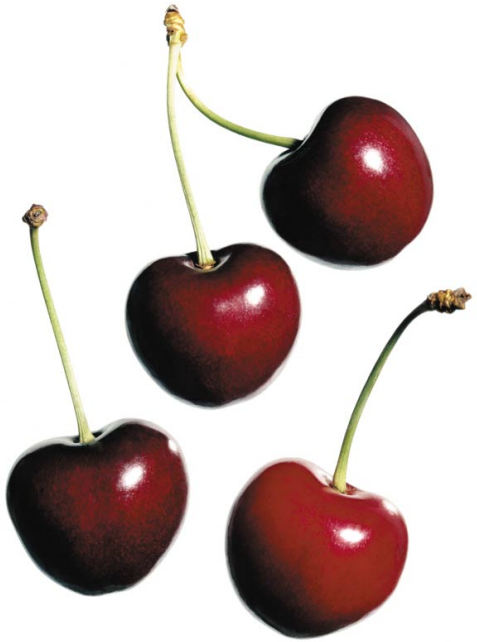
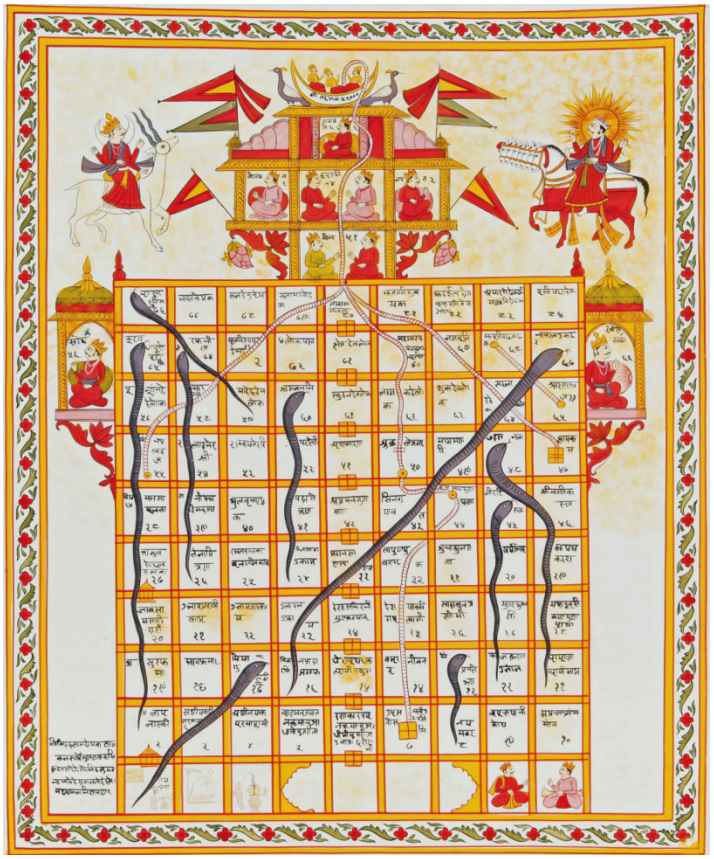
A Visual Sense of Number

David Burr

University of Florence





Outline

- Numerosity and density
- Attention and the *numberline:* logarithmic encoding?
- A generalized sense of number: sequential, cross-modal and cross-format enumeration

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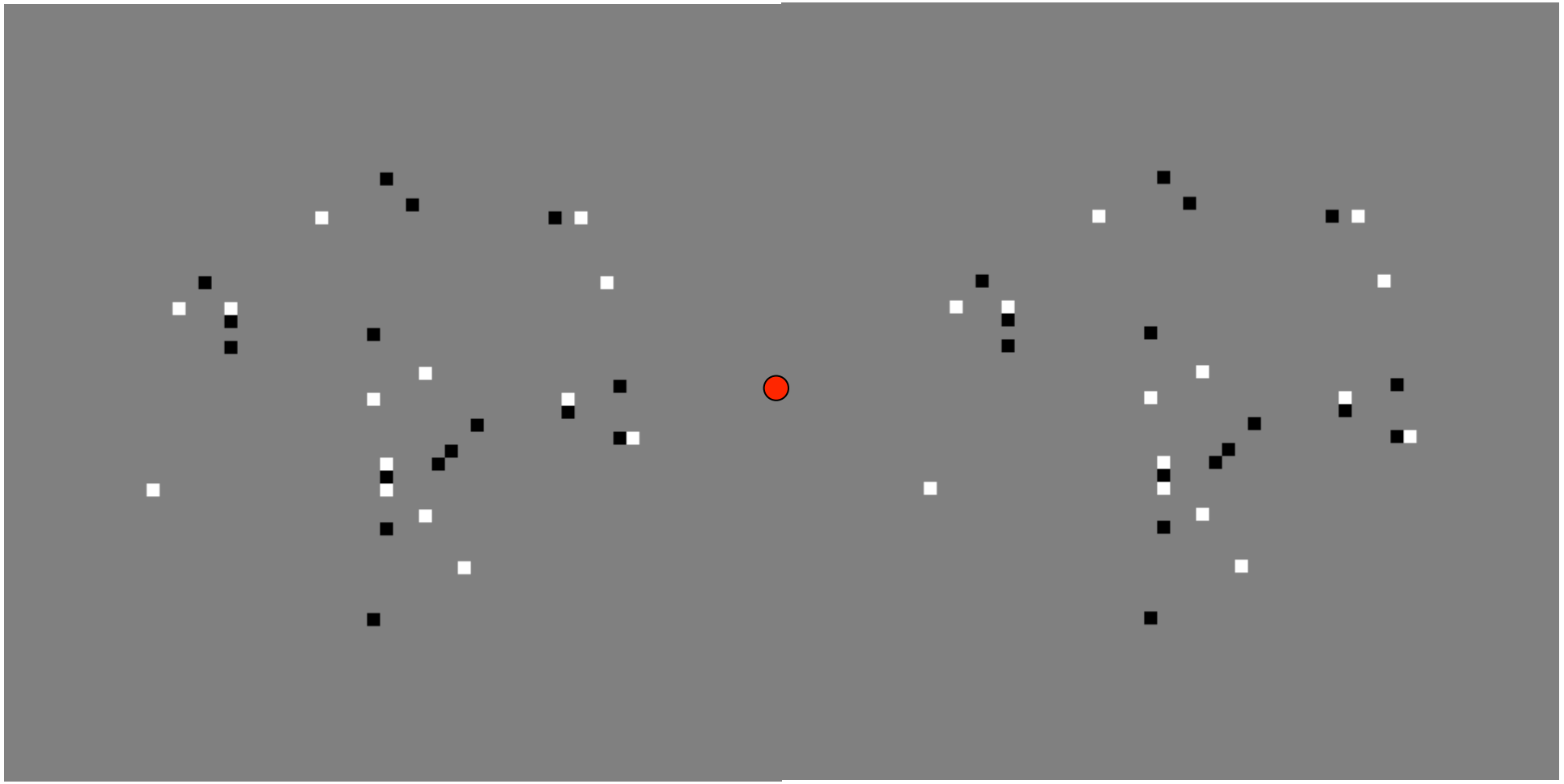
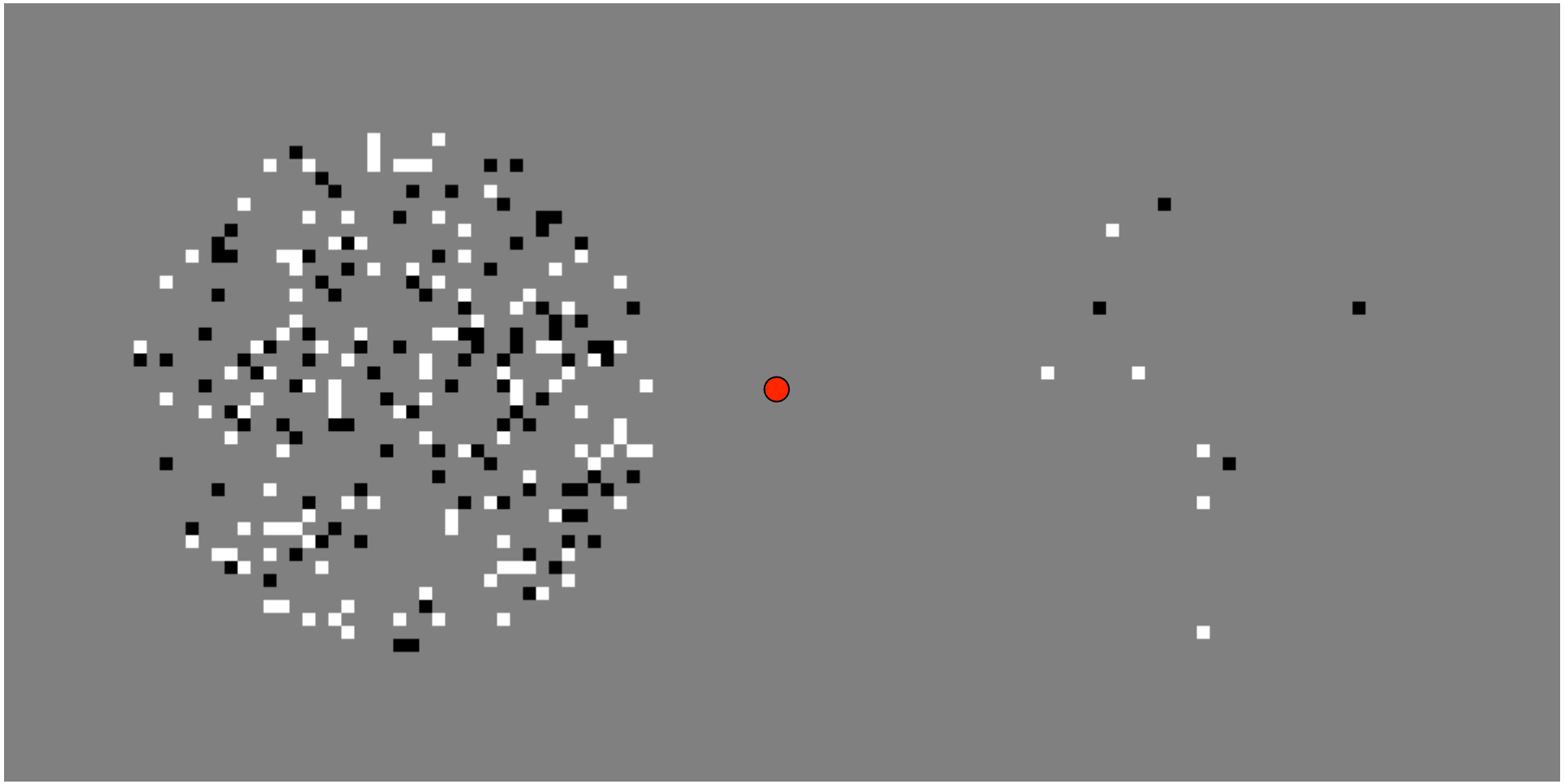
A Visual Sense of Number

David Burr[1,2,*] and John Ross[2]

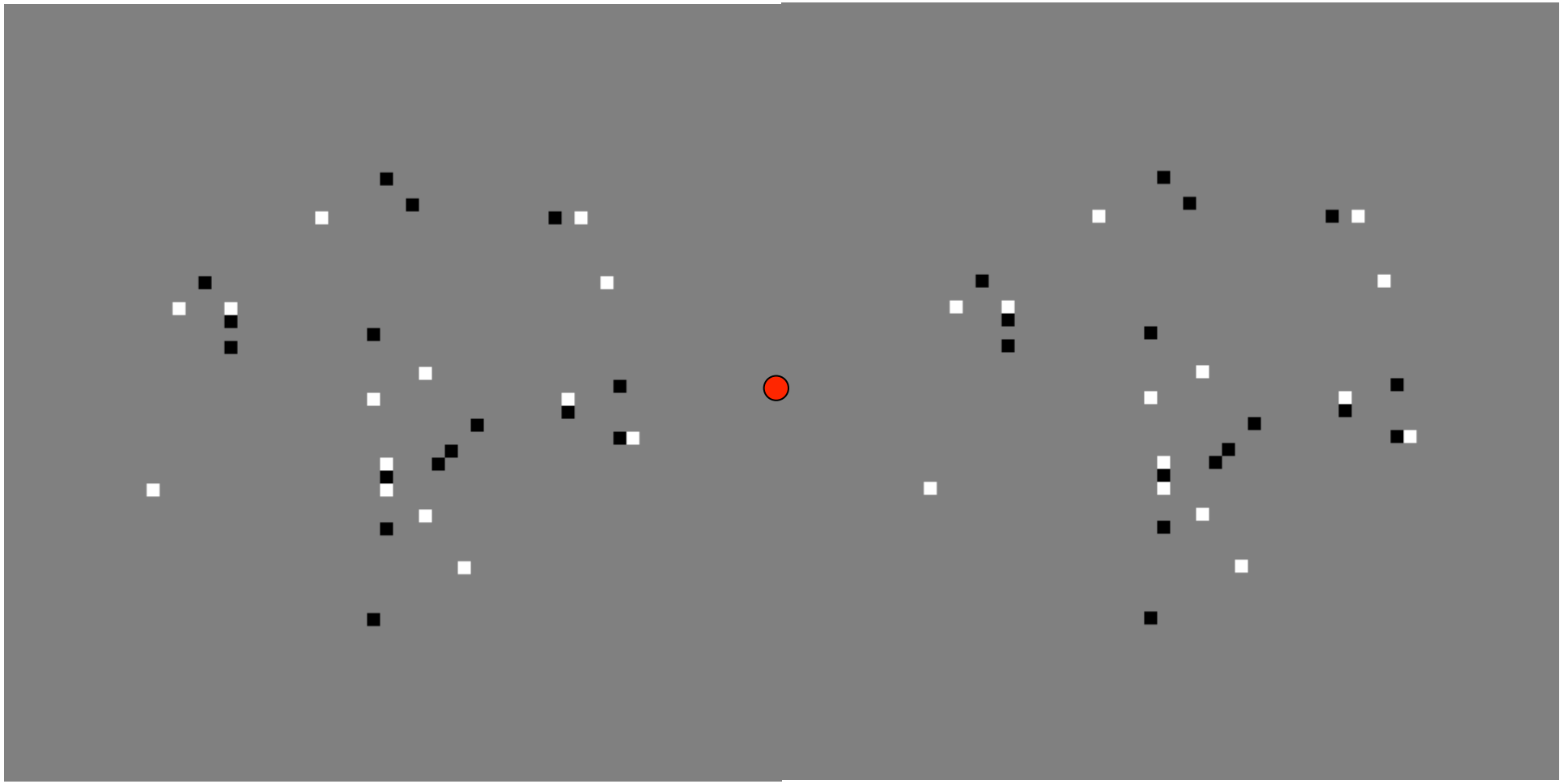
Adaptation to numerosity



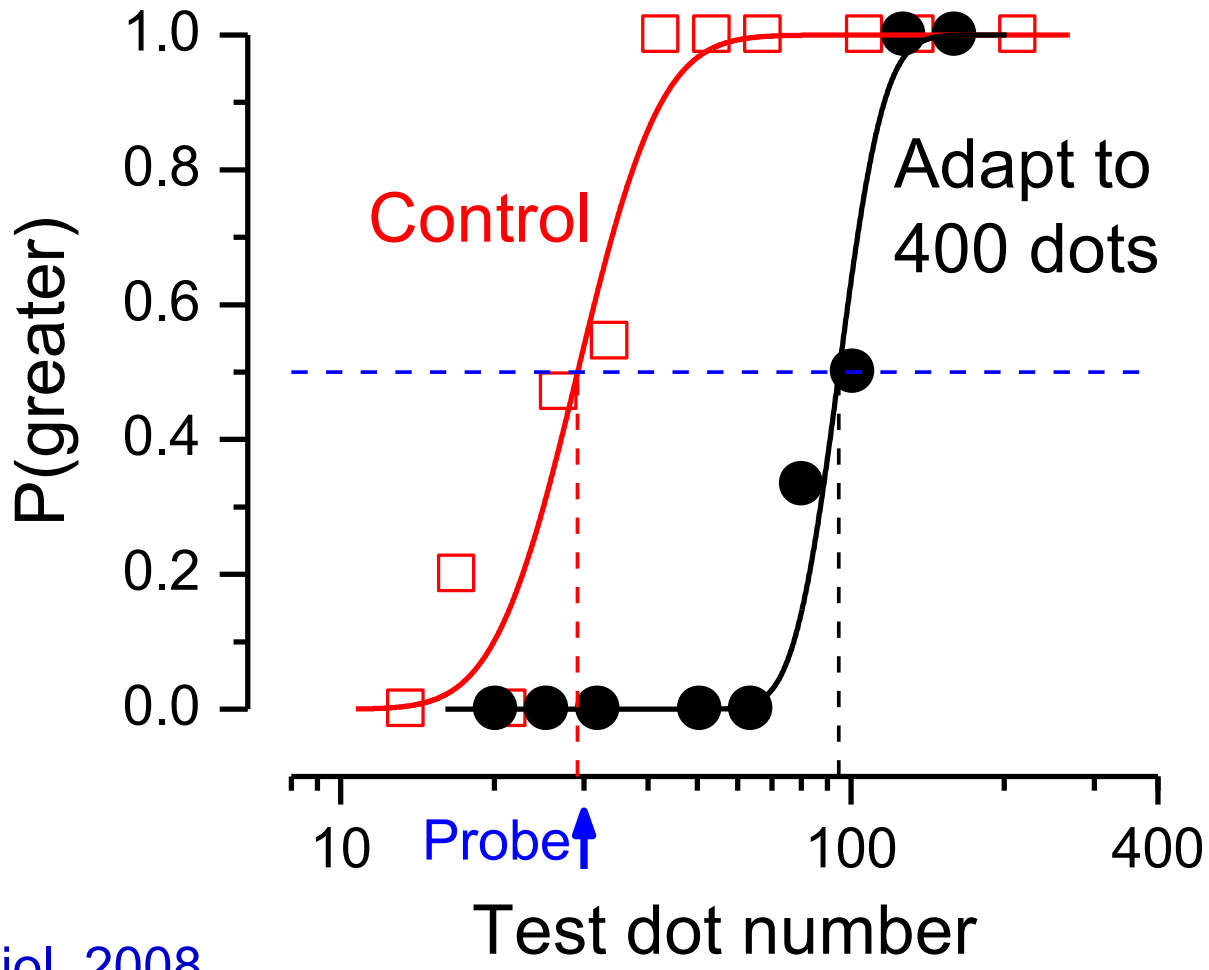
Adaptation to numerosity



Adaptation to numerosity

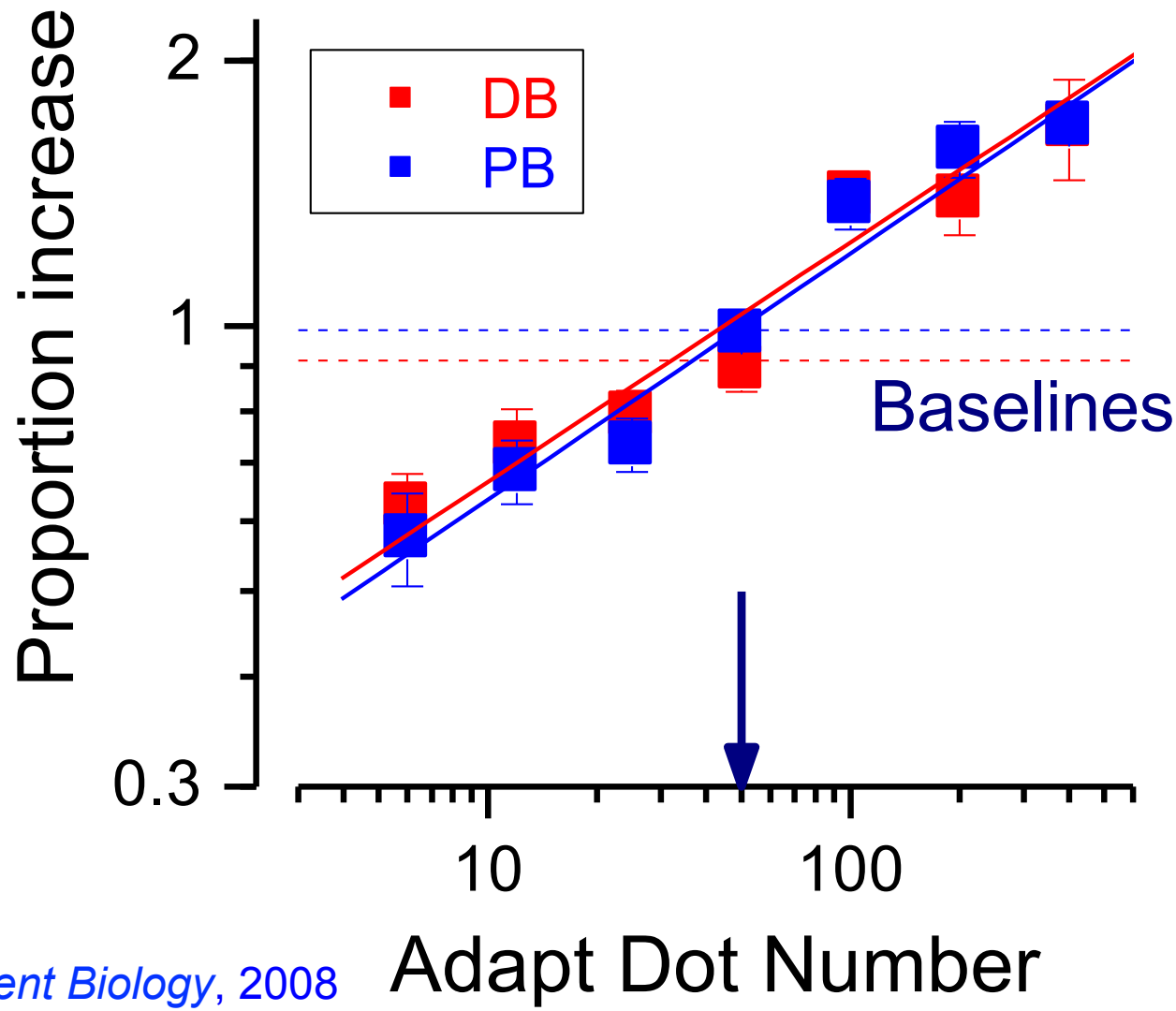


Psychometric functions with adaptation



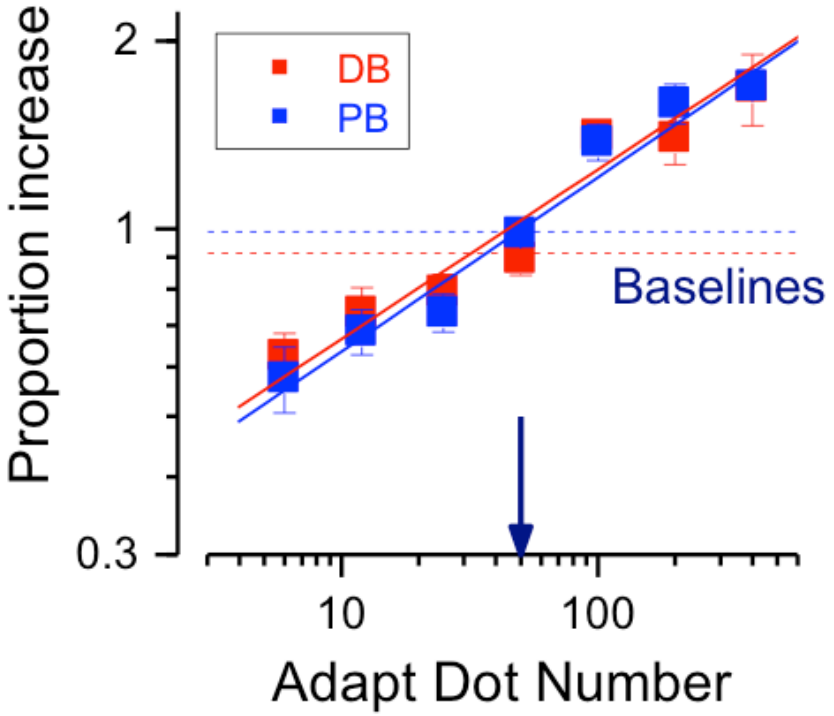
Burr & Ross, Curr. Biol, 2008

Effect of number of adaptor dots

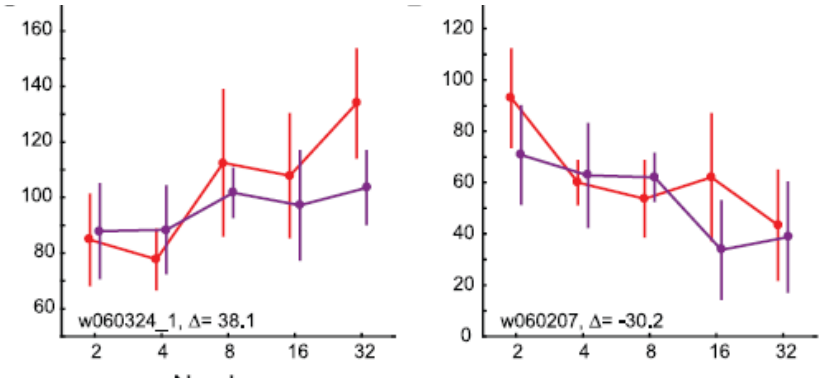


Ross & Burr, *Current Biology*, 2008

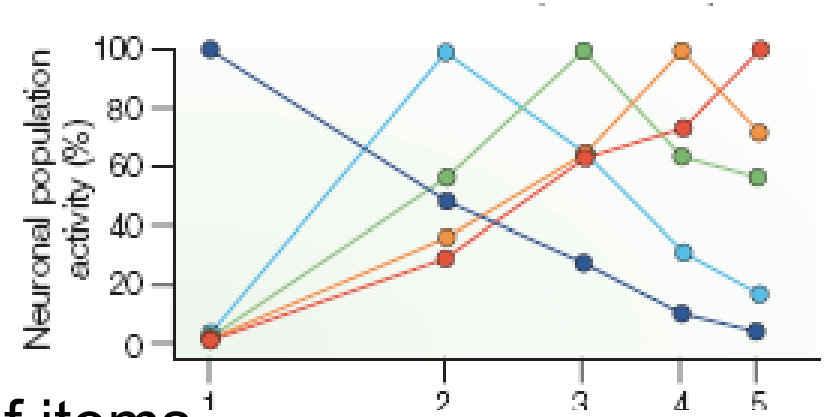
Pattern of adaptation resembles the graded response in LIP



LIP: graded response



Pre-frontal & PPC: number tuning



Number of items

Is numerosity a "side effect" of density perception?

Texture density adaptation and visual number revisited *Current Biology* Frank Durgin

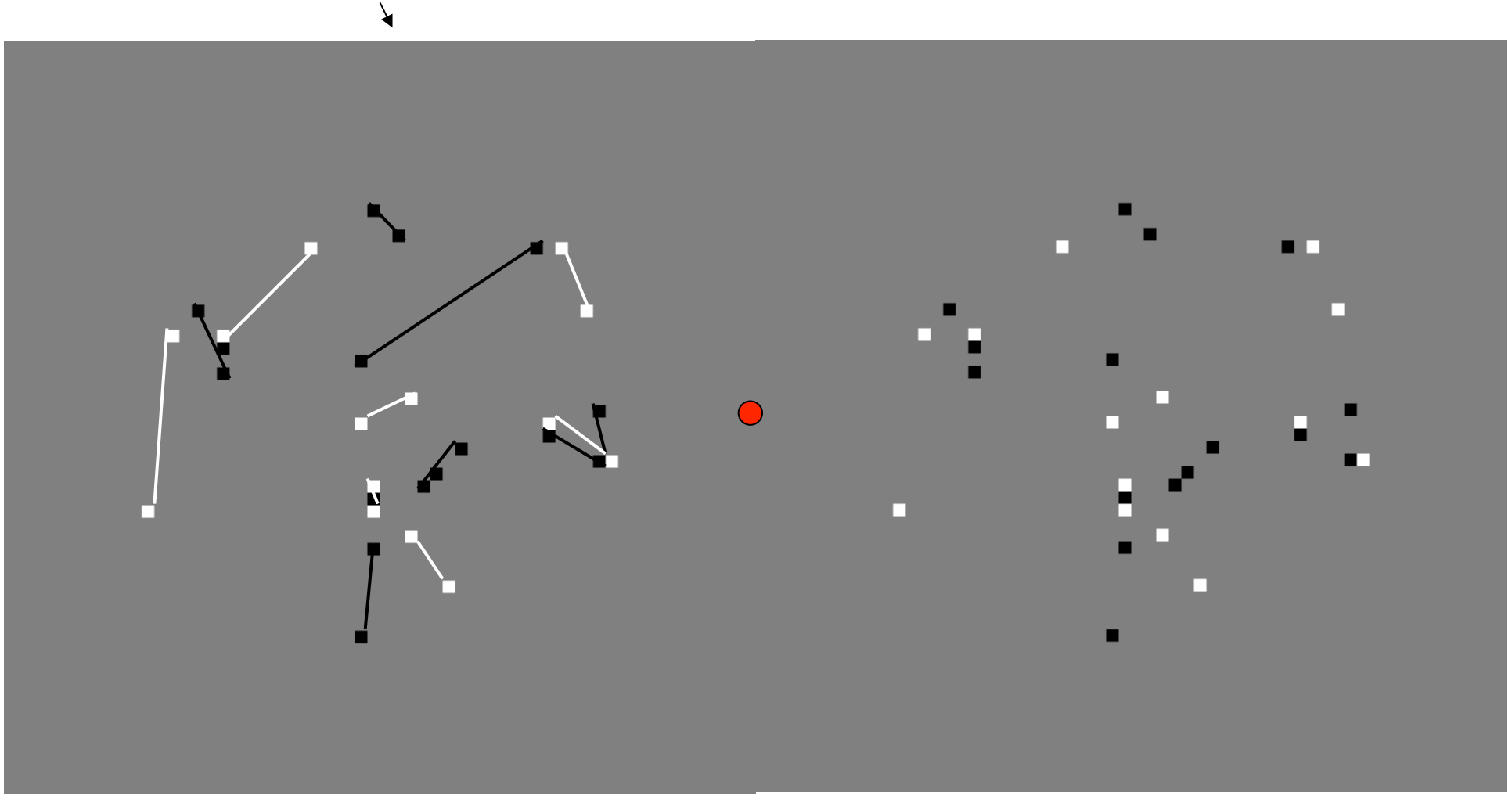
What is the unit? Texture density, not visual number, determines adaptation. *Perception Psychophysics* Frank Durgin and Daniel Abdul-Malak

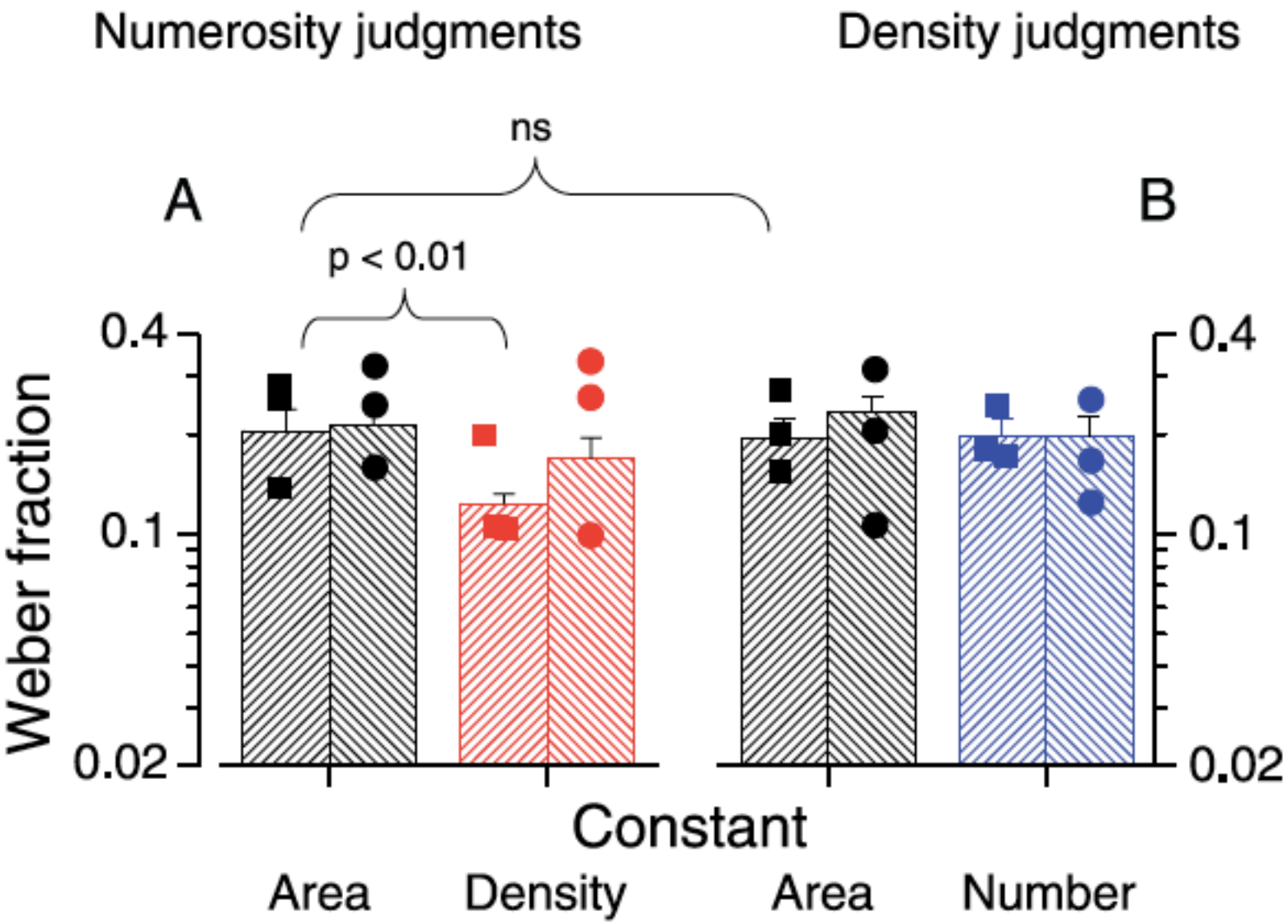
A common visual metric for approximate number and density

Steven C. Dakin[a,1], Marc S. Tibber[a], John A. Greenwood[a,b], Frederick A. A. Kingdom[c], and Michael J. Morgan[d,e]

Number is extracted from a texture representation given by the *statistical kurtosis* of the visual scene, evaluated over various scales. Durgin 2008

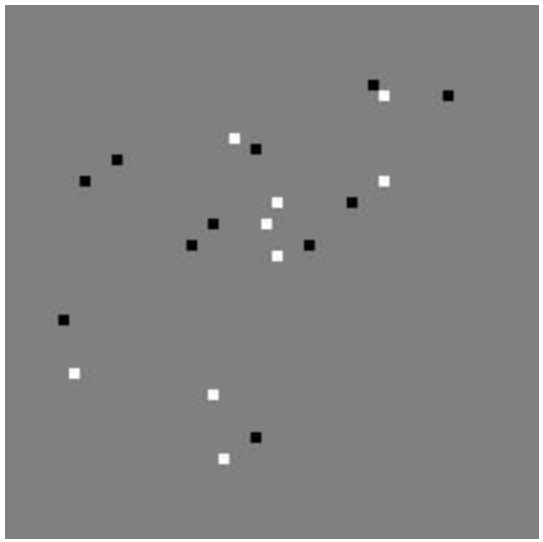
Zhang, Zhou, & Chen, *Psych. Bull:* 2009
Franconeri, Bemis & Alvarez: *Cognition* 2009




Numerosity judgments
Density judgments
ns
A
B
p < 0.01
0.4
0.1
0.02
Weber fraction
Constant
Area
Density
Area
Number

When does numerosity become texture?

20



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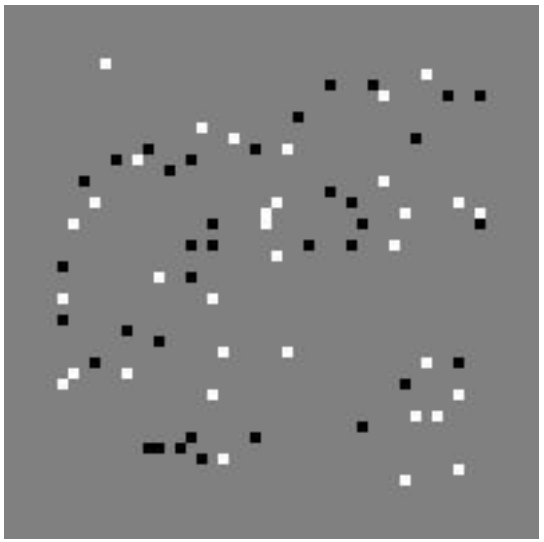

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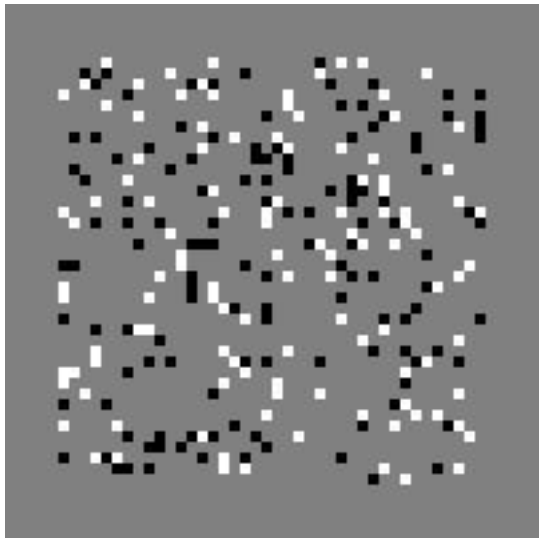
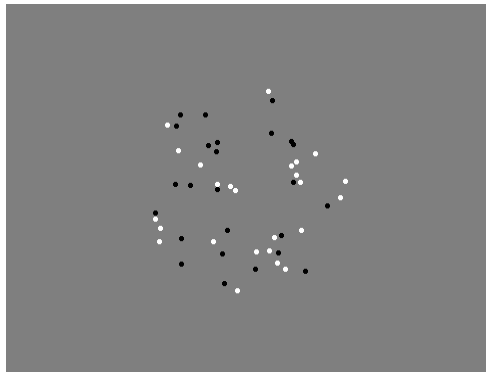
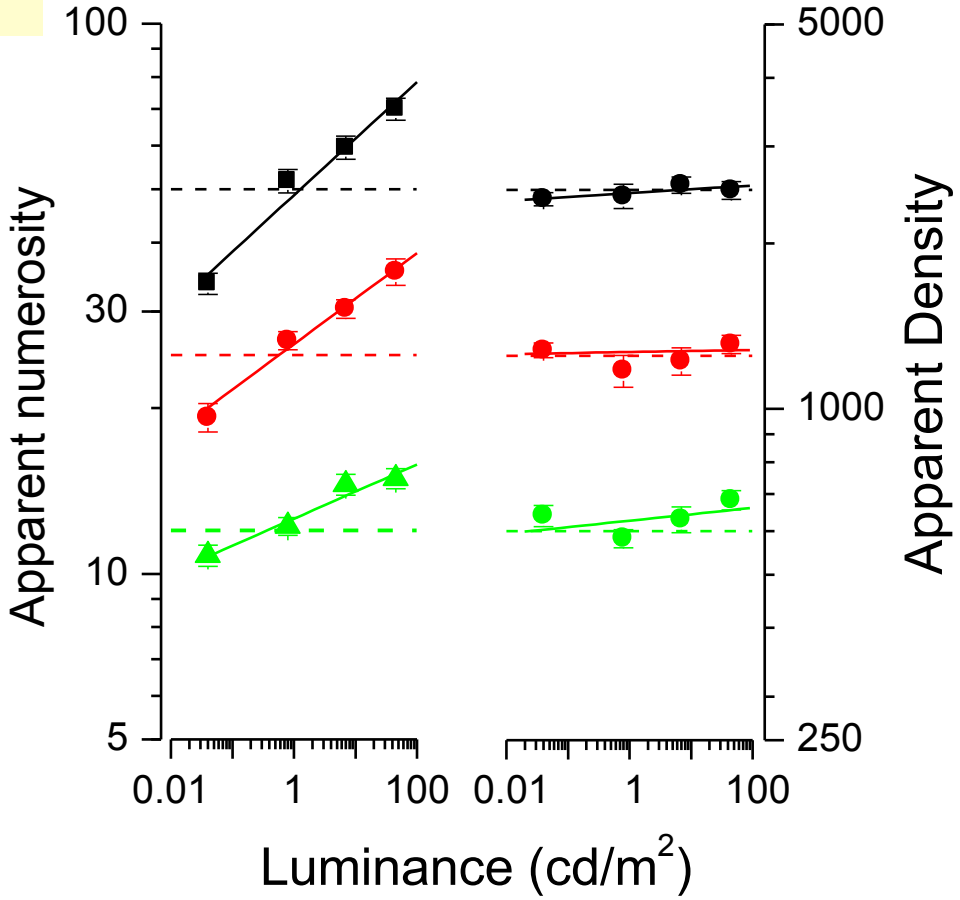


2000

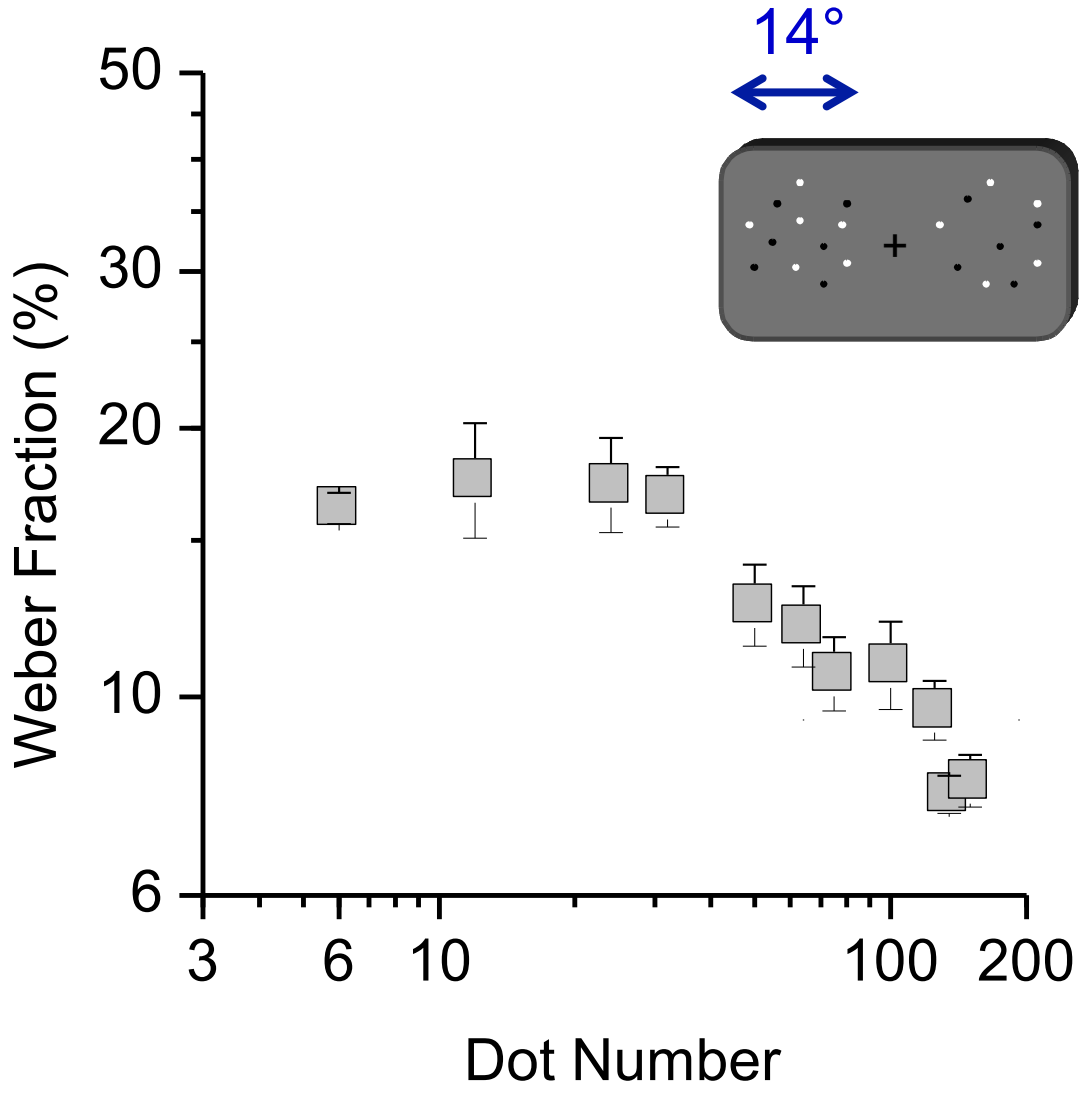
Numerosity depends on luminance, texture density does not





Ross & Burr, JoV, 2010

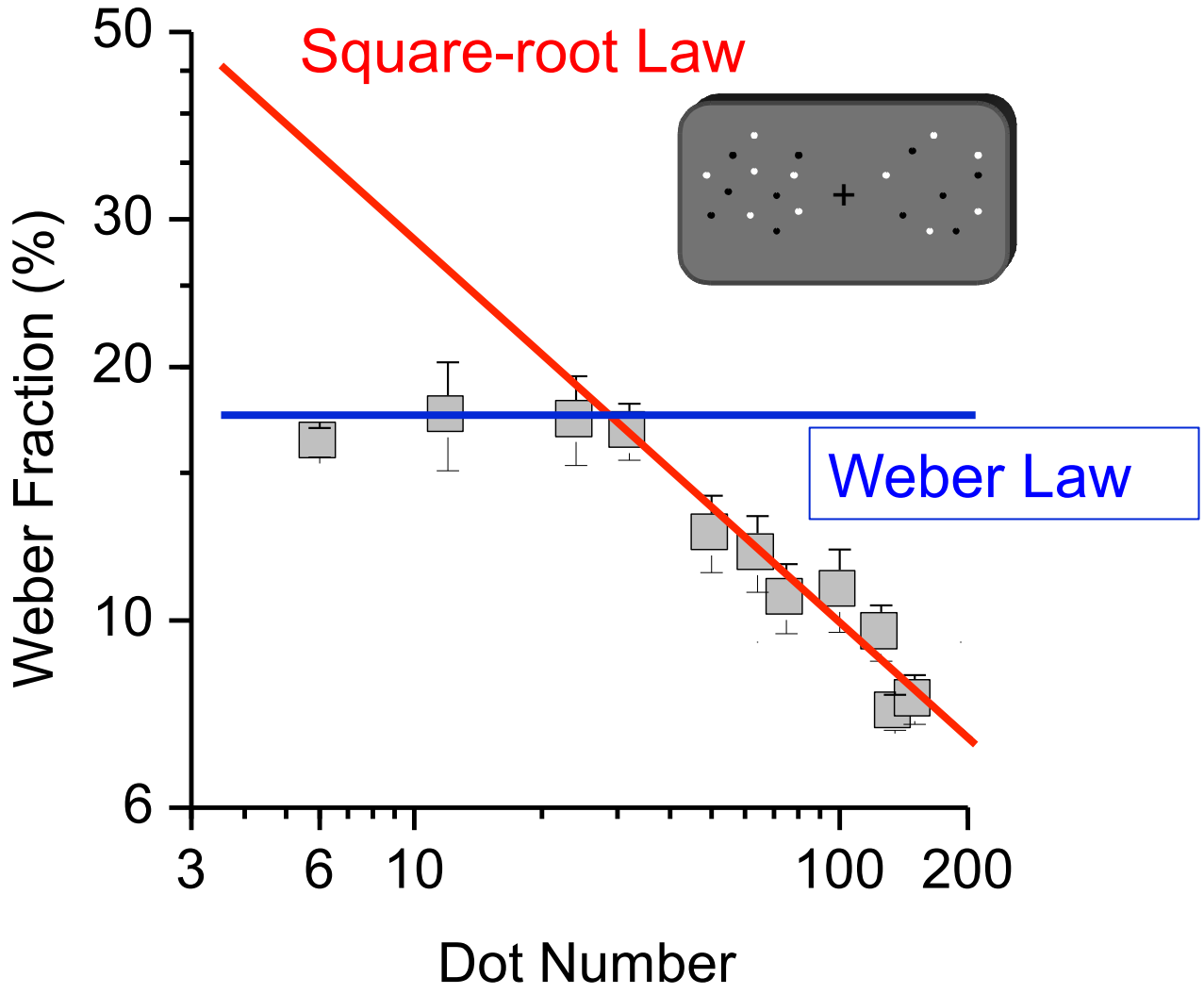
Do thresholds reveal separate mechanisms for number and density?



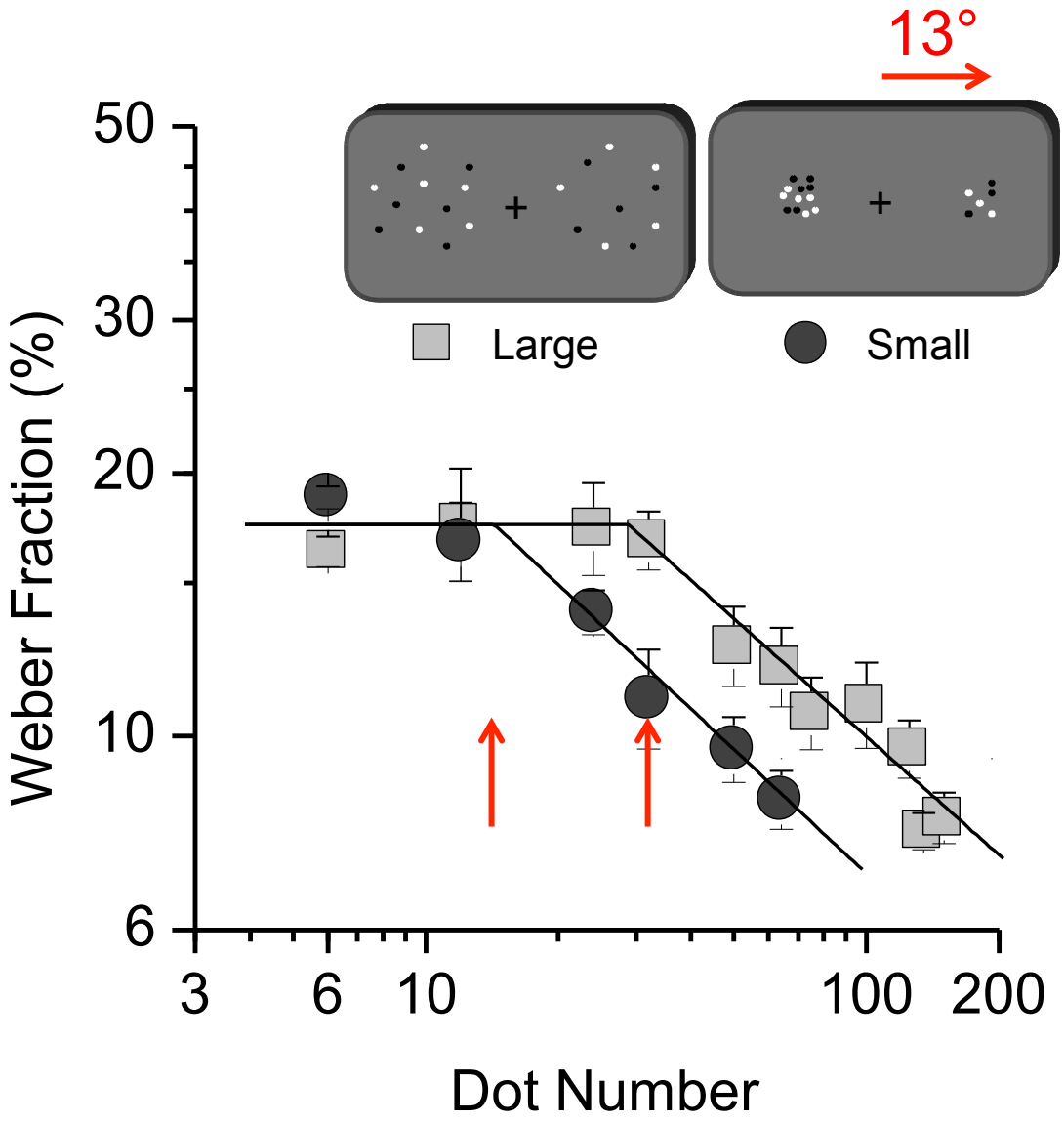
Giovanni Anobile

Marco Cicchini

Separate processes for number and density



Separate processes for number and density

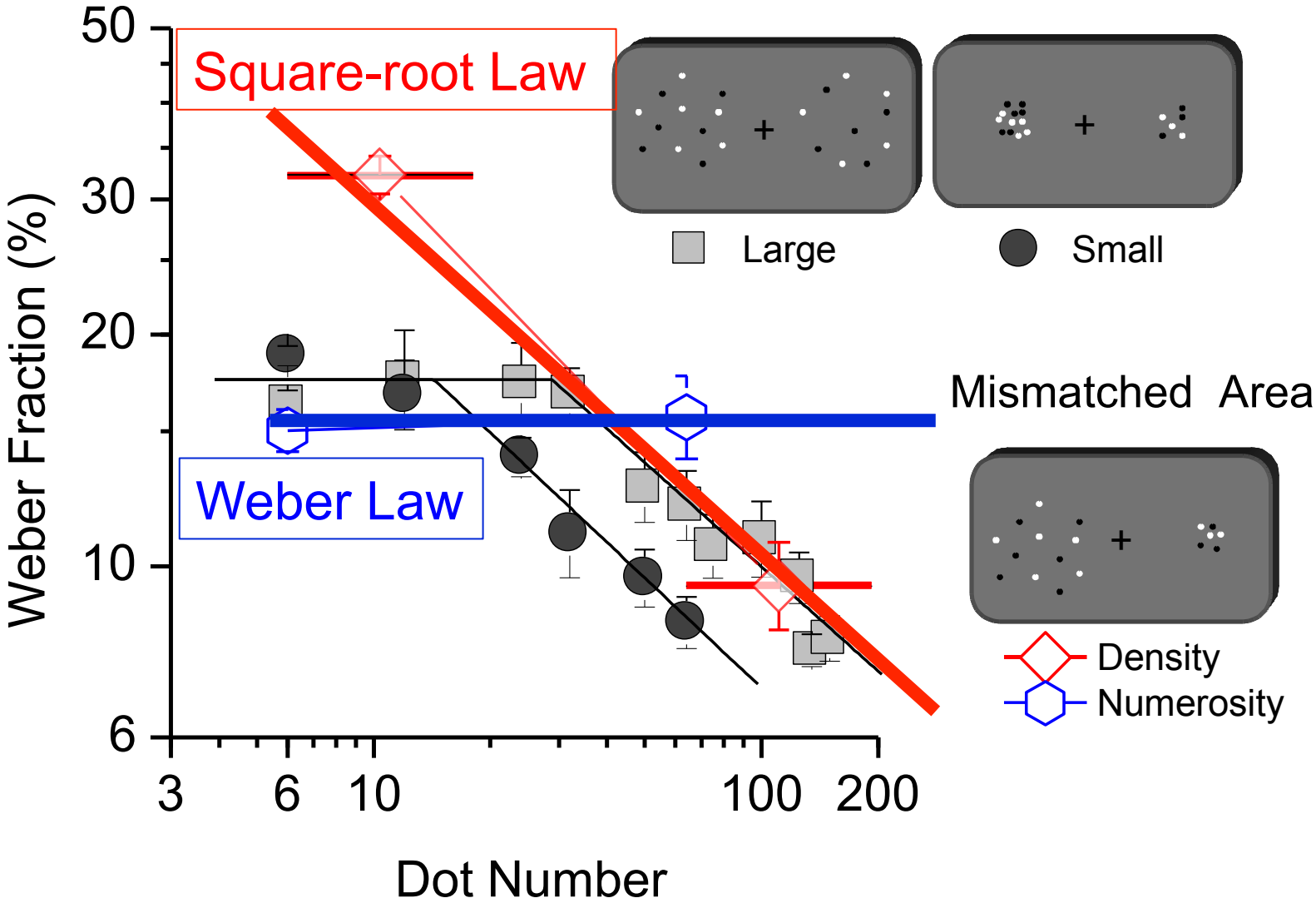


Bowma Constant ~ 0.15

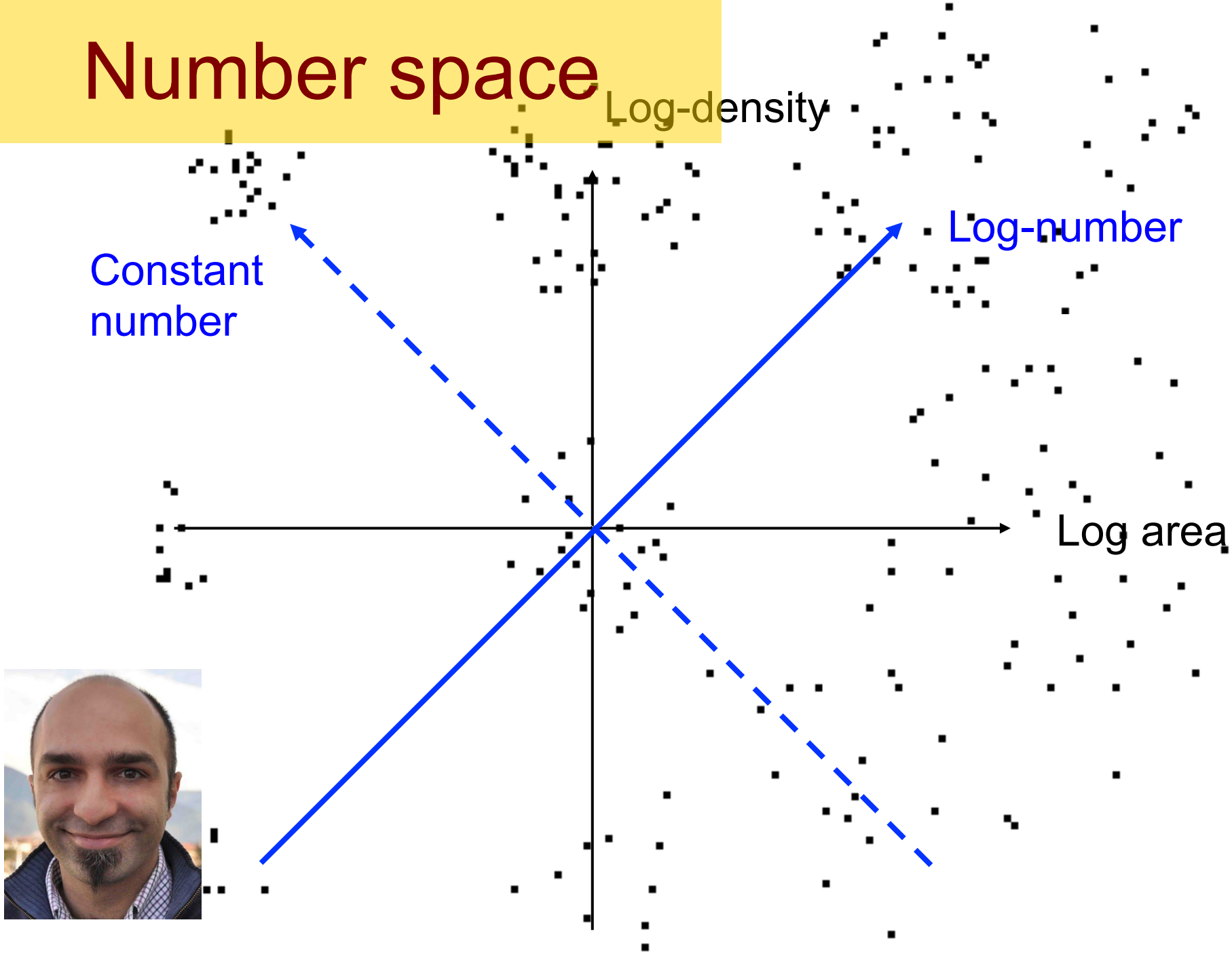
Psychophysical law changes at 0.25 dots/sq deg

Average dot spacing: 2 deg

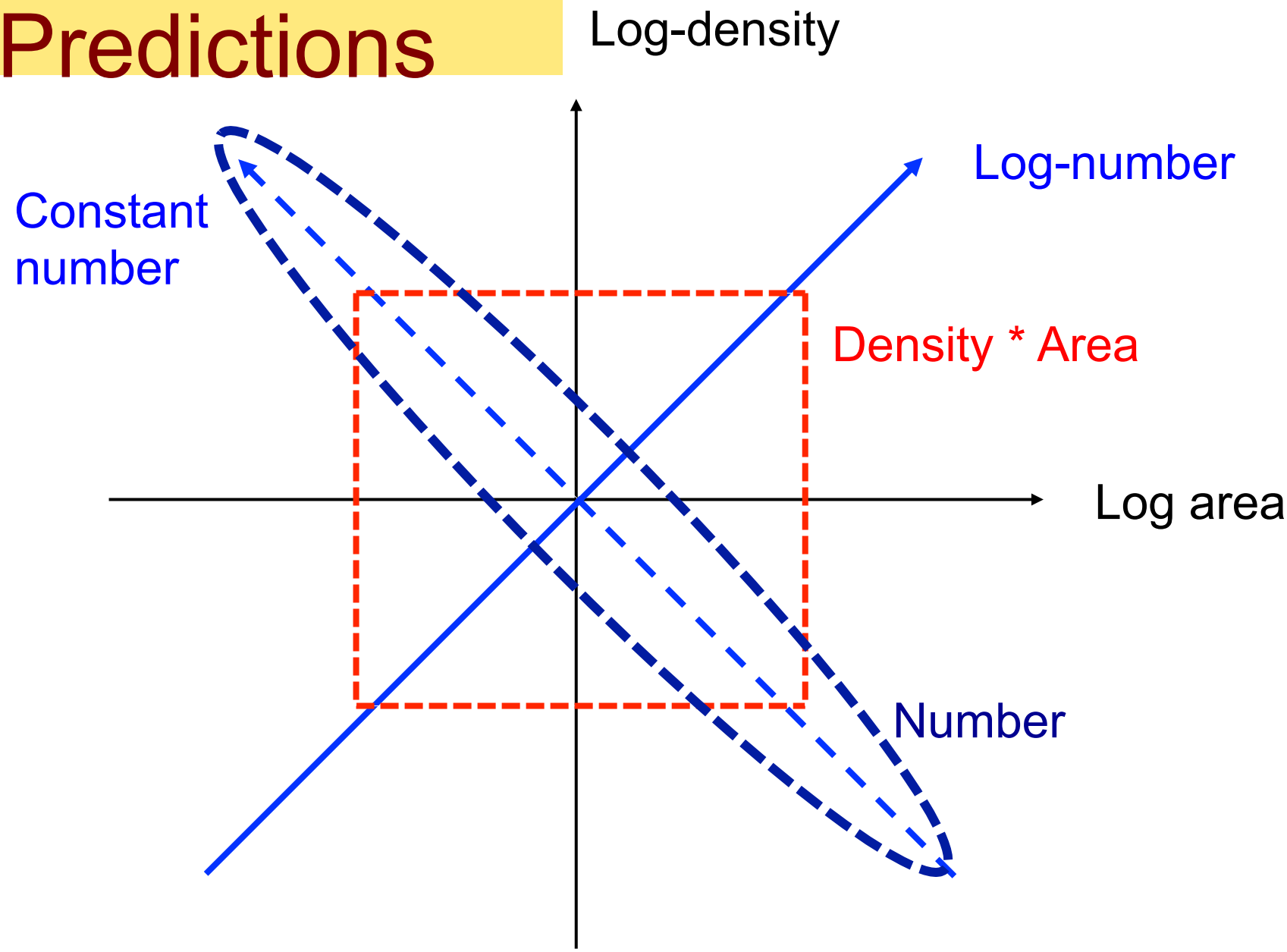
Separate processes for number and density



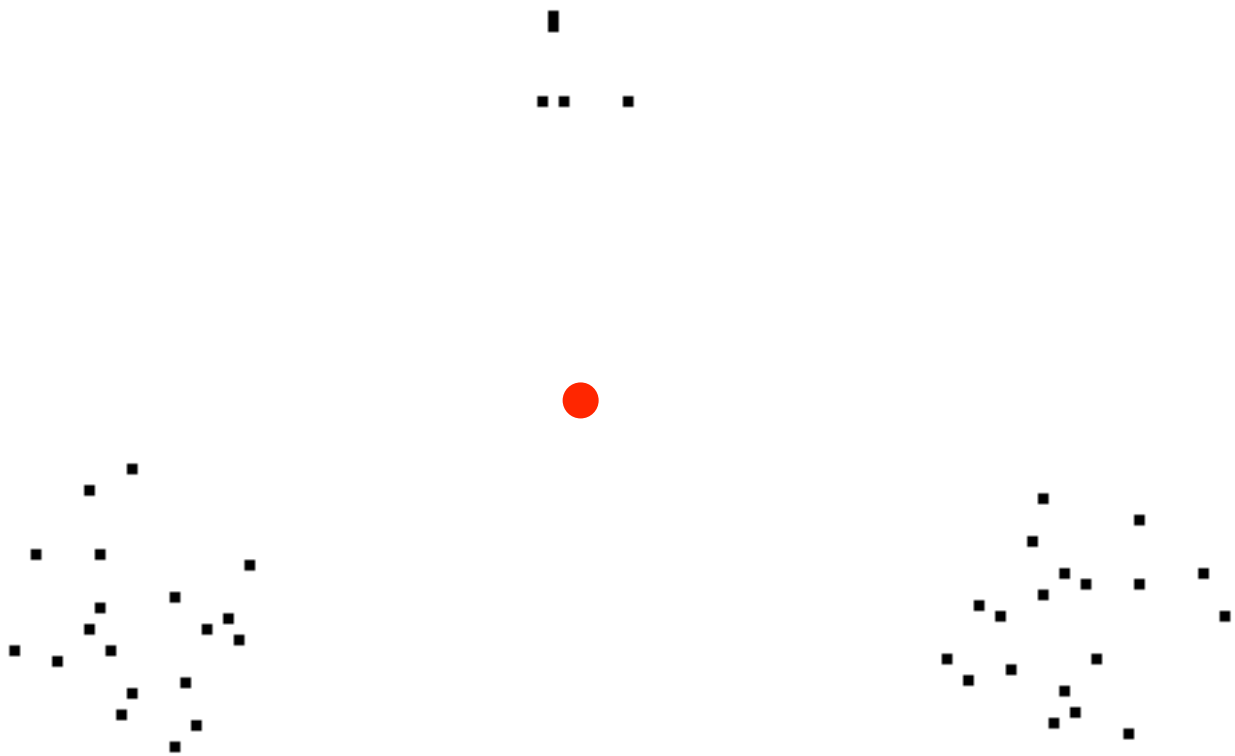
Number space



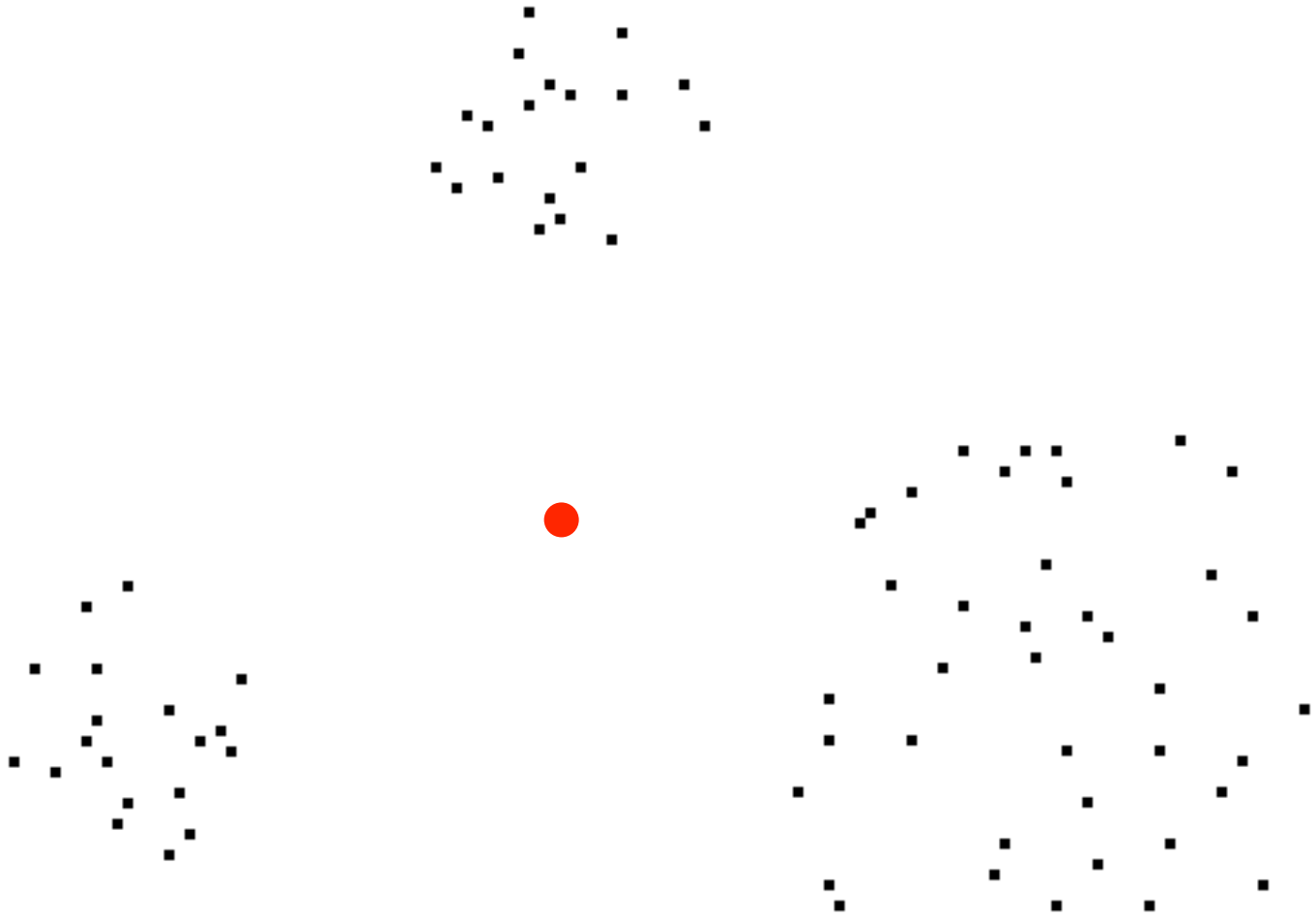
Threshold Predictions

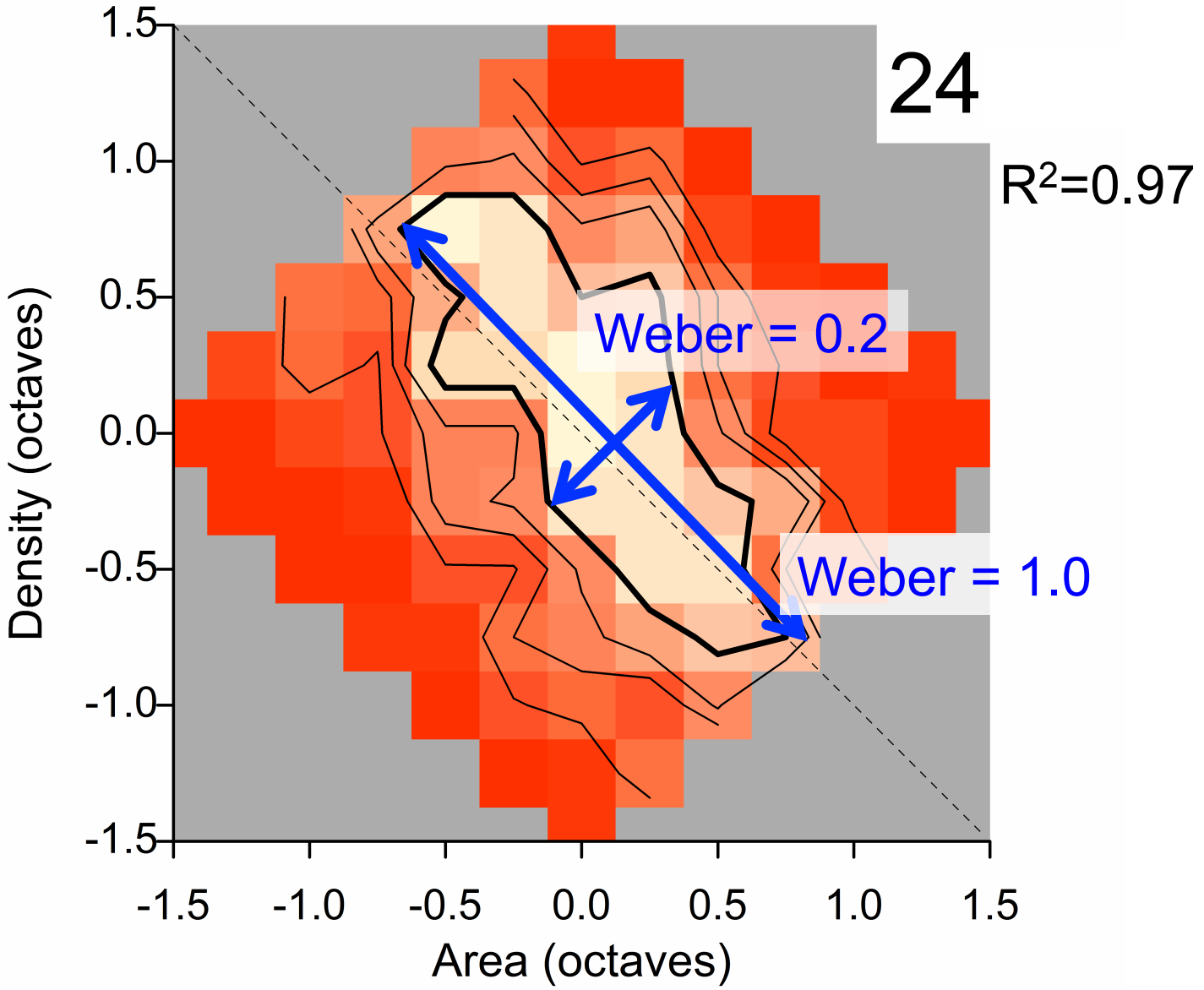


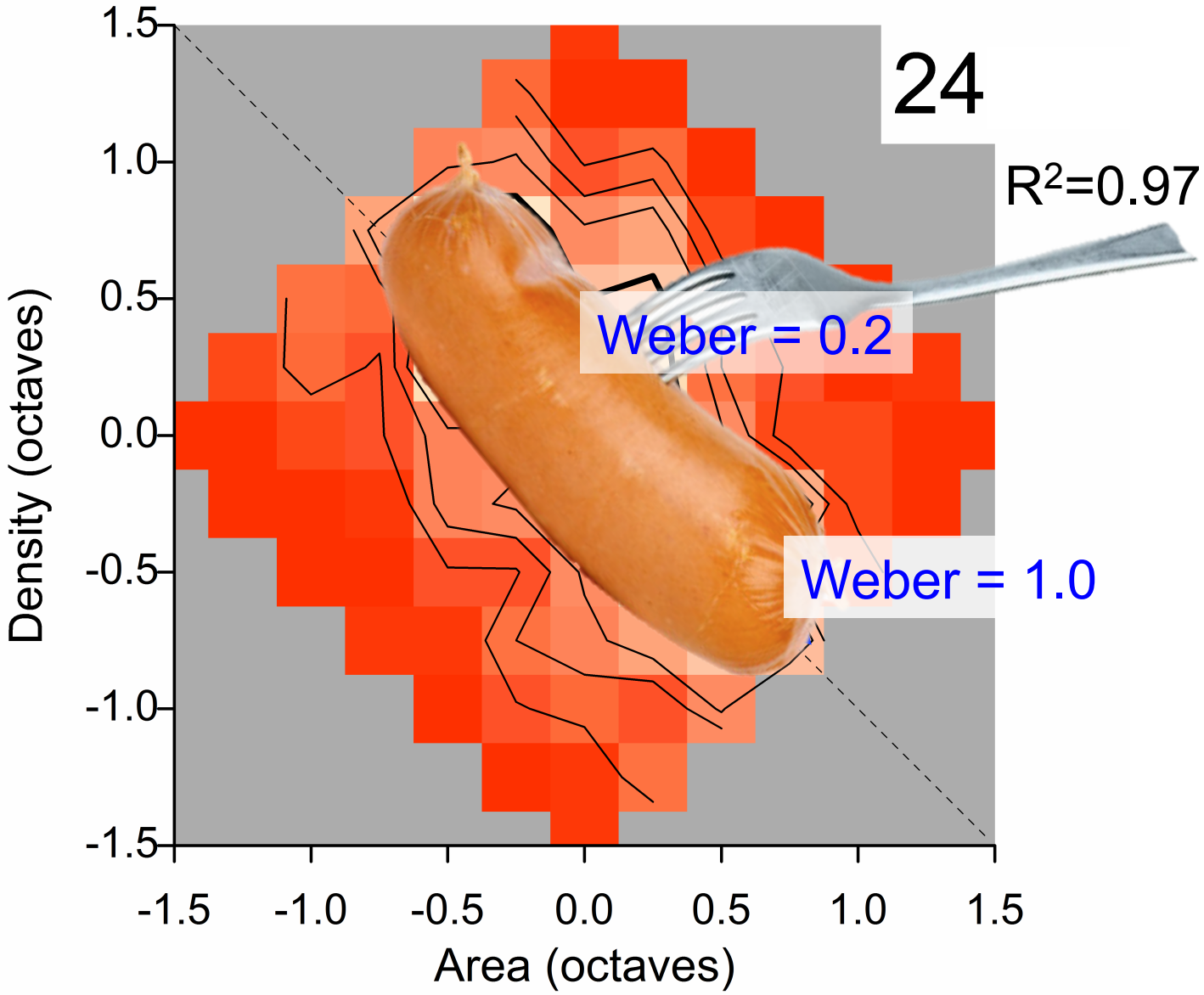
Odd man out: 3AFC



Odd man out: 3AFC




24
R²=0.97
Weber = 0.2
Weber = 1.0
Density (octaves)
Area (octaves)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5


24
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1.5
1.0
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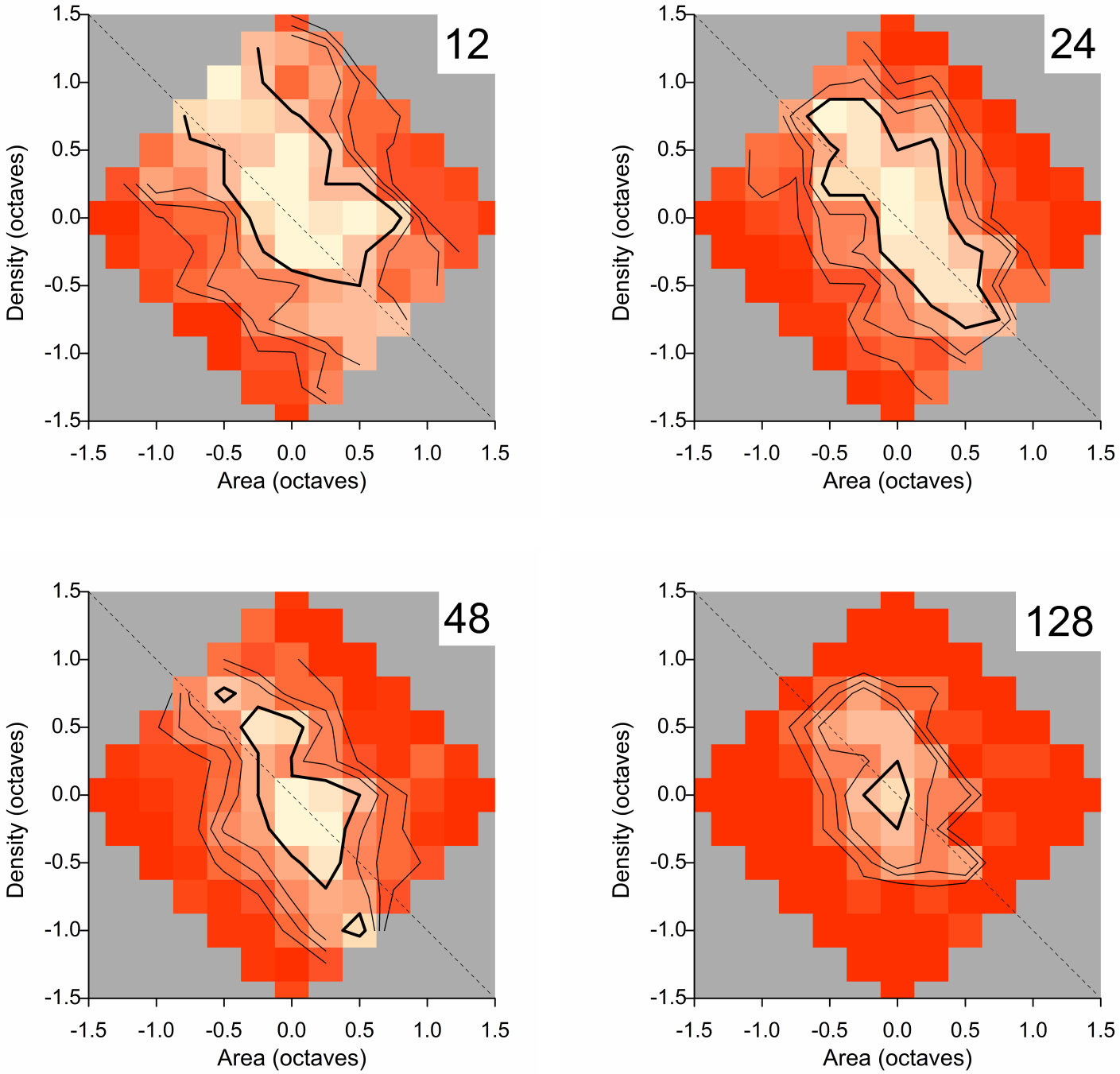
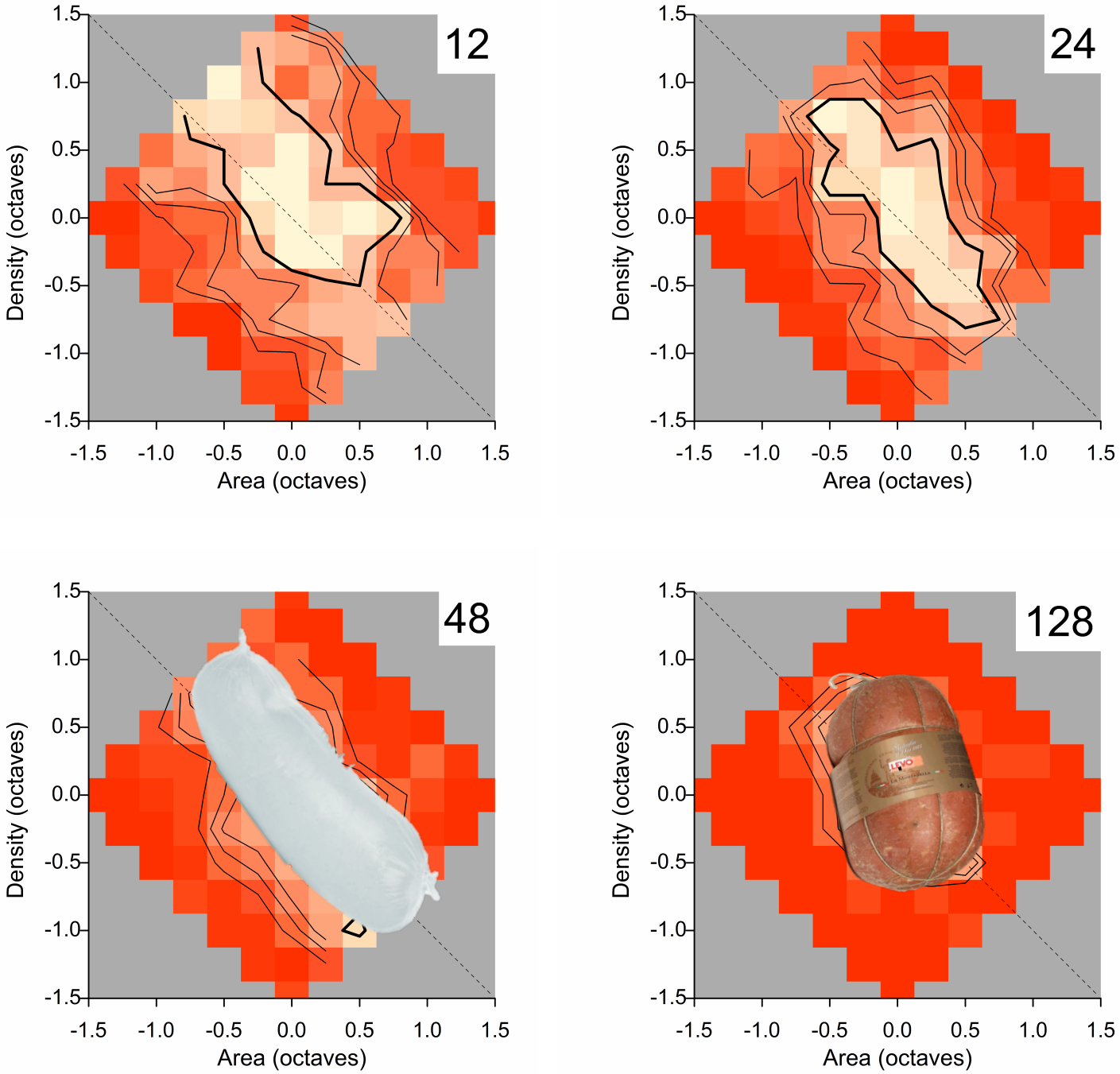
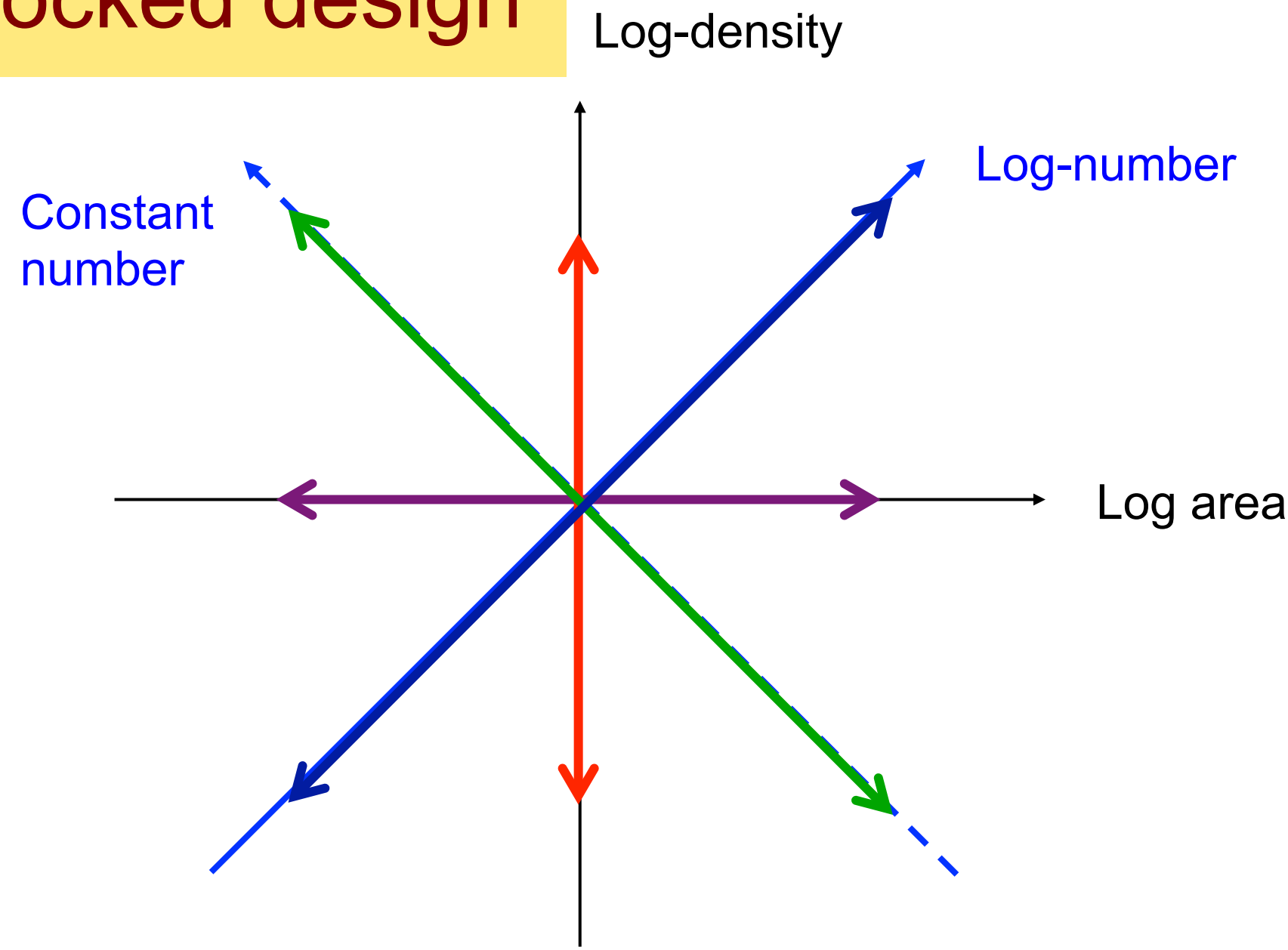
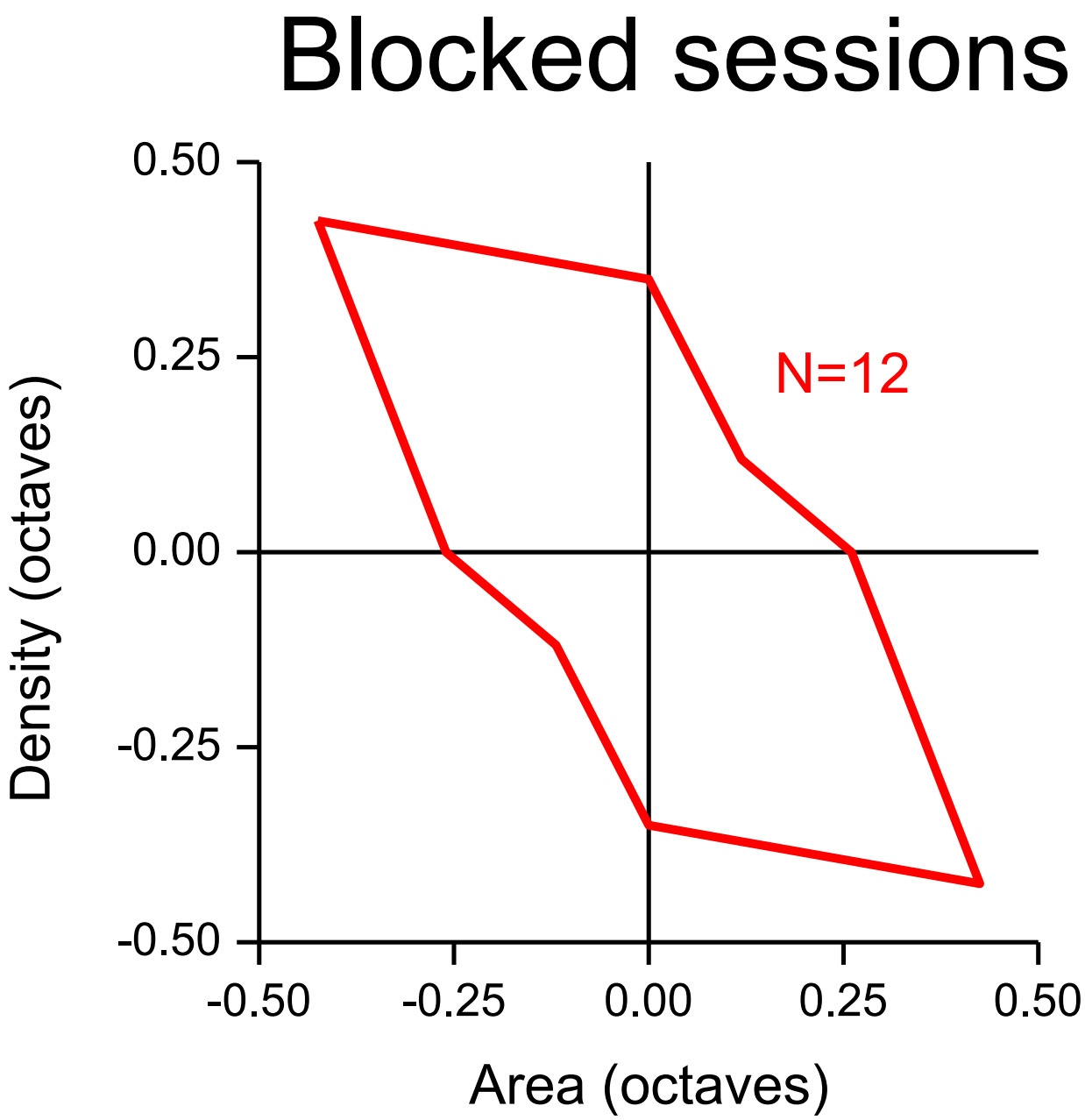
0.0
-0.5
-1.0
-1.5
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5

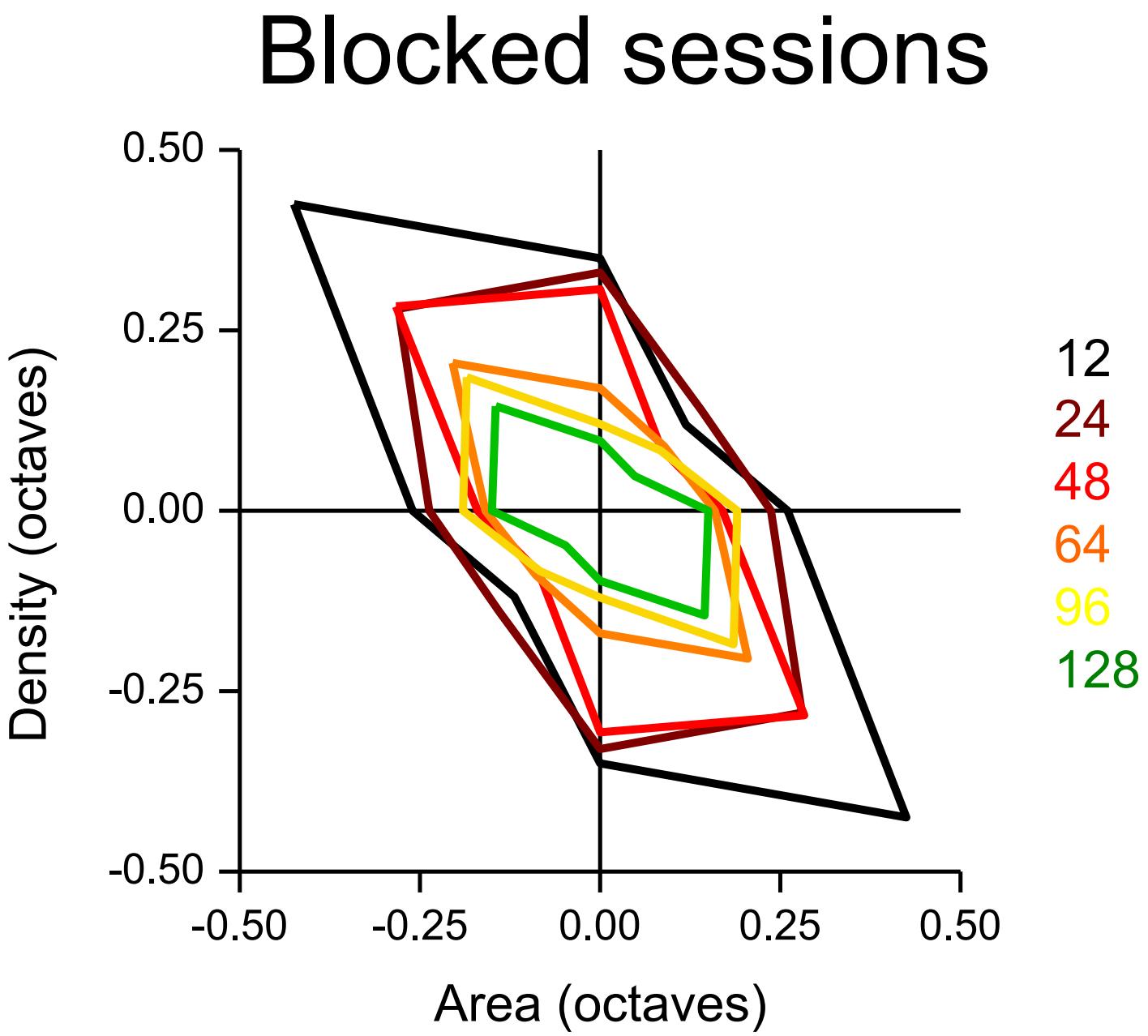

12
24
48
128
Density (octaves)
Area (octaves)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5


12
24
48
128
Density (octaves)
Area (octaves)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5

Blocked design

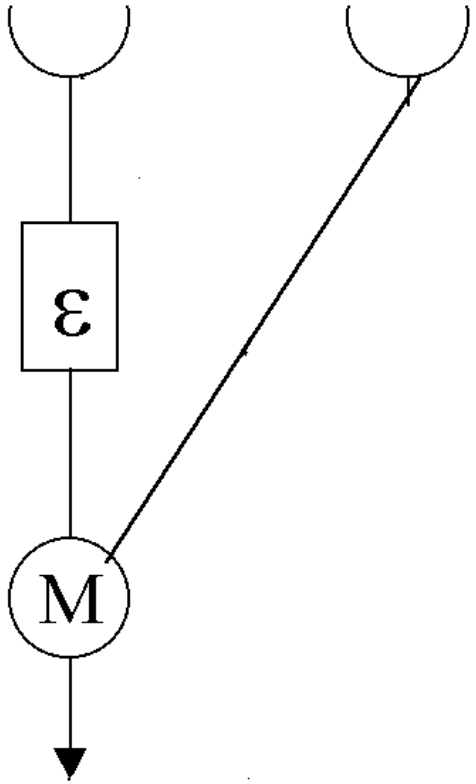



Blocked sessions
0.50
0.25
0.00
-0.25
-0.50
Density (octaves)
N=12
-0.50
-0.25
0.00
0.25
0.50
Area (octaves)


Blocked sessions
0.50
0.25
0.00
-0.25
-0.50
Density (octaves)
-0.50
-0.25
0.00
0.25
0.50
Area (octaves)
12
24
48
64
96
128

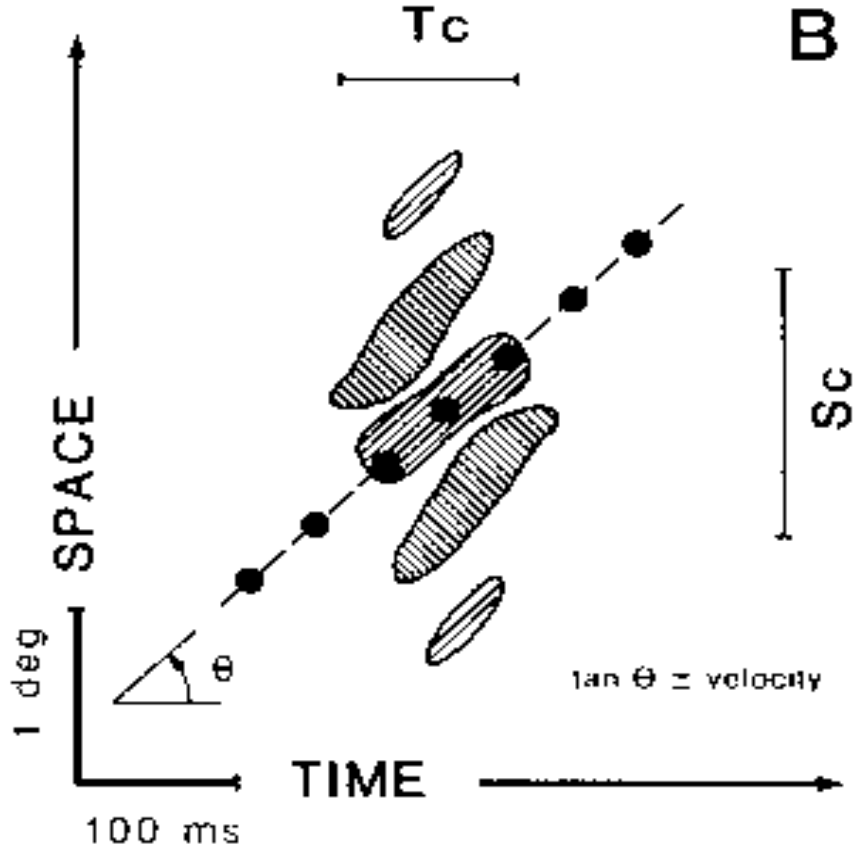
Analogous with motion detection: velocity detected directly within dedicated hardware

Reichardt detector



Reichardt, 1961

Spatiotemporal operators



Burr et al. *Proc. Roy. Soc.* 1986

Number and density

- The perception of numerosity is largely independent of density
- At moderate densities, numerosity is the primary attribute
- At high “crowded” densities, a different process is engaged, obeying different psychophysical laws

The effect of attention on number perception

Adaptation Affects Both High and Low (Subitized) Numbers Under Conditions of High Attentional Load

David C. Burr [1,2,*], Giovanni Anobile [1,2] and Marco Turi [1,2]

Subitizing but not estimation of numerosity requires attentional resources

David C. Burr [1,2],

Marco Turi [3,4] and

Giovanni Anobile [5,6]

POSTER

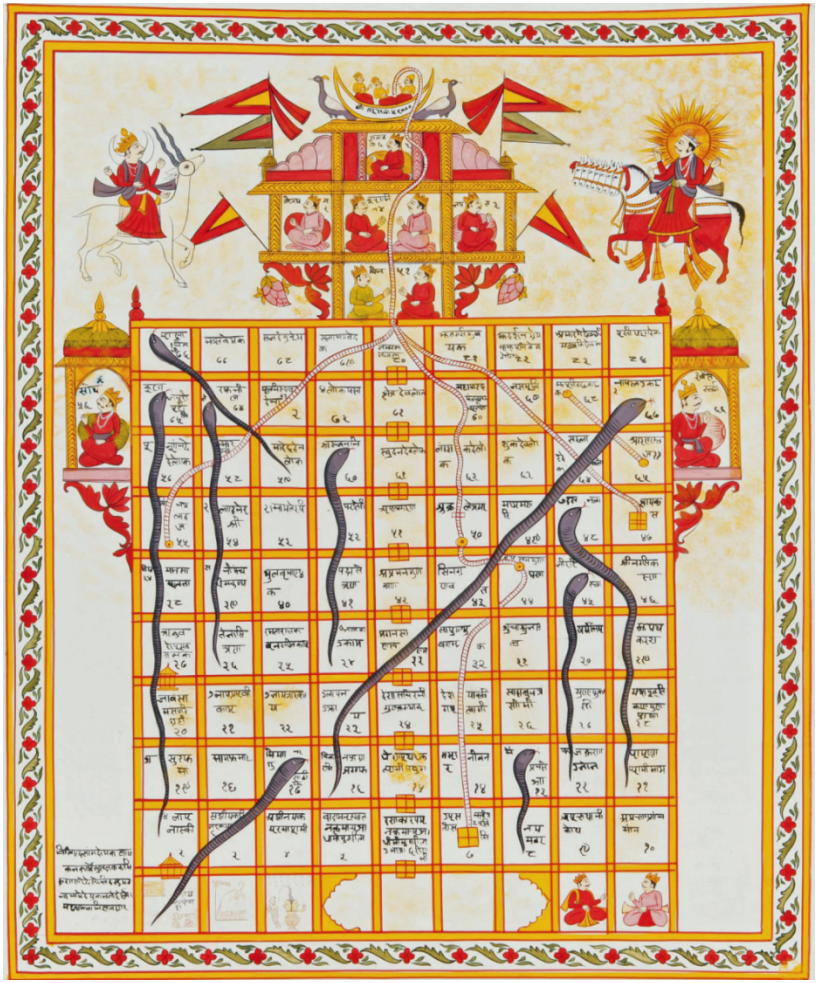
The effects of cross-sensory attentional demand on subitizing and on mapping number onto space

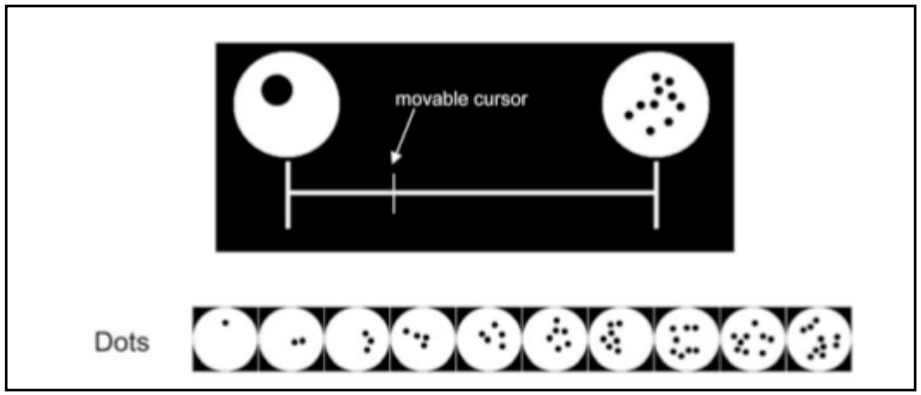
Giovanni Anobile [a,1], Marco Turi [a,b,1], Guido Marco Cicchini [c], David C. Burr [a,c,d,*]

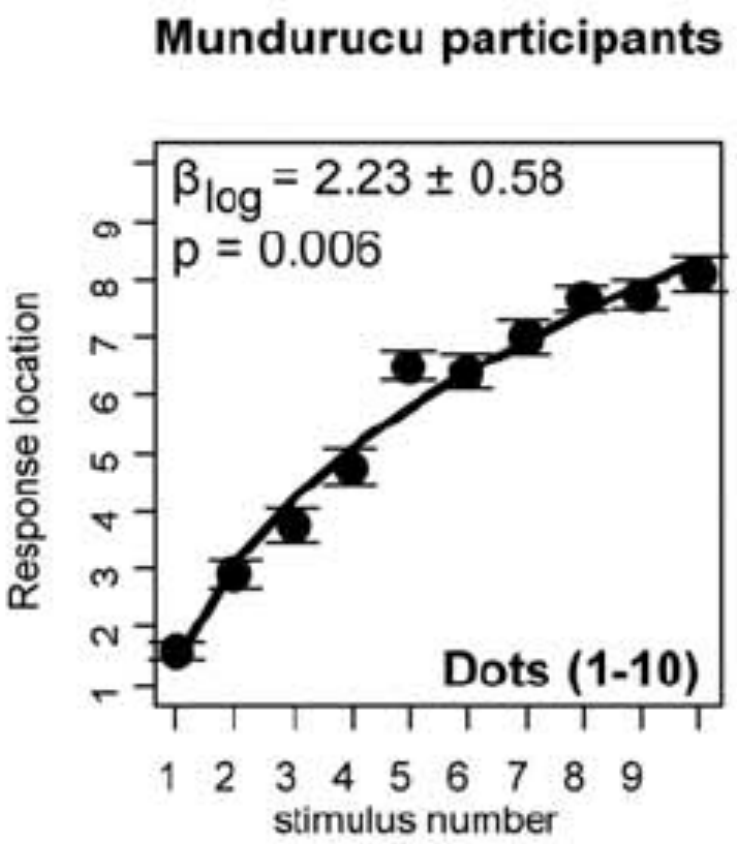
The effect of attention on mapping numbers onto space

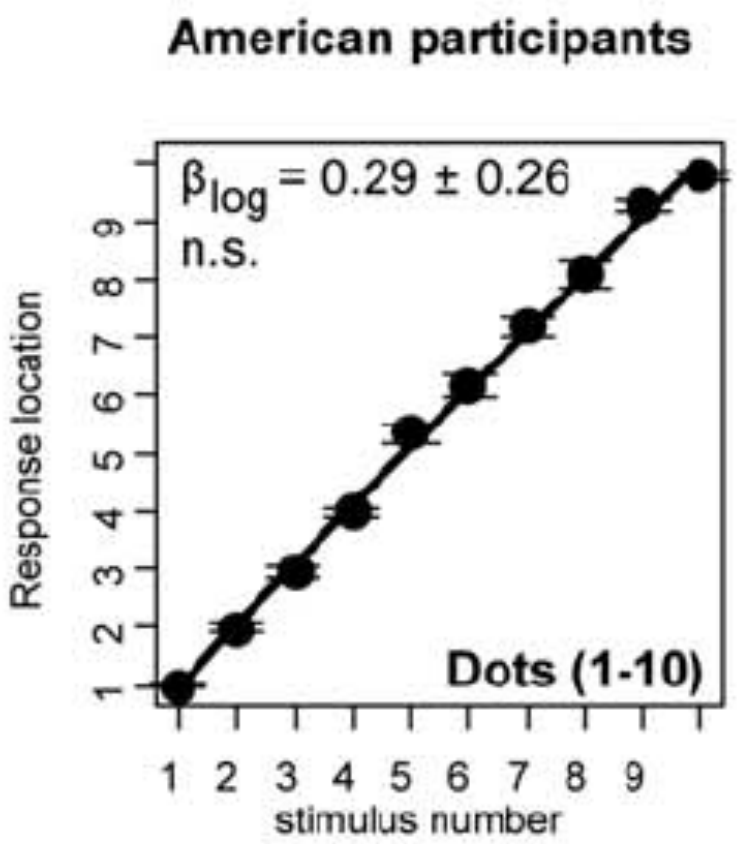
Giovanni Anobile

Marco Cicchini



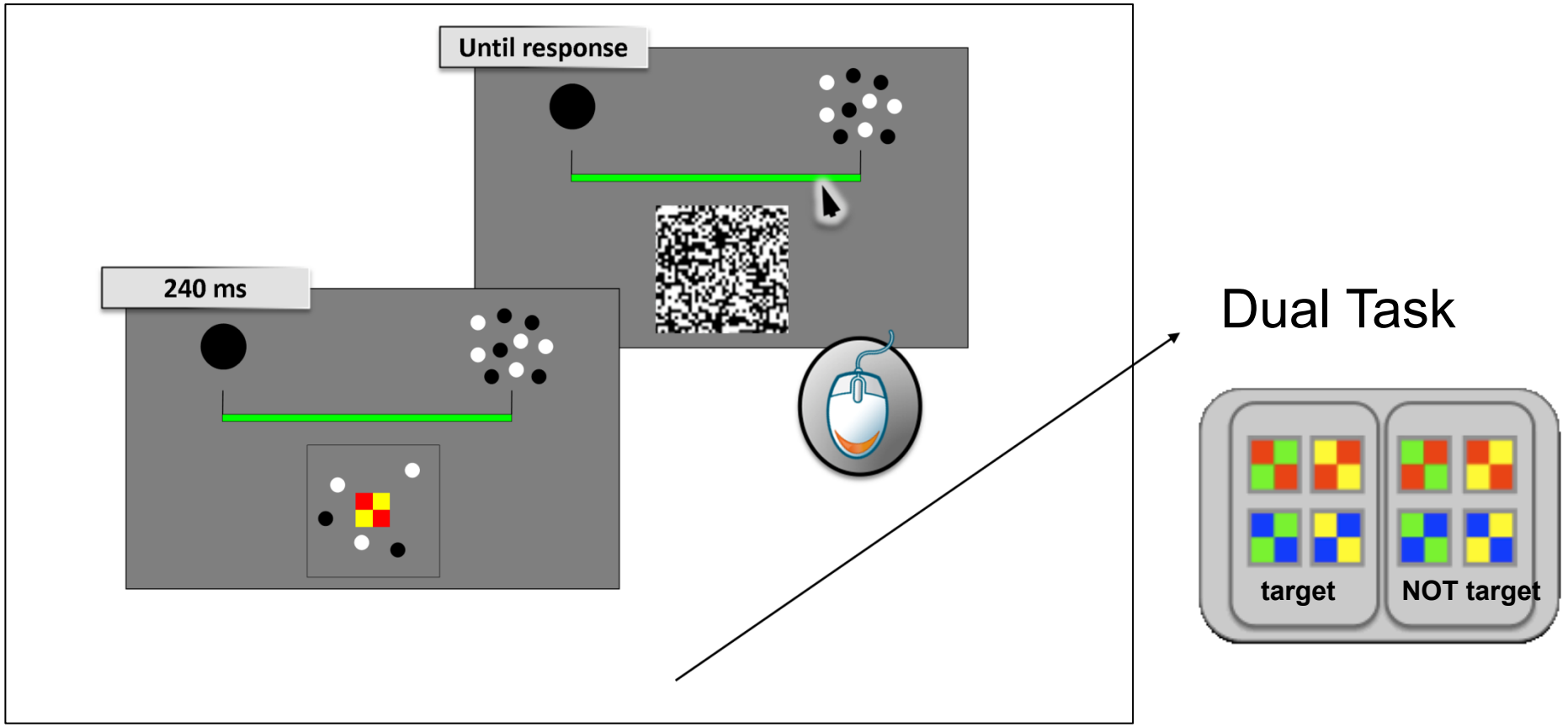


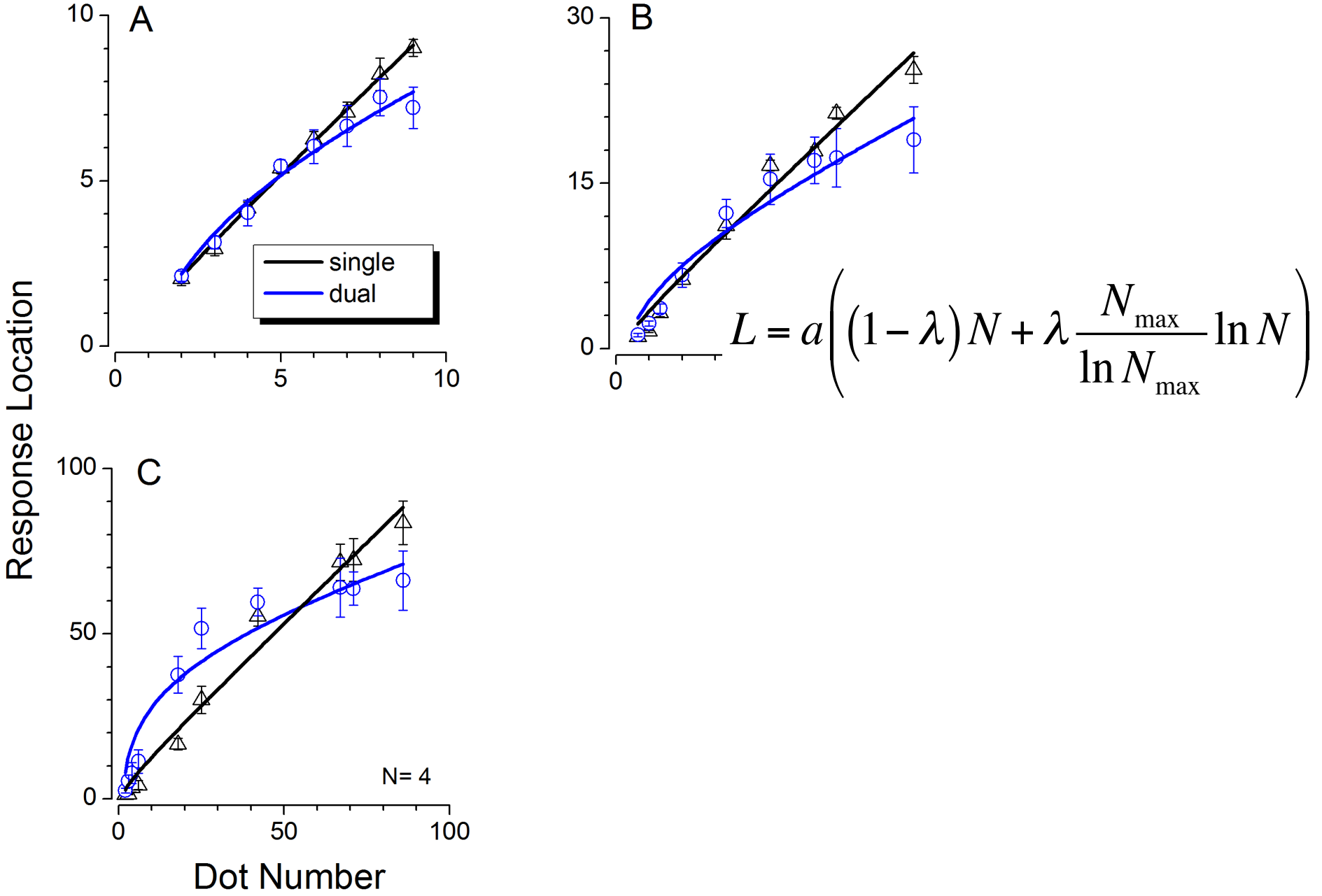




Dehaene, *Science, 2008*

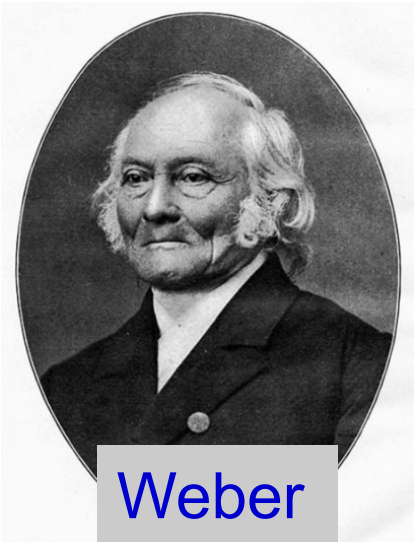
Does linear mapping of numbers depend on attention?



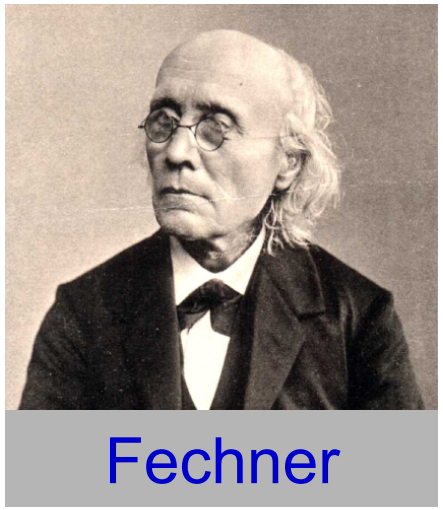


Anobile, Cicchini & Burr, *Cognition* 2012

But does this mean number is encoded logarithmically: an old controversy



Weber



Fechner

Logarithmic coding

$$p = \int k \frac{\Delta S}{S} ds = k \ln S + c$$

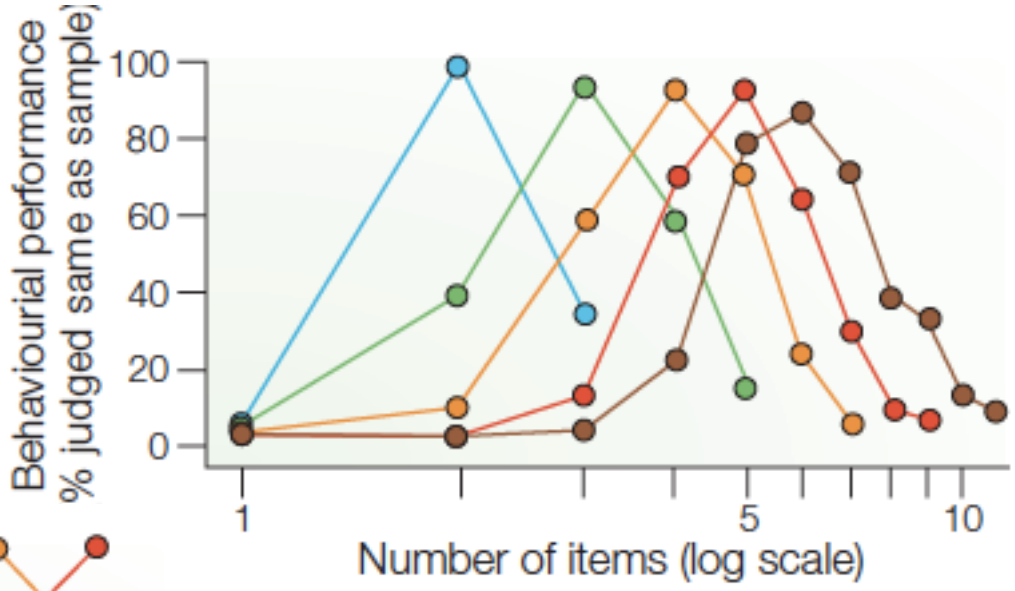
Challenged by Stevens: power law

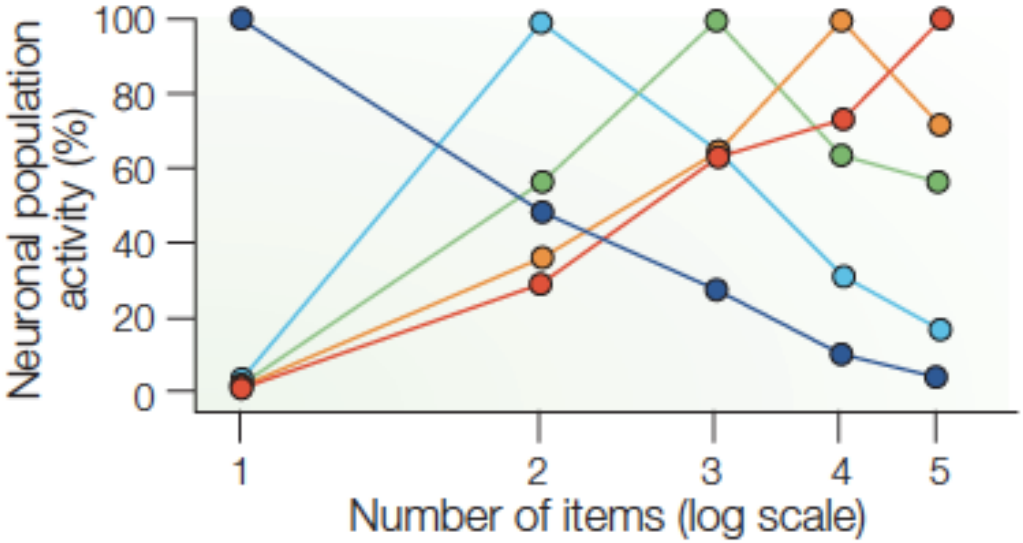
$$\Psi(I) = kI^a$$

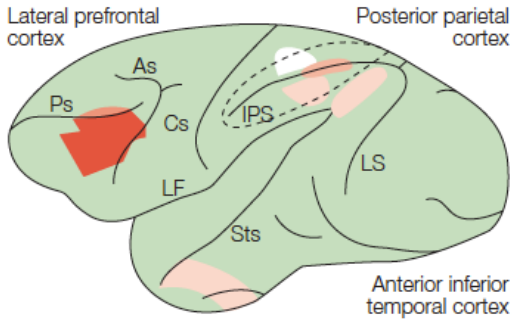
$$\ln \Psi(I) = a \ln I + \ln k$$

Germany strikes back!

Andreas Nieder





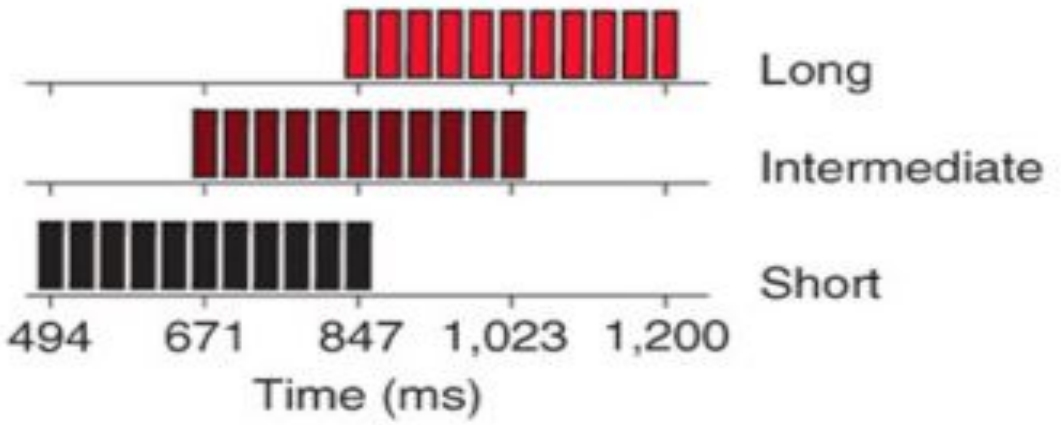


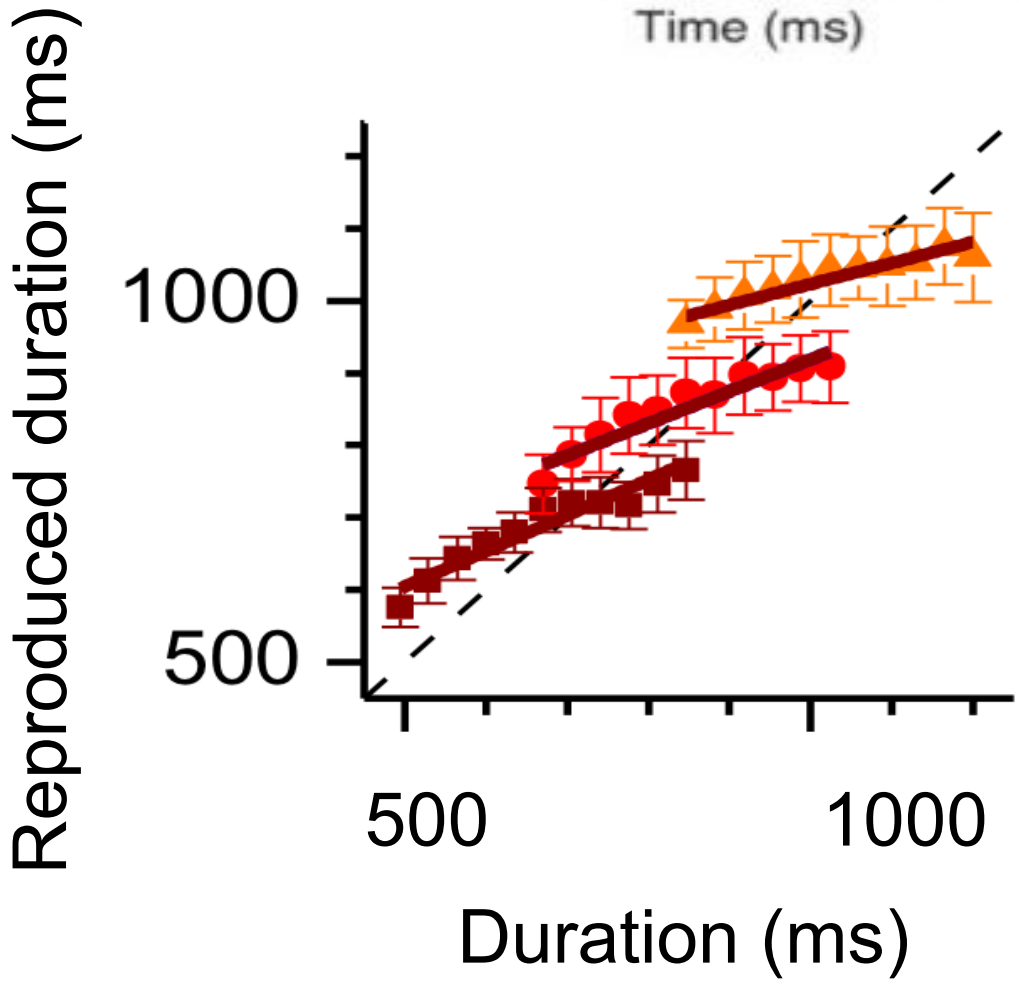
Regression to the mean or *central tendency*

Judgments of time, weight, force, brightness, extent of movement, length, area, size of angles all show the same tendency to gravitate toward a mean magnitude

Hollingworth, 1910

Three intervals



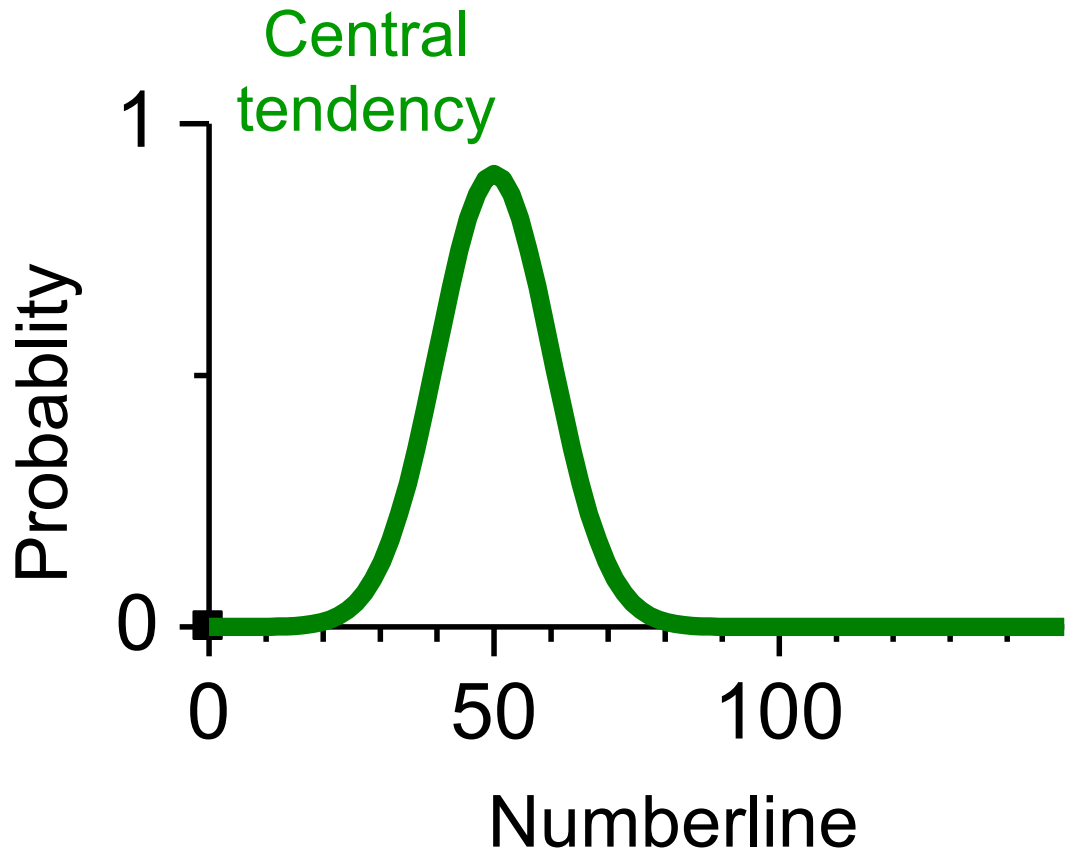


Regression to the mean

Jazayeri & Shadlen
Nat. Neurosc. 2010

Central tendency as a Bayesian *prior*

$$p(L|N) \propto p(L)p(N|L)$$



Central tendency as a Bayesian *prior*

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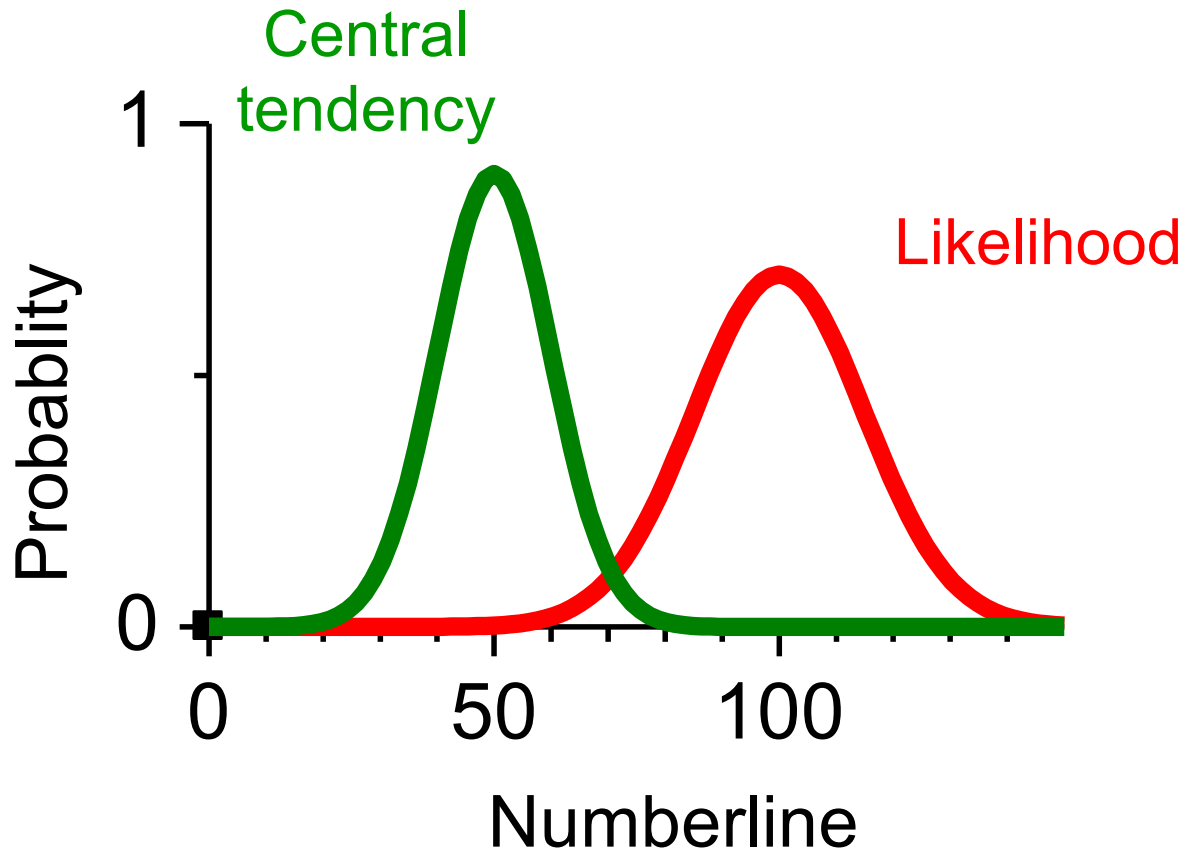

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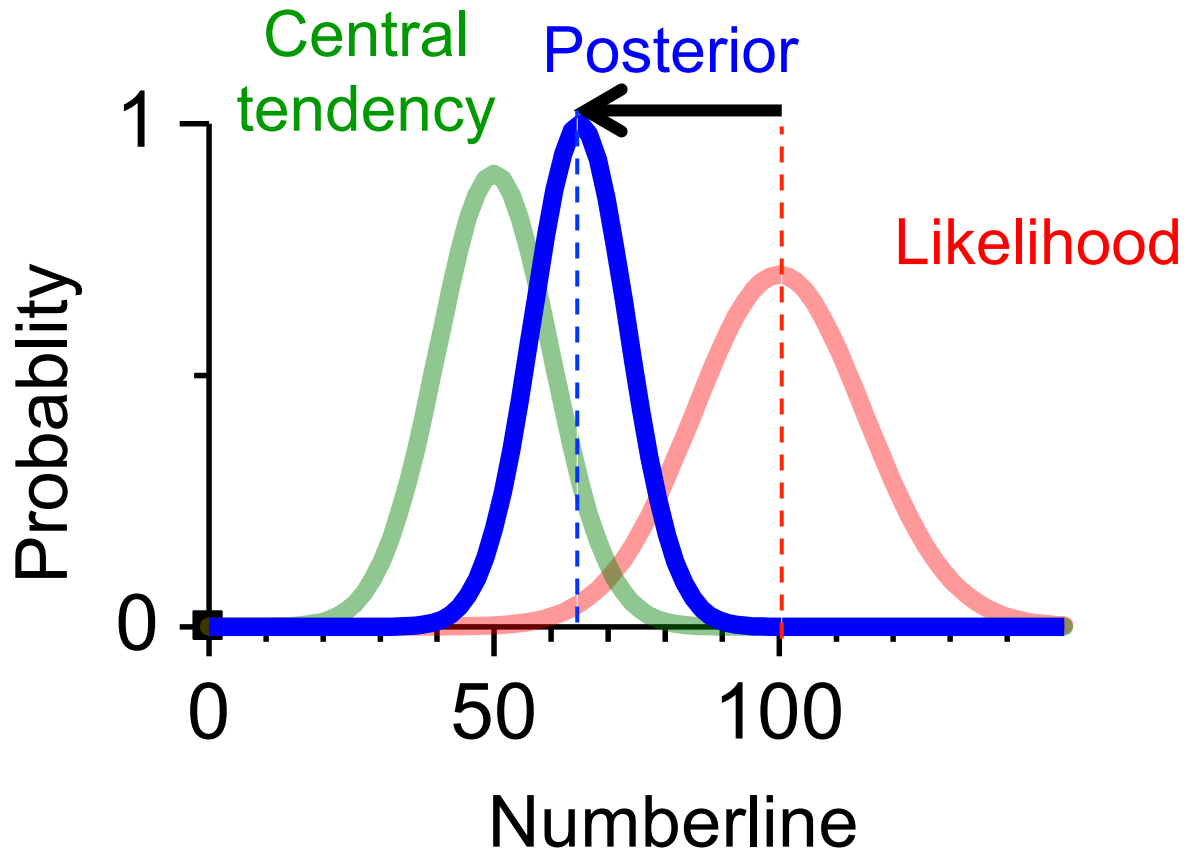

Central tendency as a Bayesian *prior*

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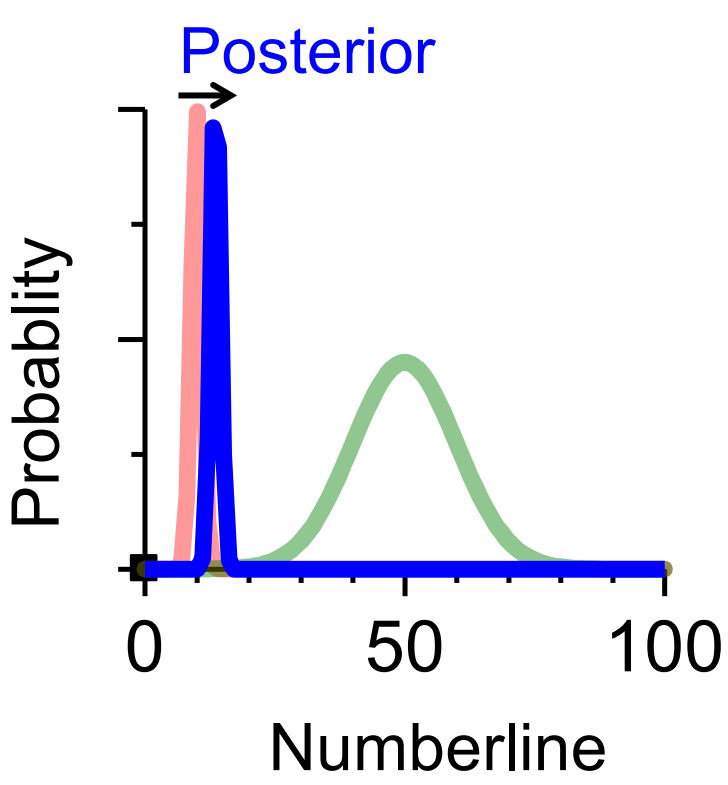
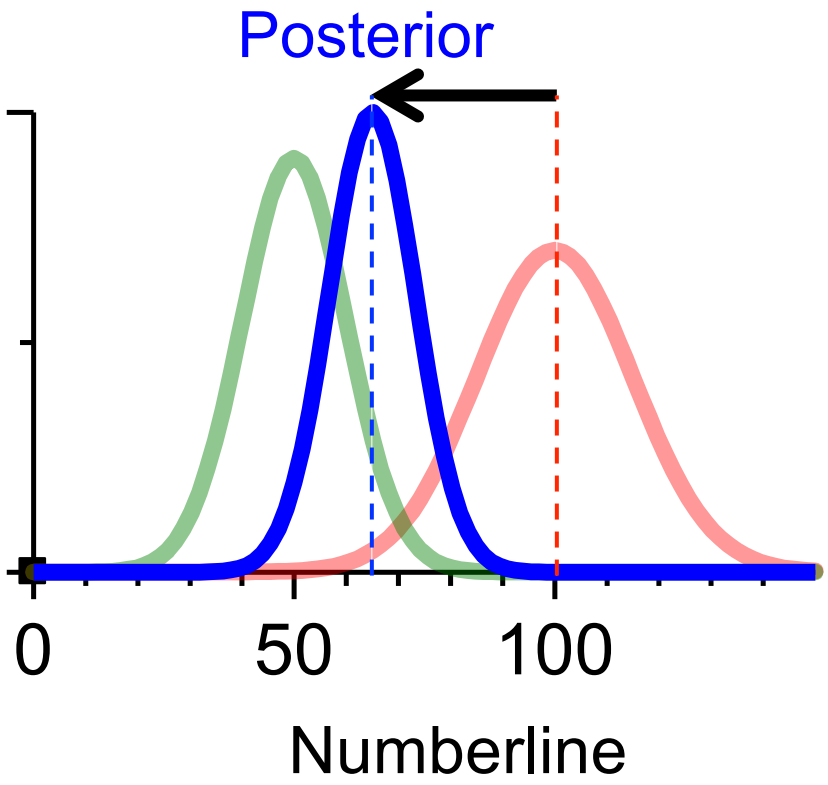


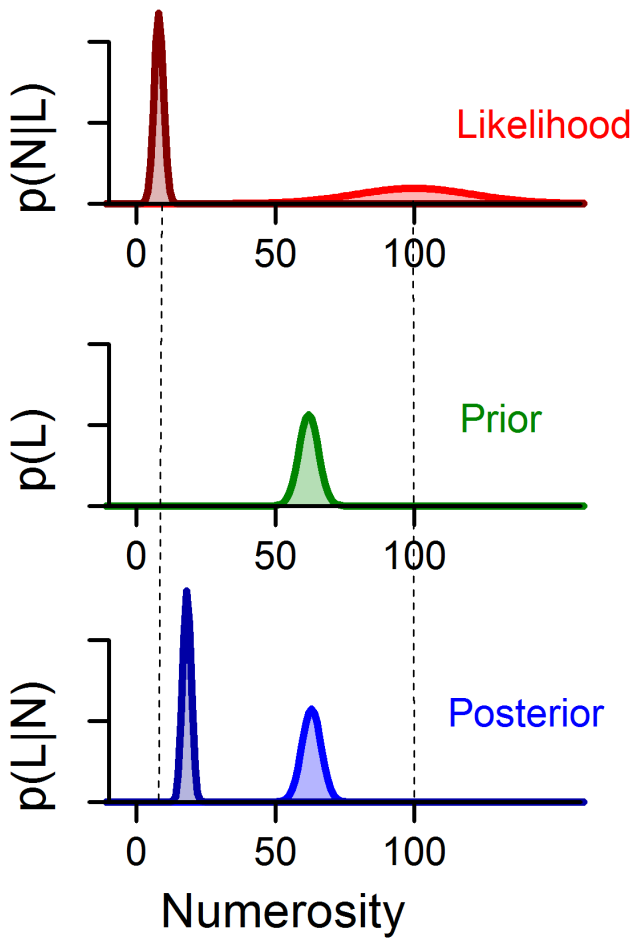


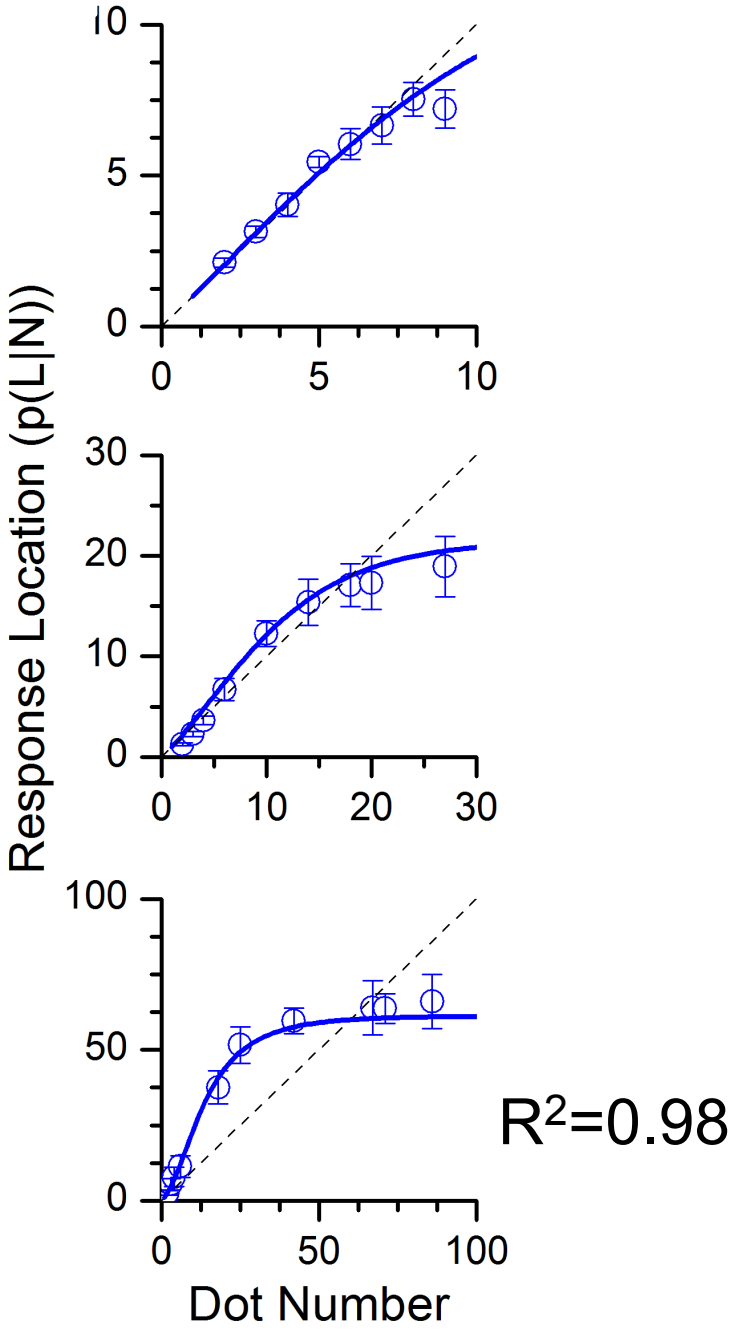
$p(L|N) \propto p(L)\, p(N|L)$

Data

Central tendency

Response





R^2=0.98

Anobile, Cicchini & Burr, *Cognition* 2012

Attention and the Numberline

- Linear mapping onto the numberline requires attention.
- When attention is deprived, mapping becomes non-linear, logarithmic-like.
- The non-linearity is well explained by a Bayesian model of central tendency.

A generalized sense of number

Simultaneous format
Sequential format
Cross-modal adaptation
Cross-format adaptation

Roberto Arrighi

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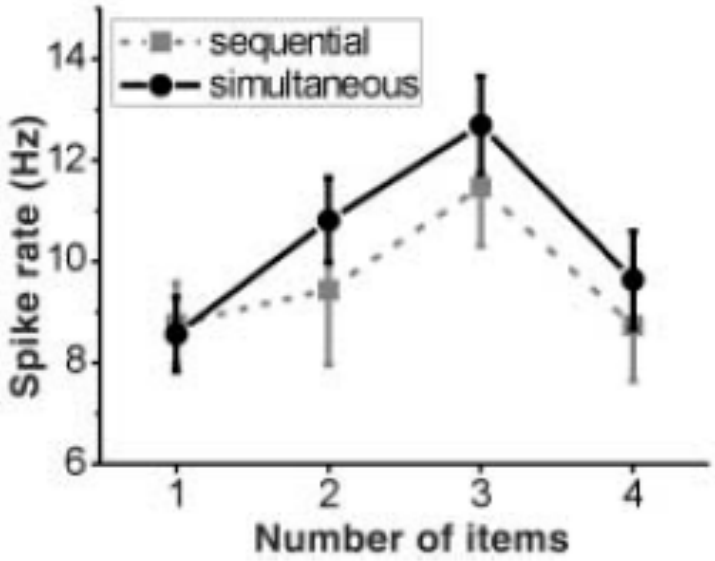
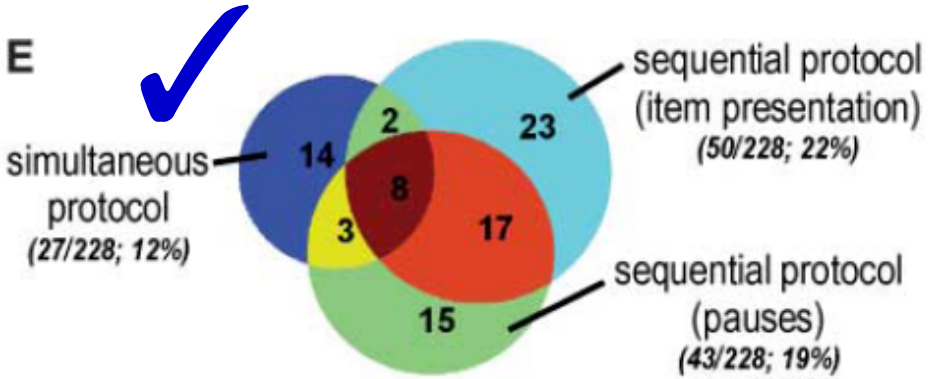
Andreas Nieder *et al.*

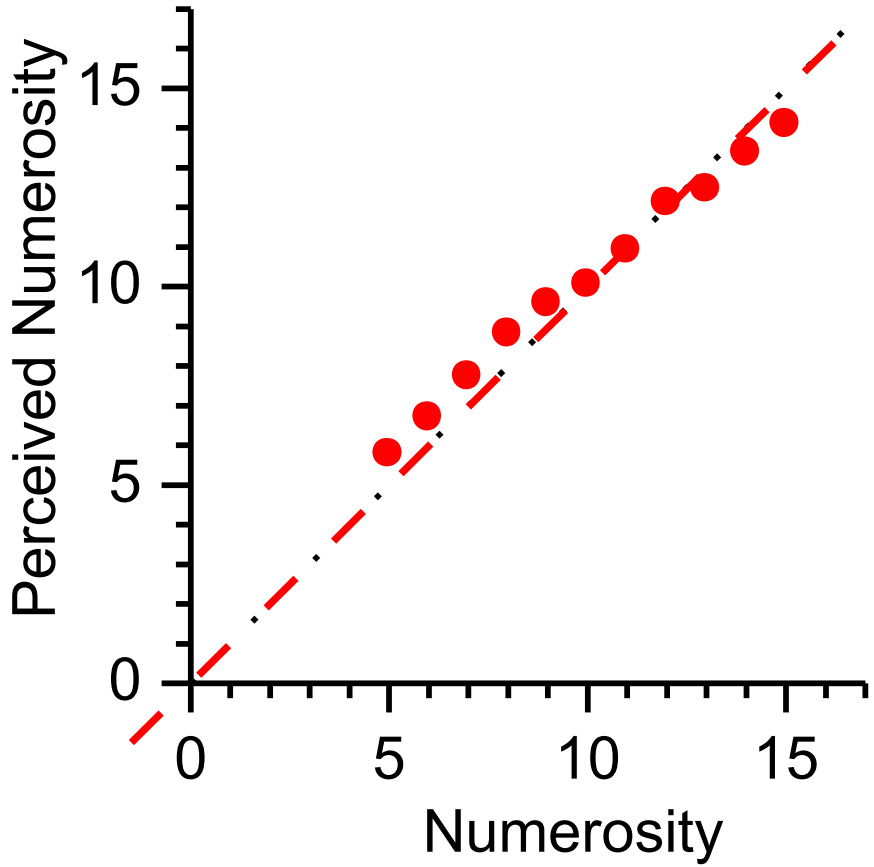
Science **313**, 1431 (2006);
DOI: 10.1126/science.1130308



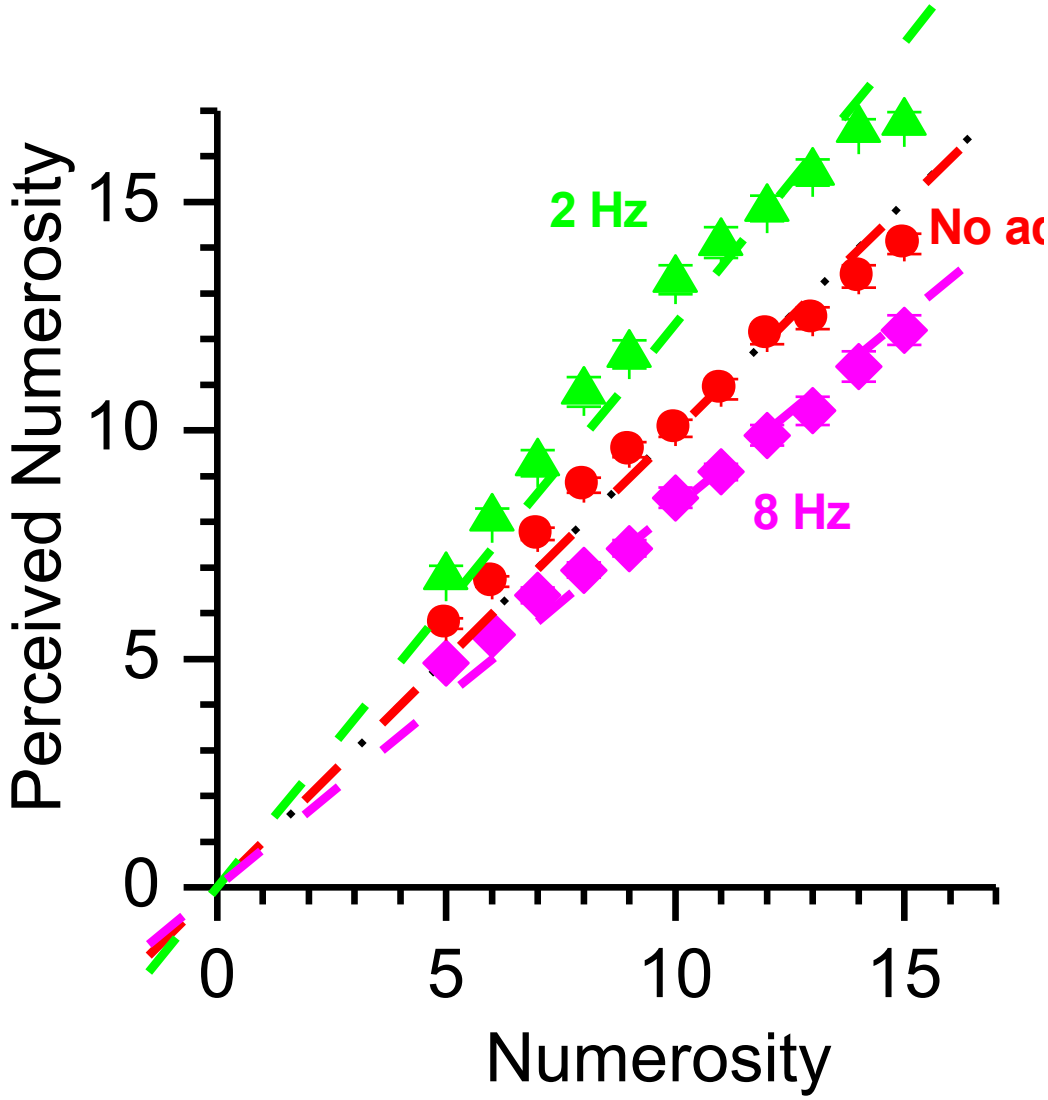


Distinct processing stages for sequential and simultaneous numerical formats, and convergence to abstract quantity representation

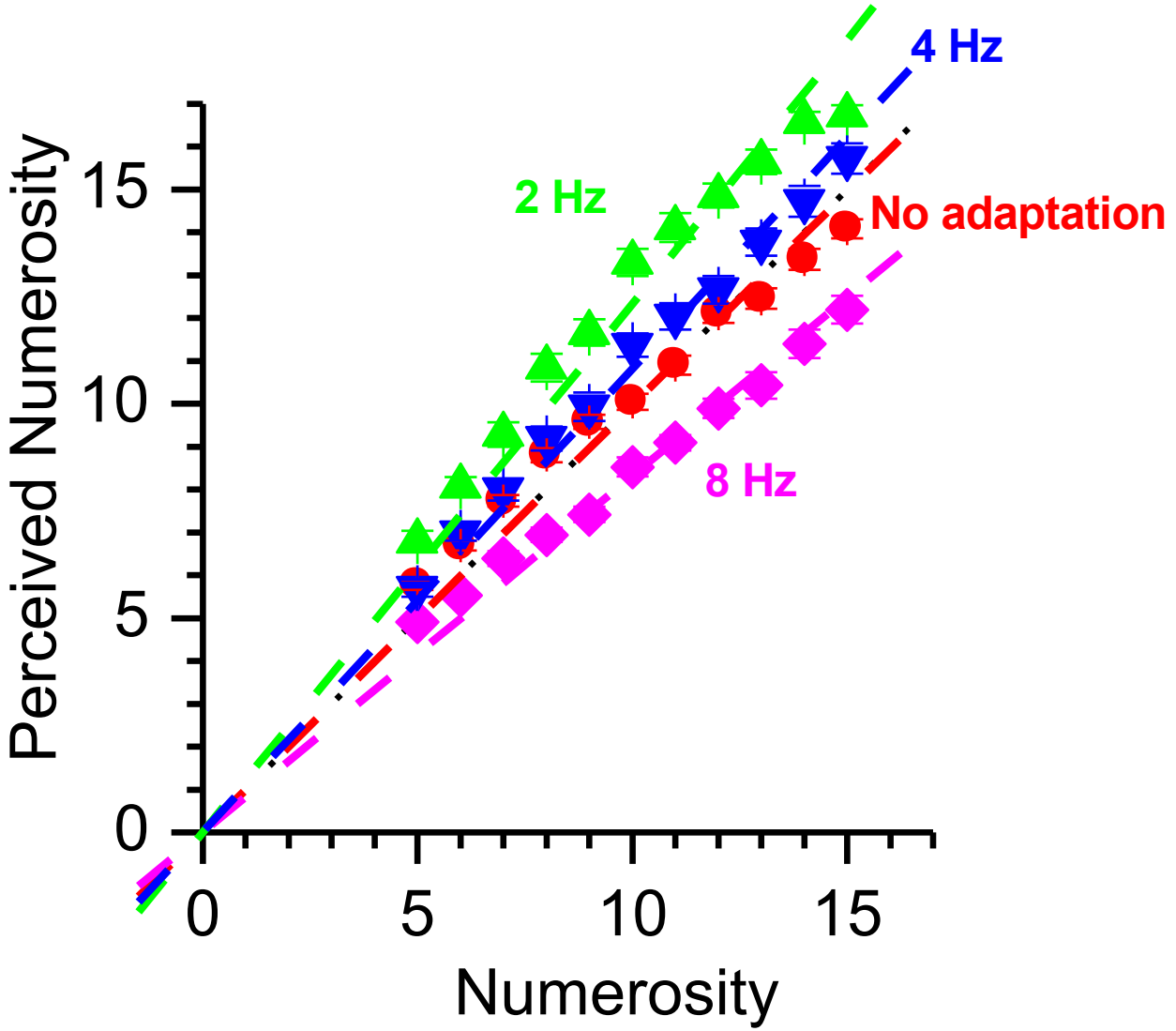
Enumeration of sequences



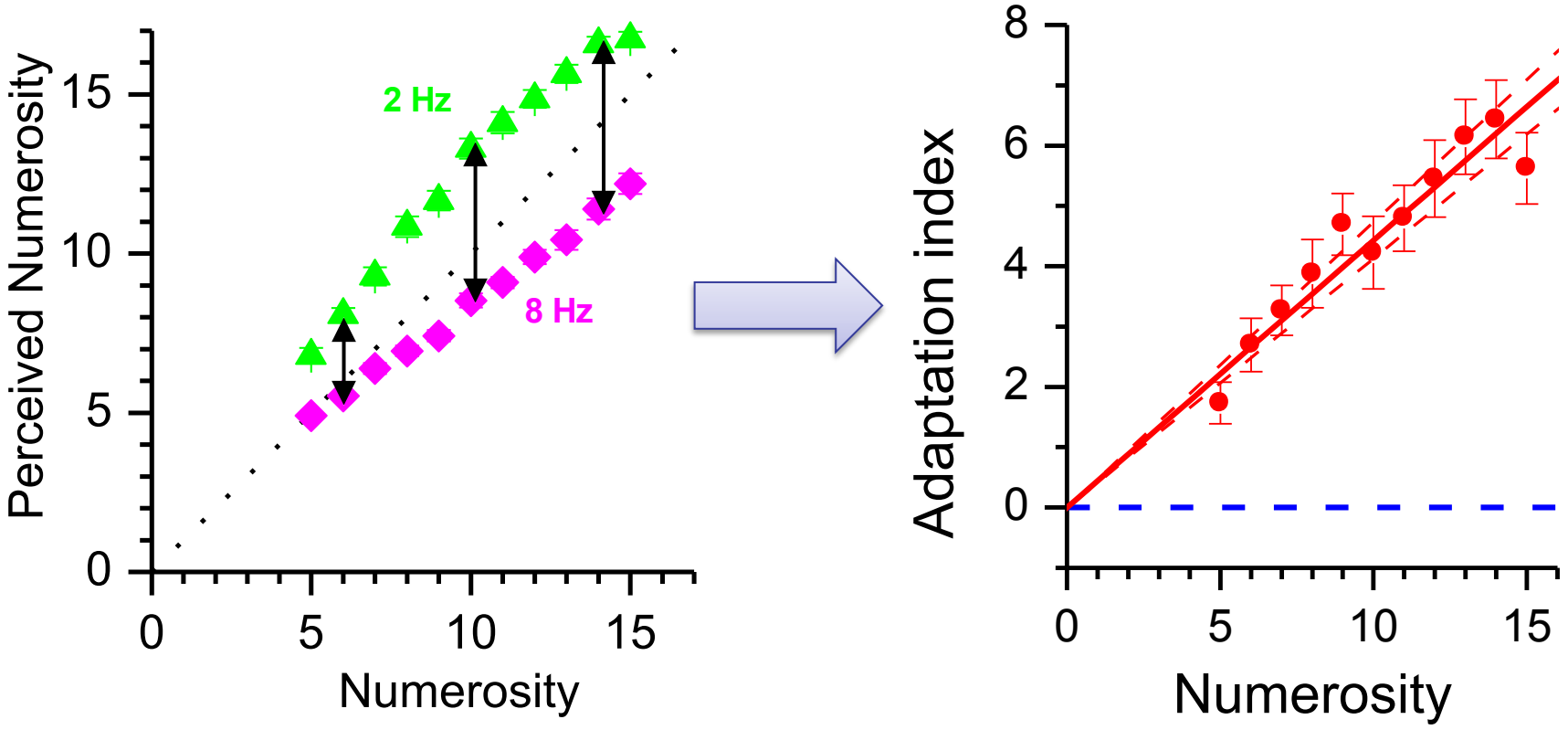
Adaptation to high and low rates



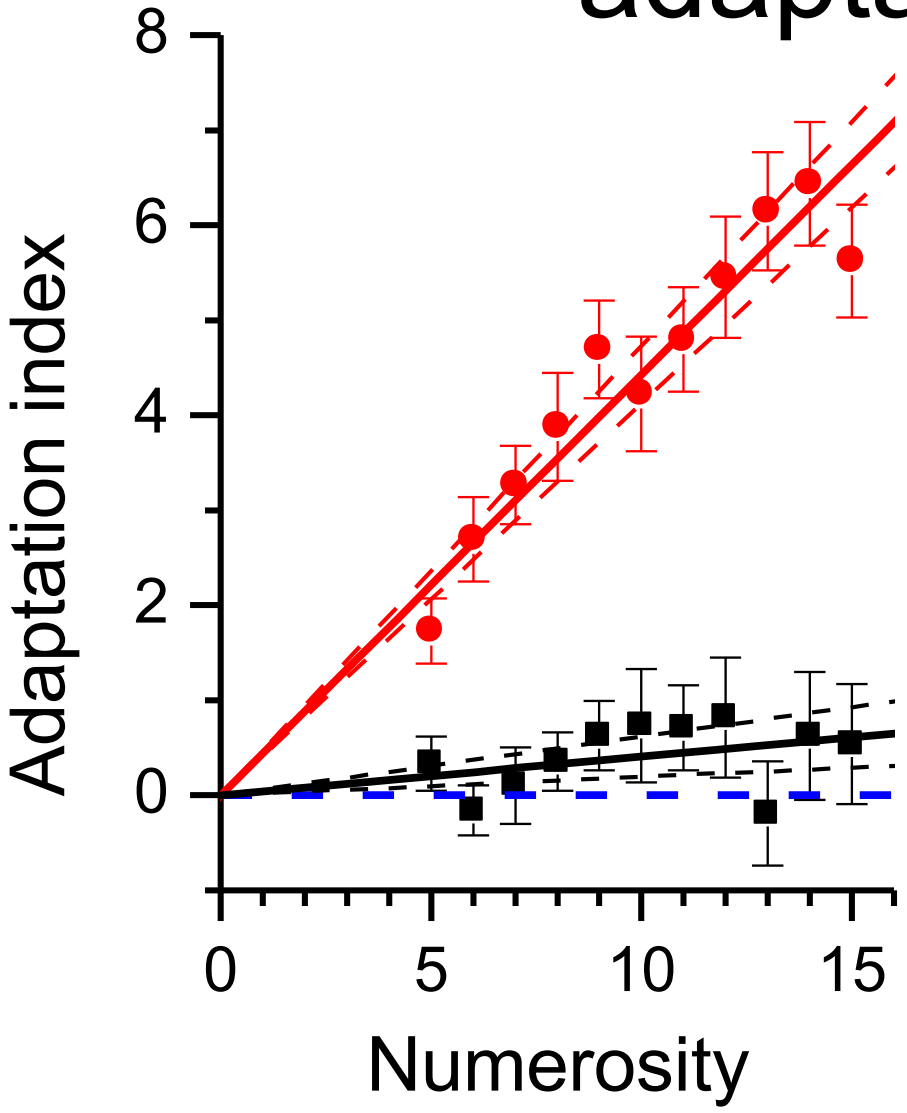
Adaptation to high, low & middle

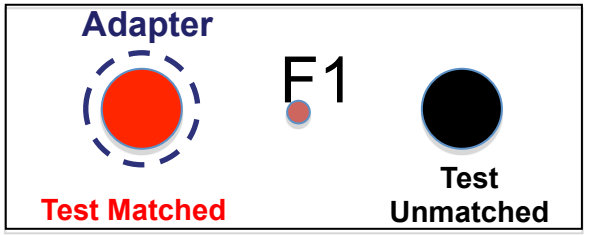


Adaptation index: difference between 2 and 8 Hz effects

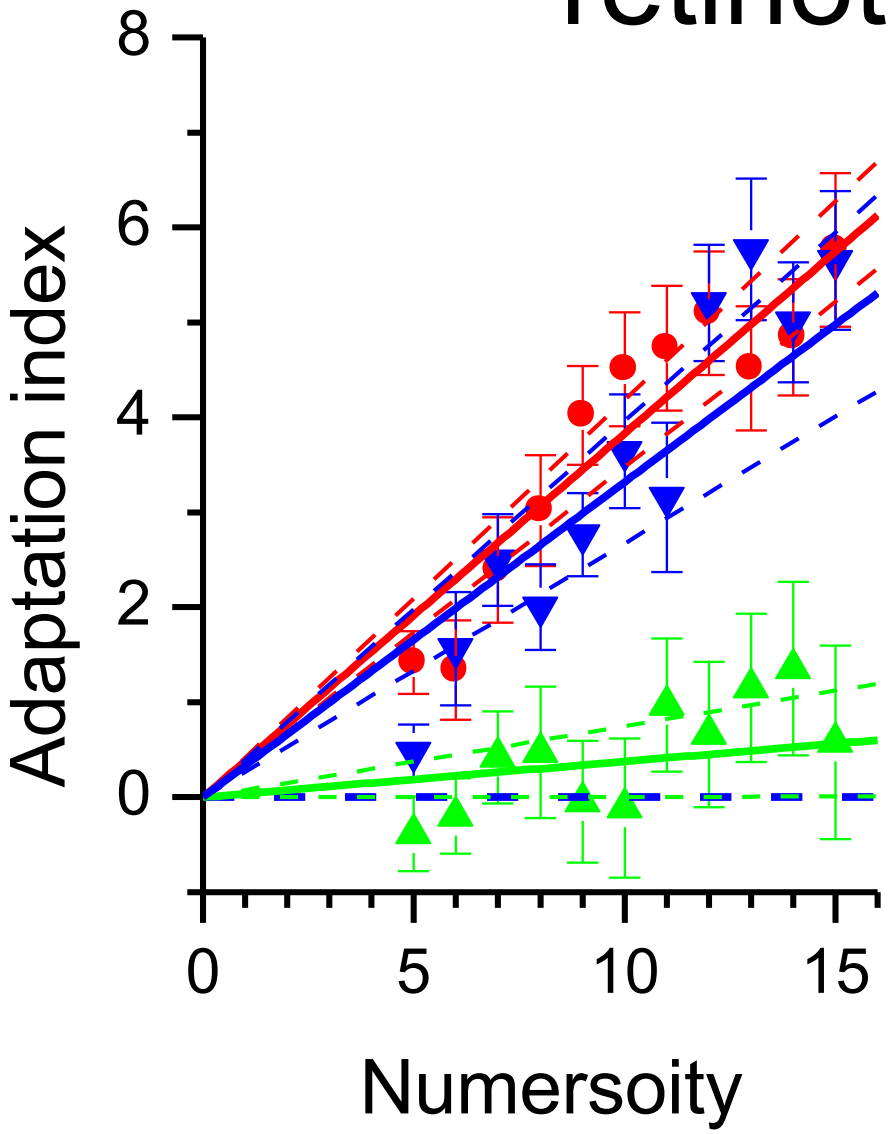


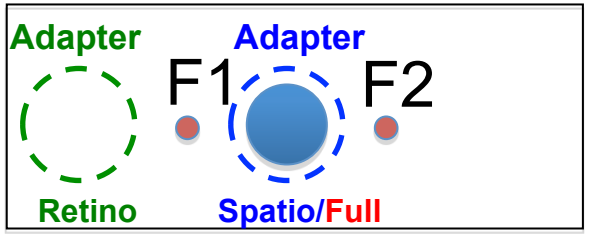
Spatial specificity of sequential adaptation



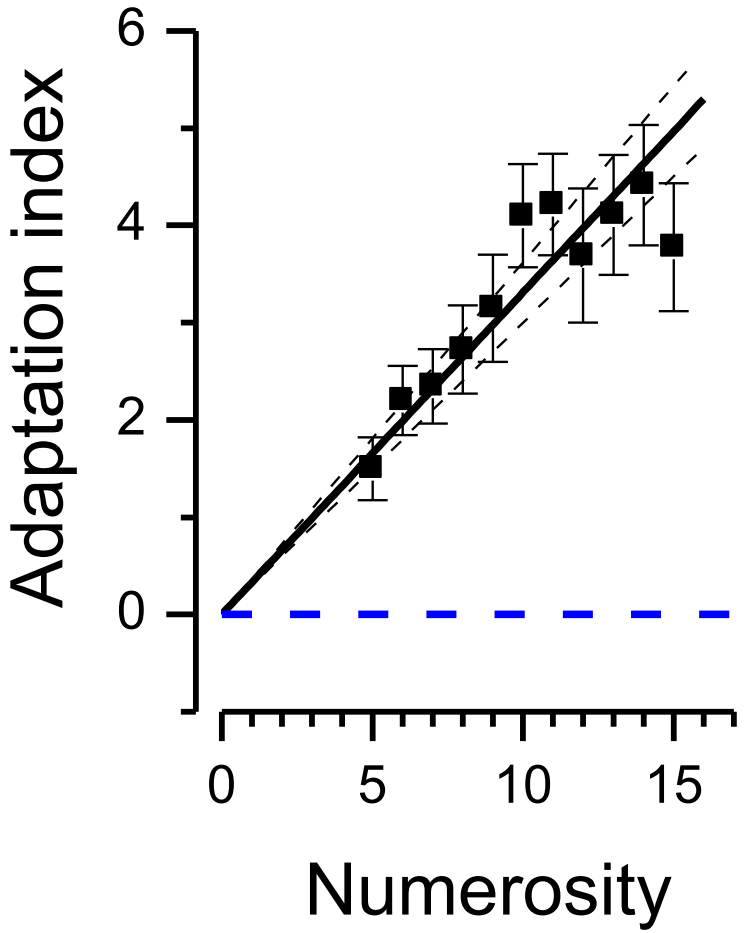


The selectivity is spatiotopic, not retinotopic

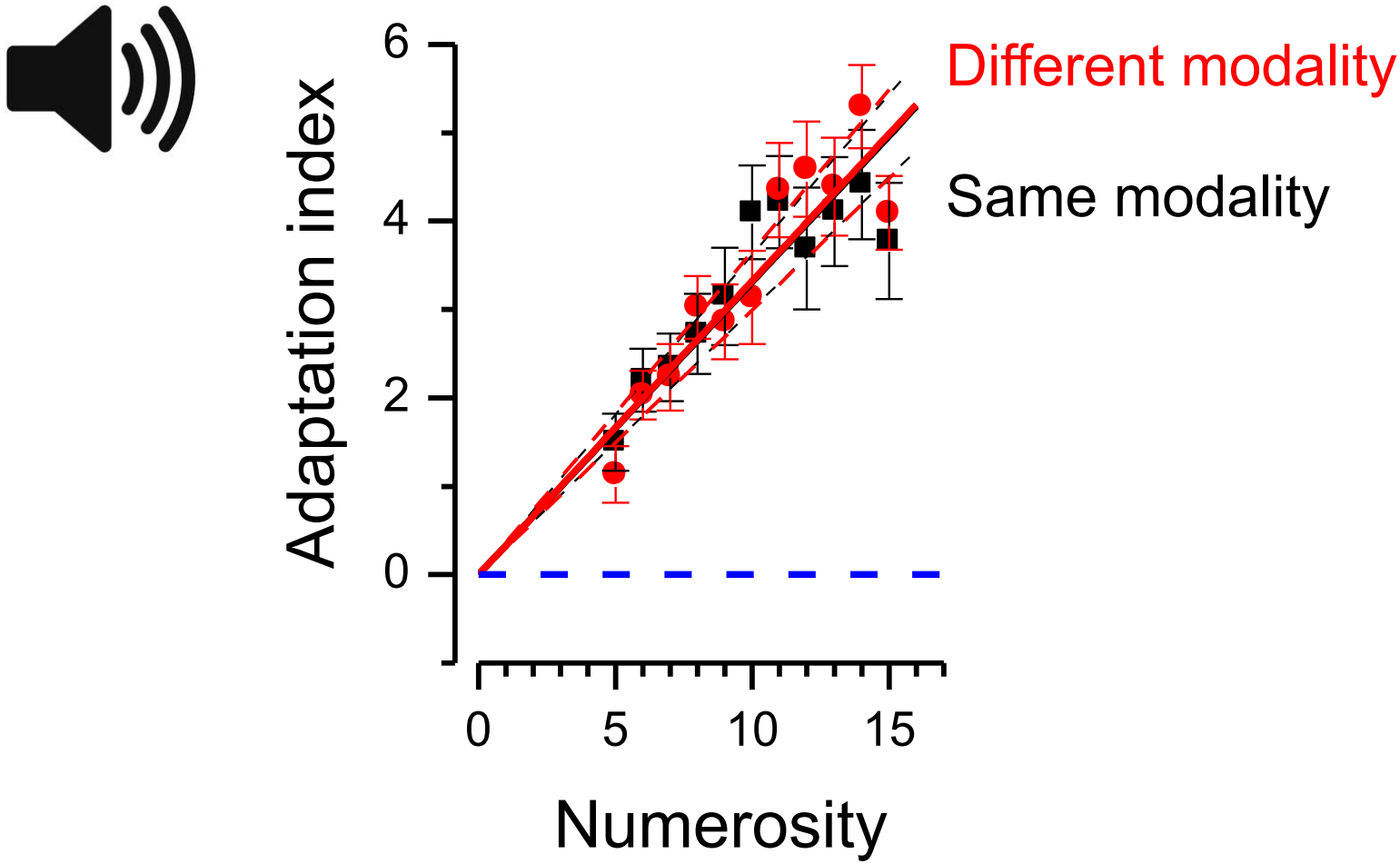




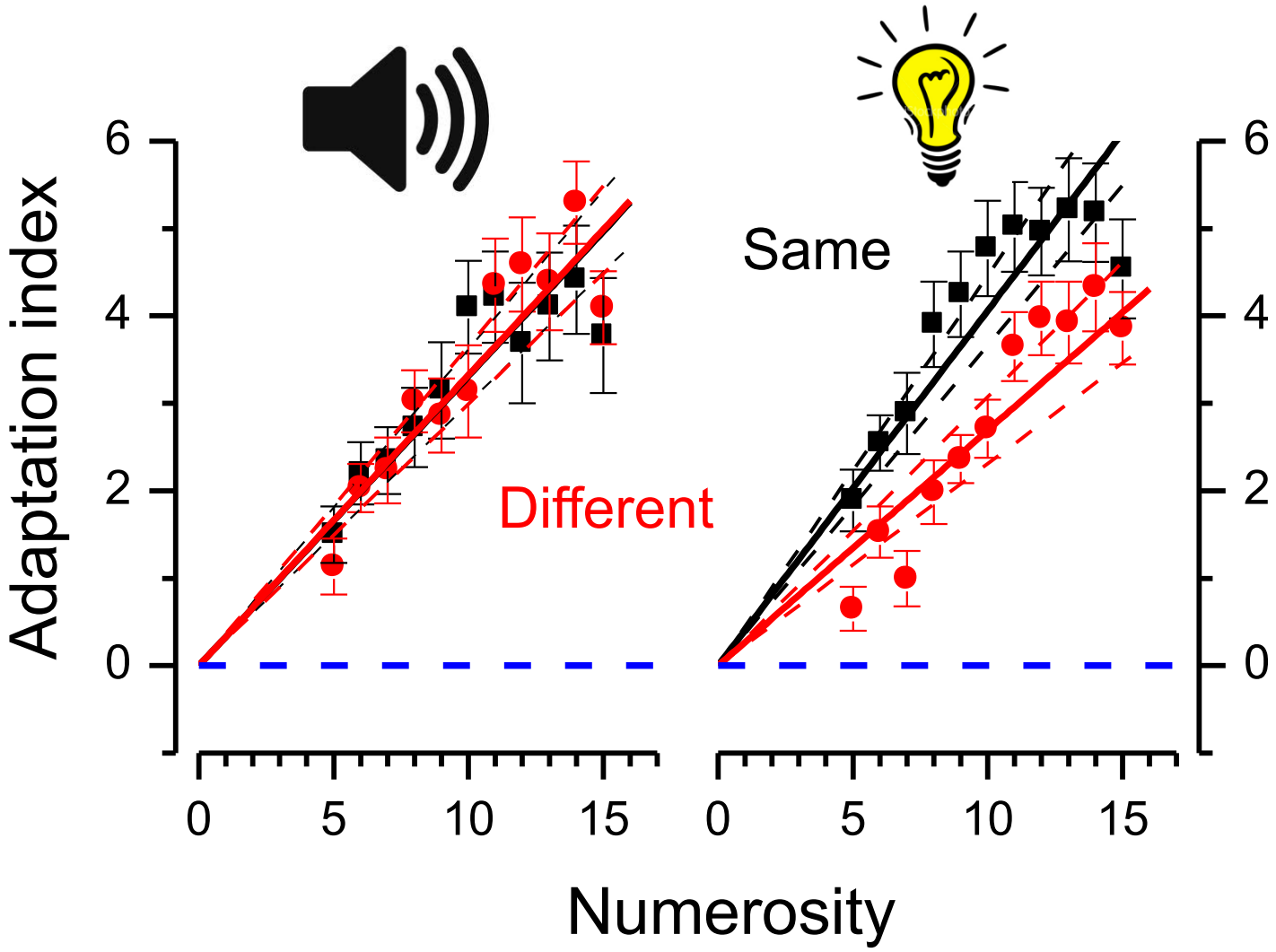
Sequential adaptation also occurs with sounds



Sequential adaptation also occurs for sounds: and cross-modally



Sequential adaptation also occurs in audition: and crossmodally



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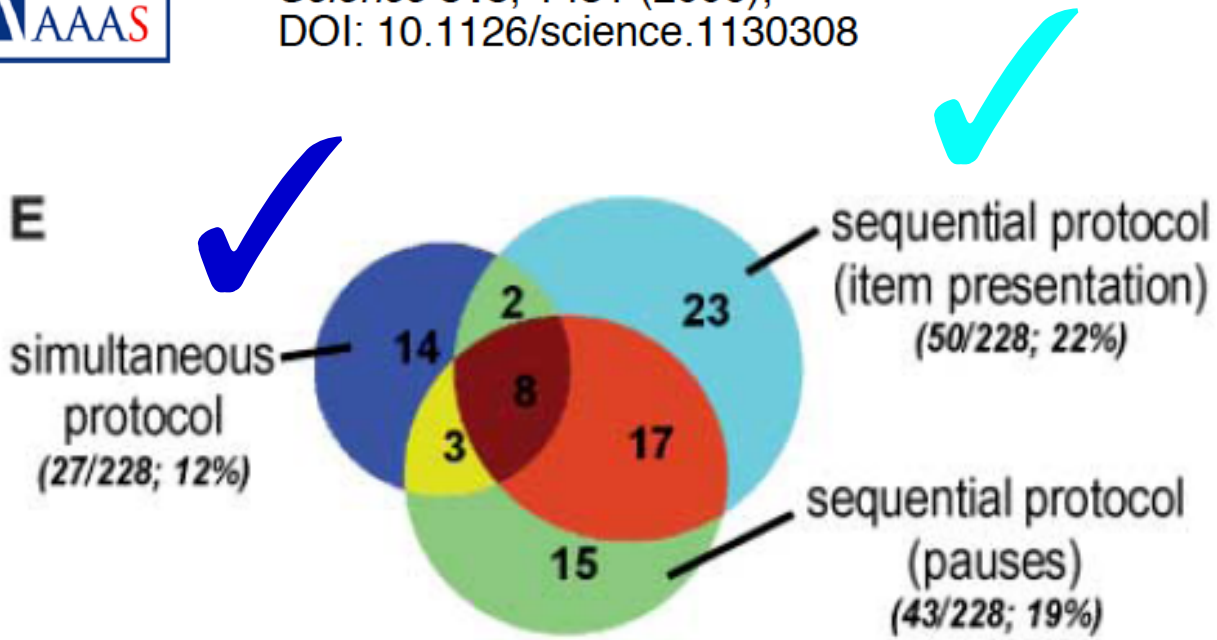
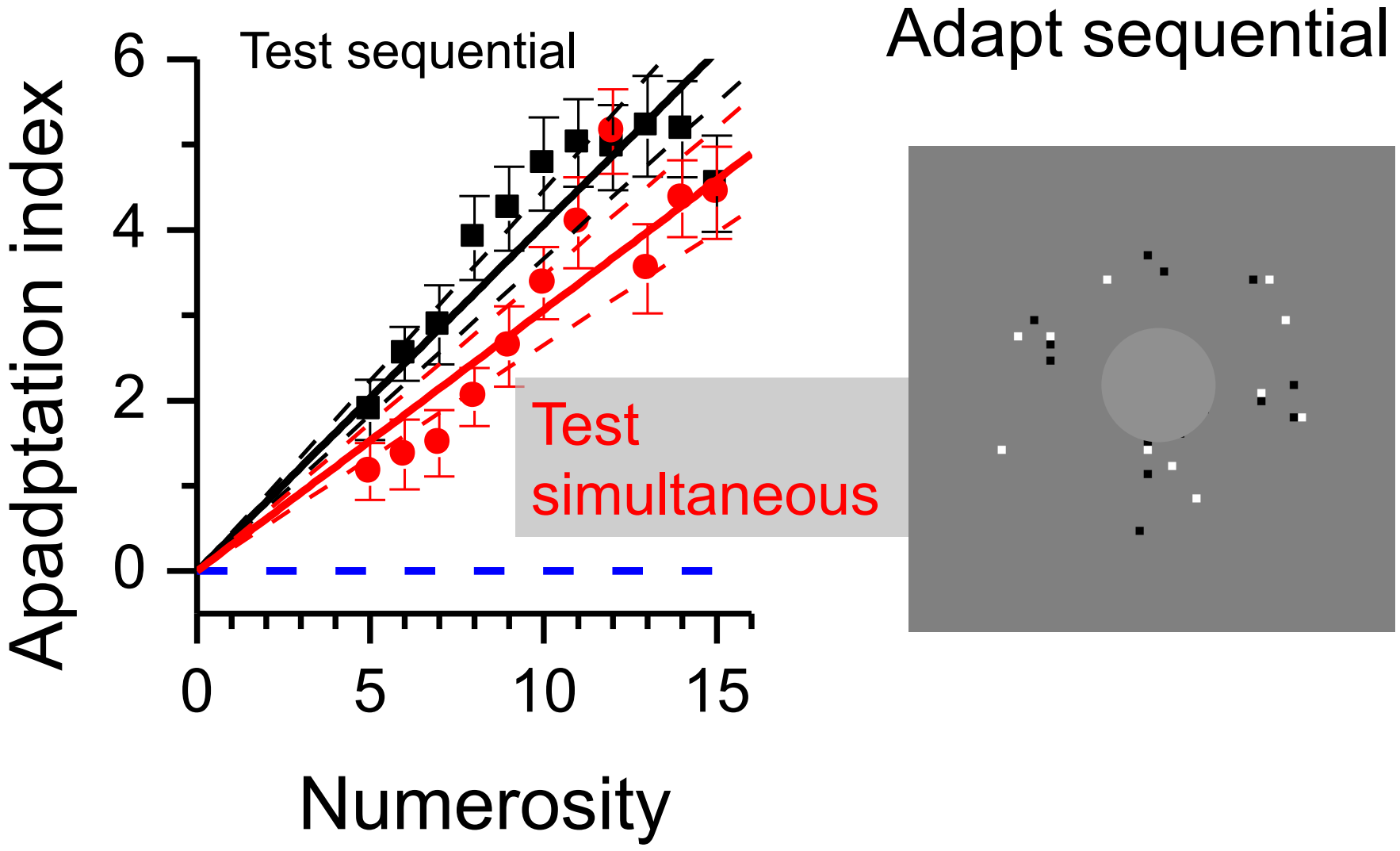


Distinct processing stages for sequential and simultaneous numerical formats, and **convergence to abstract quantity representation**

Cross-format adaptation



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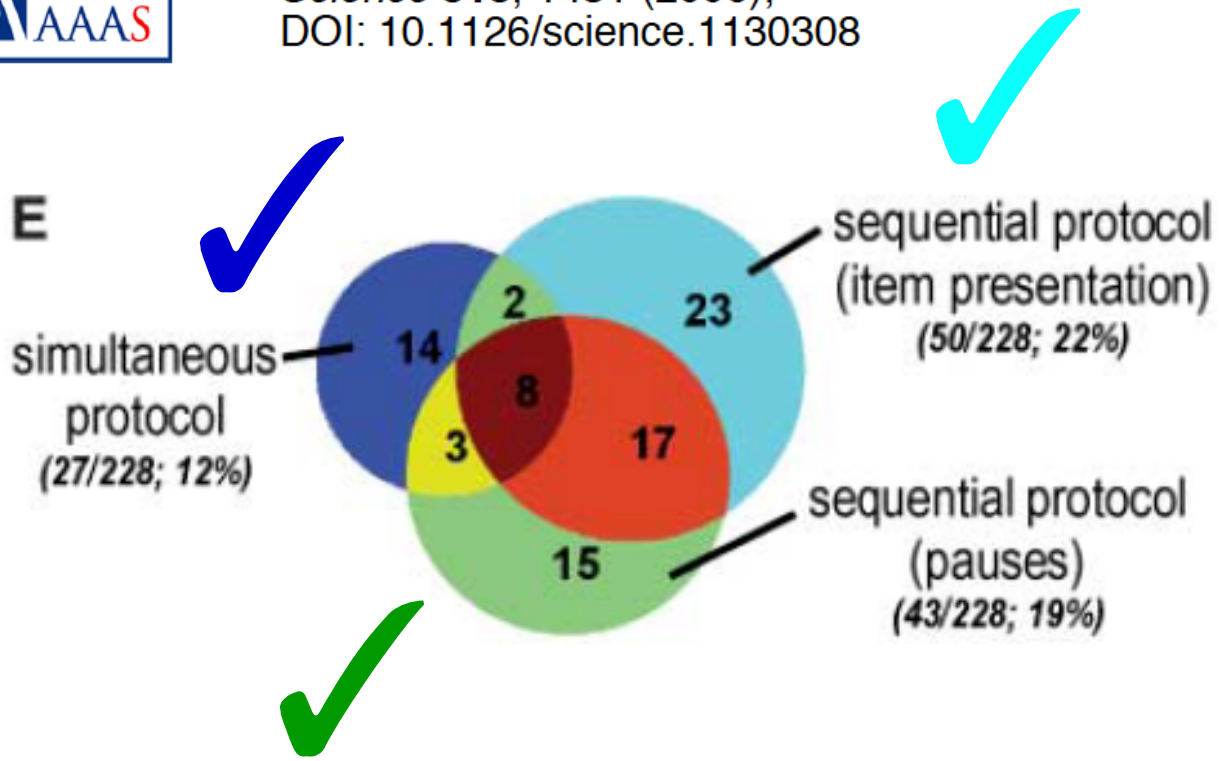

Distinct processing stages for sequential and simultaneous numerical formats, and convergence to abstract quantity representation

Conclusions

- Clear evidence for a mechanism for encoding spatial numerosity, independent of texture density
- Clear evidence for a system of sequential numerosity, in vision, audition and cross-modally
- Cross-format adaptation between sequential and simultaneous, implicating an abstract number system
- Linear mapping of numerosity requires attention: could imply a *regression to the mean*