A

Stimulus 1
(s=1)

Stimulus 2
(s=2)

Neural activity

Behavioral
choice

Choice 1 (c=1)
go left

Choice 2 (c=2)
go right

Sensory
coding

Information
readout

Sensory
information

Intersection

Readout

B

Intersection

Information for
task performance

Task performance

c=2

c=1

Intersection-guided
intervention

Intervention-evoked
neural activity

Task performance

c=2

c=1

A

Population **1** *vs* Population **2**

$r_1 = \sum_i \triangle_i$ $r_2 = \sum_i \triangle_i$

s=1

s=2

Neural activity

High

Low

r_2 = spike count 2

Low   High

r_1 = spike count 1

B

Component **1** *vs* Component **2**

$r_1 = \sum_i \alpha_i \triangle_i$ $r_2 = \sum_i \alpha_i \triangle_i$

r_2 = component 2

PCA

r_1 = component 1

C Spike timing *vs* Spike count

r_1 = spike timing

Early   Late

Low   High

r_2 = spike count

s=1

s=2

D Spike regularity *vs* Spike count

r_1 = regularity

High   Low

Low   High

r_2 = spike count

s=1

s=2

A₁ Response scatterplot   **A₂** Intersection information of r_1 r_2 **A₃**

B₁ Response scatterplot   **B₂** Intersection information of r_1 r_2 **B₃**

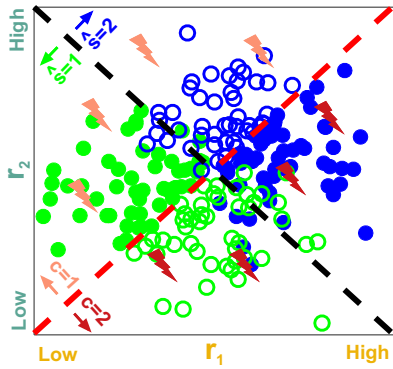**C₁** Response scatterplot   **C₂** Intersection information of r_1 r_2 **C₃**

- - - Sensory boundary   ● Correct choice c=1 with s=1   ● Correct choice c=2 with s=2
- - - Decision boundary   ○ Incorrect choice c=2 with s=1   ○ Incorrect choice c=1 with s=2

Permissive and instructive roles in coding and information flow
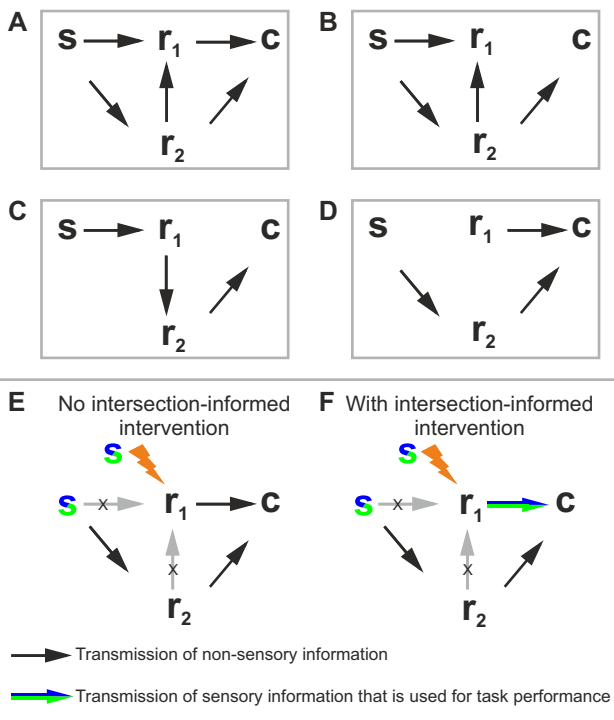
A Null (chance) intersection   **B** Intermediate intersection   **C** Large intersection
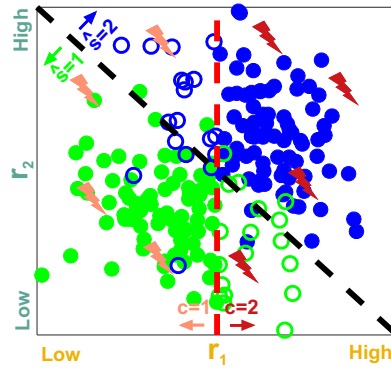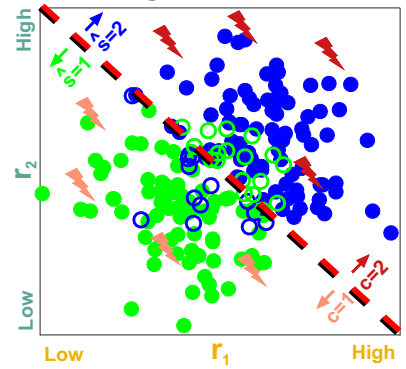
Intervention-imposed r_1 r_2 values eliciting c=1 — — Sensory boundary ● Correct choice c=1 with s=1 ● Correct choice c=2 with s=2

Intervention-imposed r_1 r_2 values eliciting c=2 — — Decision boundary ○ Incorrect choice c=2 with s=1 ○ Incorrect choice c=1 with s=2

A

Touch texture with whiskers

B

Turn to collect reward

C

Rate template (non-zero mean)

Rate
response = 4

Timing template (zero mean)

Timing
response = -0.3

Rate&timing
response = 4 & -0.3

D Stimulus information

x 10^{-2}

Information (bits)

Rate   Timing   Rate&timing

E Choice information

x 10^{-2}

Information (bits)

Rate   Timing   Rate&timing

F Intersection

x 10^{-2}

fII > chance

Rate   Timing   Rate&timing

A

NO   YES

No lick   Lick
('no')   ('yes')

Pole location task
and virtual pole sensation

B

Location decoding

Discrimination performance, spike timing
0.9
0.7
0.5
        0.5   0.7   0.9
Discrimination performance,
spike rate

Choice decoding

Discrimination performance, spike timing
0.9
0.7
0.5
        0.5   0.7   0.9
Discrimination performance,
spike rate

Spike rates and spike
timing carry stimulus
and choice information

C

θ
5°
0.5 s

YES
NO
YES
NO

Yes
No

0   50   100 150 200 250
Trials in session

Fraction yes
1.0

0.5

        No stim

Fooling
index

Optogenetically-evoked spike rates
lead to virtual pole perception

D

Delayed light

Δt = {0, 5, 10, ...} ms

Crossings   Light

θ   10°
                           0.5 s

Δt = 50 ms

θ   10°

stim delay = touch delay

Fooling index
0.4
0.3
0.2
0.1
0
-0.1
    0   5   10   20   50
Delay to stim, Δt (ms)

Adding optogenetic
spike timing information
does not improve
virtual pole perception

A Virtual sensation

No sensory
stimulus

Neural activity

Optogenetic
intervention

Imposed activity
mimics that evoked
by the stimulus

B Override/bias sensation

s=1

Neural activity

Optogenetic
intervention

Imposed activity
overrides or biases
that evoked by
the stimulus

C Wide-field illumination

Cell number

7
6
5
4
3
2
1

Time

Neural activity

D Patterned illumination

Cell number

7
6
5
4
3
2
1

Time

Neural activity

A₁

r_1, r_2

$s \rightarrow \boxed{\begin{array}{c} r_1 + r_2 \\ r_1 - r_2 \end{array}} \rightarrow c$

$s \rightarrow r_3 \rightarrow c$

A₂

Fraction correct

1

0.75

0.5

neurometric

psychometric

10^{-3} 10^{-2} 10^{-1} 10^{0}

Signal intensity

B

$c=1$ $c=2$

$s=1$ $s=2$

$c=2$ $s=2$

$c=1$ $s=1$

$s=2$ $s=1$

$c=1$ $c=2$

Low r_1 High

High r_2 Low

A₃

High

r_2

Low

Low r_1 High

A₄

High

r_2

Low

Low r_1 High

A₅

High

r_2

Low

Low r_1 High

C₁ Intersection of r_1

r_2

$\hat{s}=2$
$c=2$

$\hat{s}=1$
$c=1$

r_1

C₂ Intersection of r_2

r_2

$\hat{s}=2$
$c=2$

$\hat{s}=1$
$c=1$

r_1

C₃ Intersection of $r_1 r_2$

r_2

$\hat{s}=2$
$c=2$

$\hat{s}=1$
$c=1$

r_1

C₄

Intersection information

a.u.

r_1 r_2 $r_1 \& r_2$

D₁

1

0.5

Stimulus
information II II^n
(chance)

D₂

1

0.5

Stimulus
information II II^n
(chance)

D₃

1

0.5

Stimulus
information II II^n
(chance)