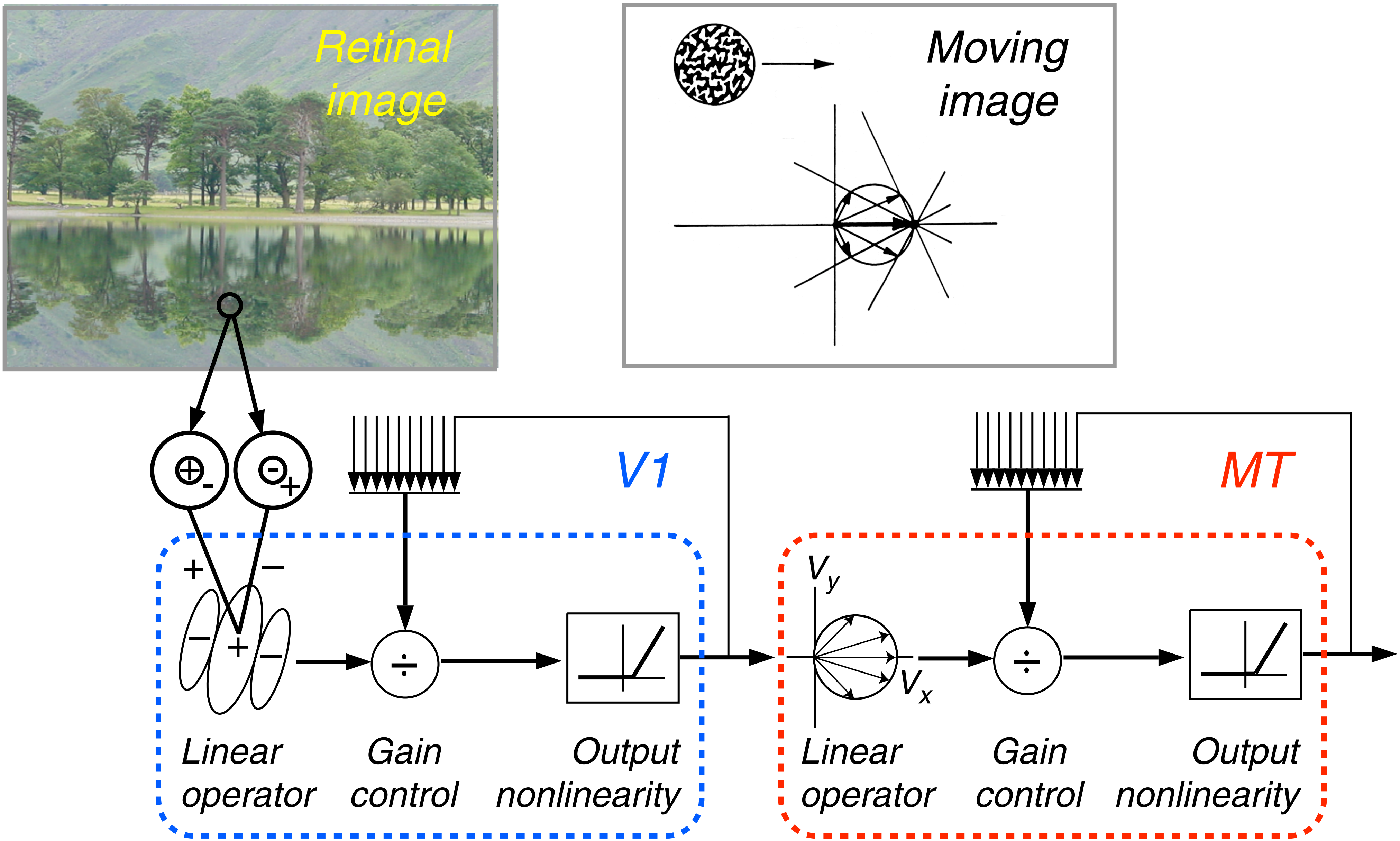
Rust, Mante, Simoncelli & Movshon, 2007


Component cell
90
180
0
270
90
180
0
270
Pattern cell
360
180
0
Direction 2 (deg)
0
180
360
360
180
0
Direction 2 (deg)
0
180
360
Direction 1 (deg)
Rust, Mante, Simoncelli & Movshon, 2006

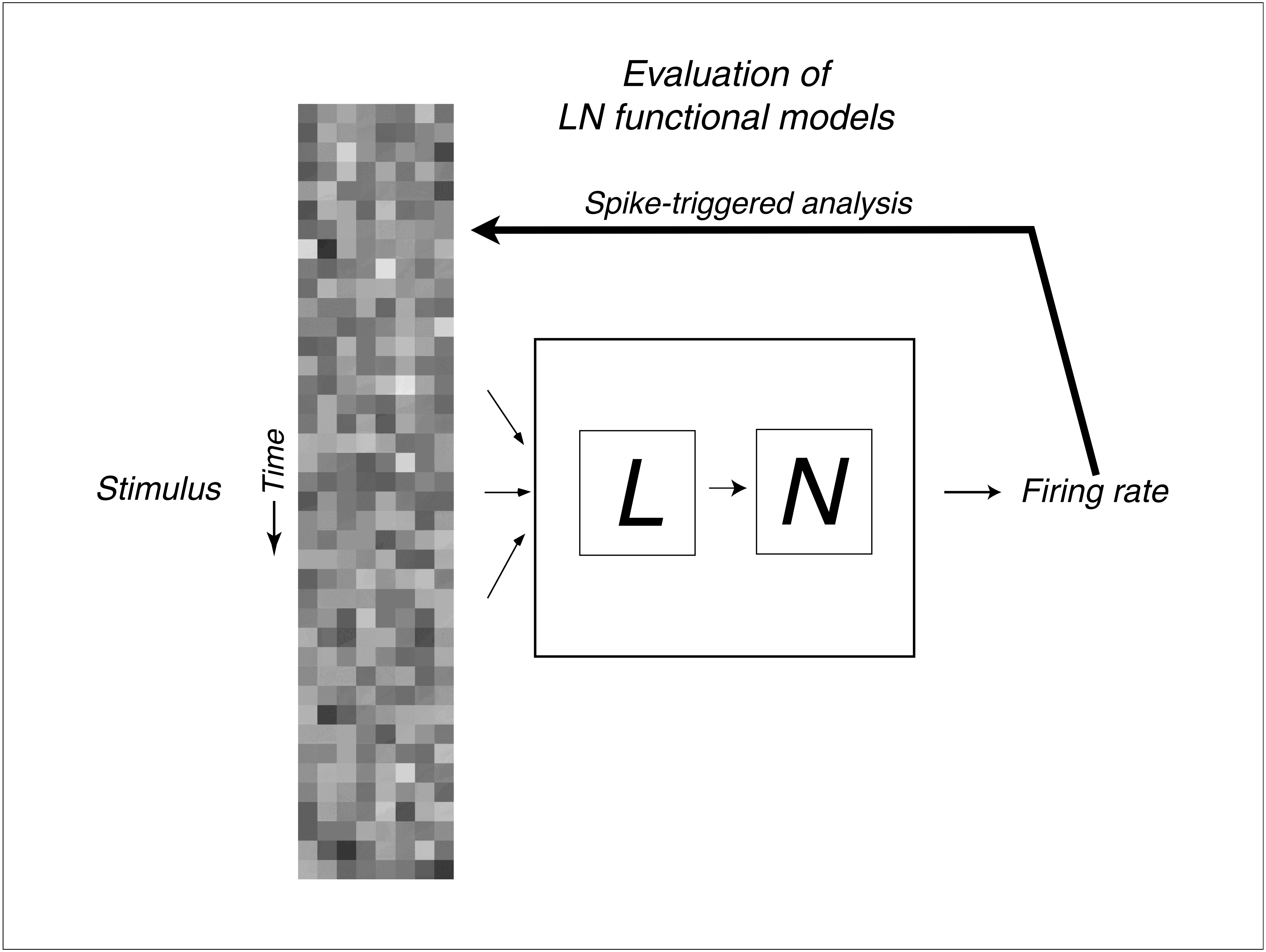
Recovering and validating the model:

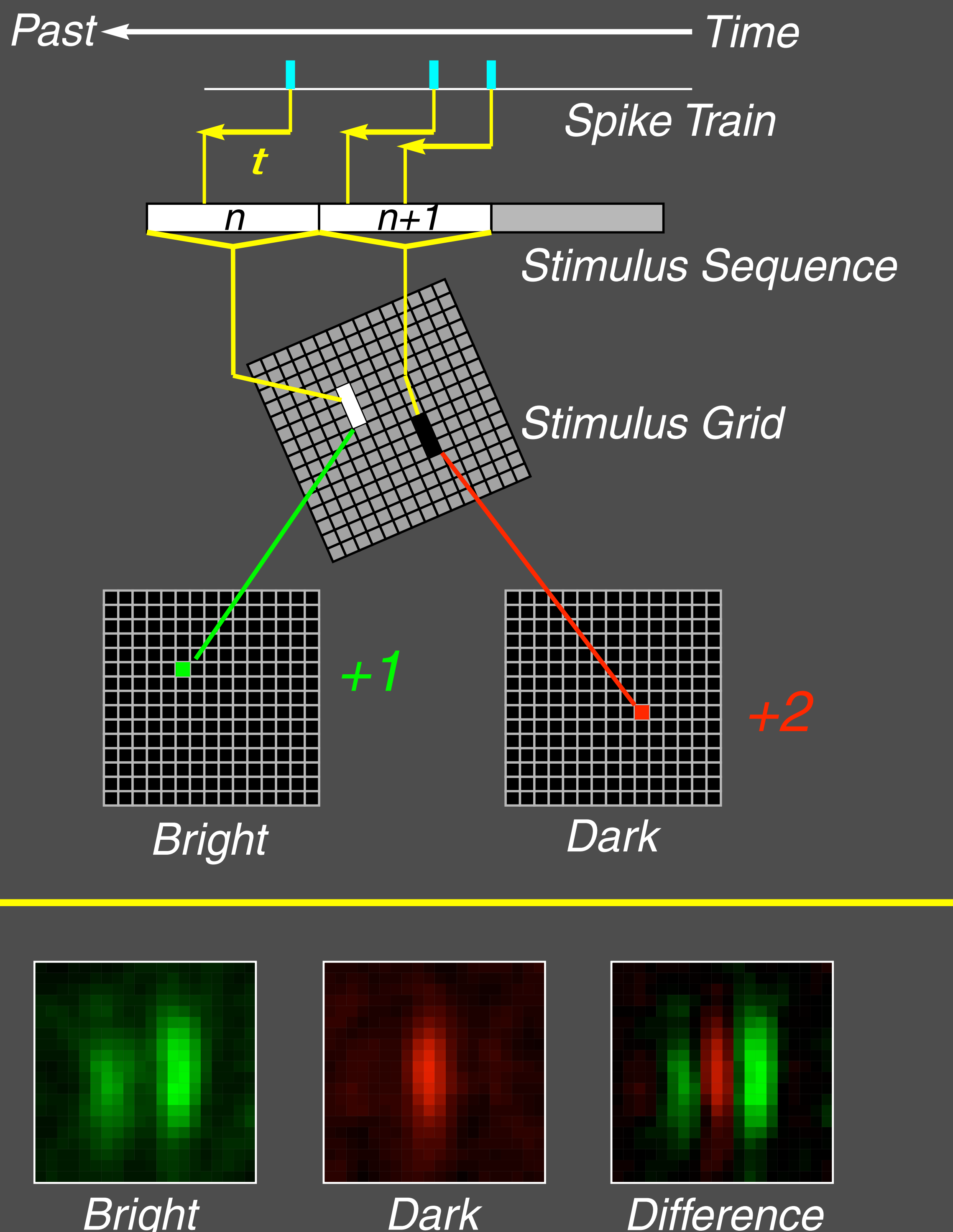
1. A rich test set

2. An evaluation method

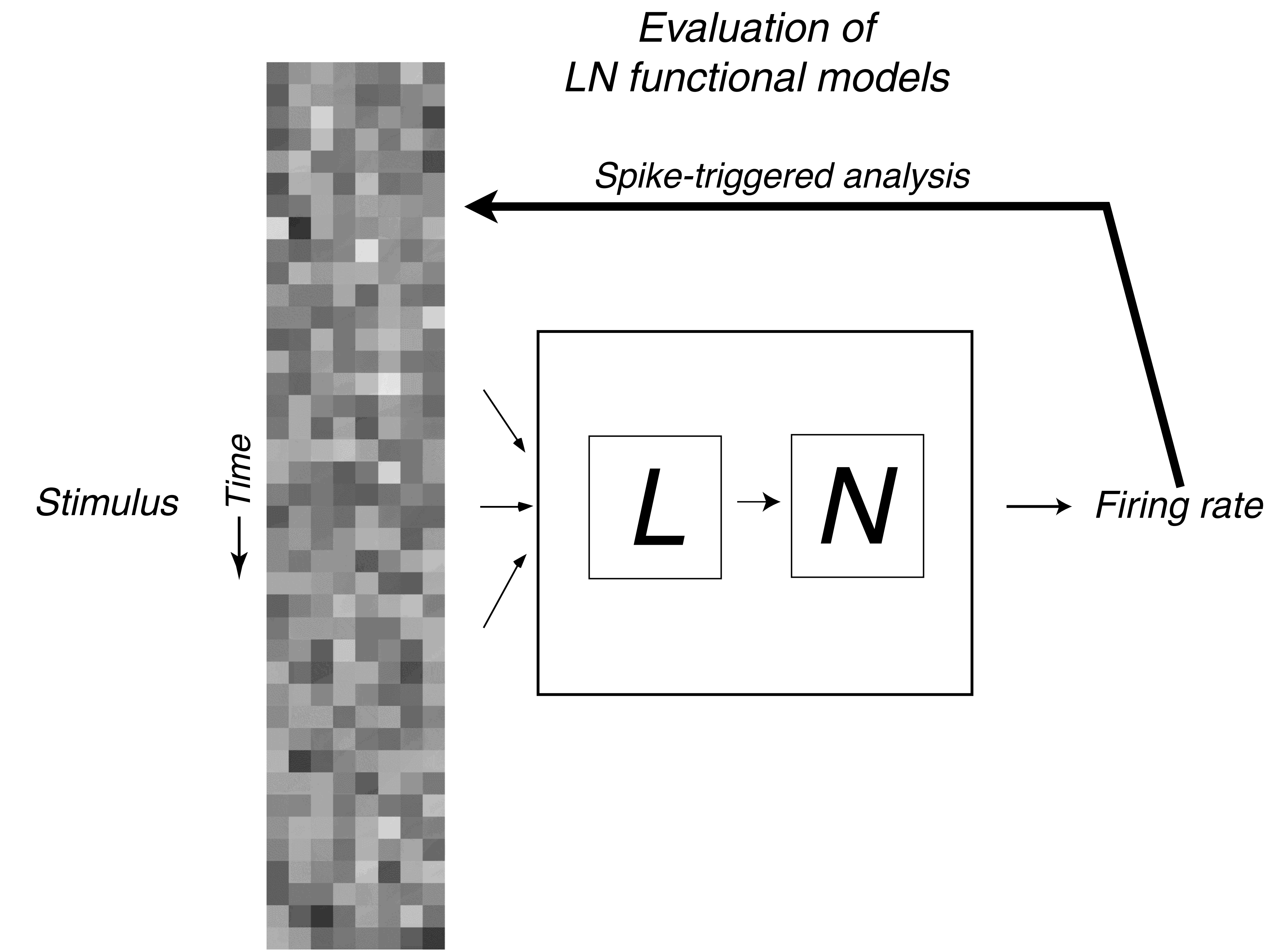


Simoncelli & Heeger, 1998

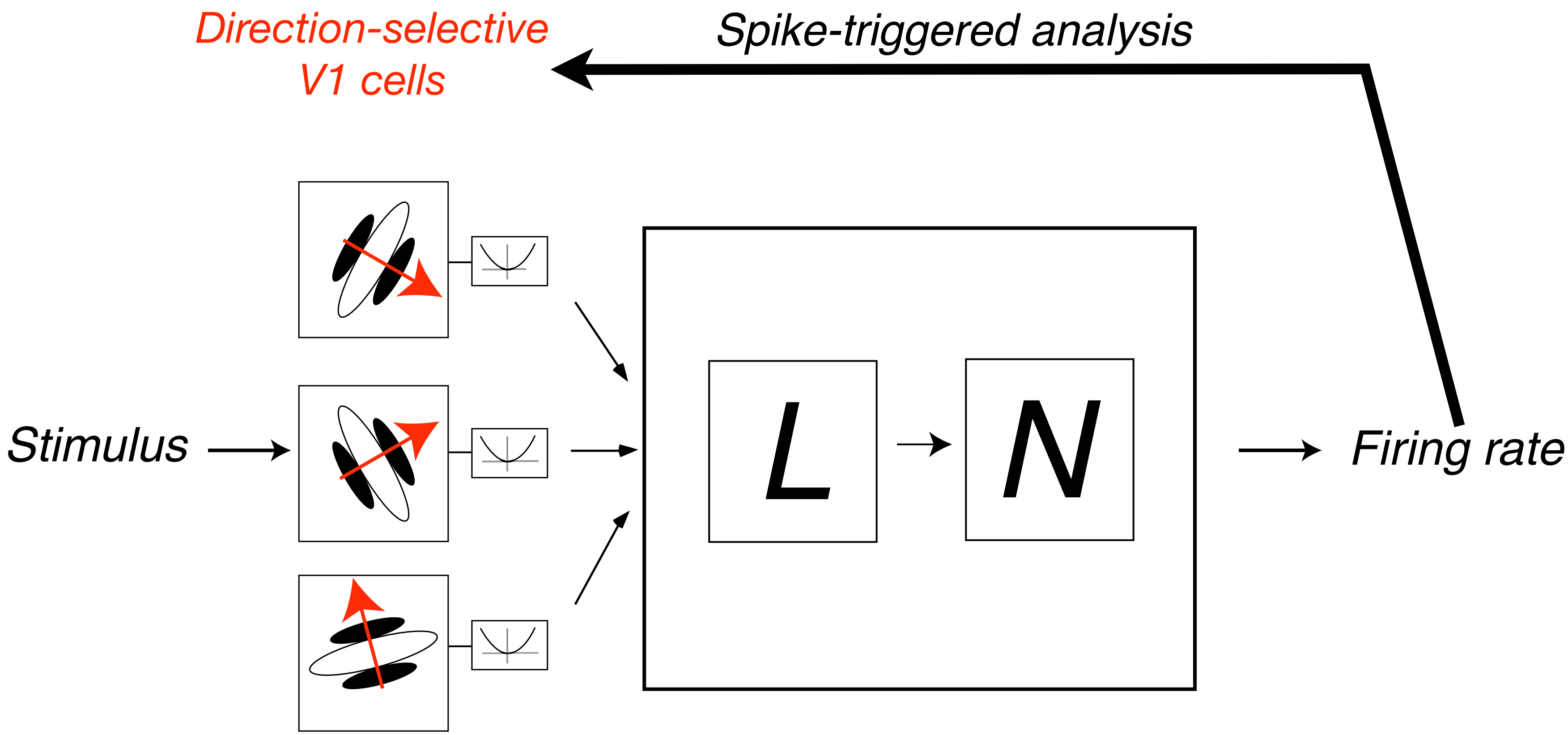

Evaluation of
LN functional models
Spike-triggered analysis
Stimulus
Time
L
N
Firing rate

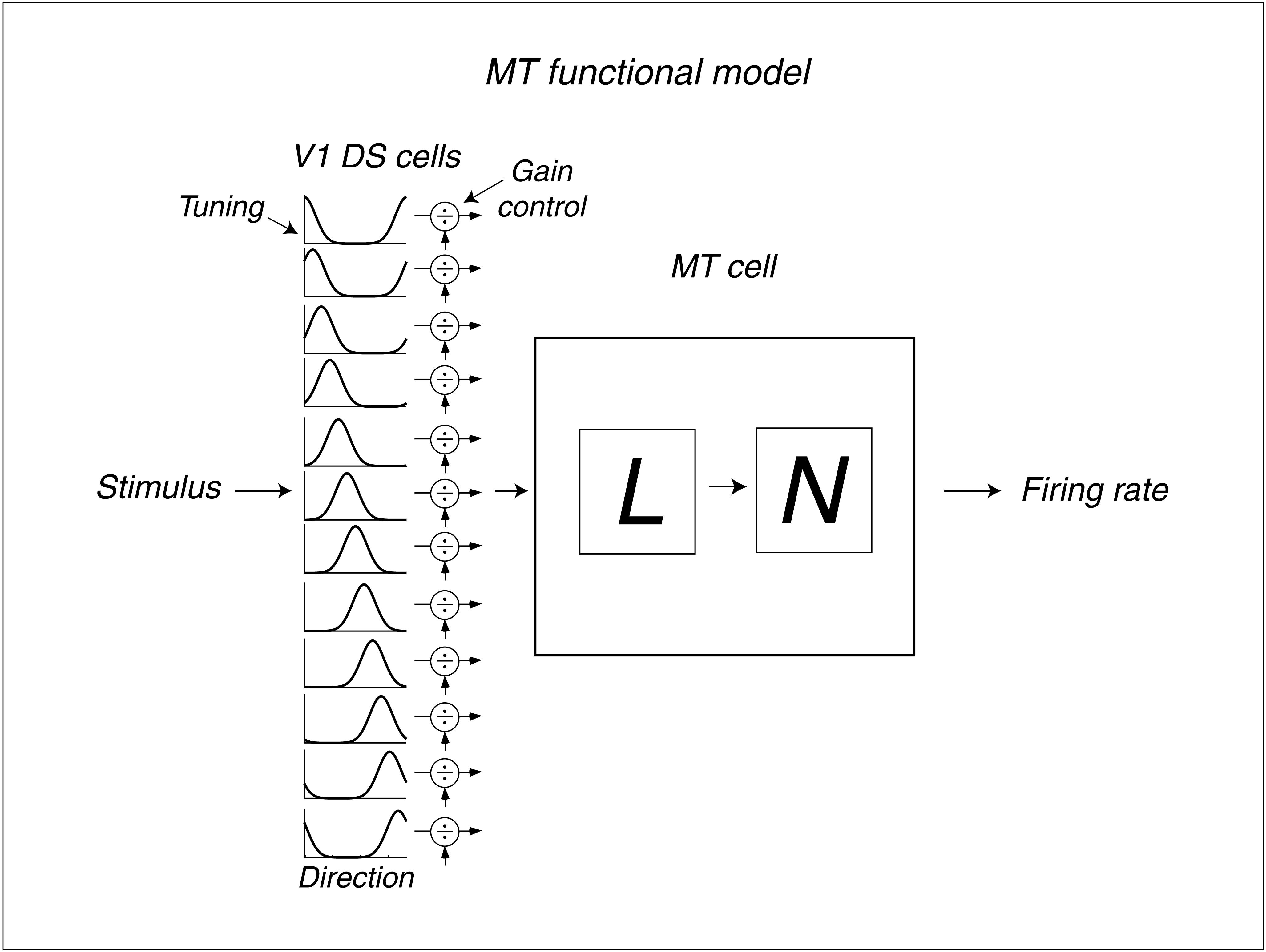


DeAngelis, Ohzawa & Freeman, 1995

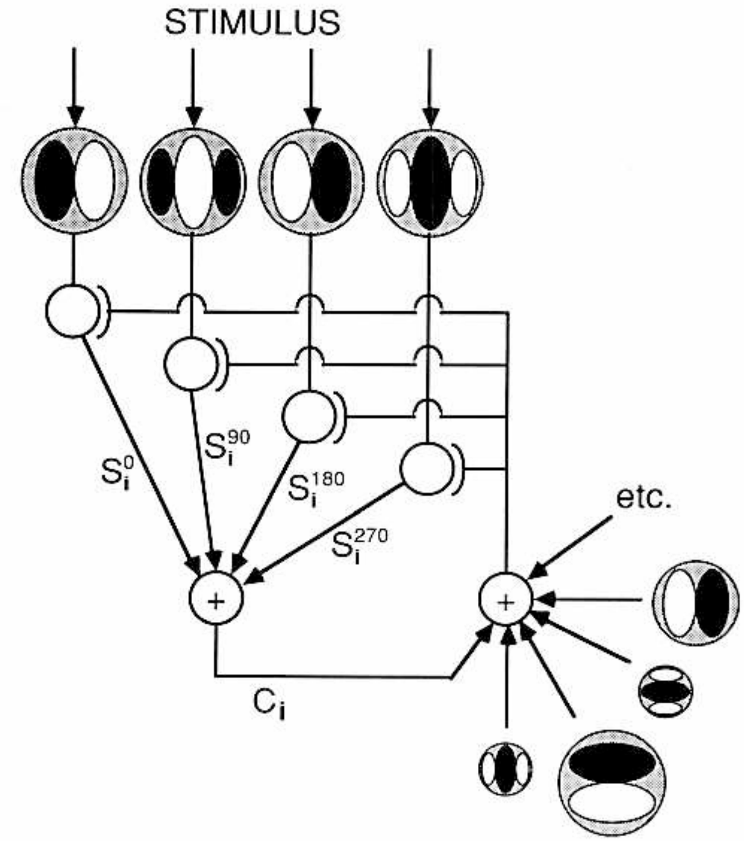

Evaluation of
LN functional models
Spike-triggered analysis
Stimulus
Time
L
N
Firing rate

MT functional model

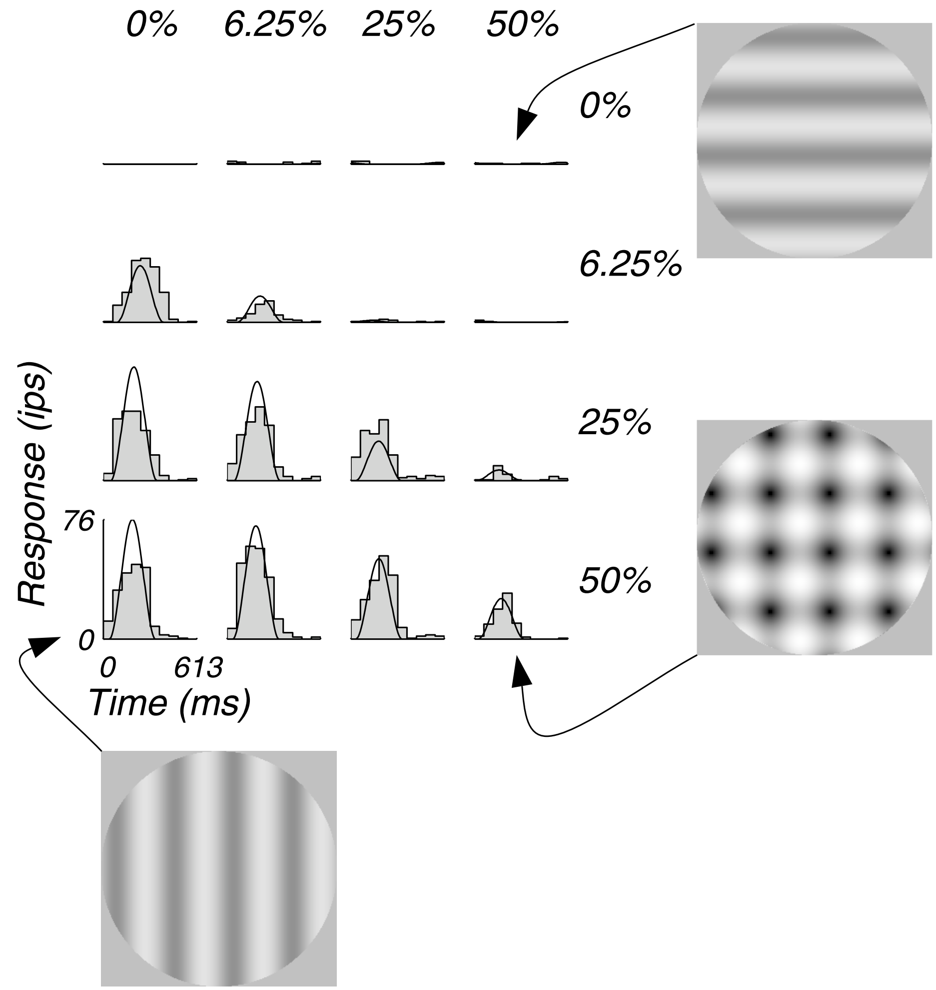



MT functional model
V1 DS cells
Gain
control
Tuning
MT cell
Stimulus
L
N
Firing rate
Direction

Gain control in V1: the untuned component

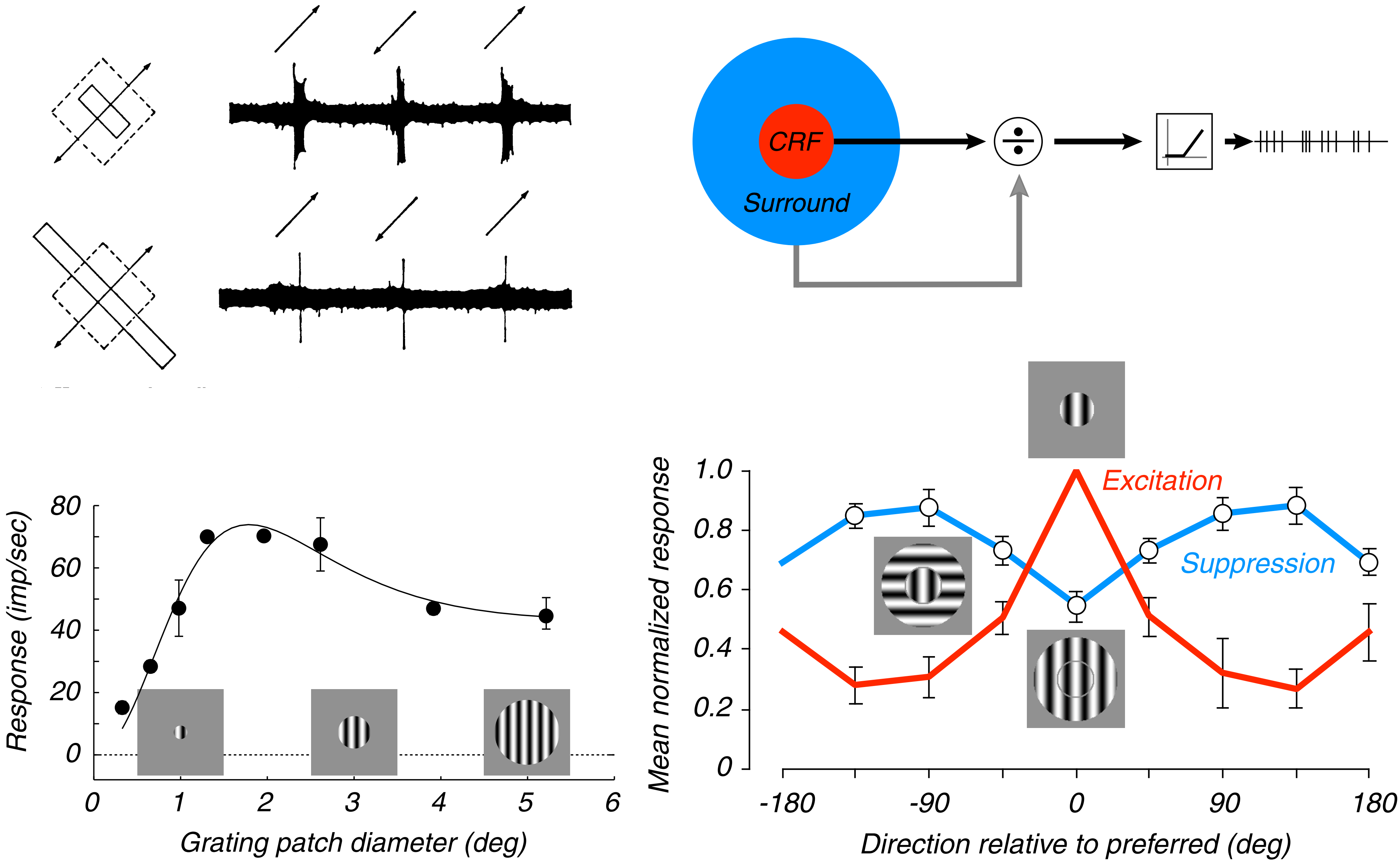


Heeger, 1992



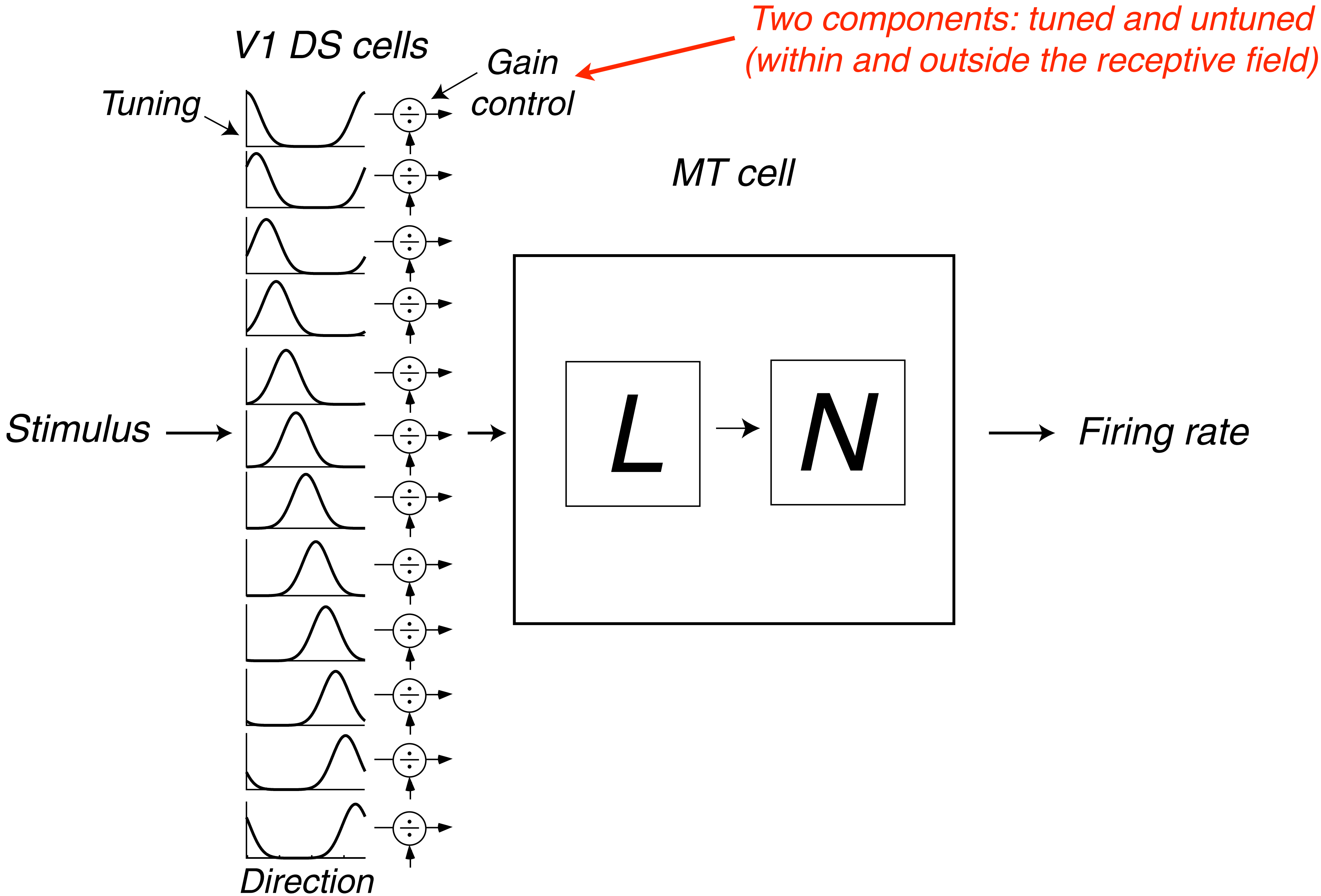
Carandini, Heeger & Movshon, 1997

Gain control in V1: the tuned component

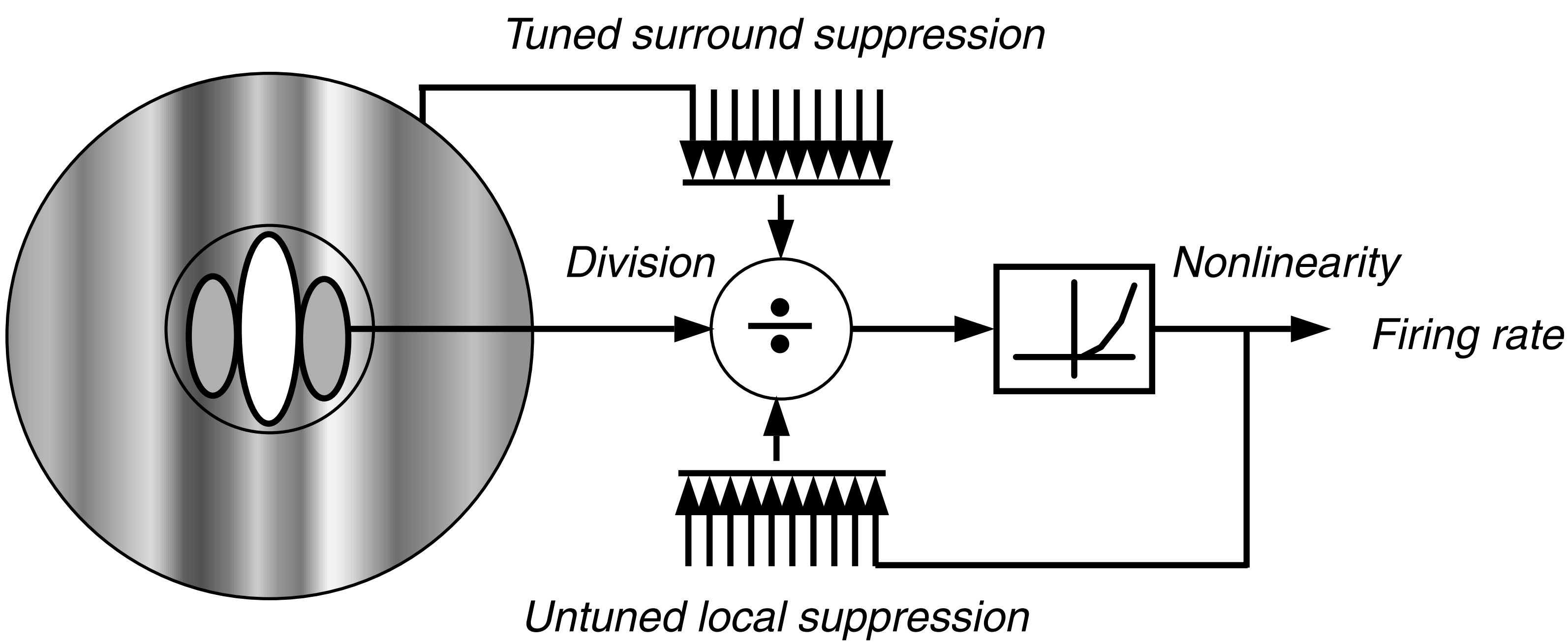


Hubel & Wiesel, 1968; Cavanaugh, Bair & Movshon, 2002

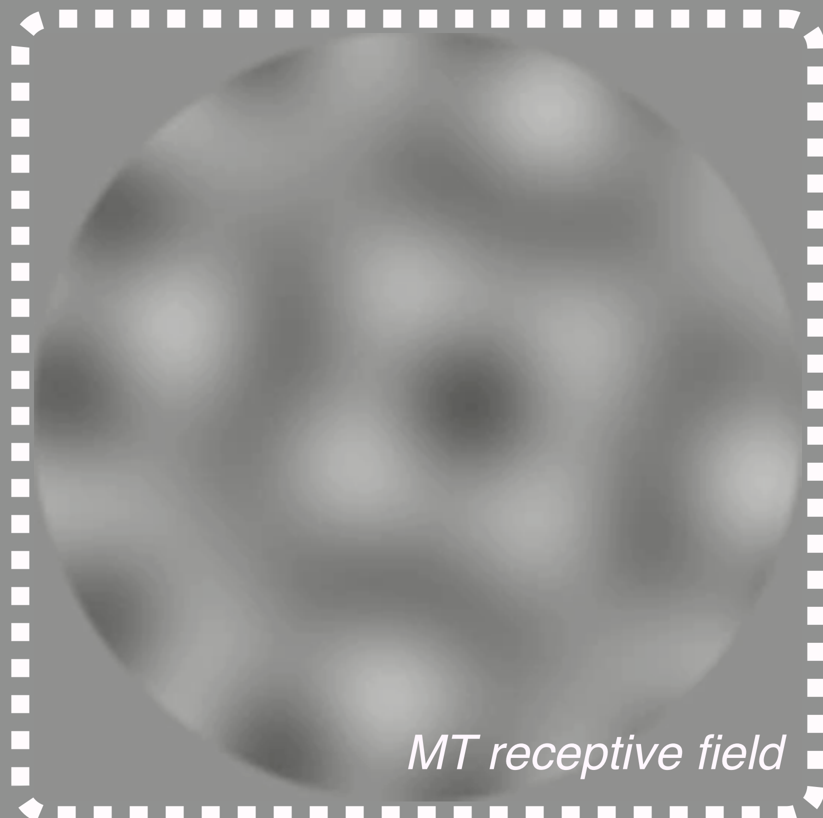
MT functional model

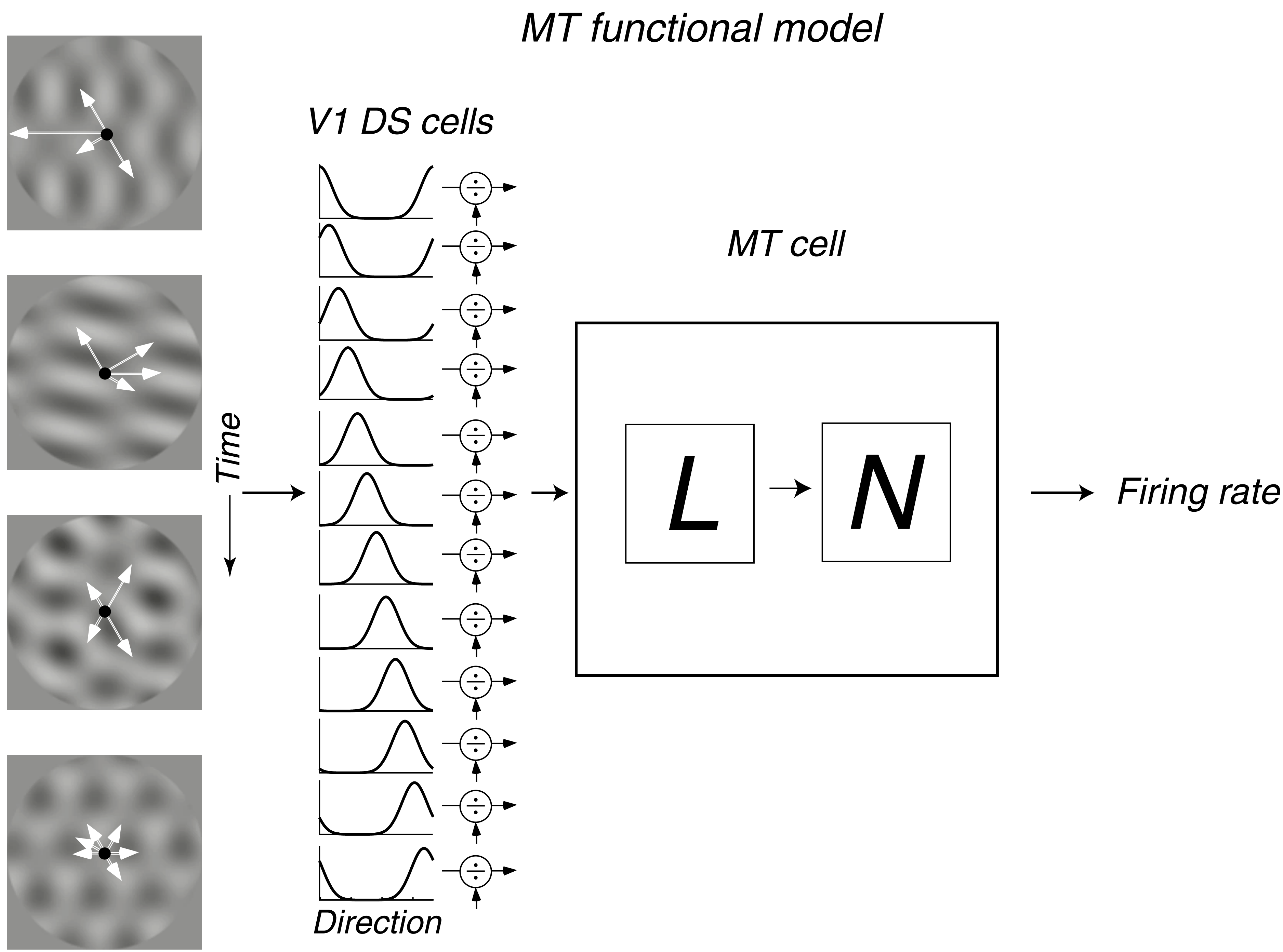


Gain control in V1

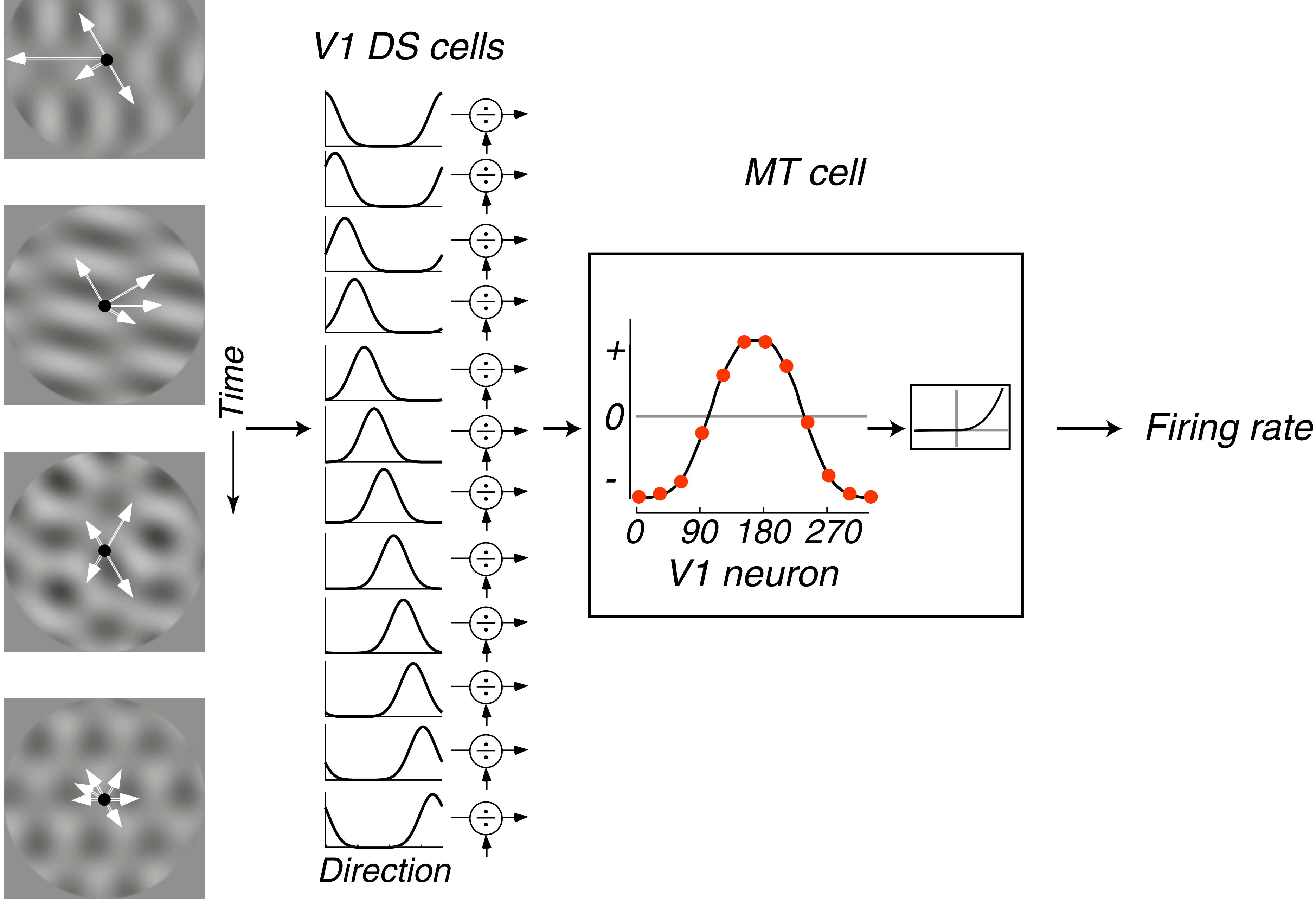


MT functional model:
the characterization stimulus

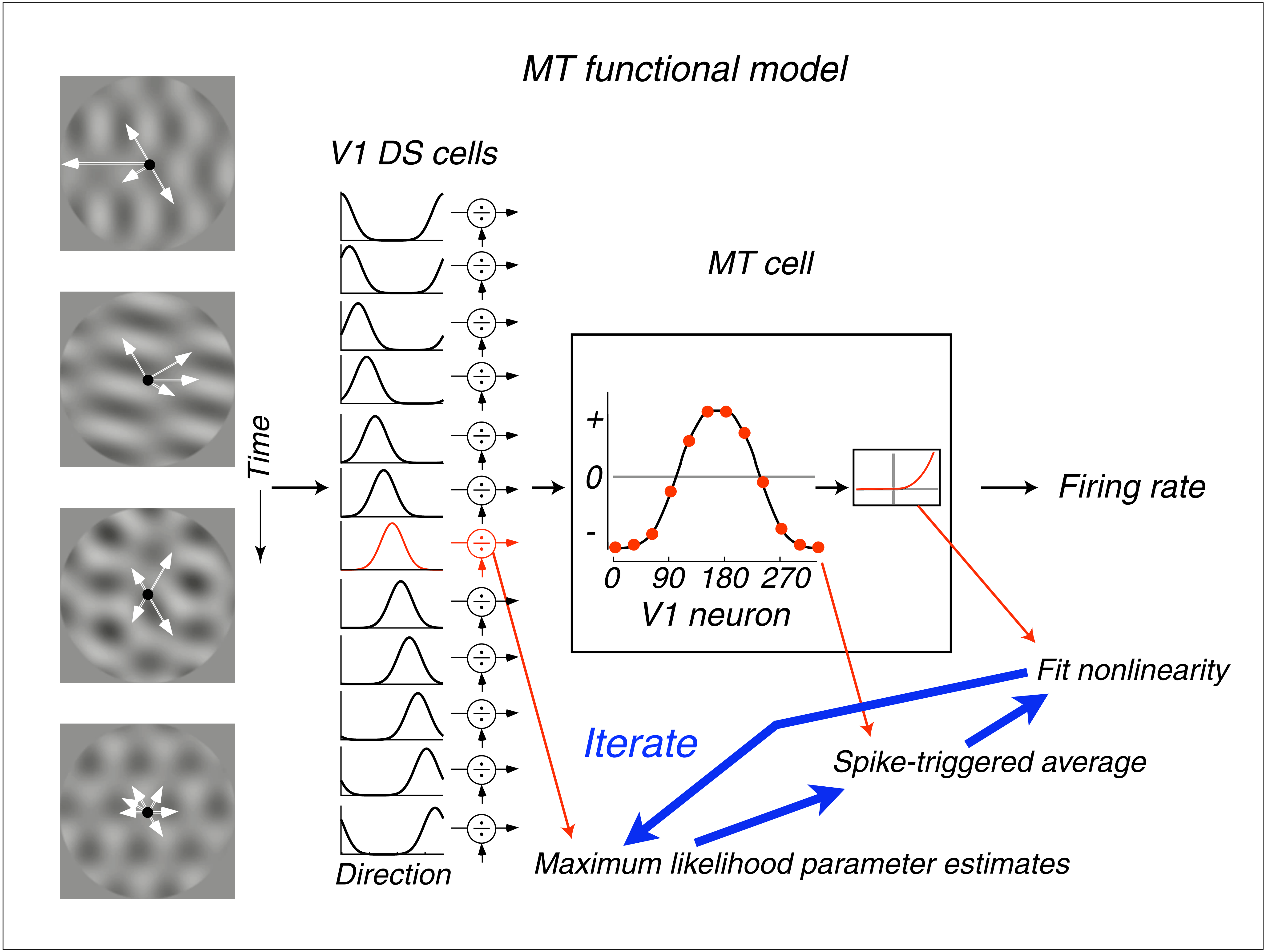



MT functional model
V1 DS cells
Time
Direction
MT cell
L
N
Firing rate

MT functional model

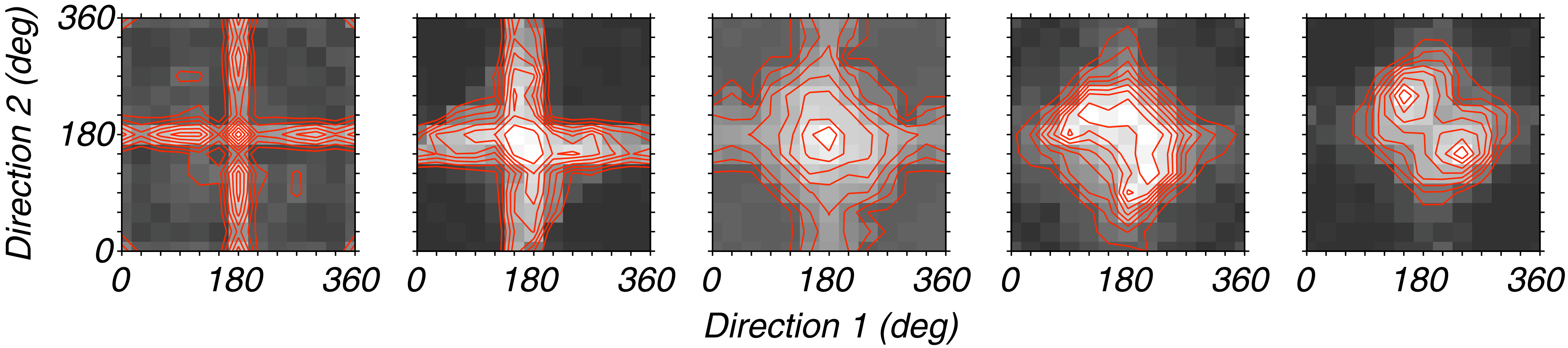


Rust, Mante, Simoncelli & Movshon, 2006

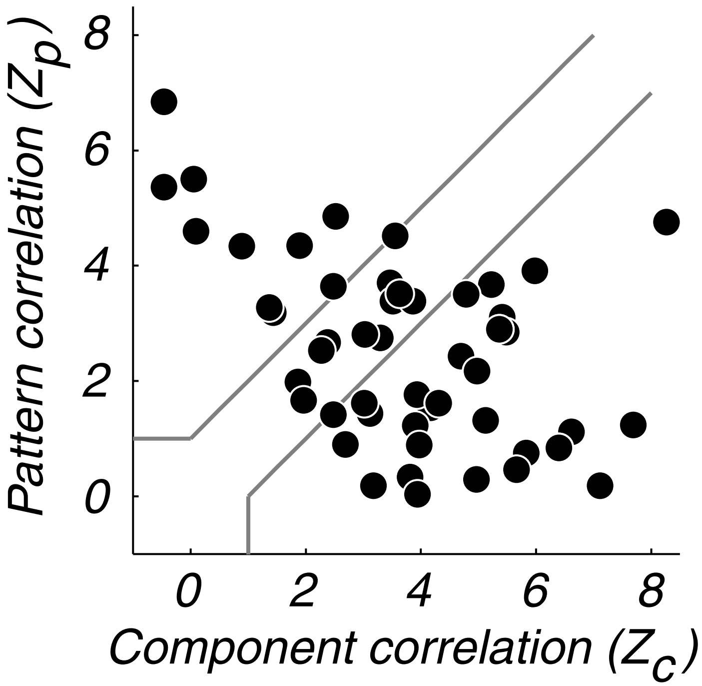

MT functional model
V1 DS cells
Time
Direction
MT cell
+
0
-
0
90
180
270
V1 neuron
Firing rate
Fit nonlinearity
Iterate
Spike-triggered average
Maximum likelihood parameter estimates

Performance of the MT functional model

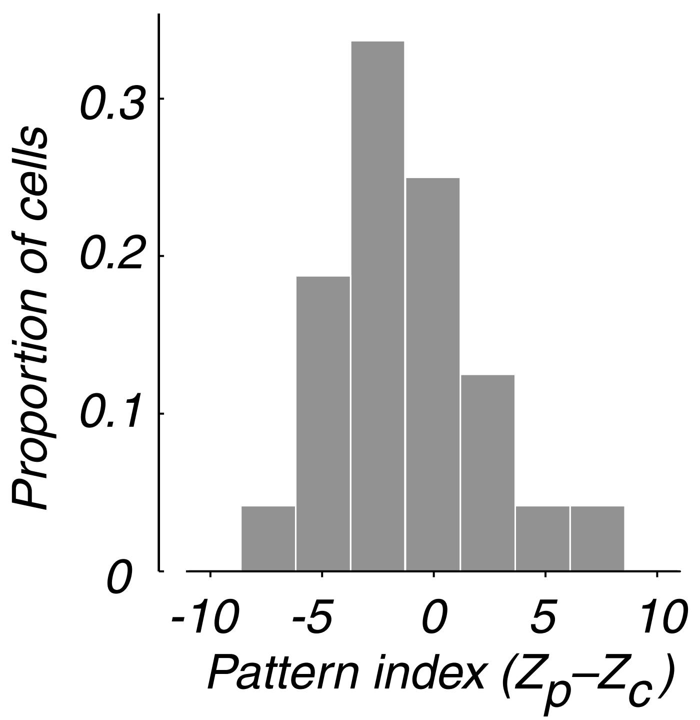
Data



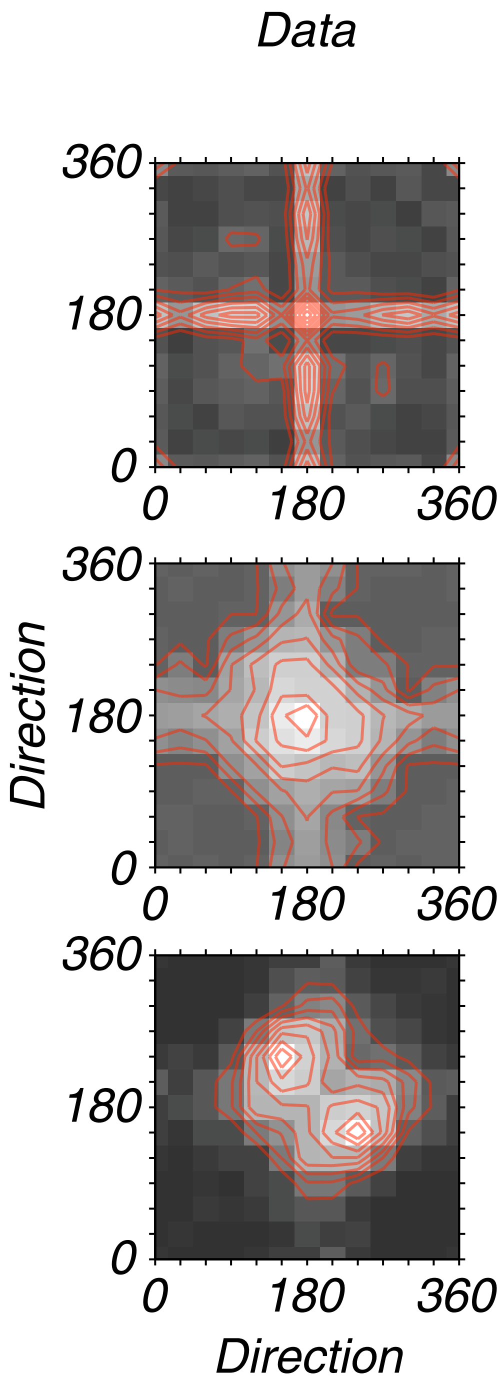
Rust, Mante, Simoncelli & Movshon, 2006

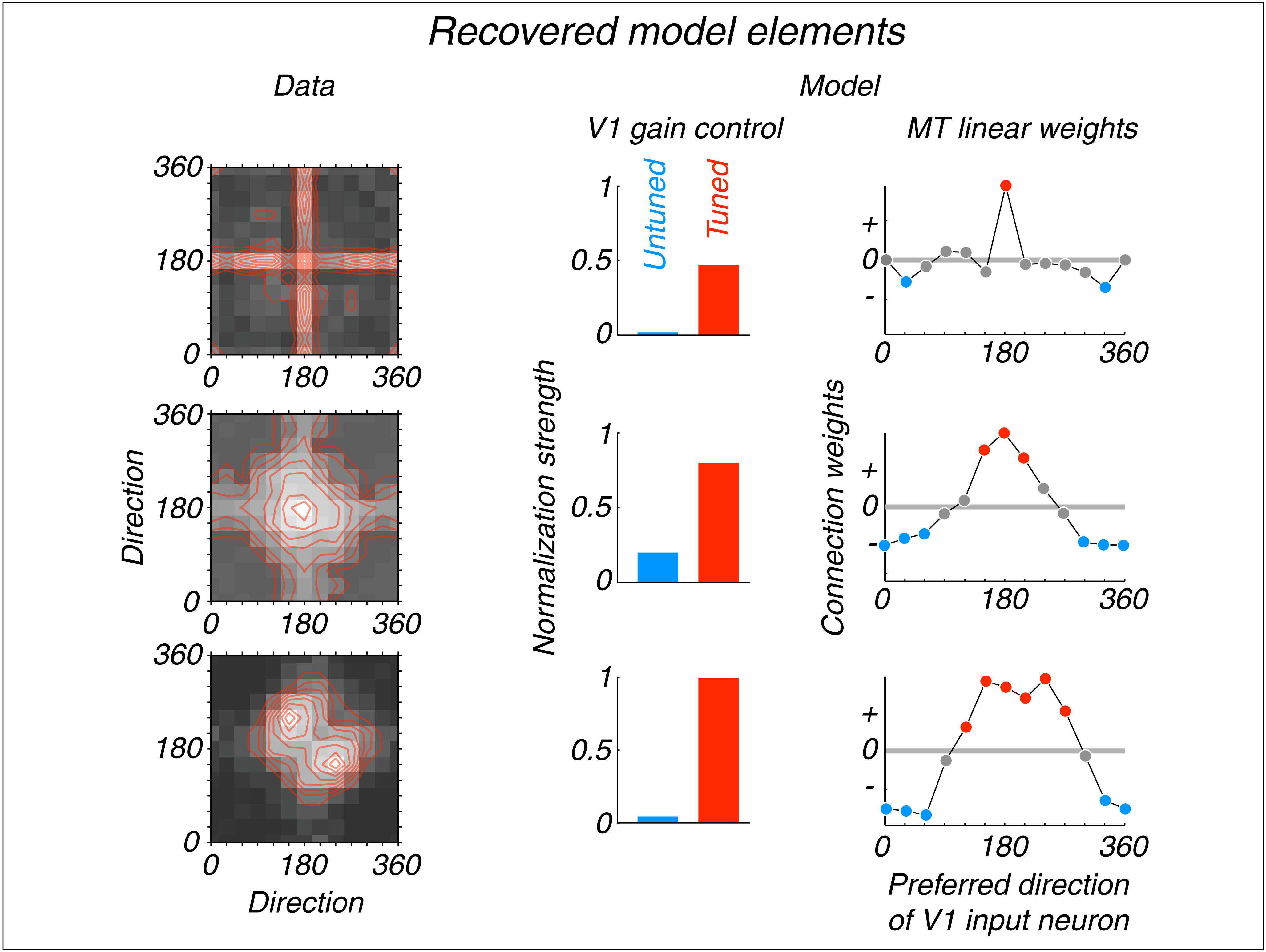


Performance of the MT functional model



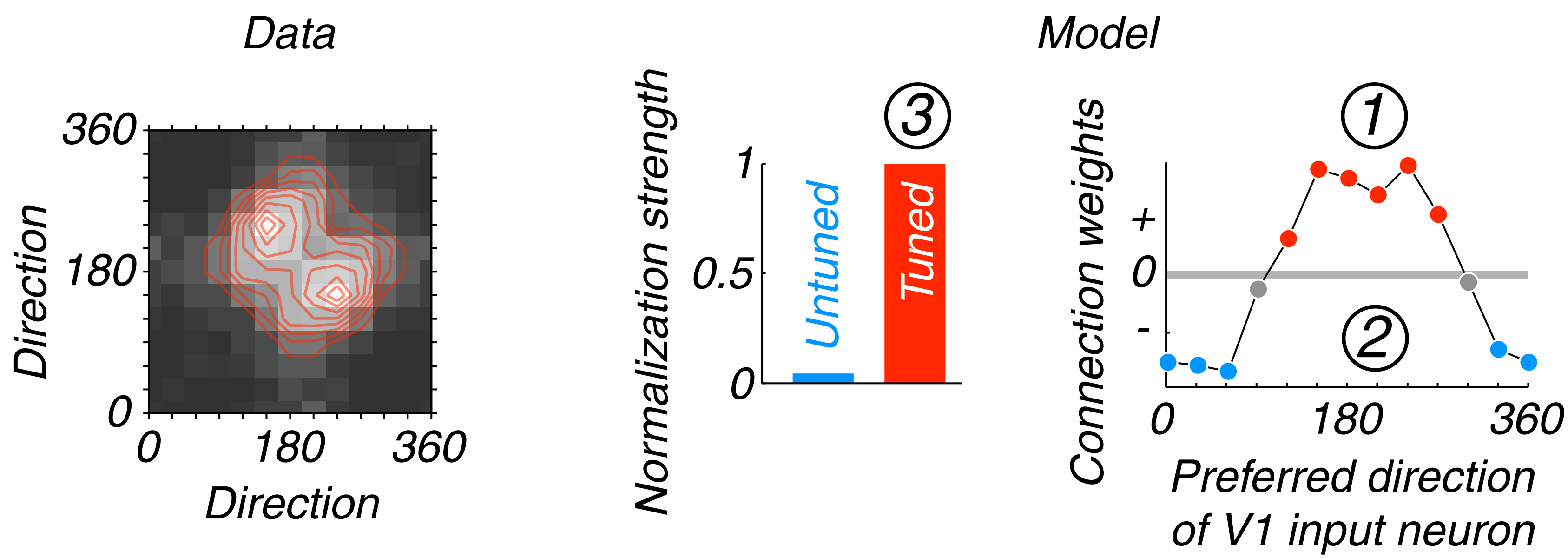
Recovered model elements



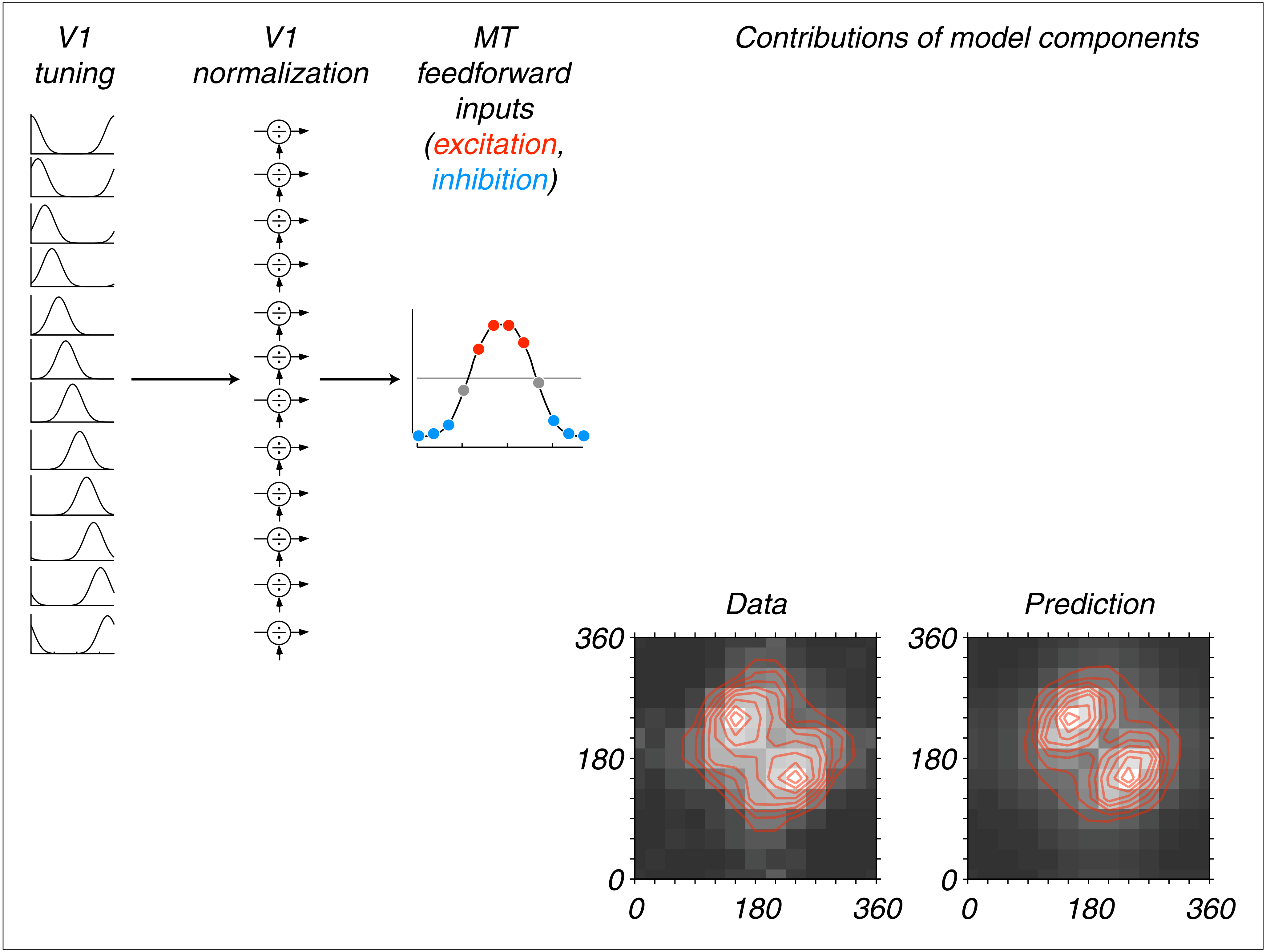

Recovered model elements
Data
Model
V1 gain control
MT linear weights
Untuned
Tuned
Direction
Normalization strength
Connection weights
Preferred direction of V1 input neuron
0
180
360
0.5
1
+
-

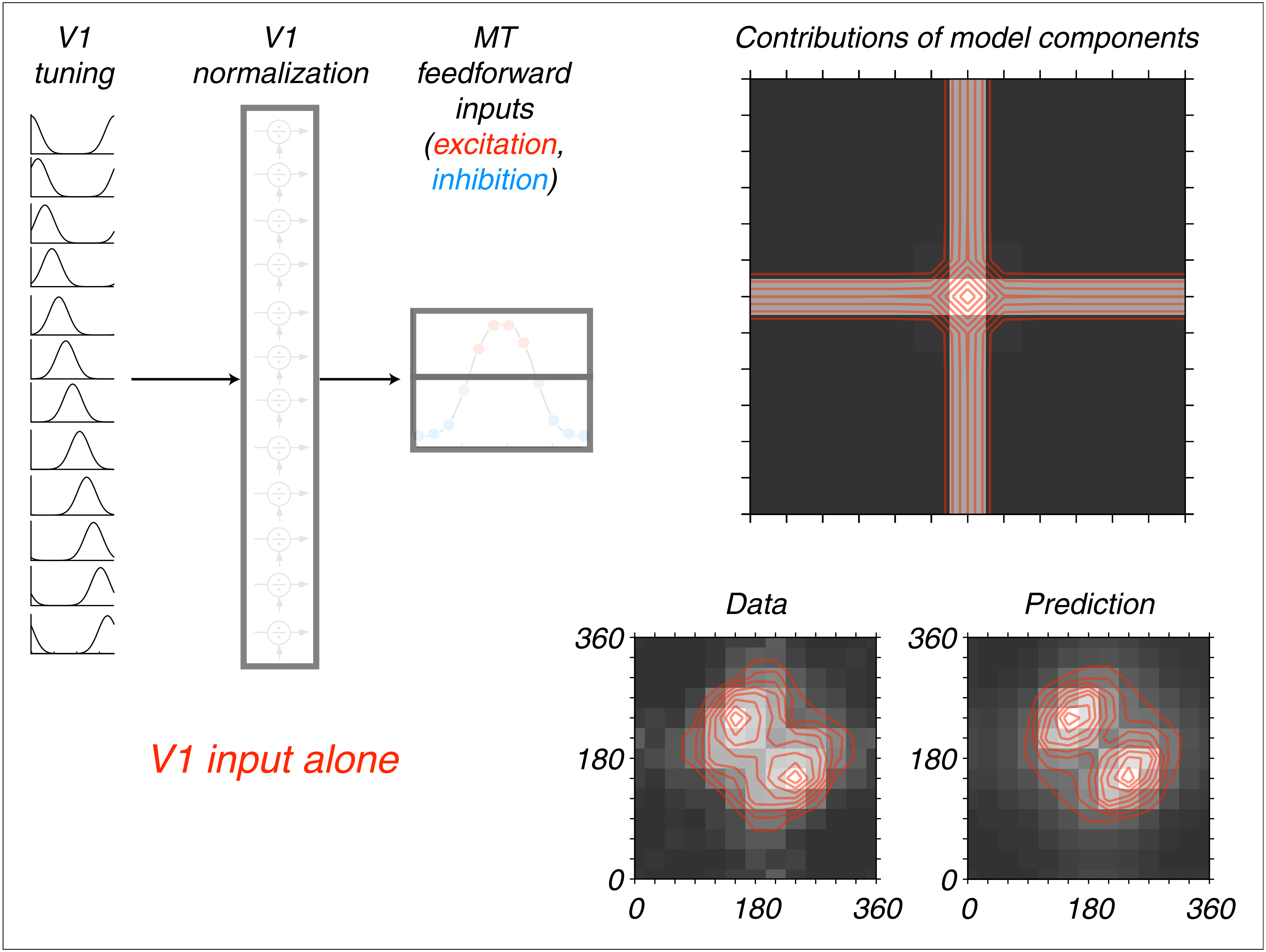
Pattern direction selectivity arises from:

1. *Broad convergence of excitatory inputs*
2. *Strong motion opponent suppression*
3. *Strong tuned gain control*

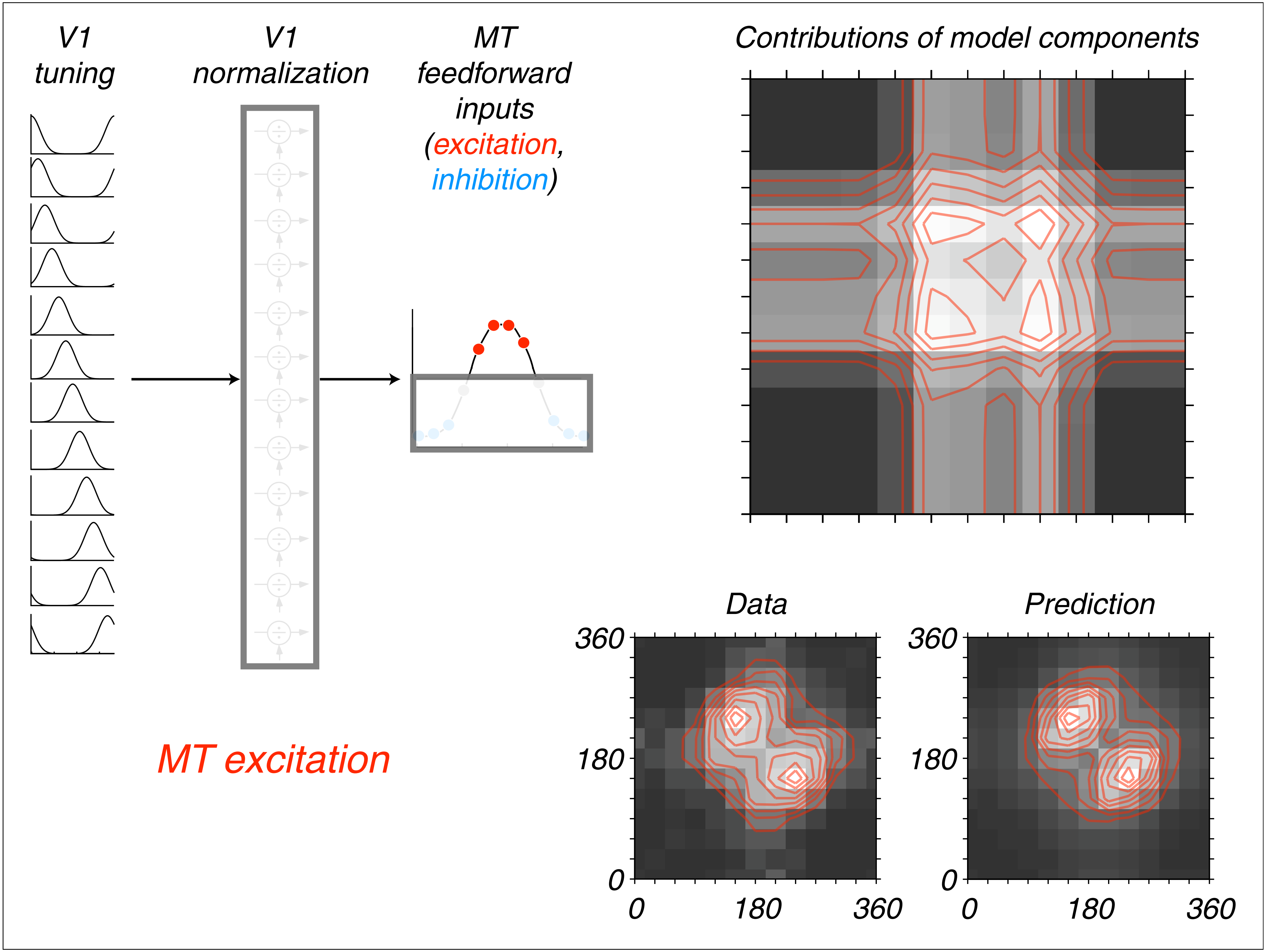


Rust, Mante, Simoncelli & Movshon, 2006

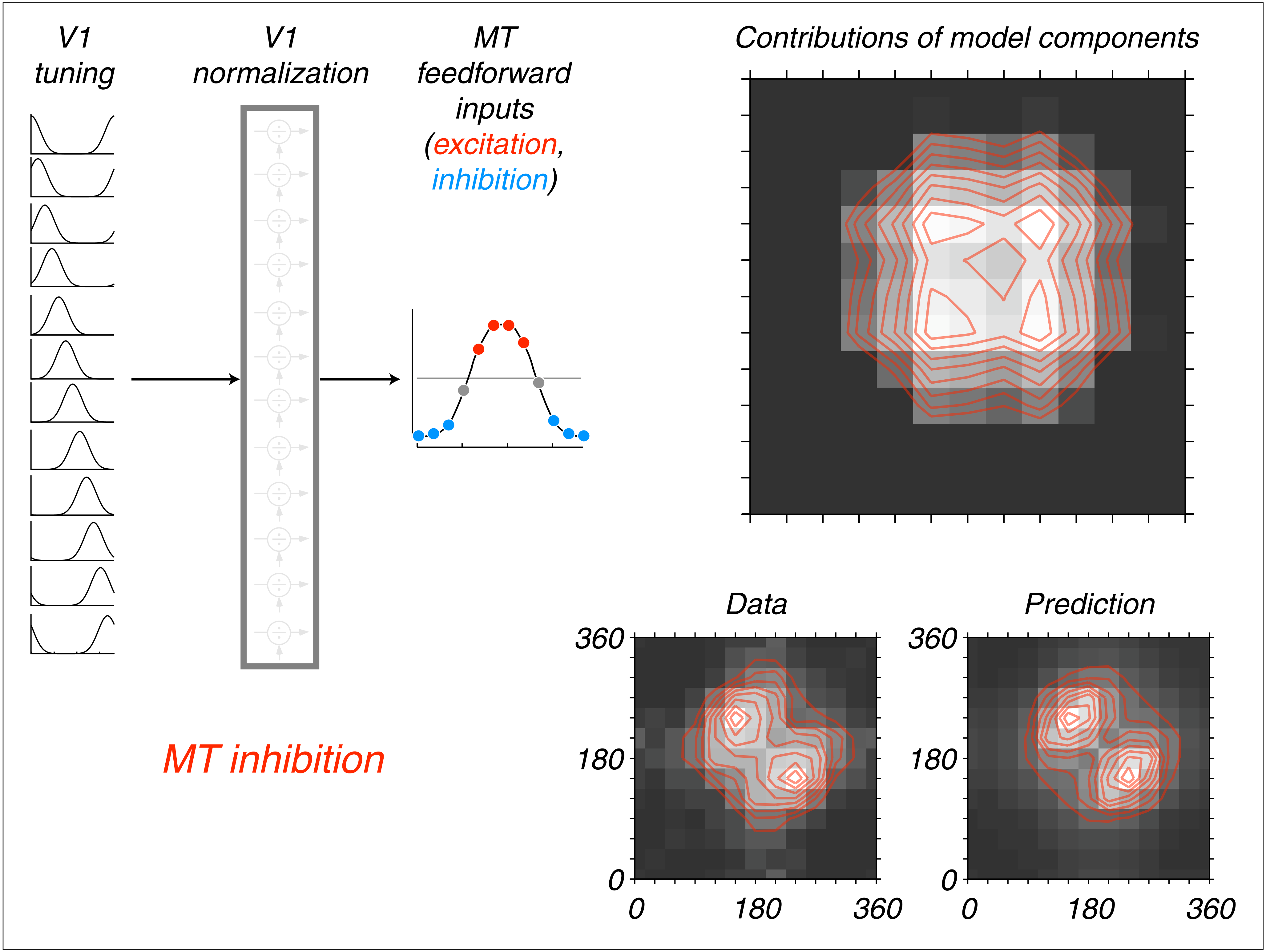

V1
tuning
V1
normalization
MT
feedforward
inputs
(excitation,
inhibition)
Contributions of model components
Data
Prediction
360
180
0
0
180
360
360
180
0
0
180
360

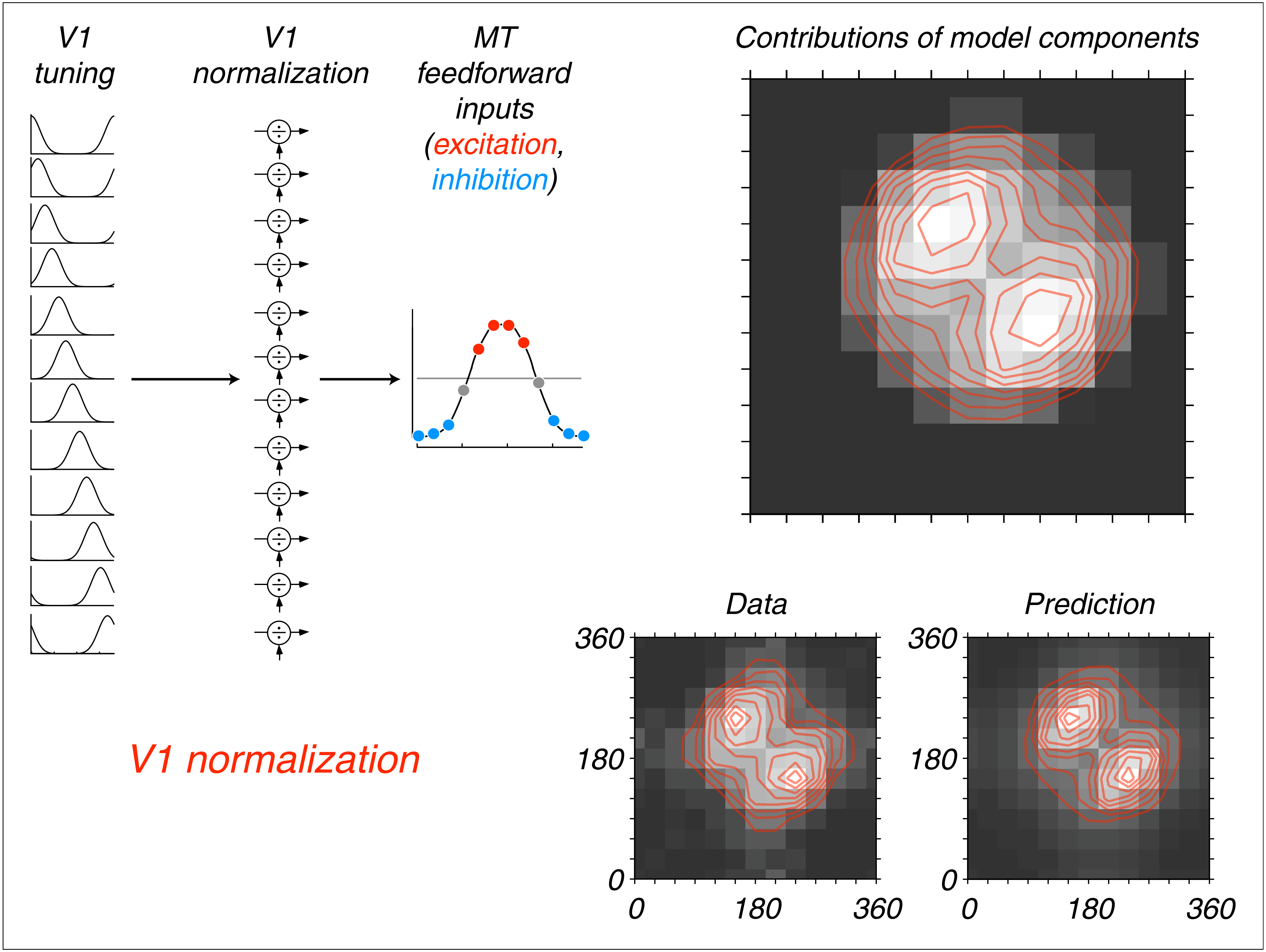


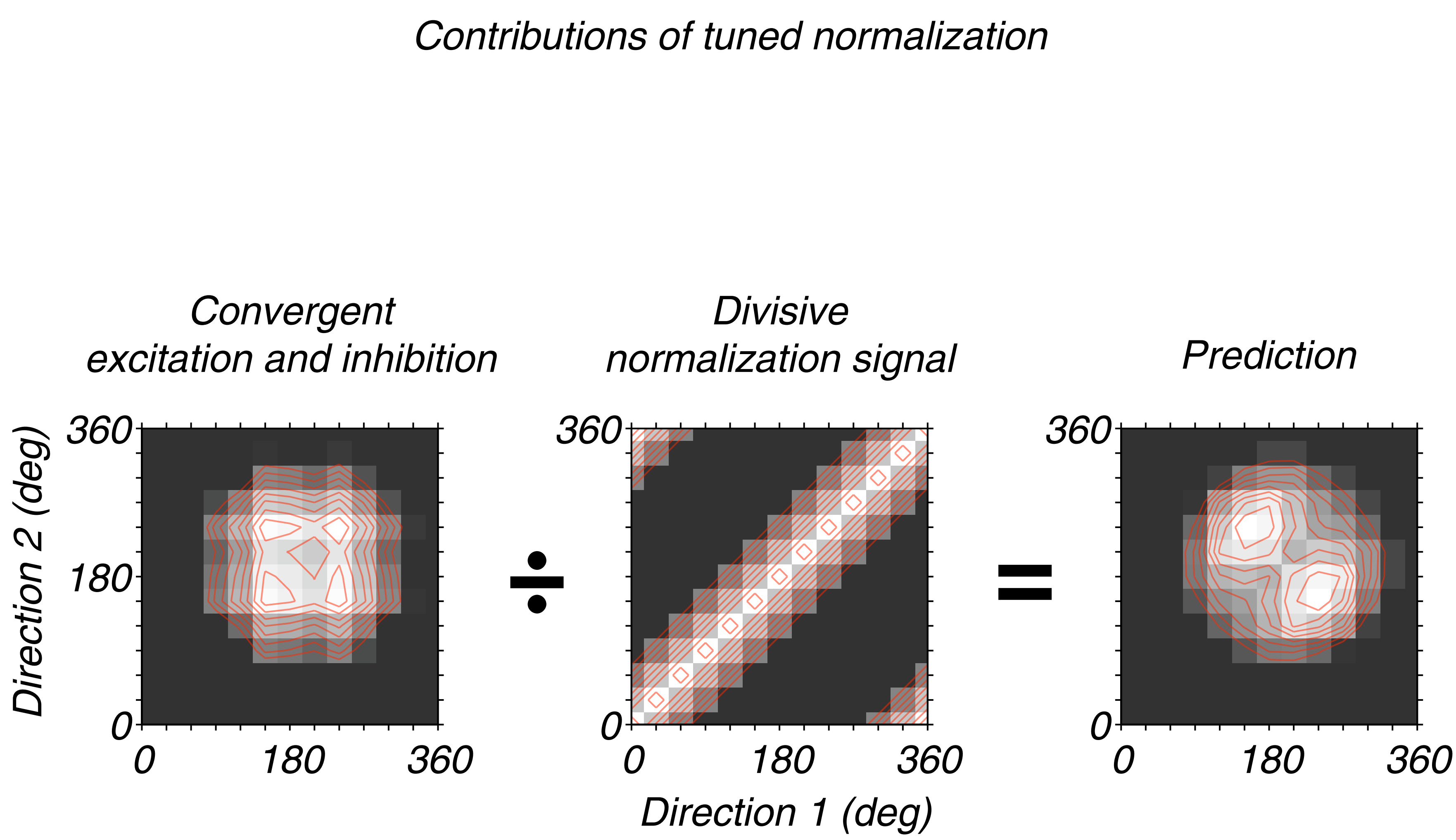
V1 tuning
V1 normalization
MT feedforward inputs (excitation, inhibition)
Contributions of model components
Data
Prediction
360
180
0
0
180
360
V1 input alone



V1 tuning
V1 normalization
MT feedforward inputs (excitation, inhibition)
Contributions of model components
Data
Prediction
360
180
0
0
180
360
MT excitation

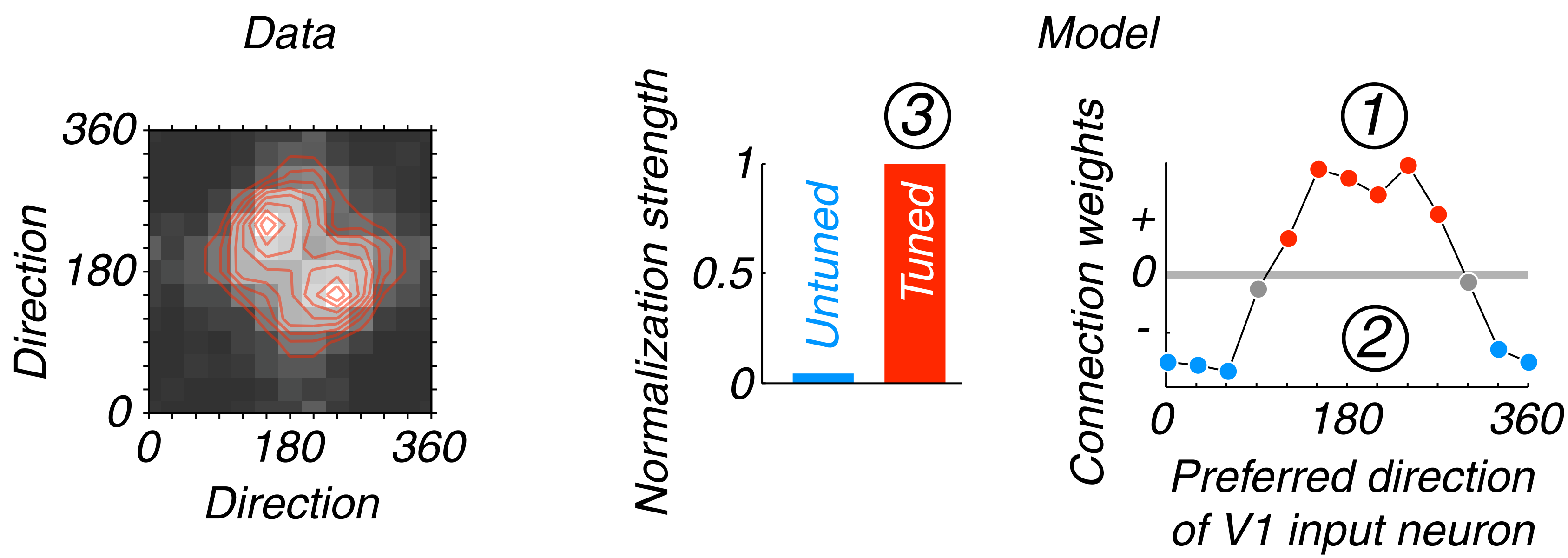

V1
tuning
V1
normalization
MT
feedforward
inputs
(excitation,
inhibition)
Contributions of model components
MT inhibition
Data
Prediction
360
180
0
0
180
360
360
180
0
0
180
360


V1 tuning
V1 normalization
MT feedforward inputs (excitation, inhibition)
Contributions of model components
Data
Prediction
360
180
0
0
180
360
V1 normalization


Contributions of tuned normalization
Convergent
excitation and inhibition
Divisive
normalization signal
Prediction
Direction 2 (deg)
360
180
0
0
180
360
Direction 1 (deg)

Pattern direction selectivity arises from:

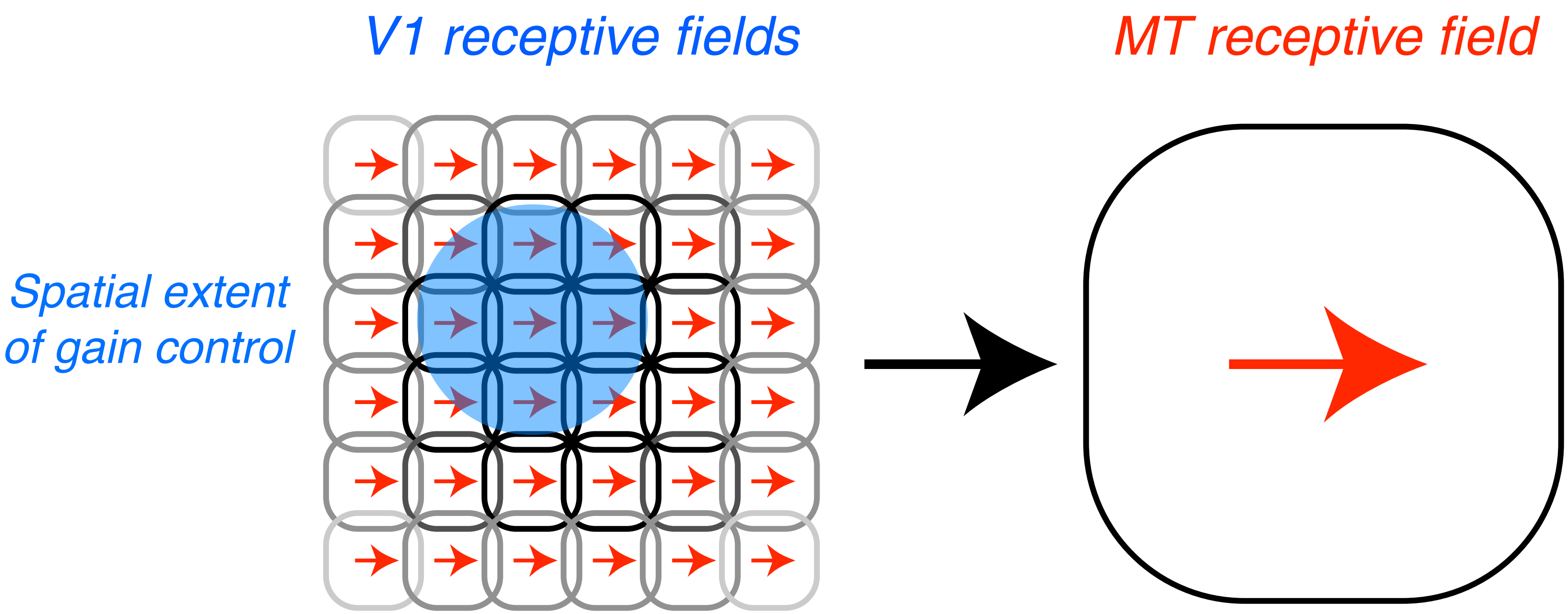
1. *Broad convergence of excitatory inputs*
2. *Strong motion opponent suppression*
3. *Strong tuned gain control*



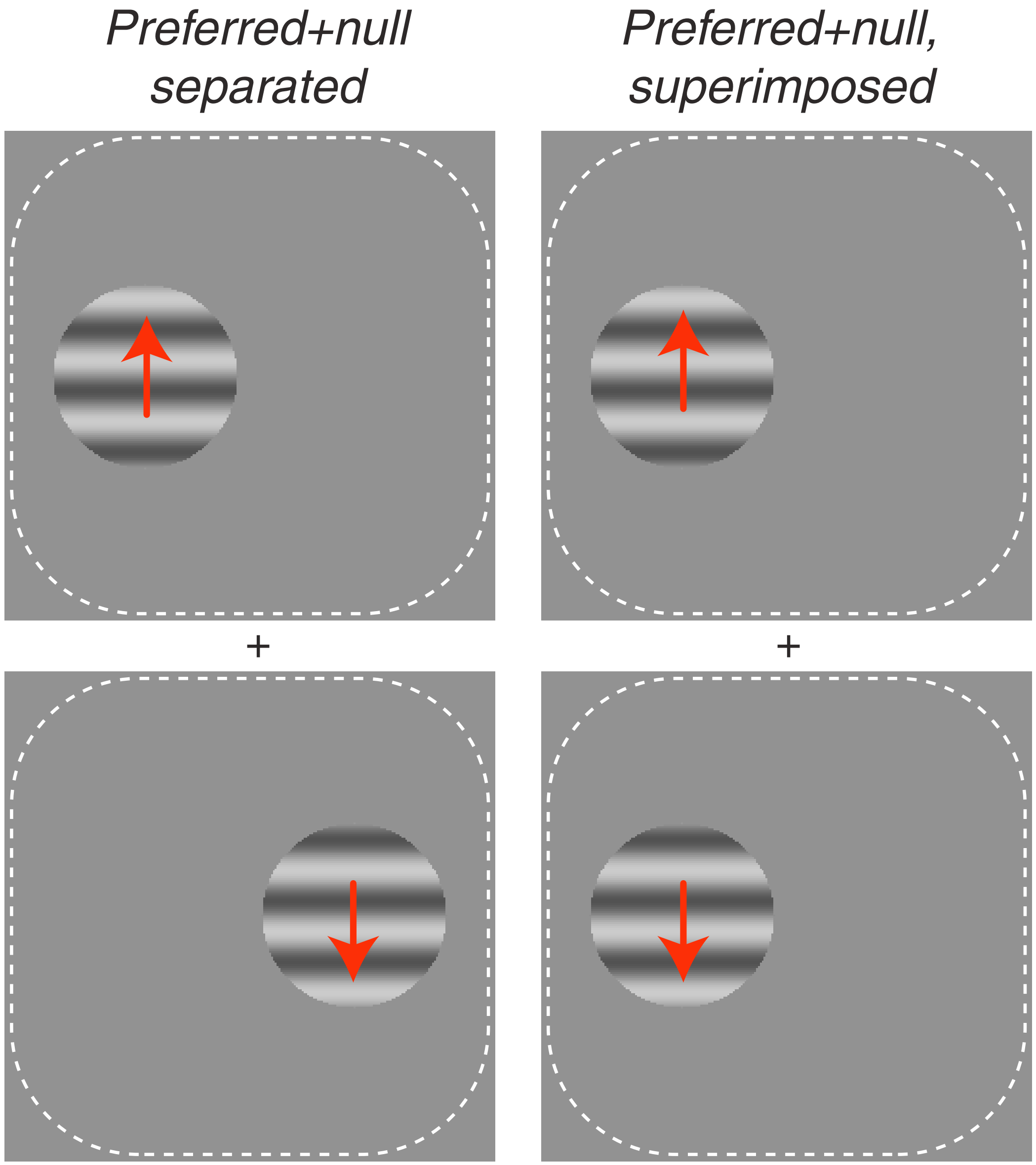
Rust, Mante, Simoncelli & Movshon, 2006

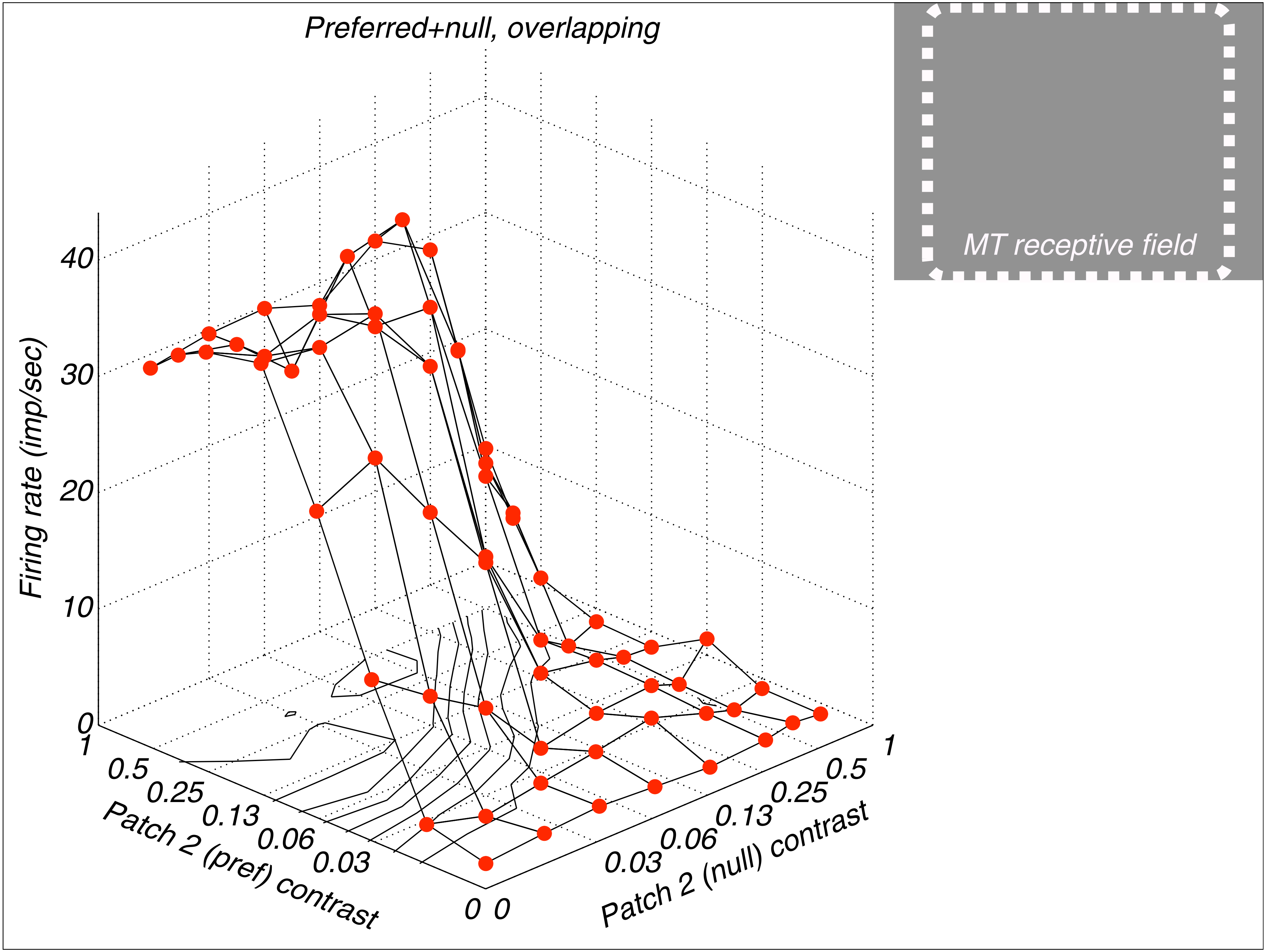
Pattern direction selectivity arises from:

1. *Broad convergence of excitatory inputs*
2. *Strong motion opponent suppression*
3. *Strong tuned gain control*

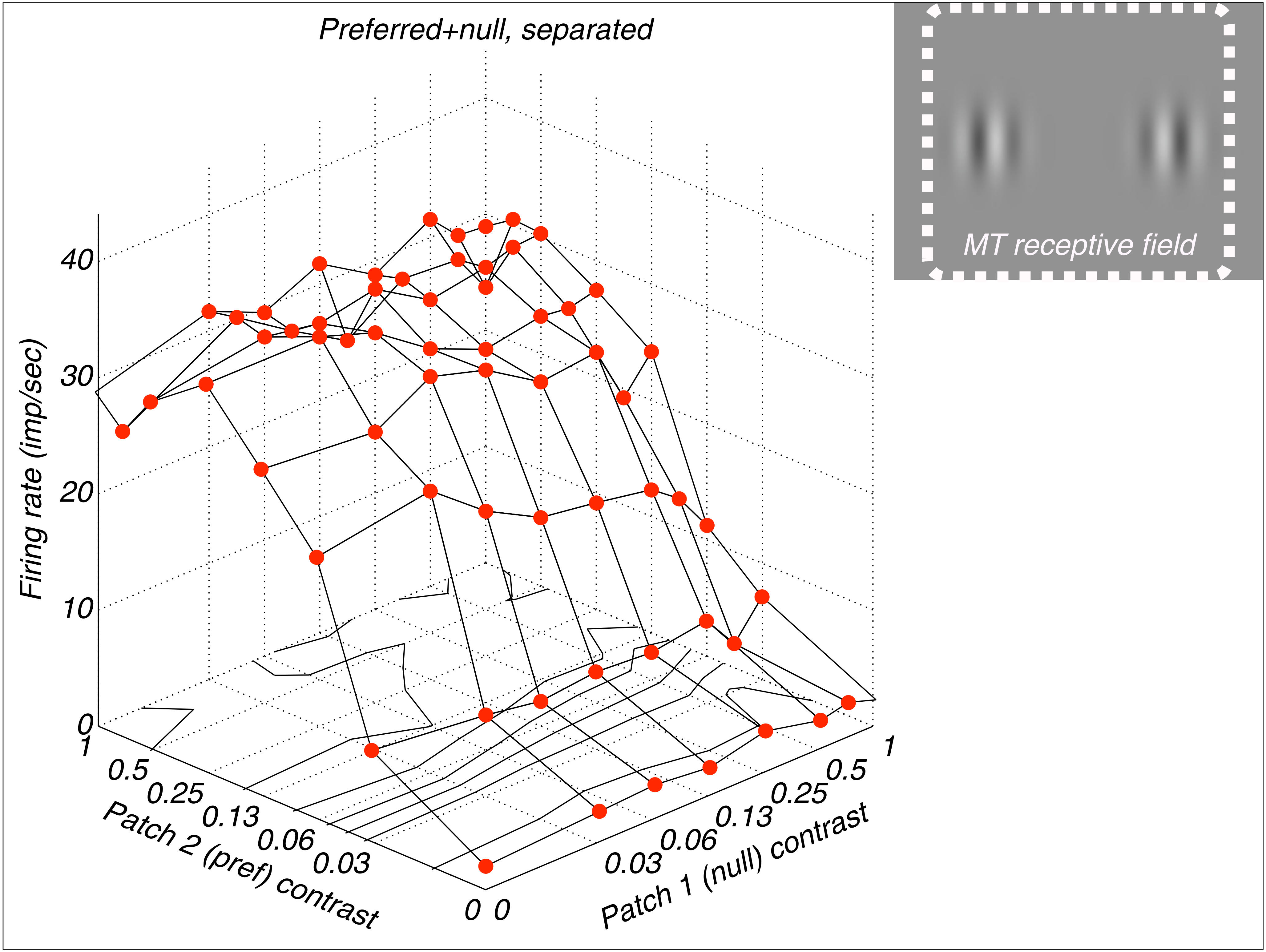


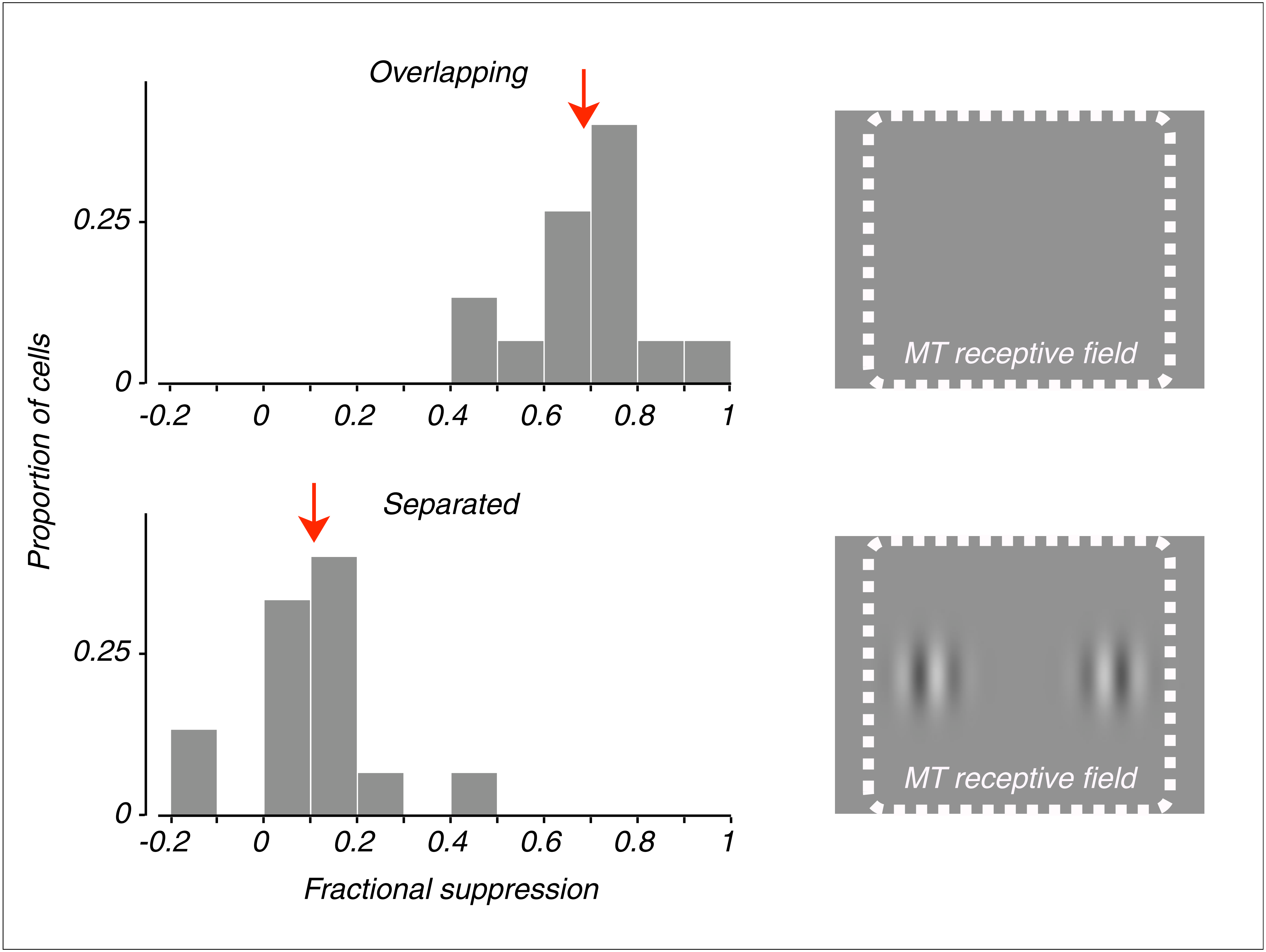
Does opponent-motion suppression act globally?





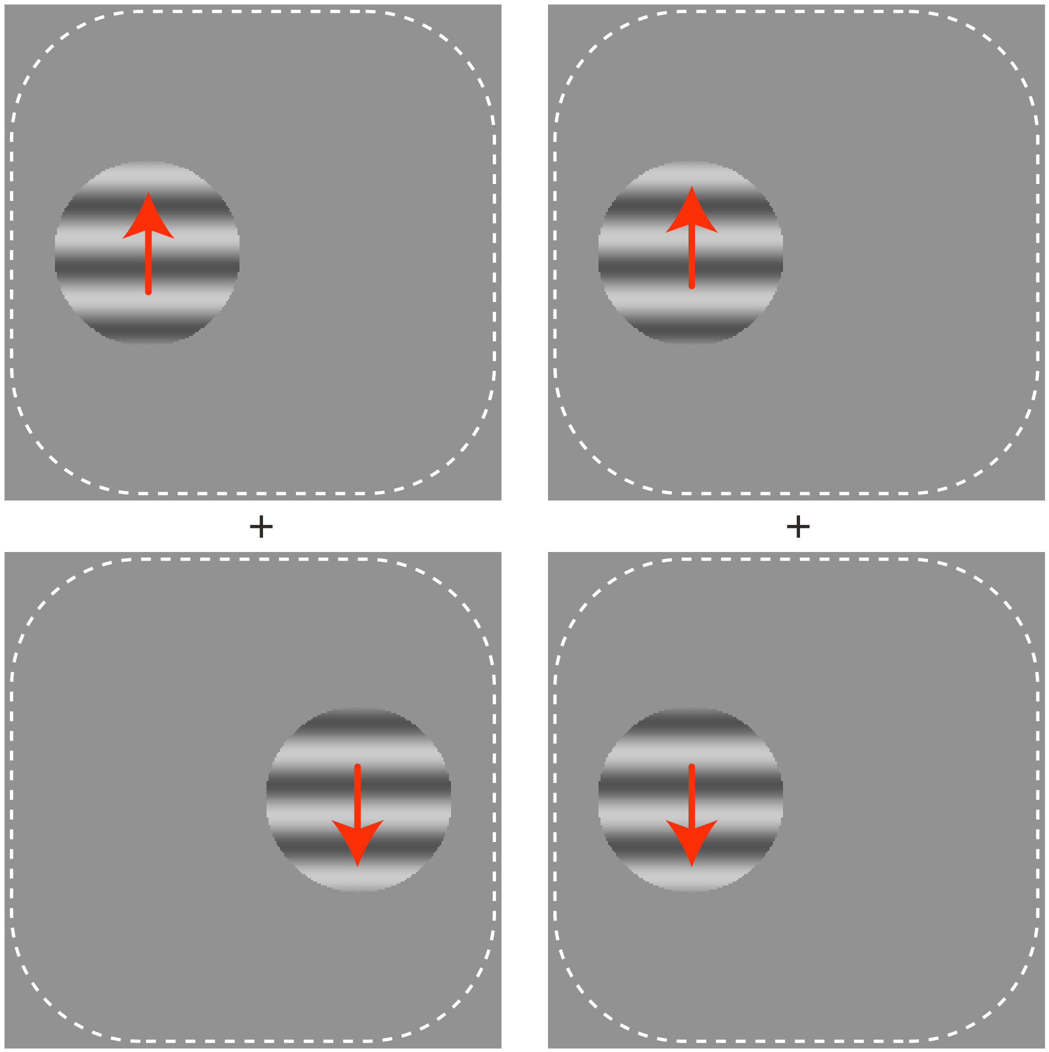
Preferred+null, overlapping
MT receptive field
Firing rate (imp/sec)
0
10
20
30
40
1
0.5
0.25
0.13
0.06
0.03
0
Patch 2 (pref) contrast
0
0.03
0.06
0.13
0.25
0.5
1
Patch 2 (null) contrast


Preferred+null, separated
MT receptive field
Firing rate (imp/sec)
0
10
20
30
40
Patch 2 (pref) contrast
1
0.5
0.25
0.13
0.06
0.03
0
Patch 1 (null) contrast
0
0.03
0.06
0.13
0.25
0.5
1

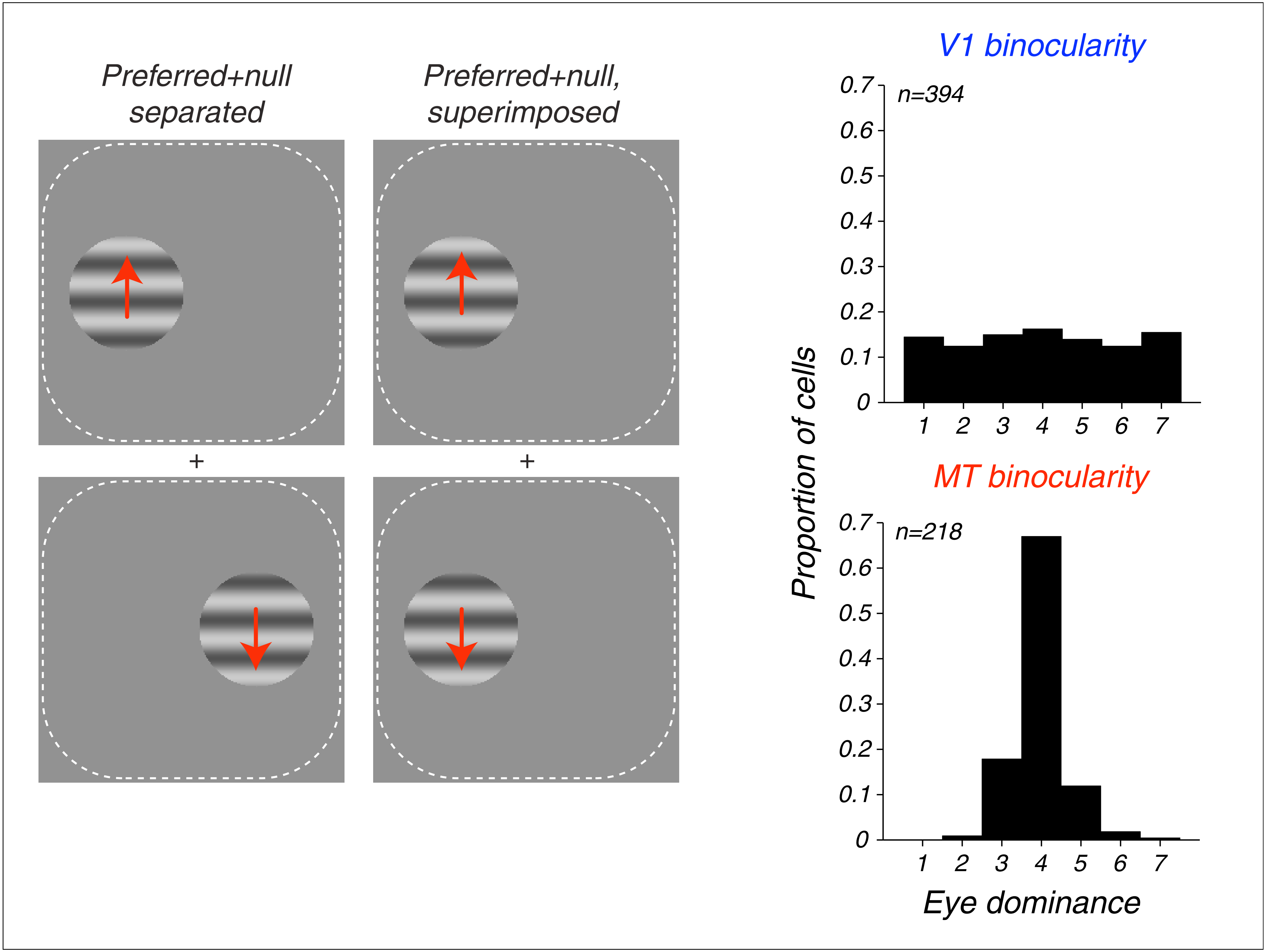

Overlapping
Separated
Proportion of cells
0.25
0
-0.2
0
0.2
0.4
0.6
0.8
1
Fractional suppression
MT receptive field
MT receptive field

Preferred+null separated

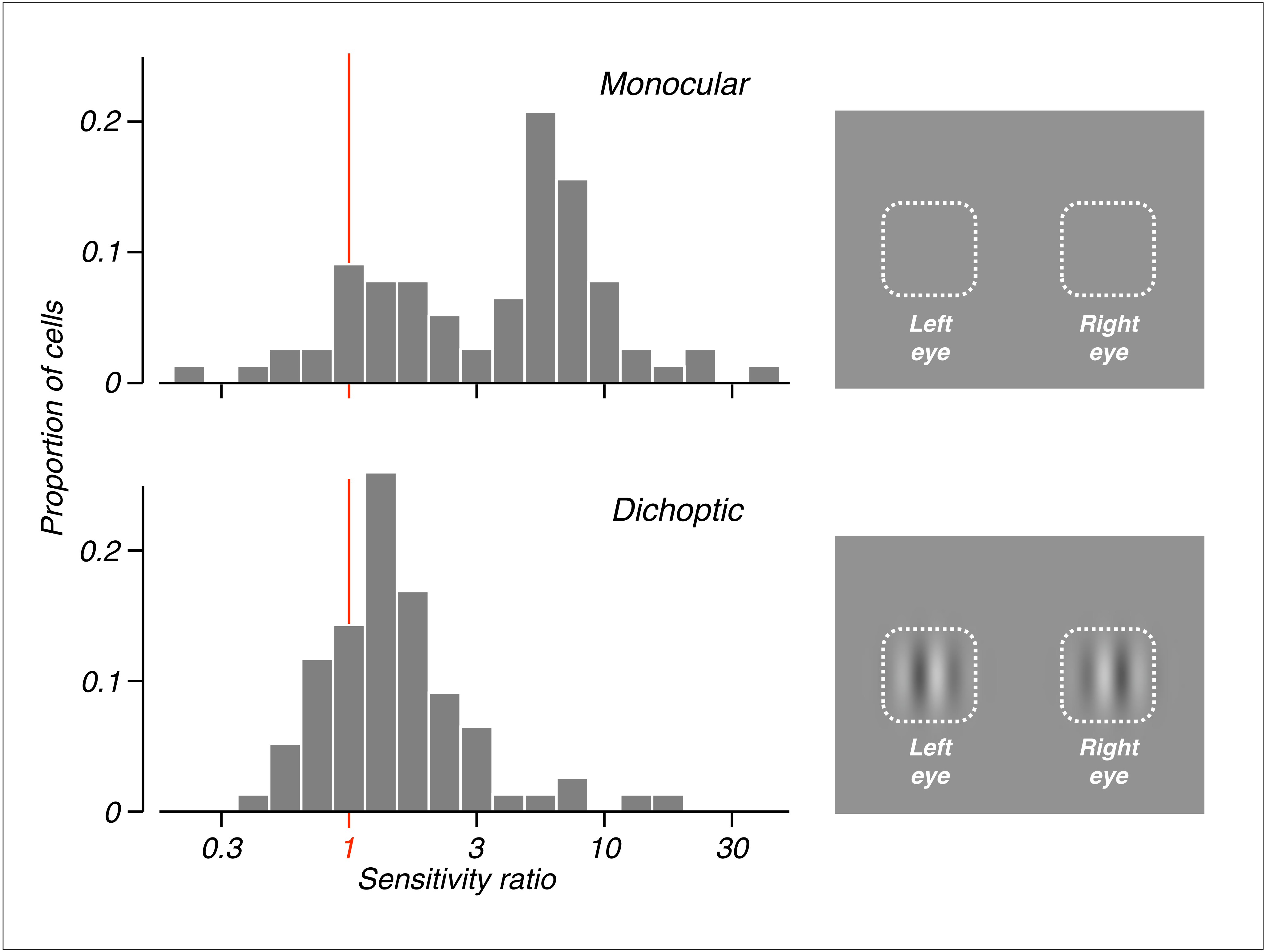
Preferred+null, superimposed

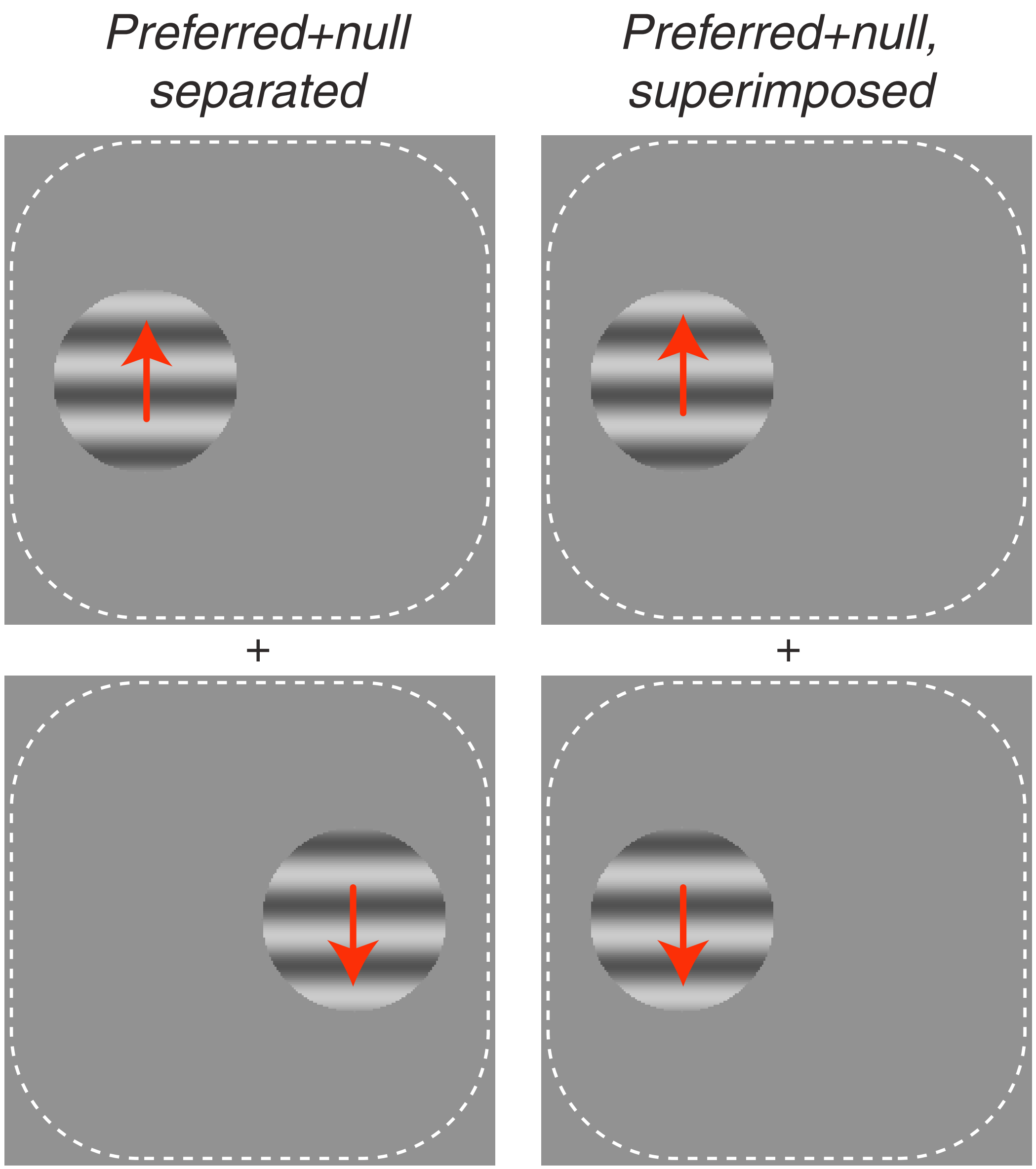


Opponent-motion suppression acts locally



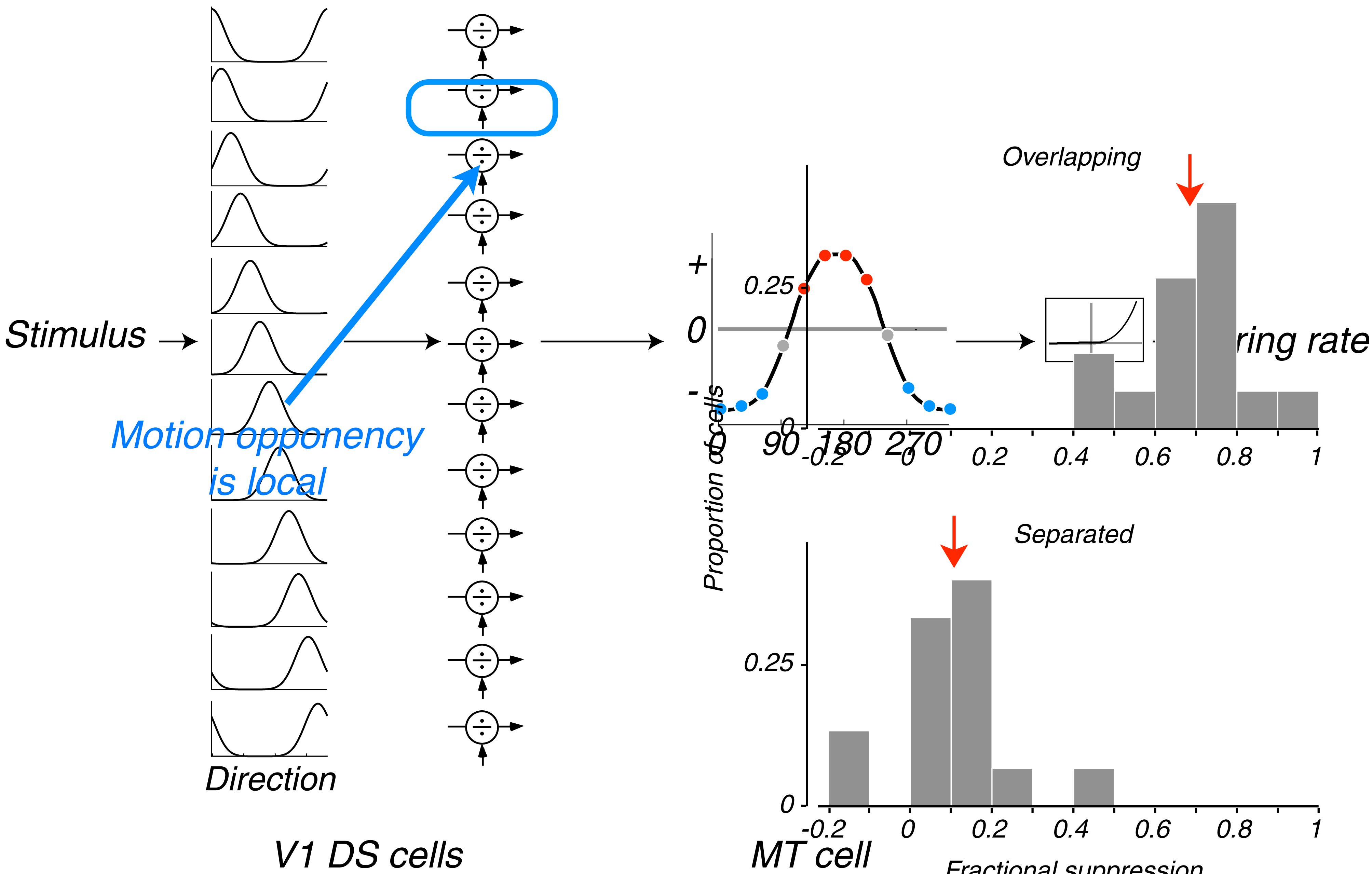
Preferred+null separated
Preferred+null, superimposed
+
+
V1 binocularity
n=394
MT binocularity
n=218
Proportion of cells
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
1
2
3
4
5
6
7
Eye dominance


Monocular
Dichoptic
Proportion of cells
0.2
0.1
0
0.3
1
3
10
30
Sensitivity ratio
Left eye
Right eye
Left eye
Right eye

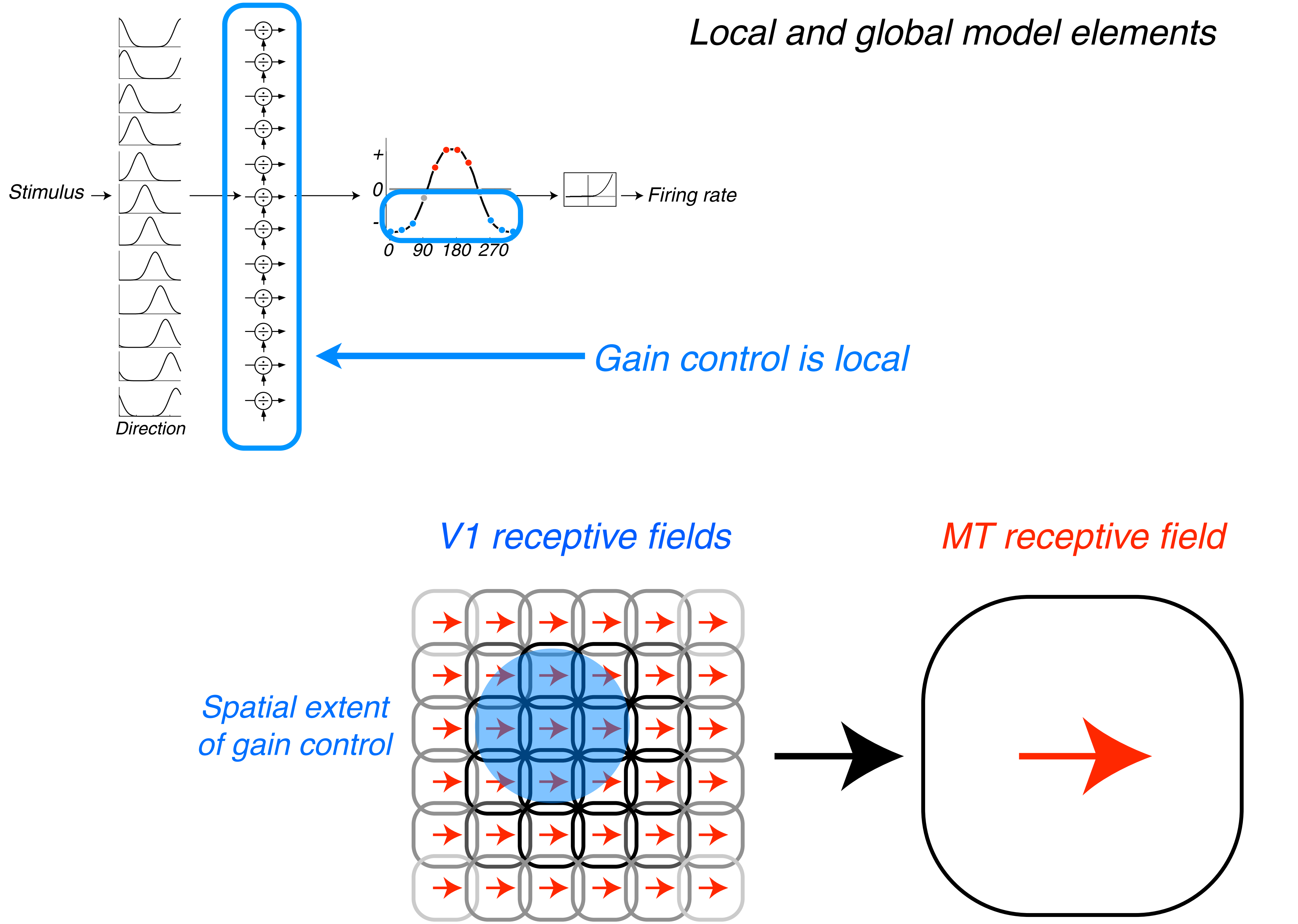


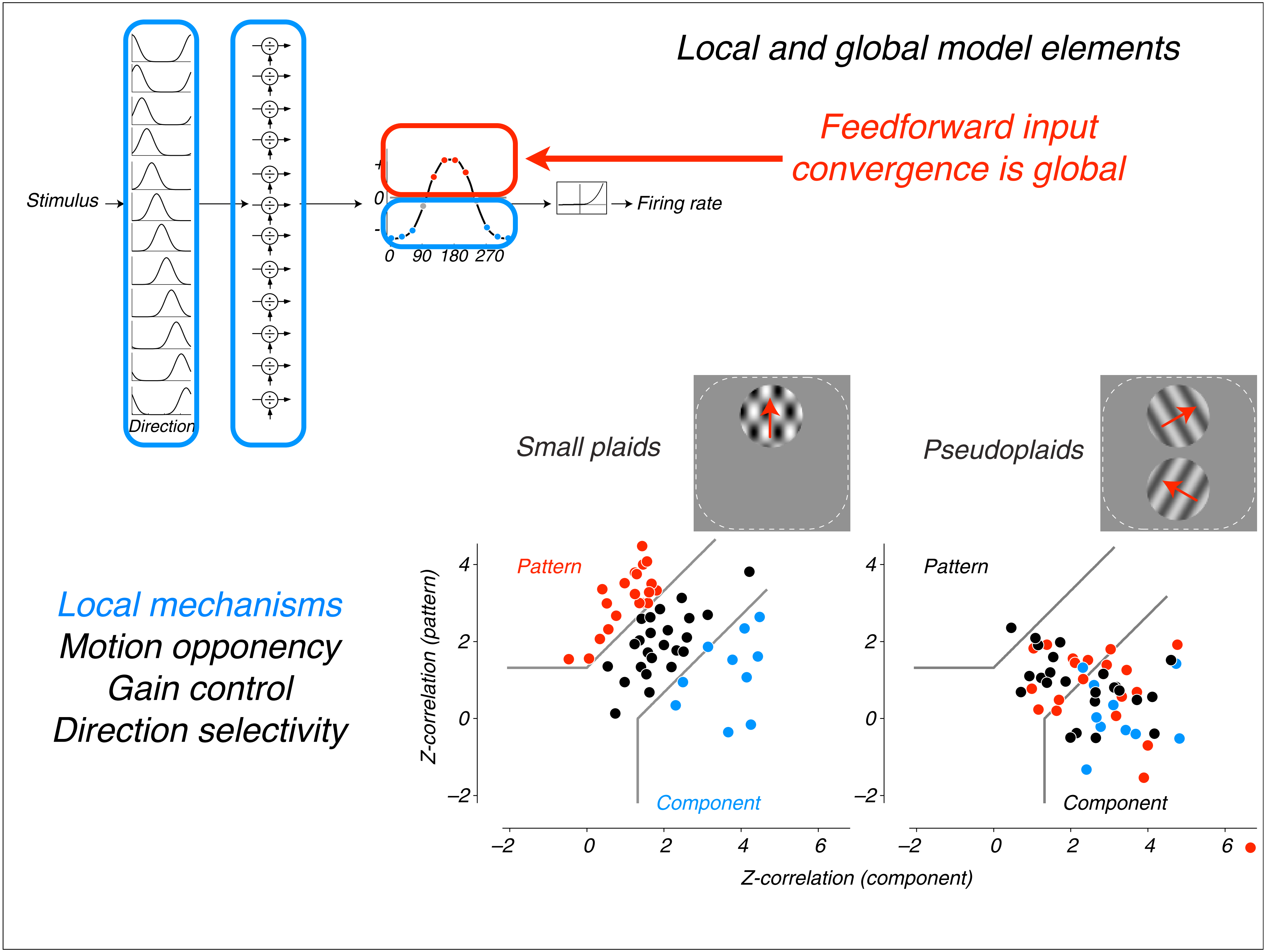
Opponent-motion suppression acts locally and monocularly

Local and global model elements



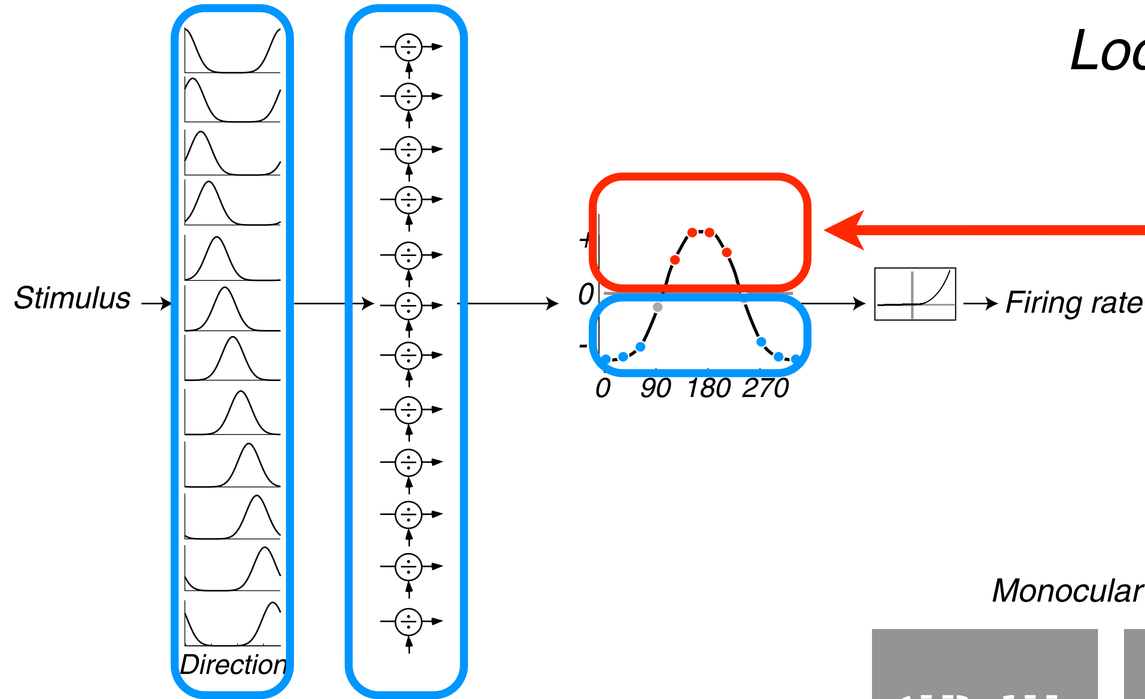
Local and global model elements



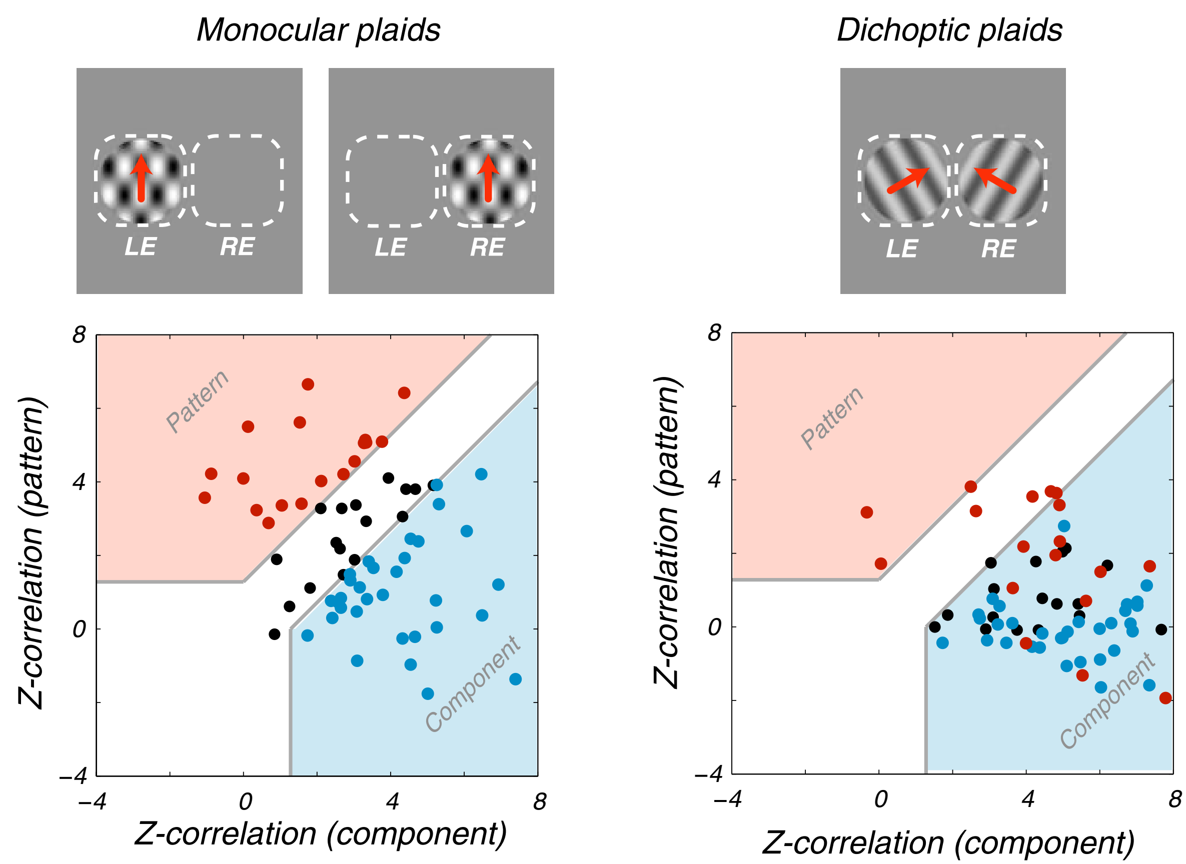


Local and global model elements
Stimulus
Direction
0
+
-
0
90
180
270
Firing rate
Feedforward input convergence is global
Small plaids
Pseudoplaids
Local mechanisms
Motion opponency
Gain control
Direction selectivity
Pattern
Component
Pattern
Component
Z-correlation (pattern)
Z-correlation (component)
4
2
0
−2
−2
0
2
4
6

Local and global model elements



Feedforward input convergence is global



Monocular mechanisms

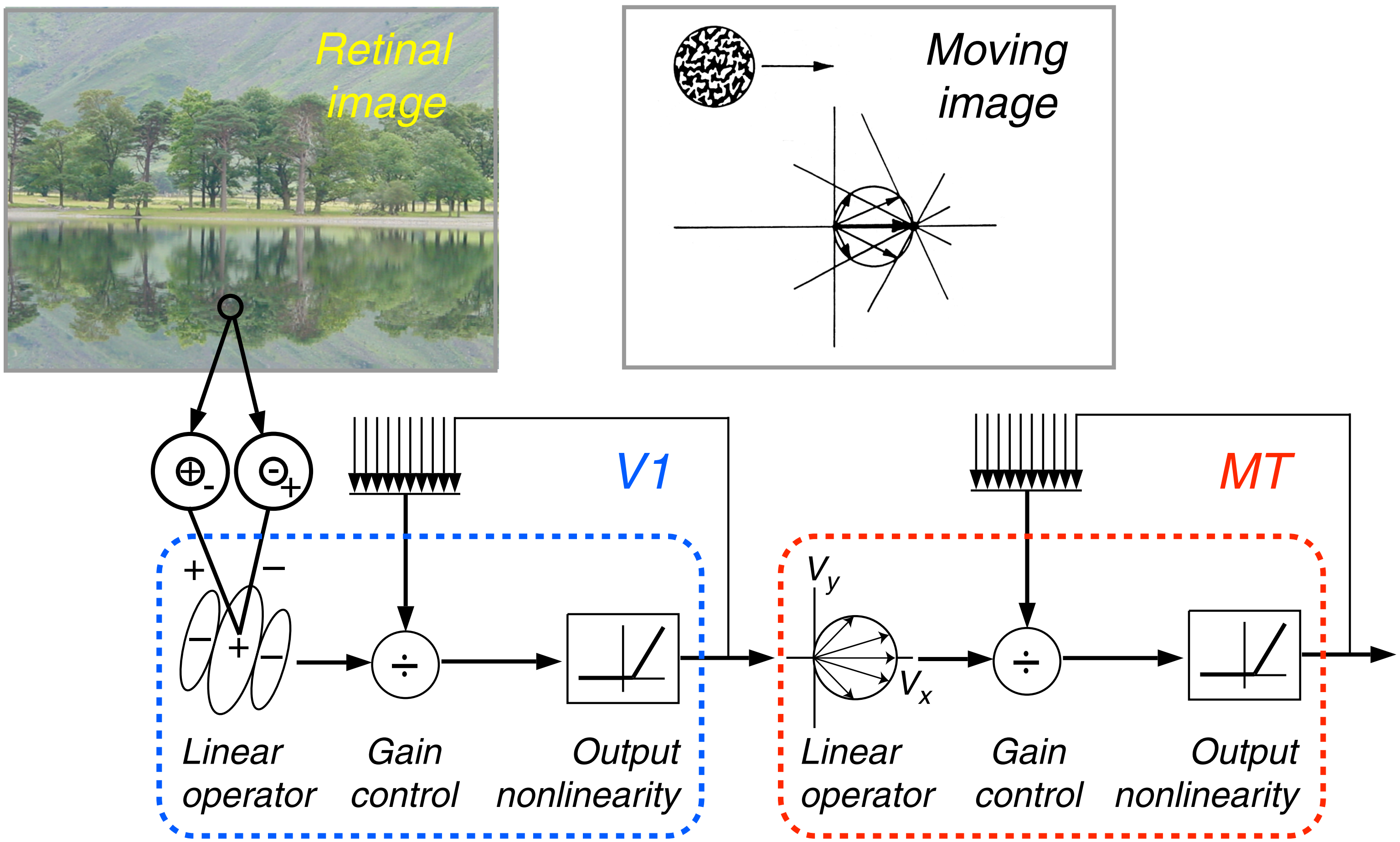
Motion opponency

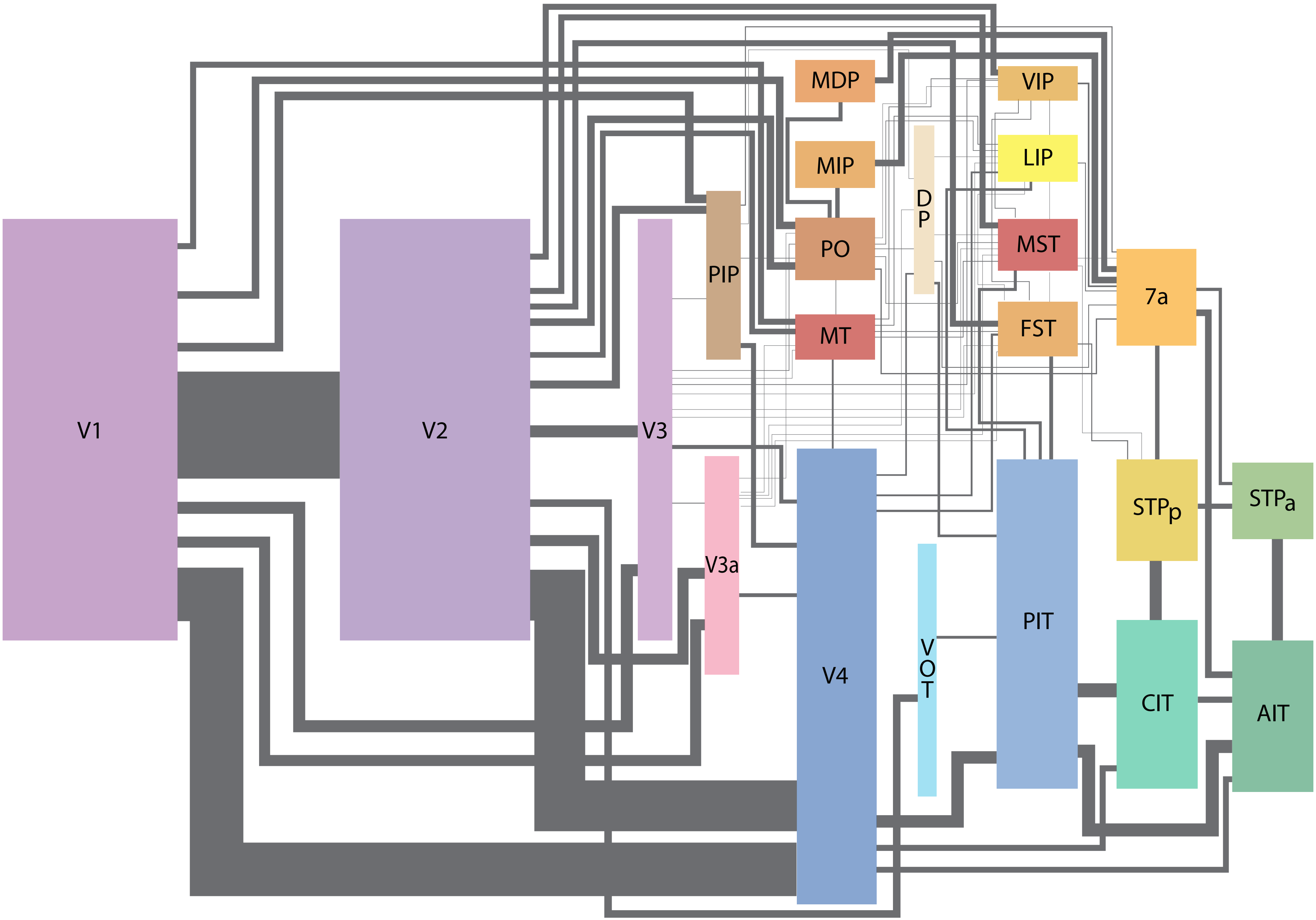
Gain control

Direction selectivity

Pattern direction selectivity arises from:

1. *Broad convergence of excitatory inputs* ← Global/MT
2. *Strong motion opponent suppression* ← Local/Monocular V1
3. *Strong tuned gain control*





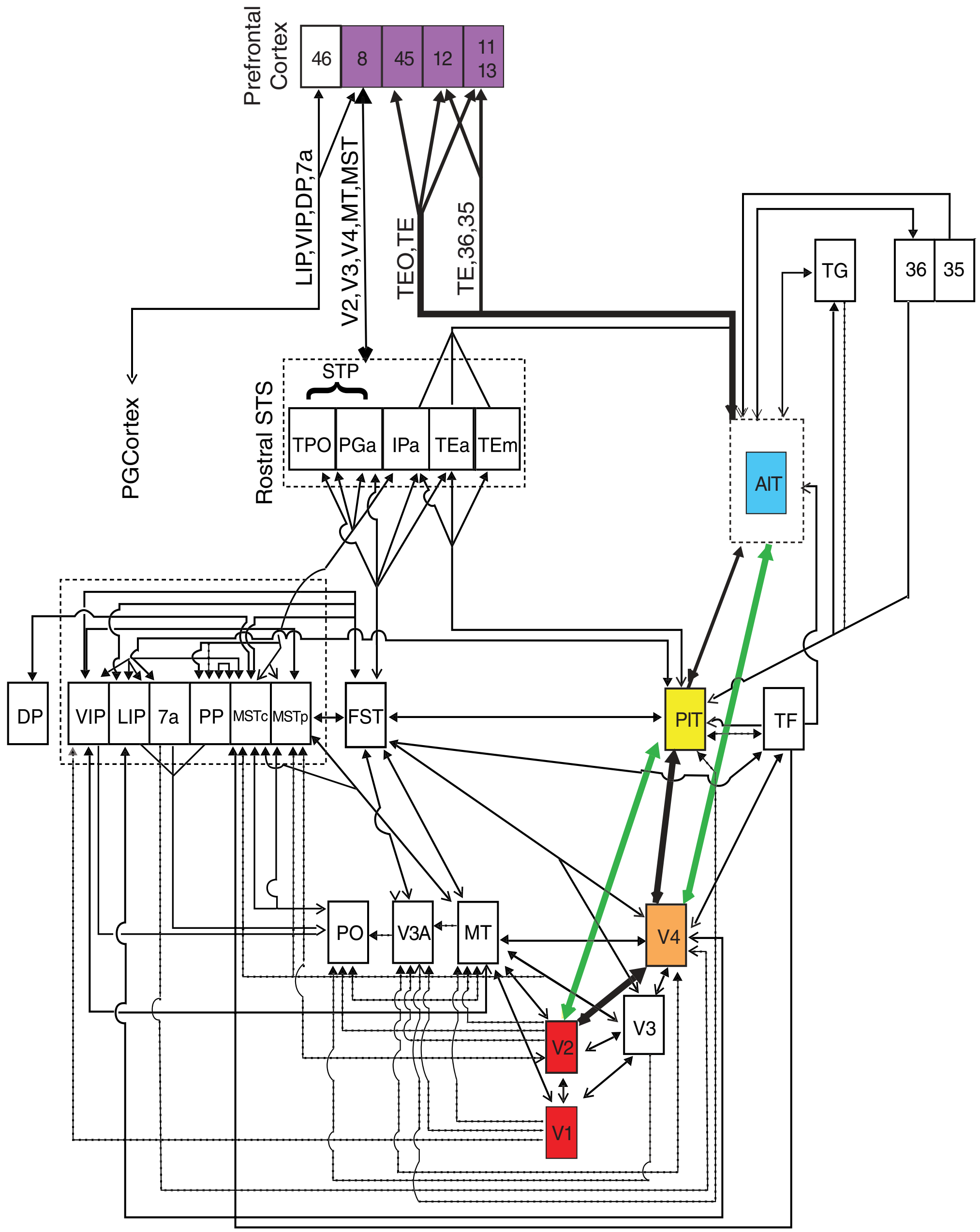
Wallisch & Movshon, 2008

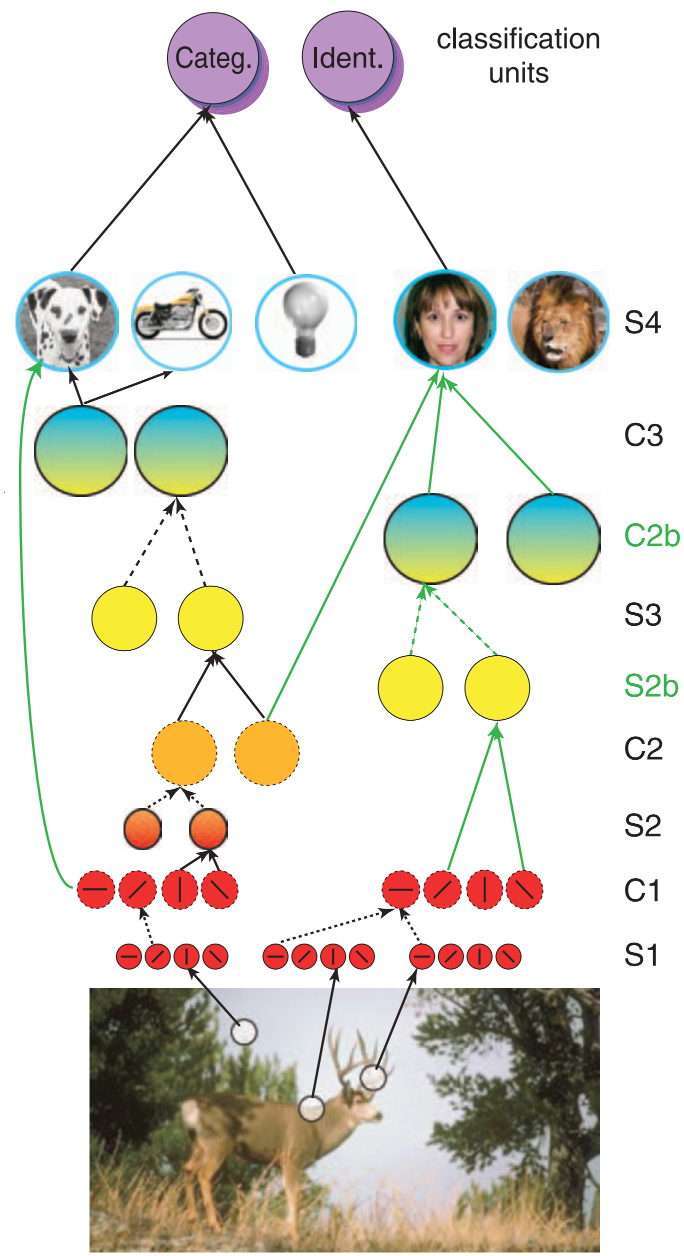
after Felleman & Van Essen, 1991

Complex shape selectivity in the ventral pathway

Scott Brincat & Ed Connor

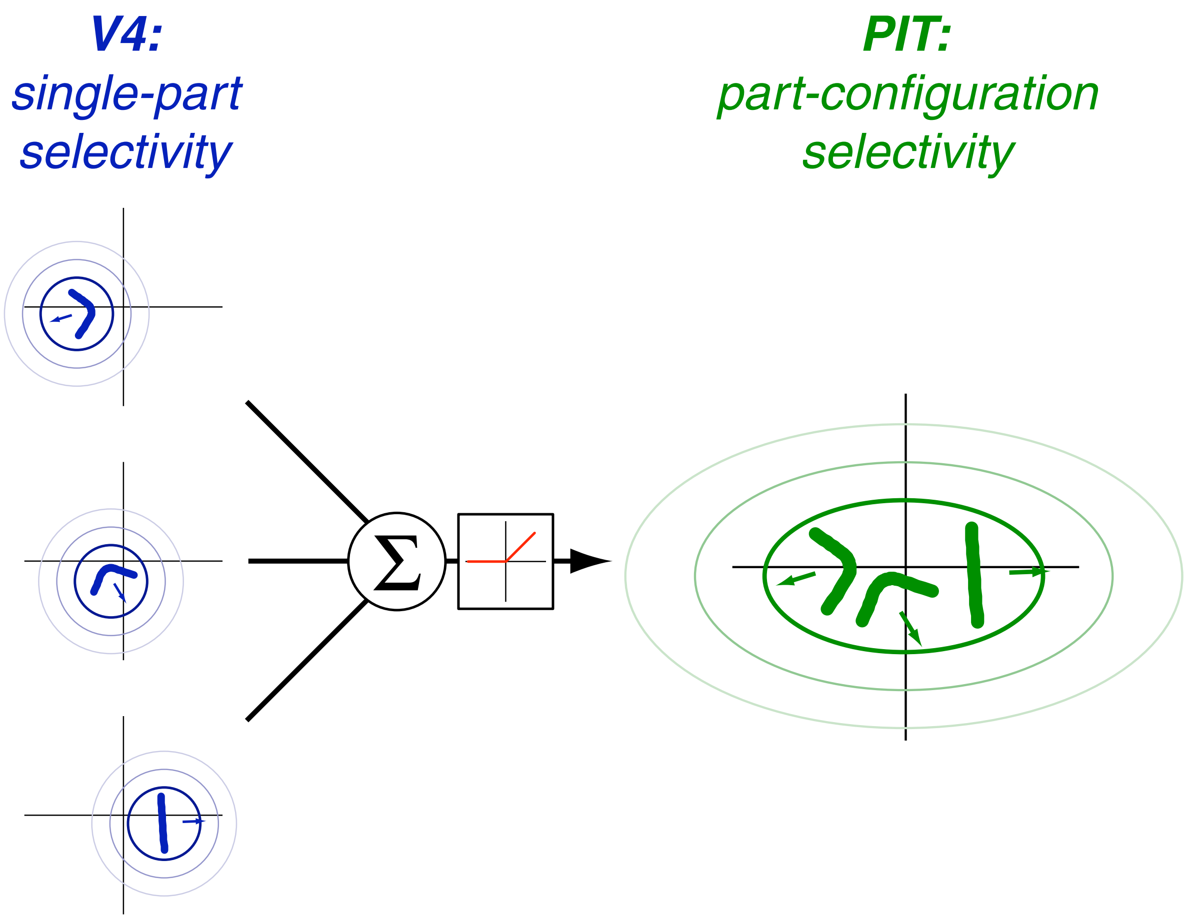
Complex shape selectivity in the ventral pathway

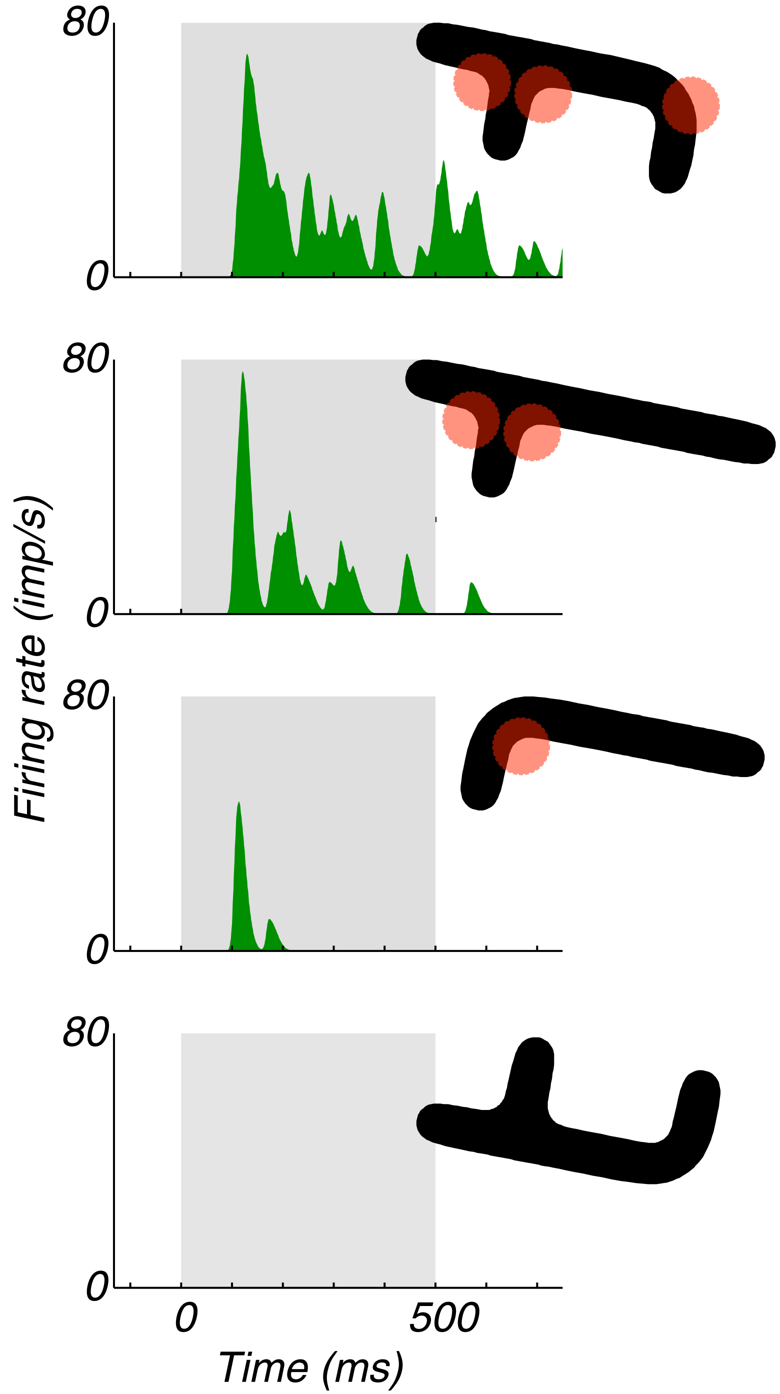




Serre, Oliva & Poggio, 2007

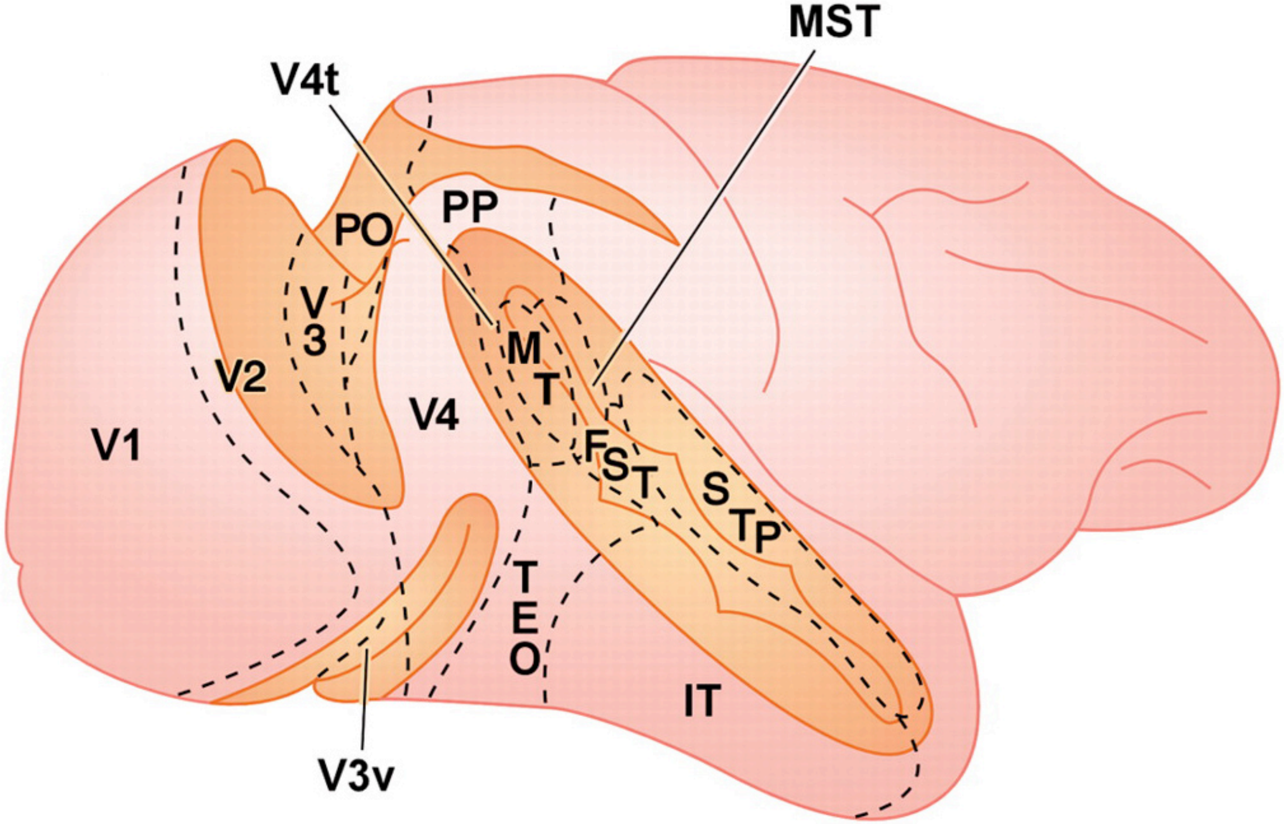
Feedforward analysis of complex shape selectivity in the ventral pathway





Pasupathy & Connor (2001)

Brincat & Connor (2004)



Dorsal pathway
Space, motion, action

Ventral pathway
Form, recognition, memory

Ungerleider & Mishkin, 1982

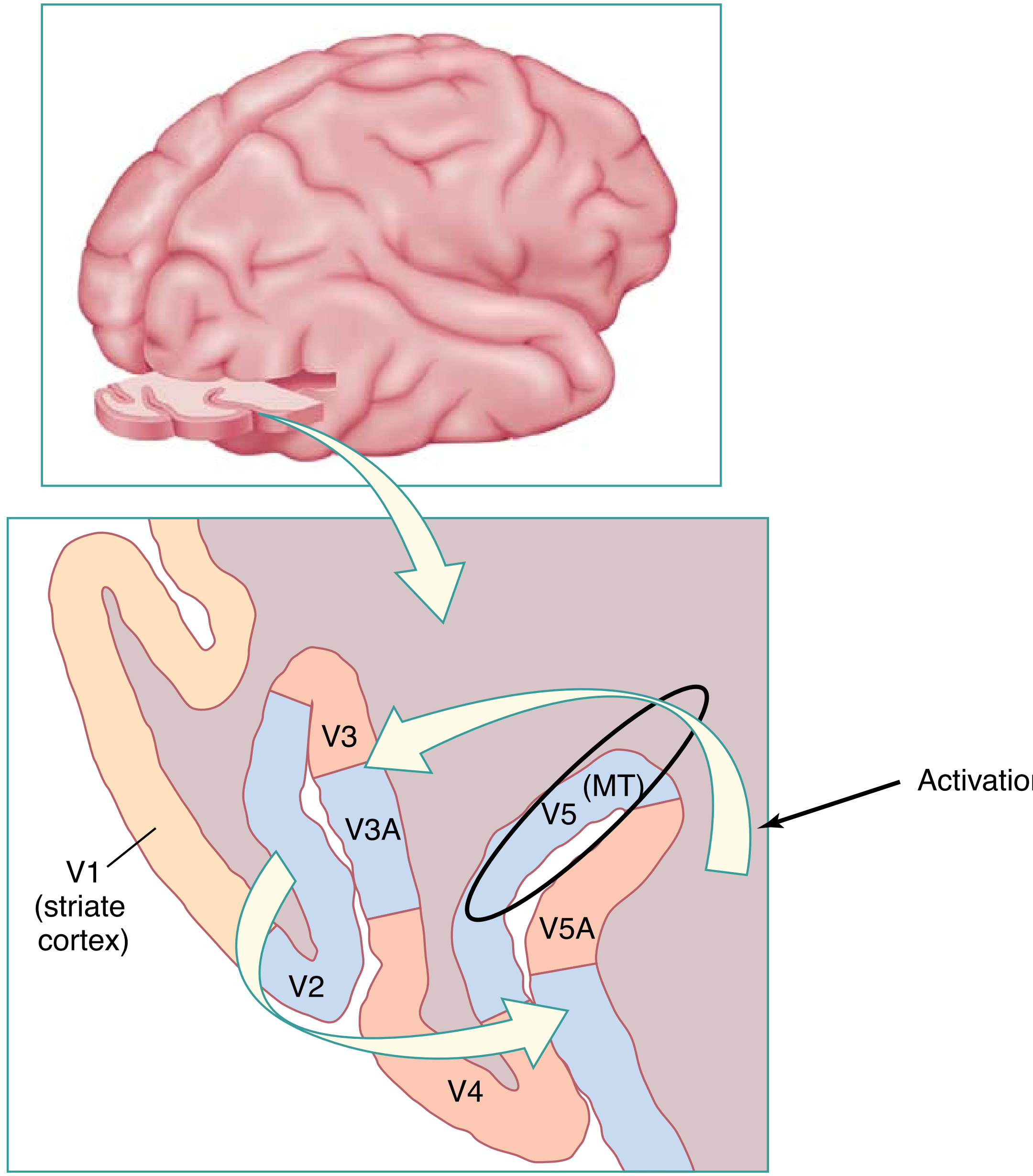
What MT doesn't do

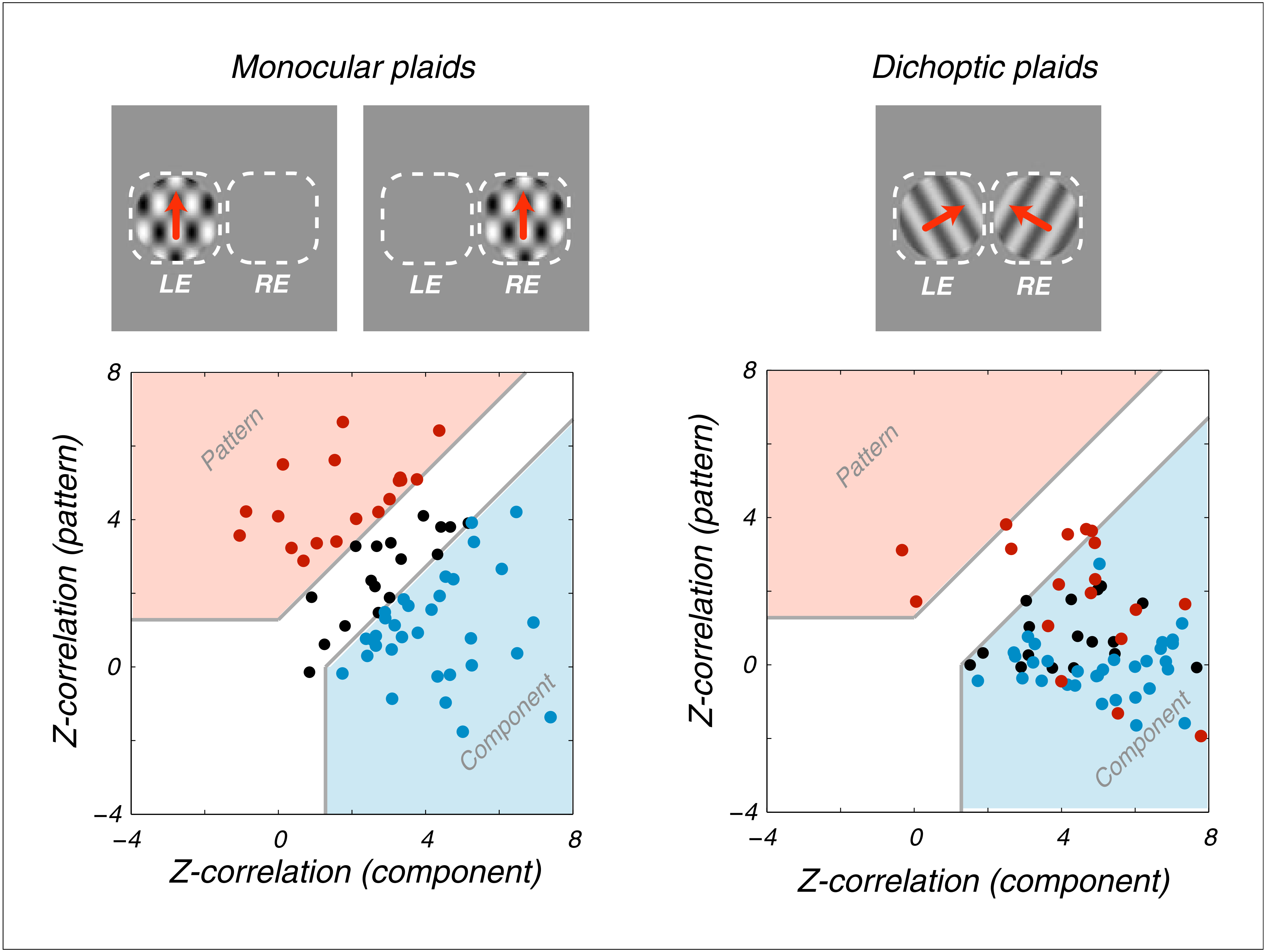
Opinion TRENDS in Cognitive Sciences Vol.9 No.2 February 2005
Full text provided by www.sciencedirect.com
SCIENCE DIRECT

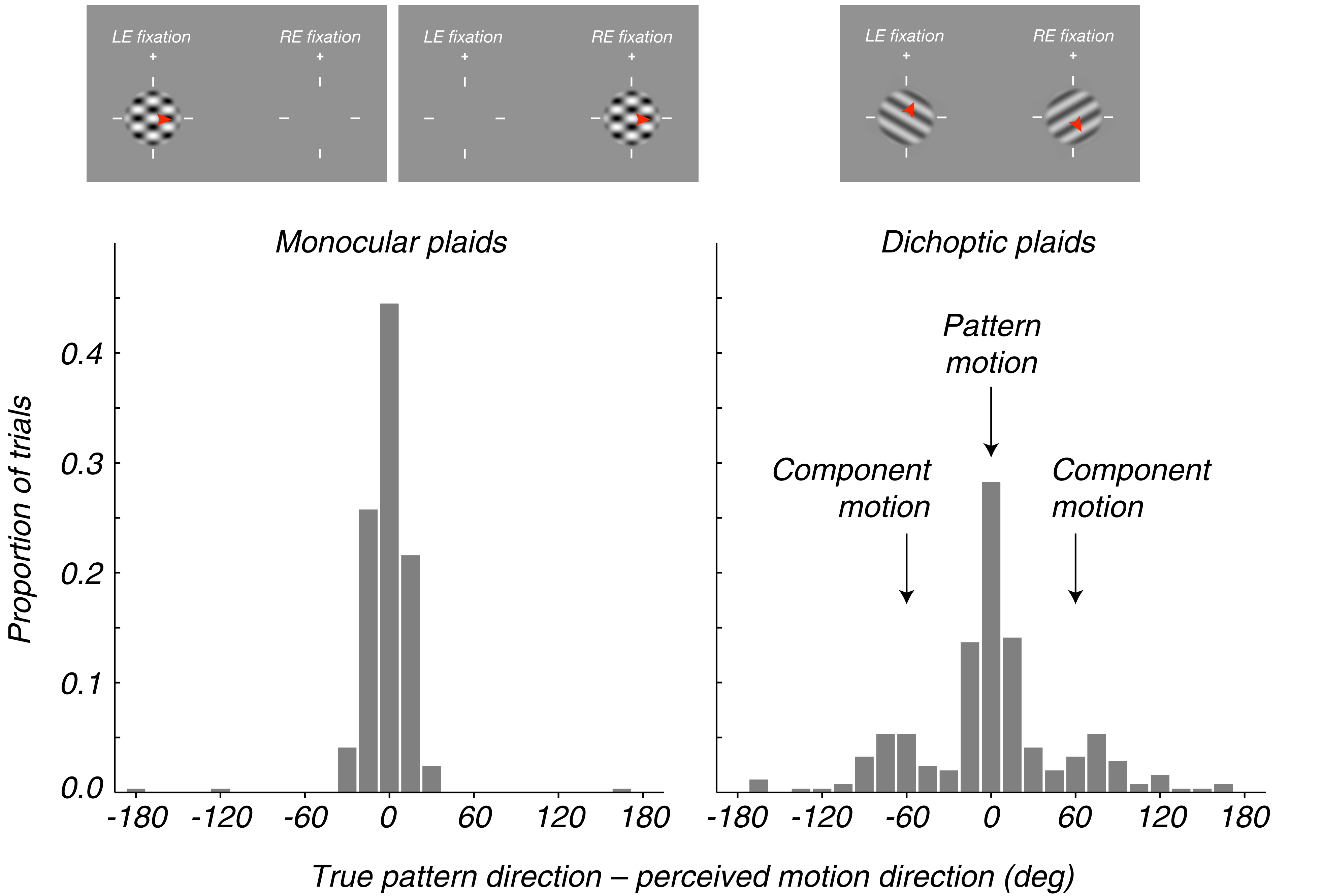
Two neural correlates of consciousness

Ned Block

Block's conjecture
MT is "the core phenomenal neural correlate of consciousness for the visual experiential content as of motion"

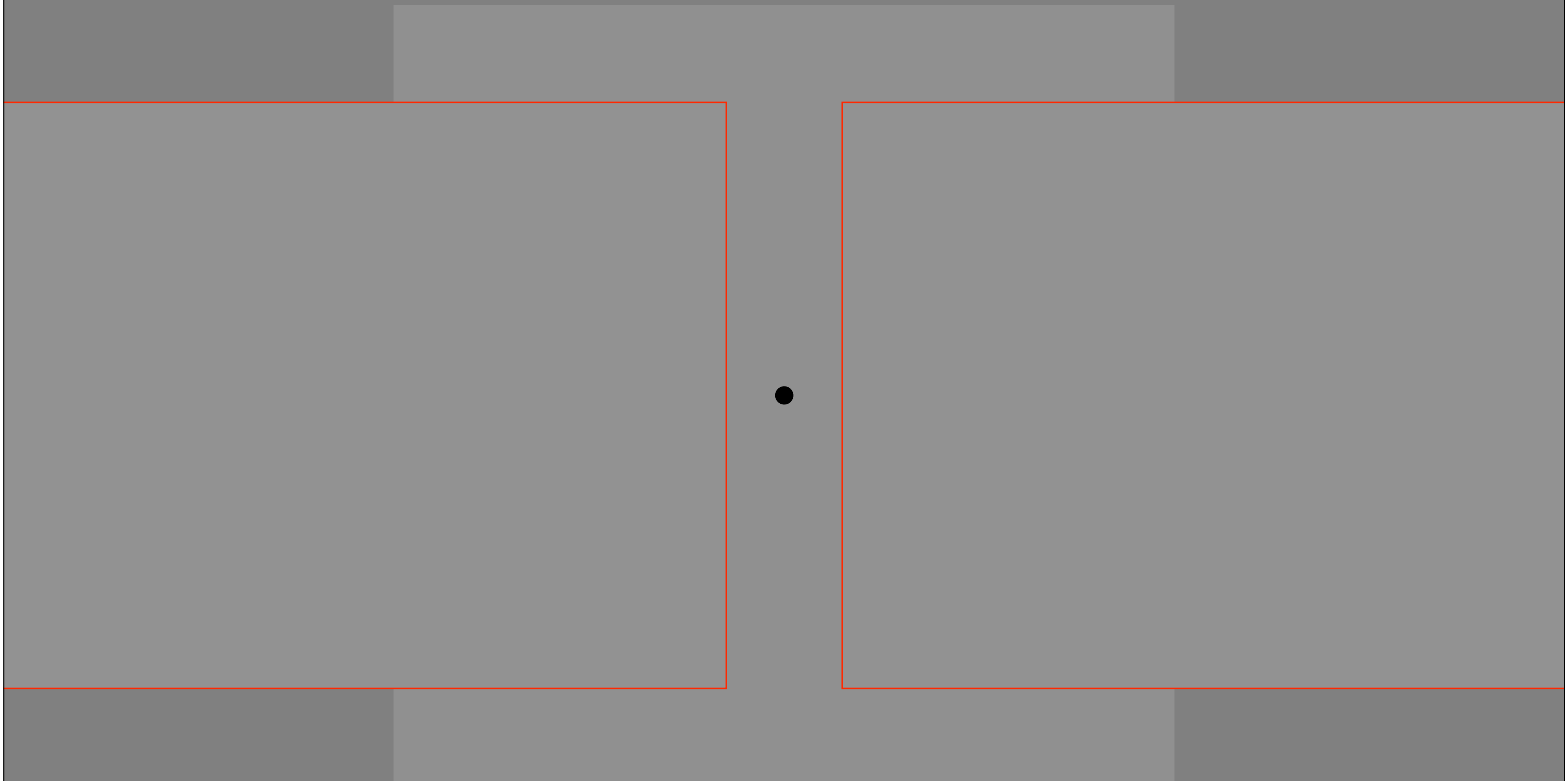



Monocular plaids
Dichoptic plaids
LE
RE
LE
RE
LE
RE
Pattern
Component
Pattern
Component
Z-correlation (pattern)
Z-correlation (component)
Z-correlation (pattern)
Z-correlation (component)
8
4
0
−4
−4
0
4
8
8
4
0
−4
−4
0
4
8

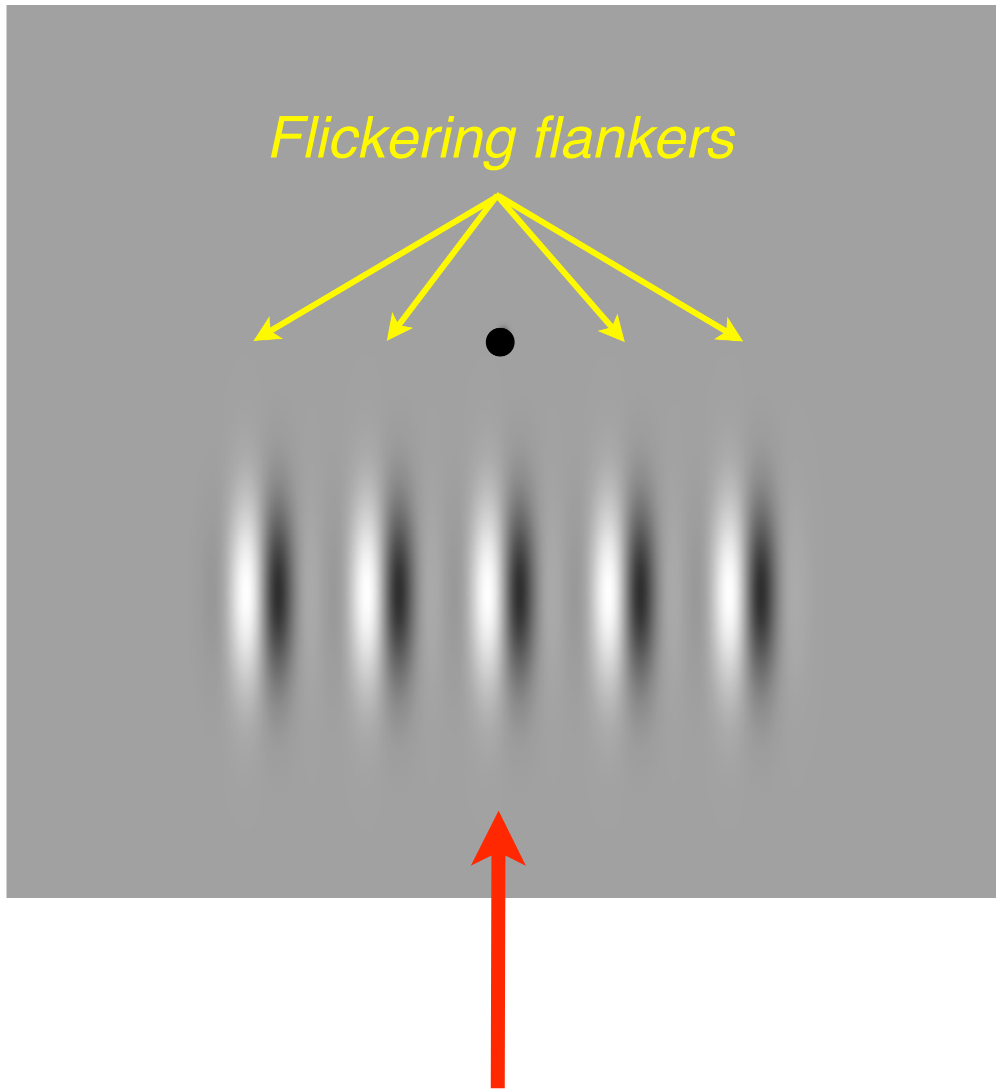


also Andrews & Blakemore (1999);
Cobo-Lewis et al. (2000)

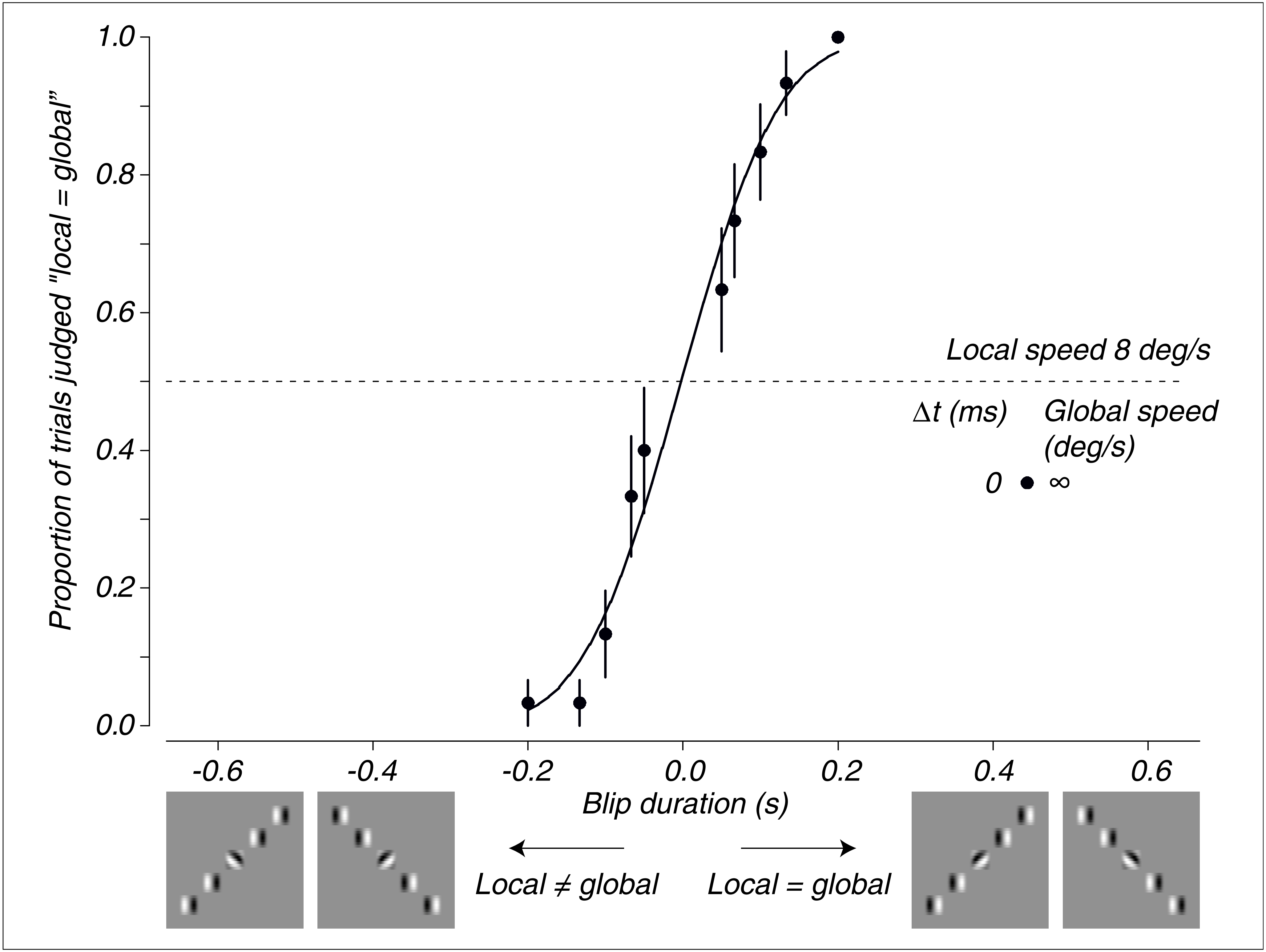
Local and global motion signals



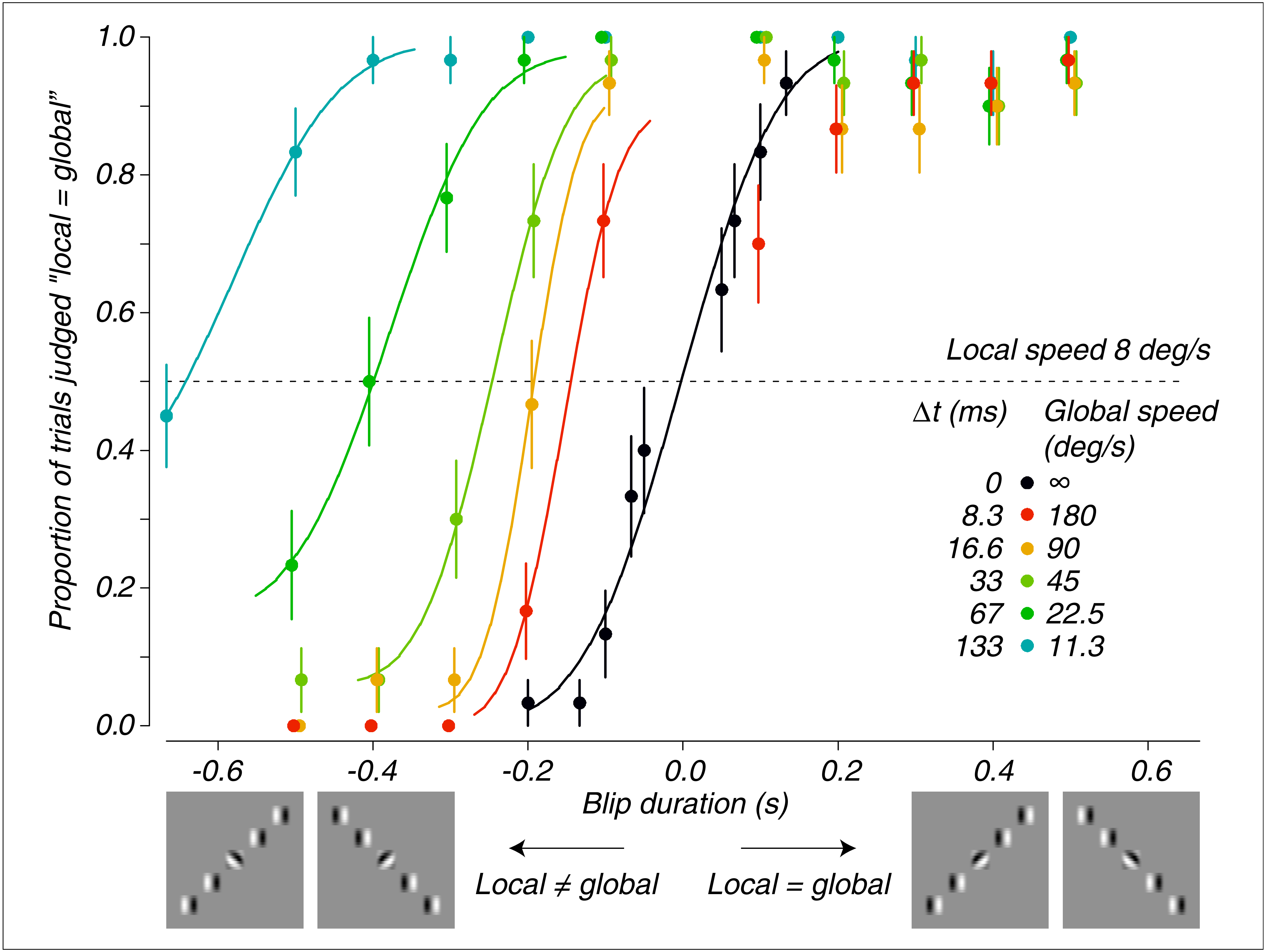
Task



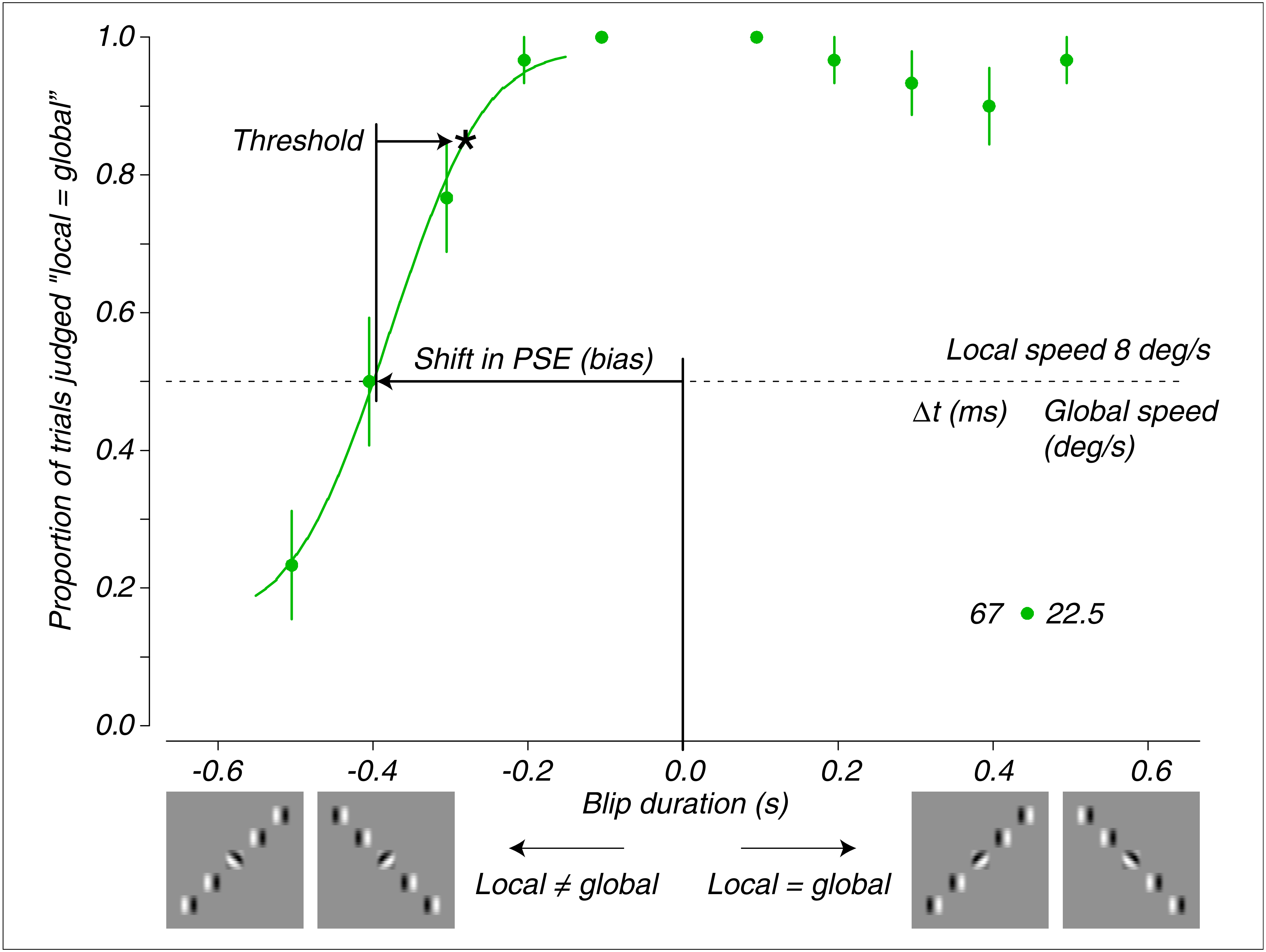
Discriminate motion of the central patch



Proportion of trials judged "local = global"
1.0
0.8
0.6
0.4
0.2
0.0
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
Blip duration (s)
Local speed 8 deg/s
Δt (ms)
Global speed (deg/s)
0
∞
Local ≠ global
Local = global

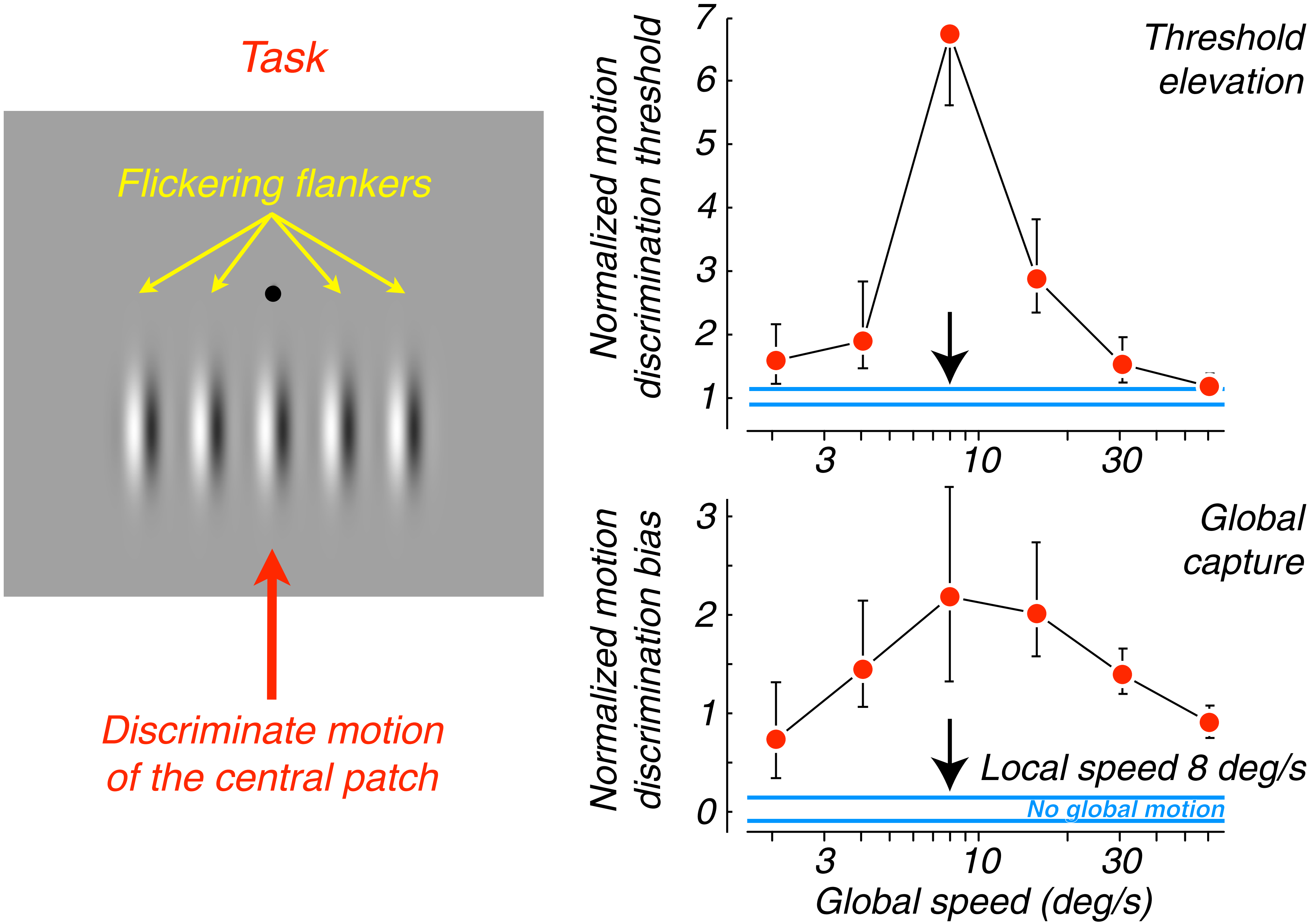


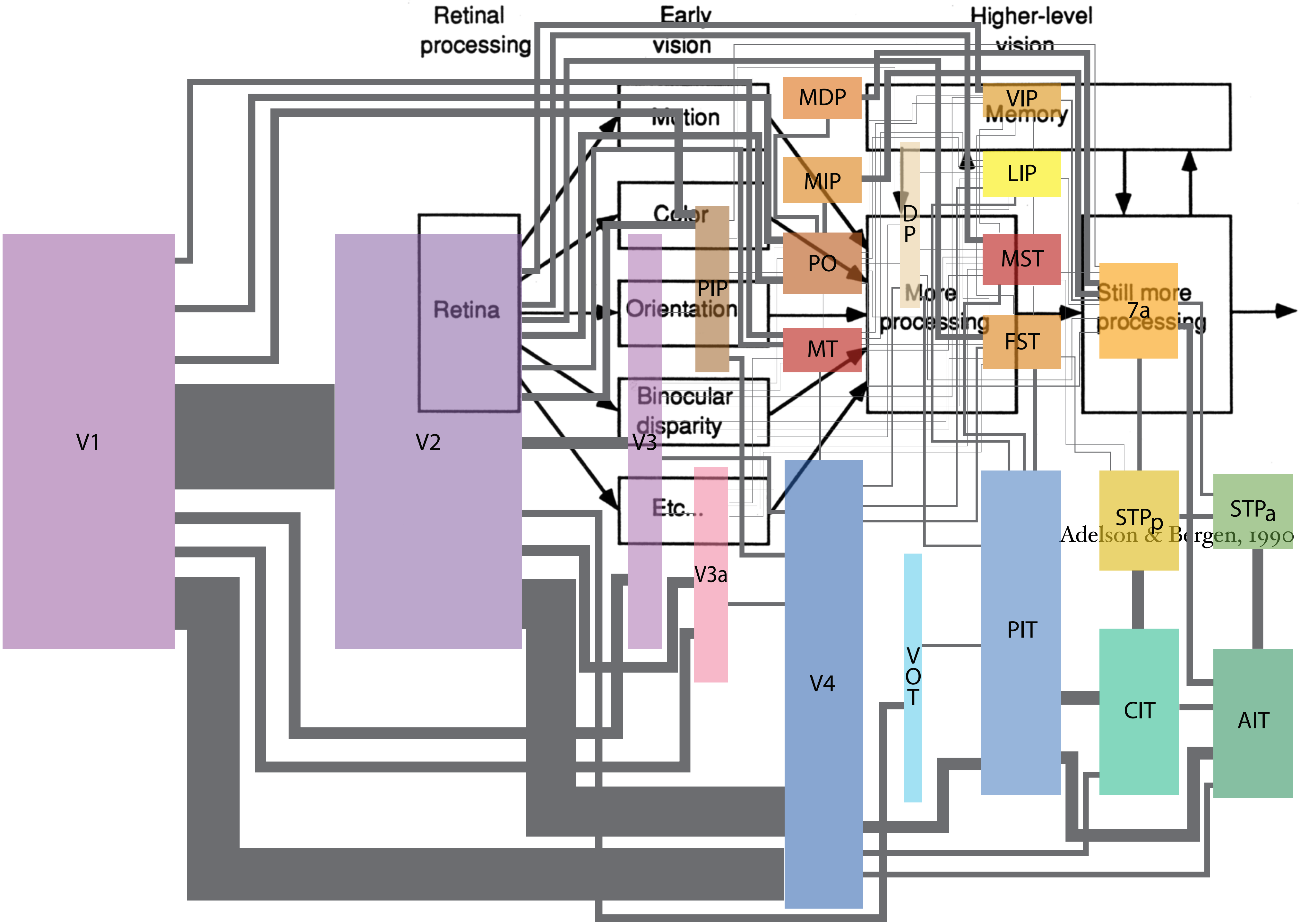
Proportion of trials judged "local = global"
1.0
0.8
0.6
0.4
0.2
0.0
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
Blip duration (s)
Local speed 8 deg/s
Δt (ms)
Global speed (deg/s)
0 ∞
8.3 180
16.6 90
33 45
67 22.5
133 11.3
Local ≠ global
Local = global



Proportion of trials judged "local = global"
1.0
0.8
0.6
0.4
0.2
0.0
Threshold
*
Shift in PSE (bias)
Local speed 8 deg/s
Δt (ms)
Global speed (deg/s)
67
22.5
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
Blip duration (s)
Local ≠ global
Local = global

Global motion masks and captures local motion





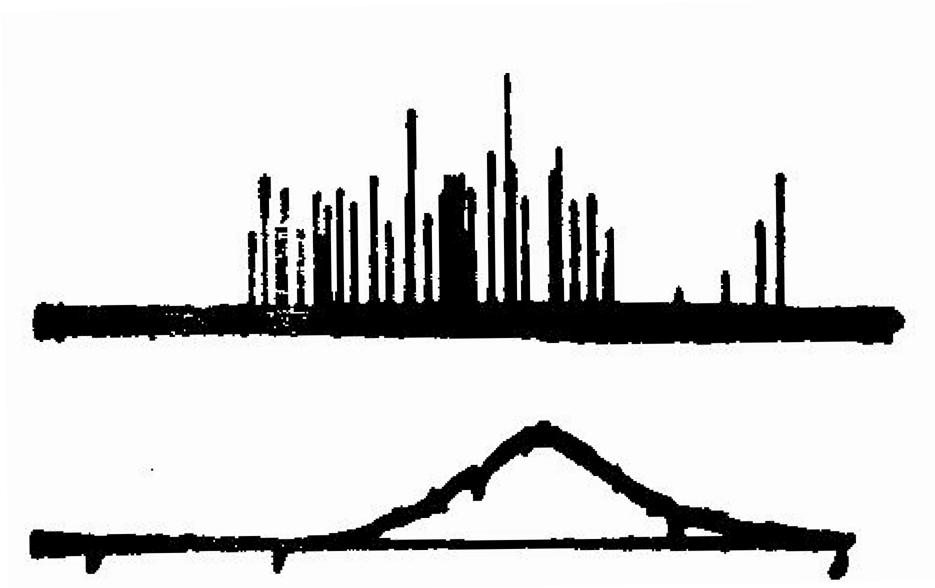
Wallisch & Movshon, 2008

after Felleman & Van Essen, 1991

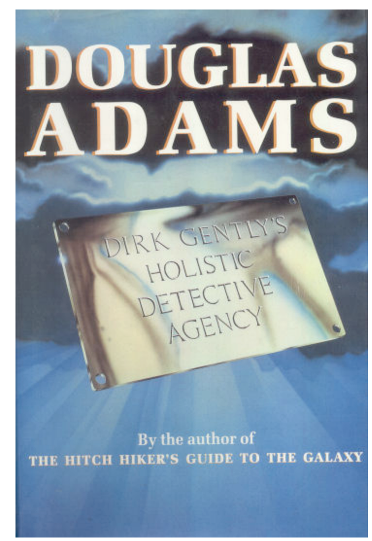
WHAT THE FROG'S EYE TELLS THE FROG'S BRAIN * †

J. Y. LETTVIN,‡ H. R. MATURANA,§
W. S. McCULLOCH,‡ AND W. H. PITTS‡

Proc. Inst. Radio Engr 47: 1940-1951, 1959

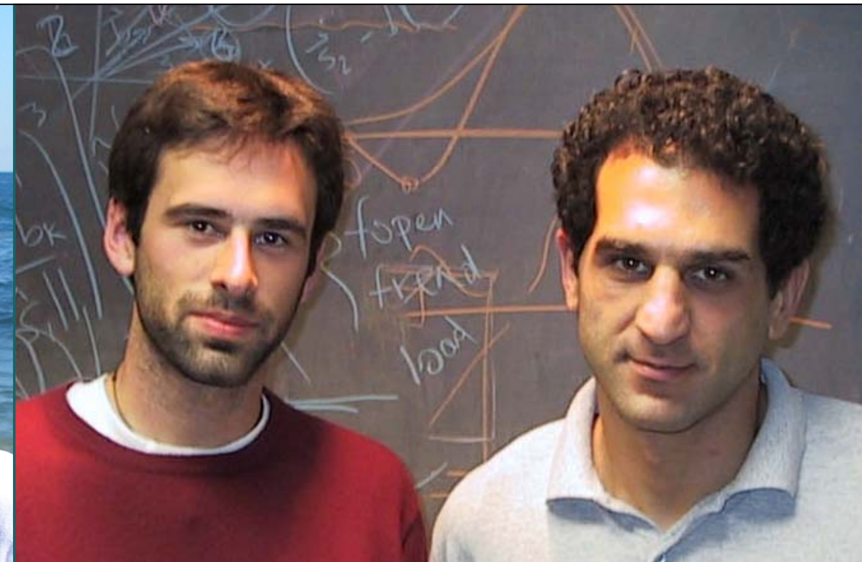


The Electric Monk was a labor-saving device, like a dishwasher or a video recorder. Dishwashers washed tedious dishes for you, thus saving you the both of watching them yourself, video recorders watched tedious television for you, thus saving you the bother of looking at it yourself; Electric Monks believed things for you, thus saving you what was becoming an increasingly onerous task, that of believing all the things the world expected you to believe.



Matteo Carandini

Nicole Rust Eero Simoncelli



Valerio Mante Najib Majaj

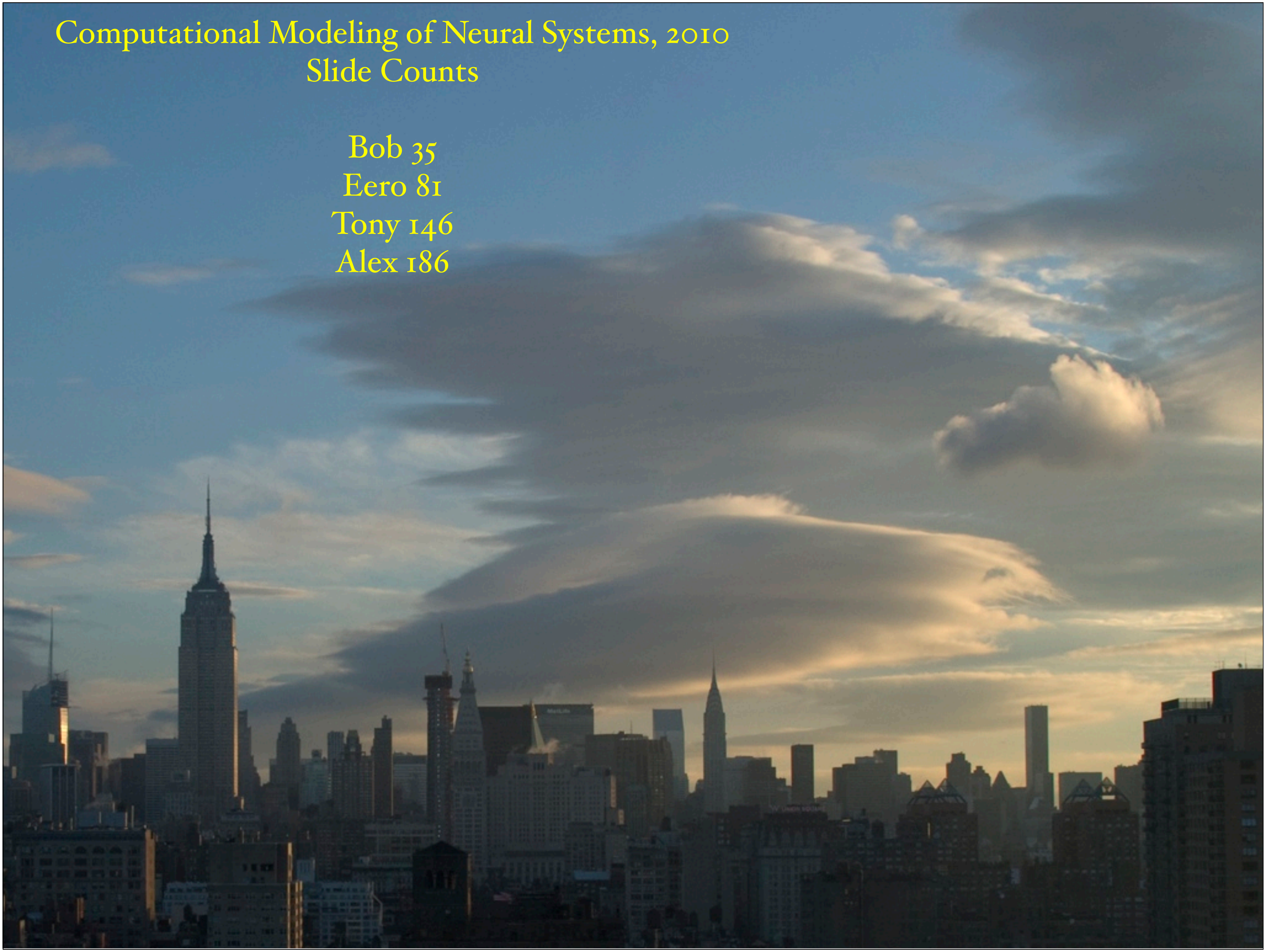
Romesh Kumbhani

Mike Shadlen

James Hedges

Jenny Gartshteyn

Chris Tailby


Computational Modeling of Neural Systems, 2010
Slide Counts
Bob 35
Eero 81
Tony 146
Alex 186

Contributions of the Visual Ventral Pathway to Long-Range Apparent Motion

Yan Zhuo,[1] Tian Gang Zhou,[1] Heng Yi Rao,[1] Jiong Jiong Wang,[1]
Ming Meng,[1] Ming Chen,[2] Cheng Zhou,[2] Lin Chen[1]*

www.sciencemag.org SCIENCE VOL 299 17 JANUARY 2003