
Some of Adrian's first recordings from very small numbers of individual nerve fibres. Each spiky deflection is a single nerve impulse. These records were taken from the sensory nerves of a cat's toe. The toe was flexed slowly, more quickly and very rapidly to produce these three traces. The frequency of firing depends on the strength of the stimulus – Adrian's law.
Relating MT responses to visual discrimination
Figure 6. The psychophysical effects of an ibotenic acid injection into MT in experiment w1. Solid line and error bars in A–D indicate the mean prelesion threshold and standard deviation for each condition tested; dashed line, postlesion thresholds obtained 24 hr after the MT injection. A, Motion thresholds for 5 different spatial intervals in the test (contralateral) hemifield. Again, the MT lesion caused striking elevations of motion thresholds in the test hemifield. B, Motion thresholds were within the normal range in the control (ipsilateral) hemifield. C, The MT injection had no effect on contrast thresholds in the test hemifield.

Newsome and Paré, 1988
Downing & Movshon, 1989
Visual stimulus

Neuronal response

Behavioral judgement
MT responses depend on motion coherence

Firing rate (impulses/trial) vs. Coherence (%)

- Preferred direction
- Null direction

Britten, Shadlen, Newsome & Movshon, 1993
Behavioral performance from one session
MT cells are as sensitive as monkeys to visual motion

Britten, Shadlen, Newsome & Movshon, 1992
MT cell firing does not require the observer to make a decision

Britten, Shadlen, Newsome & Movshon, 1992
Visual stimulus

Neurometric function

Neuronal response

Psychometric function

Behavioral judgement
Visual stimulus

Neurometric function

Neuronal response

Psychometric function

Behavioral judgement

?
MT cell firing is correlated with behavioral choice

0% coherence

Choose “preferred”

Choose “anti”

Proportion of trials

Response (impulses/sec)
MT cell firing is correlated with behavioral choice

Choose “preferred”
Choose “anti”

0% coherence

Proportion of trials

Proportion of cells

Response (impulses/sec)

Choice probability

0.555

Britten, Newsome, Shadlen, Celebrini & Movshon, 1996
MT cell firing is correlated with behavioral choice
MT cell firing is correlated with behavioral choice

Choose "antipreferred"

Choose "preferred"
MT cell firing is correlated with behavioral choice

Choose "antipreferred"

Choose "preferred"

Choice probability ~ 0.85
Correlation of activity to choice is not accidental
Choice-related activity has a “forward” time course

Britten, Newsome, Shadlen, Celebrini & Movshon, 1996
The most sensitive neurons are most correlated to choice
Choice probability for depth discrimination in V2

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

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

Neurometric function

Neuronal response

Psychometric function

Choice probability

Behavioral judgement
COLUMNAR ORGANIZATION OF MT IN MACAQUE

DIRECTION OF MOVEMENT (degrees)

TRACK DISTANCE (μ)

| 1-2 |

Albright, 1984
 motion

Mmm ... left ... right?

+ microstimulation in MT

Receptive field

Pref target

Dots Aperture

Null target

10 deg

Fixation Point

Fix Pt

Dots

Elect Stim

Targets

1 sec
Proportion of choices of the preferred direction

Coherence (%)
Equivalent visual coherence

Number of cases

Salzman, Murasugi, Britten and Newsome, 1992
Visual stimulus

Neurometric function

Neuronal response

Psychometric function

Choice probability
Microstimulation

Behavioral judgement
Decoding MT neurons for visual motion discrimination

Pooled MT Signal
\( \langle X \rangle^{up} \)

Pooled MT Signal
\( \langle X \rangle^{down} \)

Decision
\( \langle X \rangle^{up} > \langle X \rangle^{down} \)

Britten, Newsome, Shadlen, Celebrini & Movshon, 1996
Shadlen, Britten, Newsome & Movshon, 1996
Cohen & Newsome, 2009
Decoding MT neurons for visual motion discrimination

Pooled MT Signal
\[ \langle X \rangle_{\text{up}} \]

Pooled MT Signal
\[ \langle X \rangle_{\text{down}} \]

Decision
\[ \langle X \rangle_{\text{up}} > \langle X \rangle_{\text{down}} \]

Shadlen, Britten, Newsome & Movshon, 1996
Cohen & Newsome, 2009
Decoding MT neurons for visual motion discrimination

Pooled MT Signal
$\langle X \rangle^{up}$

Decision
$\langle X \rangle^{up} > \langle X \rangle^{down}$

Pooled MT Signal
$\langle X \rangle^{down}$

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

Zohary, Shadlen & Newsome, 1994
Where is sensory activity converted into decision and actions?
LIP receives projections from MT and projects to areas that are known to contribute to the generation of saccadic eye movements.
Fixate 350 msec

Targets appear 500 msec

Random dot motion 2 sec

Delay 500-1000 msec

Saccade

\( + \) recording in LIP

Shadlen and Newsome, 2001
Responses in a reaction-time version of the direction discrimination task
Bounded accumulation of evidence

MT – sensory evidence
Motion energy “step”

LIP – decision formation
Accumulation of evidence “ramp”

Spikes/s

High motion strength
Low motion strength

Stimulus on
~1 sec
Stimulus off

Spikes/s

Stimulus on
~1 sec
Stimulus off

Mike Shadlen
Momentary evidence, e.g., \( \Delta \text{Spike rate: } MT_{\text{Right}} - MT_{\text{Left}} \)

Accumulated evidence for Rightward and against Leftward

Diffusion to bound model

\[
\mu = kC
\]

\( C \) is motion strength (coherence)

Palmer et al (2005)
Responses in a reaction-time version of the direction discrimination task are well described by the “race” model of integration to a decision boundary.

\[ P = \frac{1}{1 + e^{-2k|C|B}} \]

\[ t(C) = \frac{B}{kC} \tanh(BkC) + t_{nd} \]
Firing rate (sp/s) vs. Time from saccade (ms)

Grouped by RT

Roitman & Shadlen, 2002
Speed-Accuracy Tradeoff

Hanks, Kiani & Shadlen, 2014
Speed-Accuracy Tradeoff

Hanks, Kiani & Shadlen, 2014
Speed-Accuracy Tradeoff

Hanks, Kiani & Shadlen, 2014
Speed-Accuracy Tradeoff

\[ T_{in} \text{ accumulator} \quad \text{Bound for } T_{in} \]

\[ T_{out} \text{ accumulator} \quad \text{Bound for } T_{out} \]
Speed-Accuracy Tradeoff

Hanks, Kiani & Shadlen, 2014
Where is sensory activity converted into decision and actions?

- Lateral intra-parietal area (LIP)
- Frontal eye field (FEF)
- V1
- V2d
- V2v
- V4
- 7a
- 7b
- MT/MST
Voluntary saccade
Motion
Fixation
Evoked saccade
Voluntary saccade

+ microstimulation in FEF

Gold and Shadlen, 2000
Gold and Shadlen, 2000
Weaken visual signal

Gold and Shadlen, 2000
Direction of motion map (MT)

Saccade vector map (FEF)

Leftward

Rightward

DECISION
Mmm .... left ... right?

Motion

How confident am I?

Response
**Certainty task**

**Stimulus duration:** 100-900 ms (truncated exponential)

**Sure target delay:** 500-750 ms
**Sure reward / correct reward** \( \approx 0.8 \)

*Kiani & Shadlen, 2009*
Post-decision wagering

Motion

Mmm .... left ... right?

Response

How confident am I?

sure bet

high stakes choice
Momentary evidence, e.g., $\Delta$Spike rate: $MT_{Right} - MT_{Left}$

Decision variable ($v$)

Choose right "1"

$\mu = kC$

Choose left "2"

 accumulating evidence

References:
- Link, 1992
- Ratcliff & Smith, 2004
- Palmer et al, 2005
- Laming, 1968
- Luce, 1986
Most likely correct

Uncertain

Kiani & Shadlen, 2009
Three free parameters:
- $k$, sensitivity coefficient
- $B$, bound height
- $\theta$, criterion on log-odds correct

Kiani & Shadlen, 2009
Model fits

Kiani & Shadlen, 2009
Model fits

PredicBons

Kiani & Shadlen, 2009

with sure target
without sure target

Probability correct

Motion strength (%coh)

Probability sure target

Motion strength (%coh)

Kiani & Shadlen, 2009
Firing rate (normalized)

1.5

1

0.5

100 ms

motion

sure target

eye movement

choose $T_{in}$

choose $T_{out}$

Waive good
Decline good
Reject bad

two directions remember 2 dashed lines.

Kiani & Shadlen, 2009

weak motion strength
$N = 70$ neurons