Evidence for DFT

Gregor Schöner

DFT as a theoretical language

- DFT was developed as a theoretical language that enables "discoveries": uncovering laws of behavior and of their neural basis…
- in fact, the foundational principles were developed in close theory-experiment collaboration … and thus reflected regularities observed phenomenologically

Core DFT principles

- the core principles of DFT
  - continuous, metric spaces that span possible percepts, possible actions, and possible mental states
  - time continuous evolution of neural activation structured by attractor states that are localized activation peaks…
  - instabilities as the basis for change …

Core DFT principles

- give rise to typical experimental signatures and hypotheses
  - metric effects: distances between potential states matter
  - effects of timing: time matters, spatio-temporal co-variation
  - instabilities: it matters how far a state is from becoming unstable…

Core DFT principles

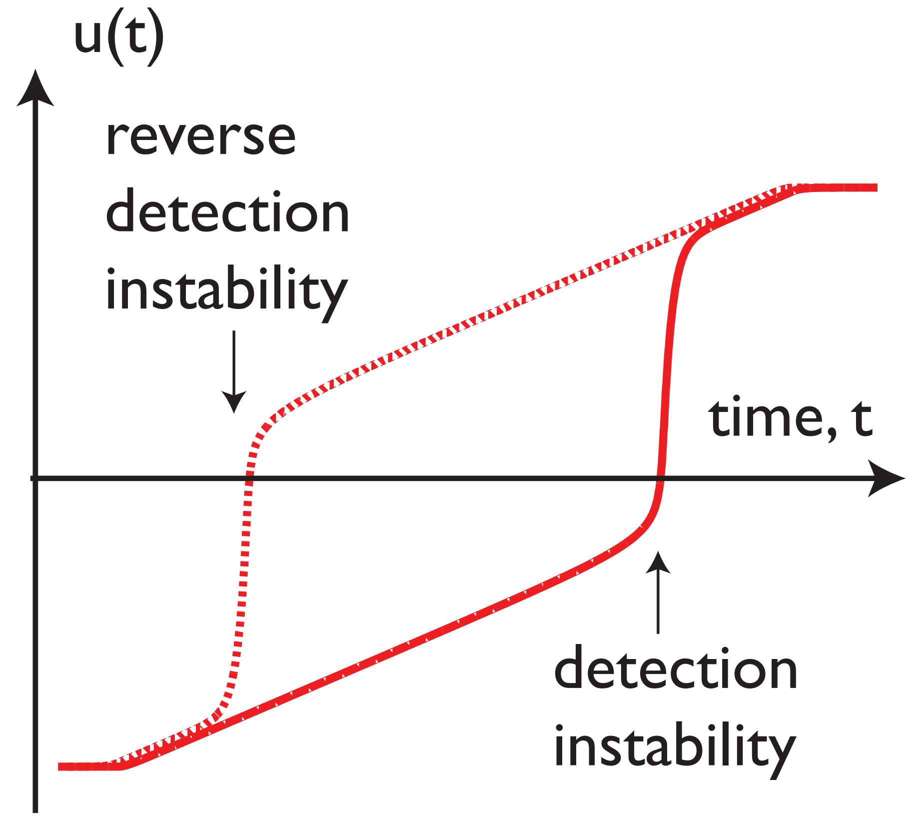
- explaining behavioral signatures in terms of the underlying dynamics
    - so that parameters of the dynamics reflect experimental conditions…

(1) Detection instability

- self-stabilized peaks are macroscopic neuronal states, capable of impacting on down-stream neuronal systems
- detection: peaks emerge from bistable regime… which stabilizes detection decisions
- [as contrasted to accounts for detection in Signal Detection Theory in which microscopic differences in neuronal activation around a threshold make the decision]

Predict: hysteresis

- detection depends on the prior state of activation
- and thus on the history of activation/stimulation



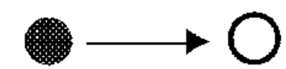
Predict: hysteresis

- in psychophysics, there is a wealth of hysteresis phenomena..
- these have not always been taken seriously…
- e.g. ascribed to response bias/decision inertia in the face of uncertainty

Apparent motion

- the basis of movies… sequences of images creates visual motion if space-time relations are right..
- [real motion perception is related due to transient detectors]
- Korte's laws: distance/ time relationships supporting motion
- perceptual uncertainty: issues of judgement…

elements of contrast alternate in location

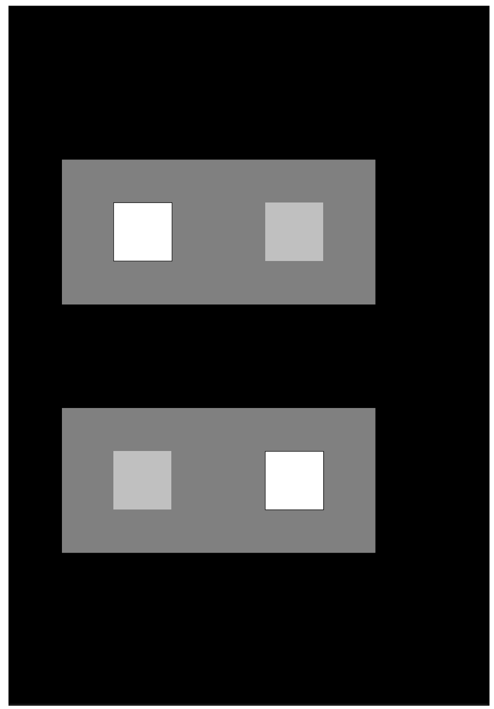


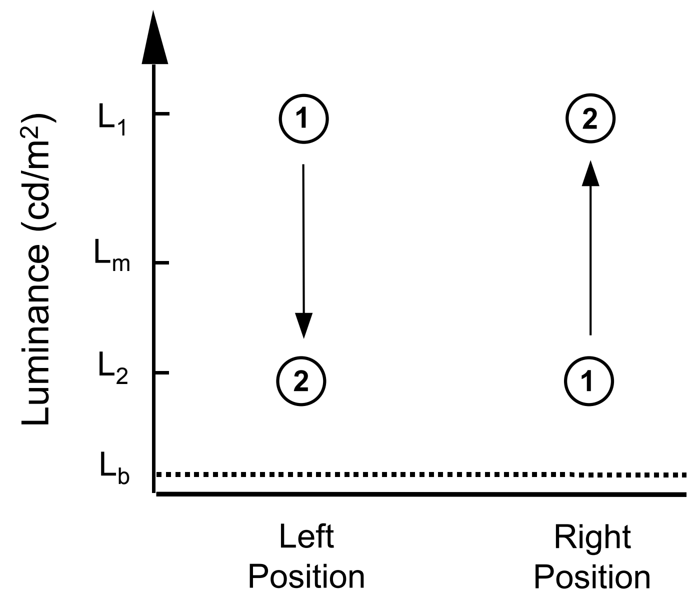
motion arises if distance/timing is right

[Hock Schöner: *Seeing and Perceiving* 2010]

Generalized apparent motion

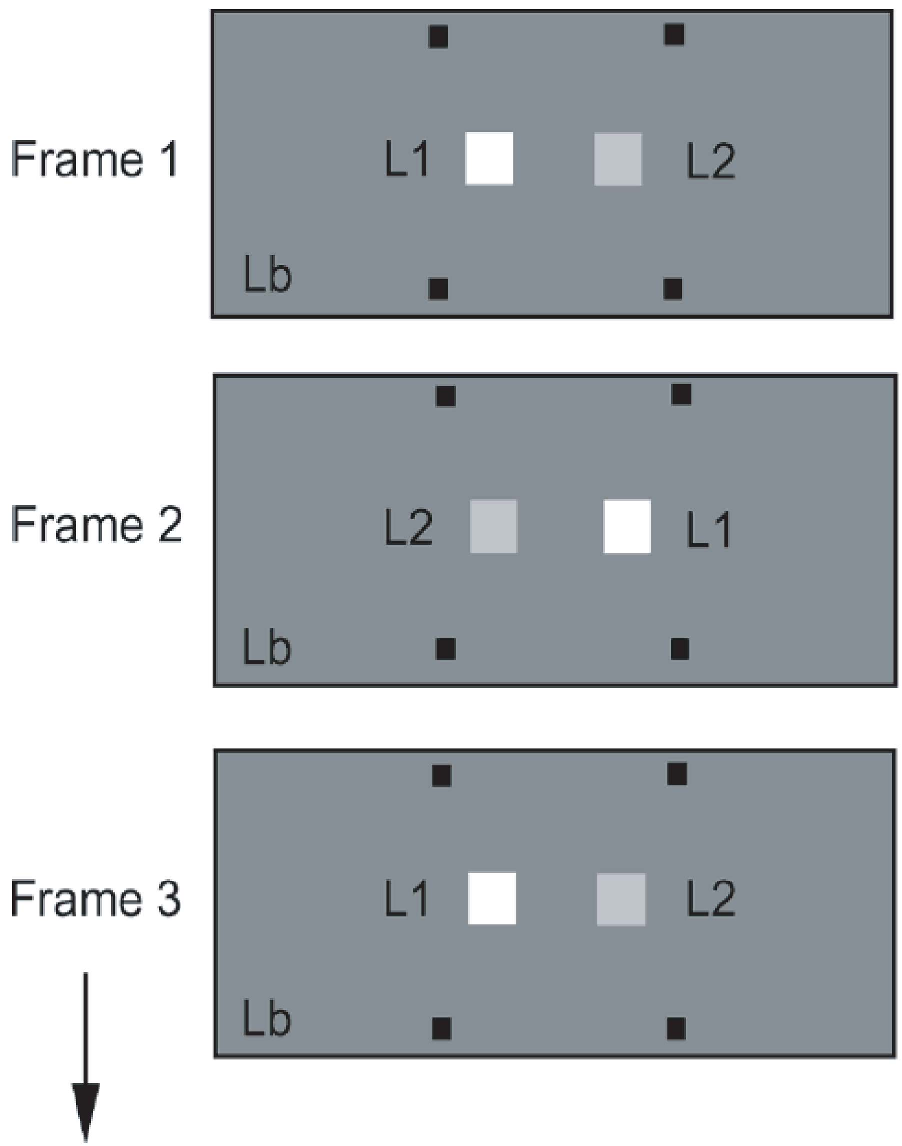
- generalized apparent motion
- motion arises at the same distance/timing as contrast is varied





[Hock Schöner: *Seeing and Perceiving* 2010]

Detection as BRLC is varied



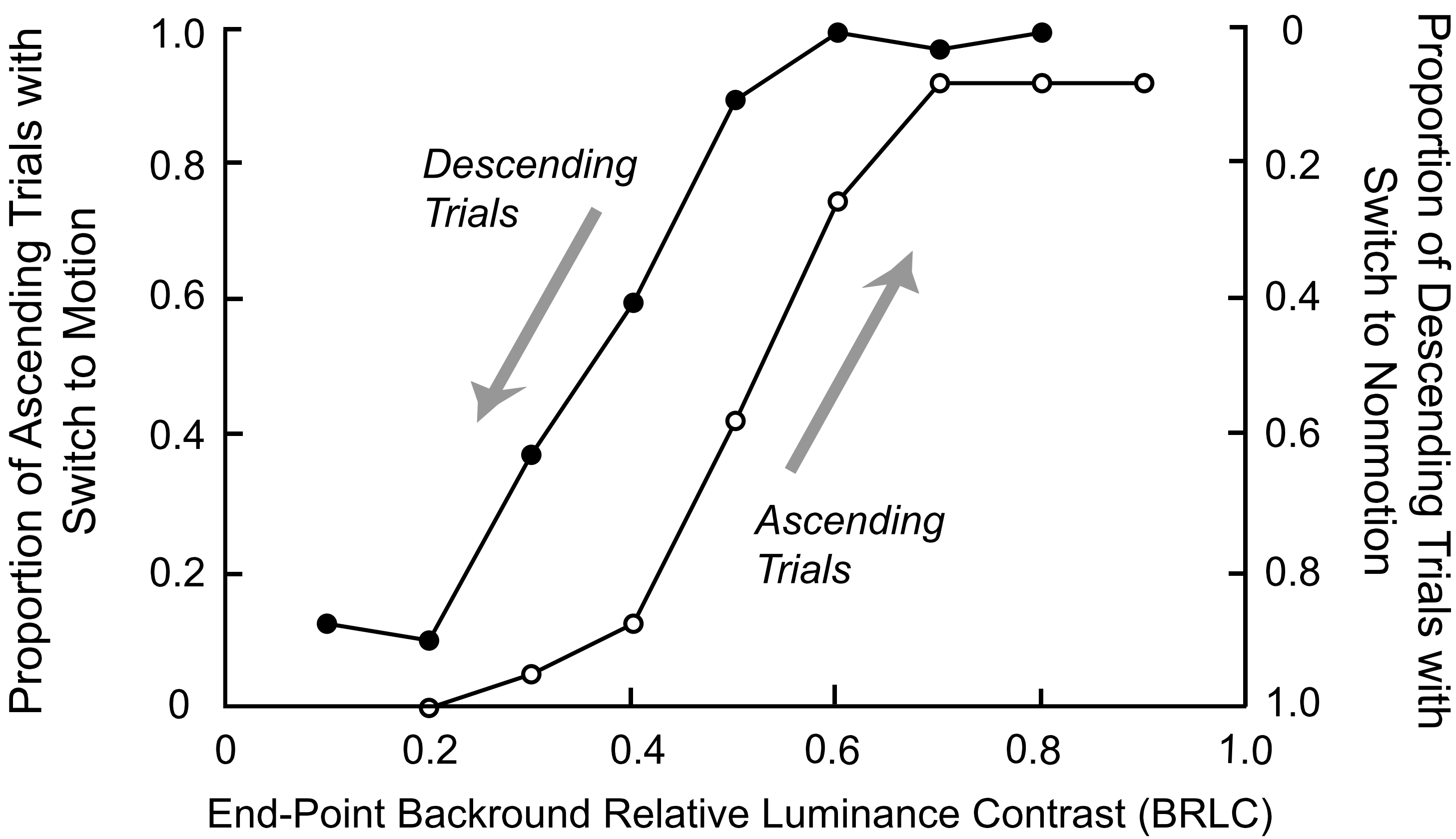
$$Lm = \frac{L1 + L2}{2}$$

$$\text{Background-Relative Luminance Change (BRLC)} = \frac{L1 - L2}{Lm - Lb}$$

Hysteresis as BRLCS is varied

- response bias is minimized in the modified method of limits [stimulus sequence ends unpredictably at different final BRLC levels]

H. S. Hock, G. Schöner / Seeing and Perceiving 23 (2010) 173–195



Contrast detection

- detection of elements of contrast
- different elements of contrast interact

Journal of Vision (2023) 0(0):08639, 1–28

The stabilization of visibility for sequentially presented, low-contrast objects: Experiments and neural field model

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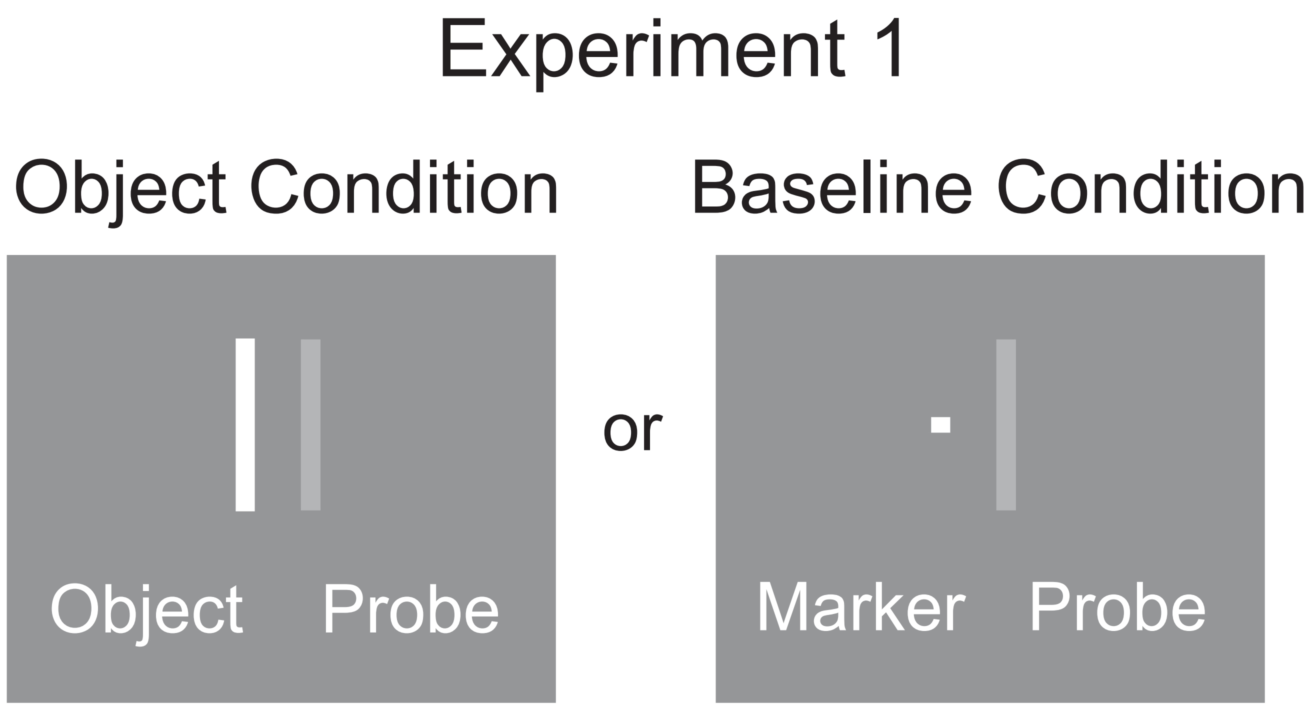
Q1
Gregor Schöner
Institute for Neural Computation, Ruhr-Universität Bochum, Bochum, Germany

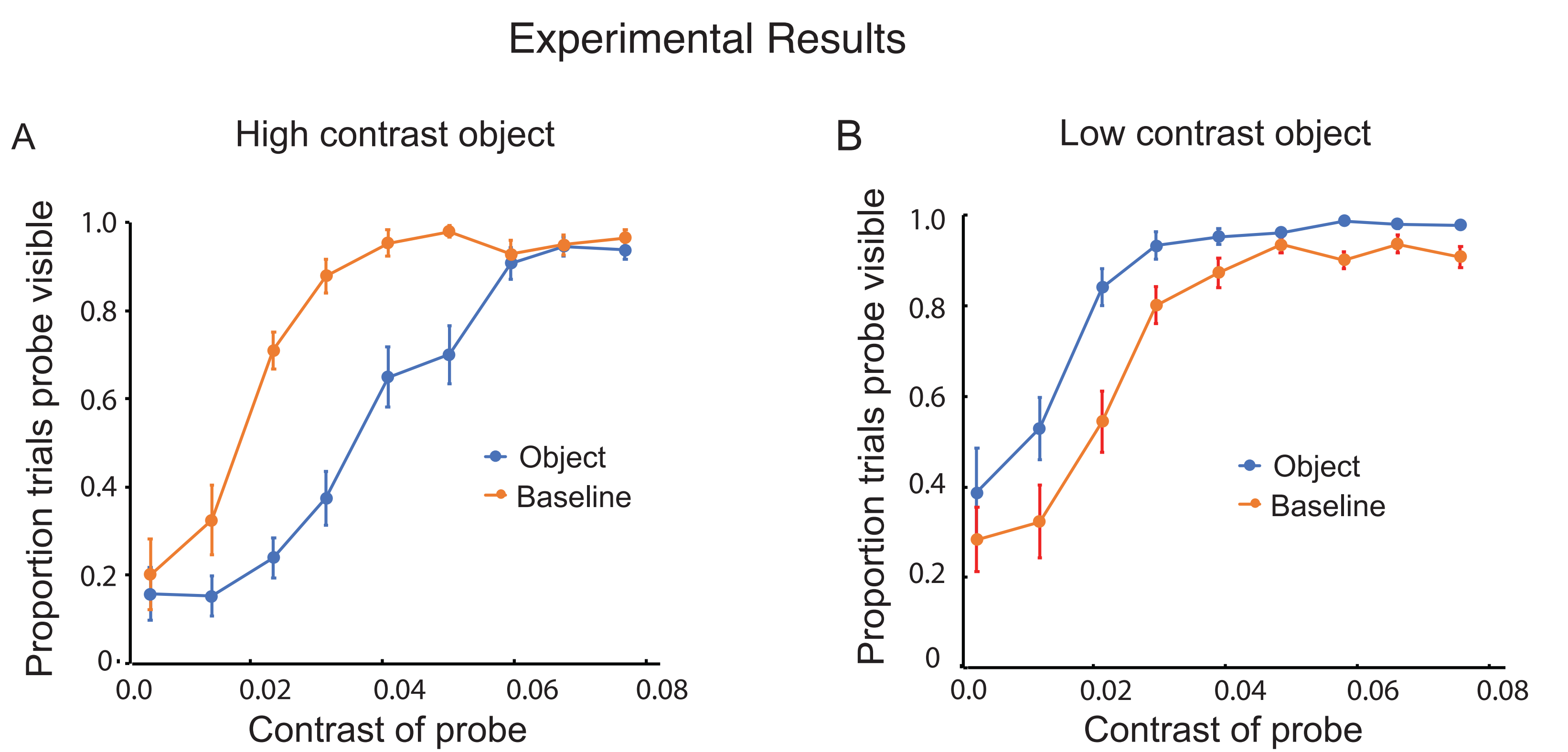
Base phenomenon

- detect a probe element of contrast in the absence/presence of a flanker object



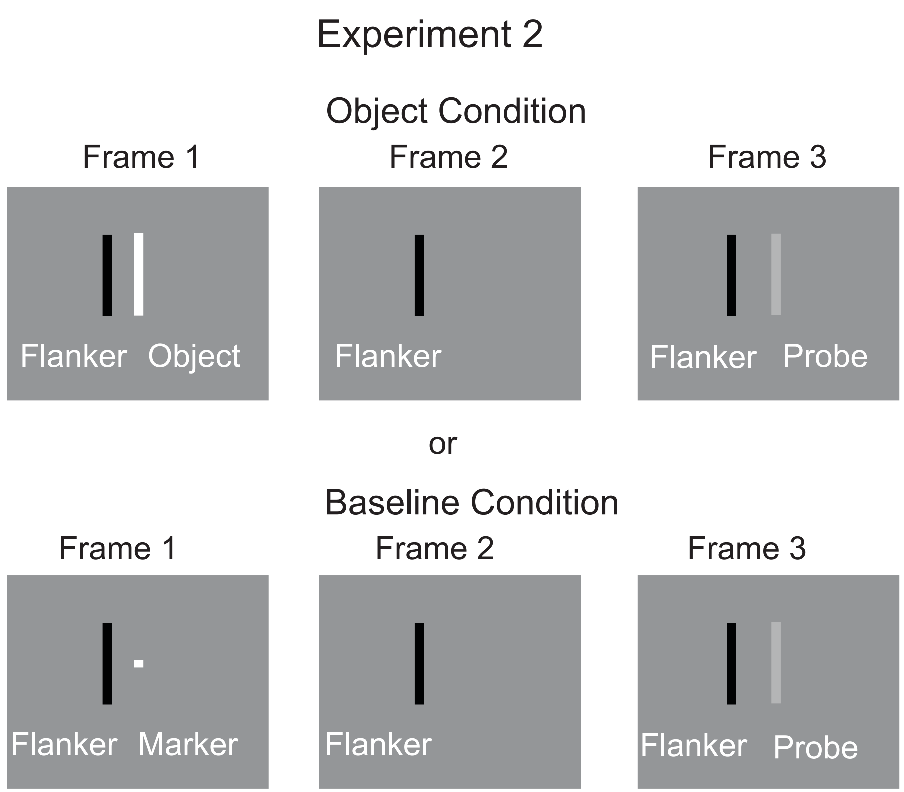
Base phenomenon

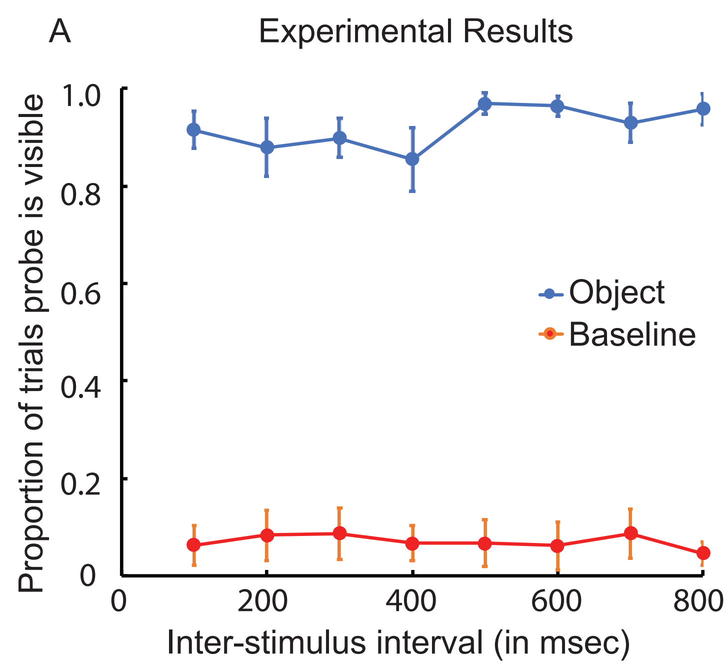
- if the flanker object is high in contrast, it inhibits probe detection
- if the flanker object is low in contrast, it facilitates probe detection



ISI

- The facilitatory effect is sustained through interstimulus intervals (ISI) up to 800 ms (or longer)



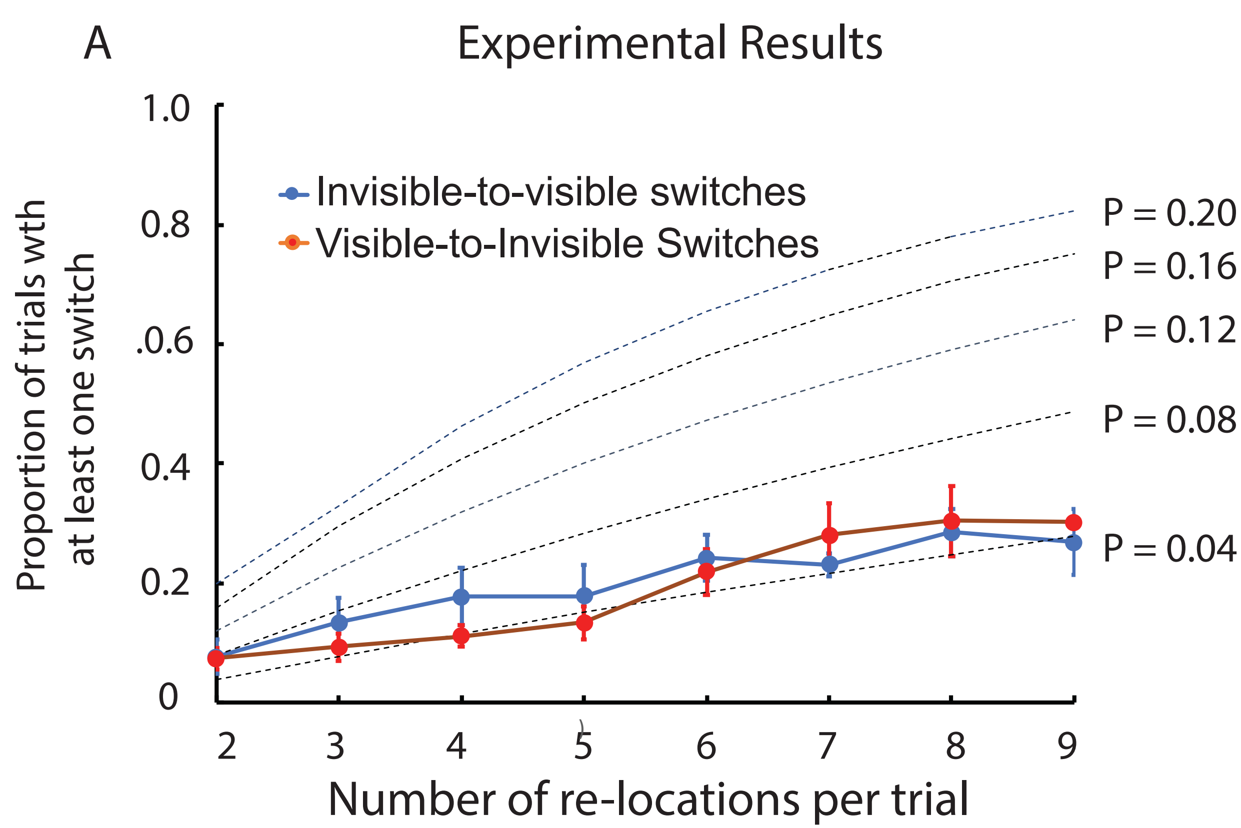


ISI

Bistability

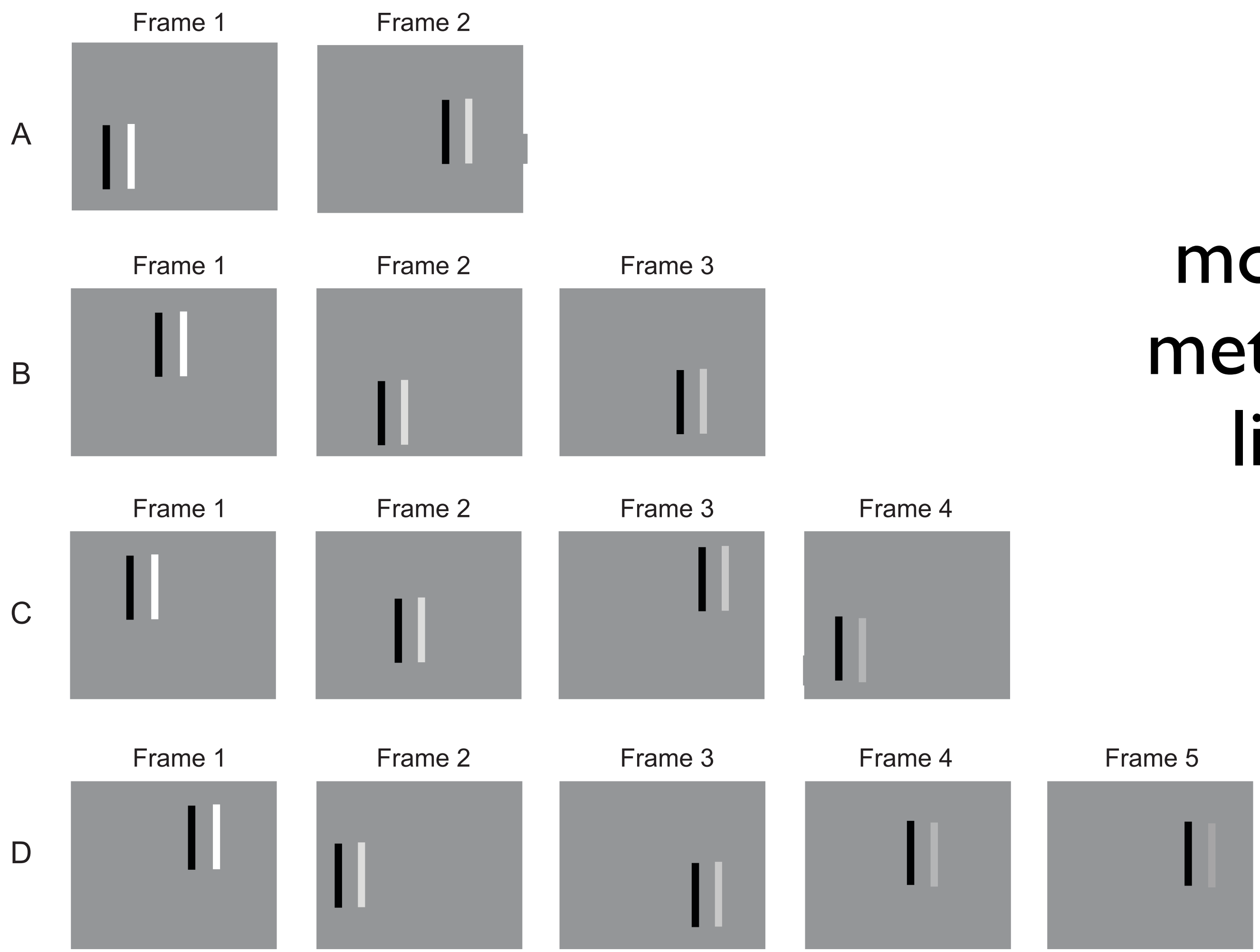
- near critical contrast, detection is stochastic from trial to trial, but persists once established over repeated presentations

initial probability of detection ~ 50%



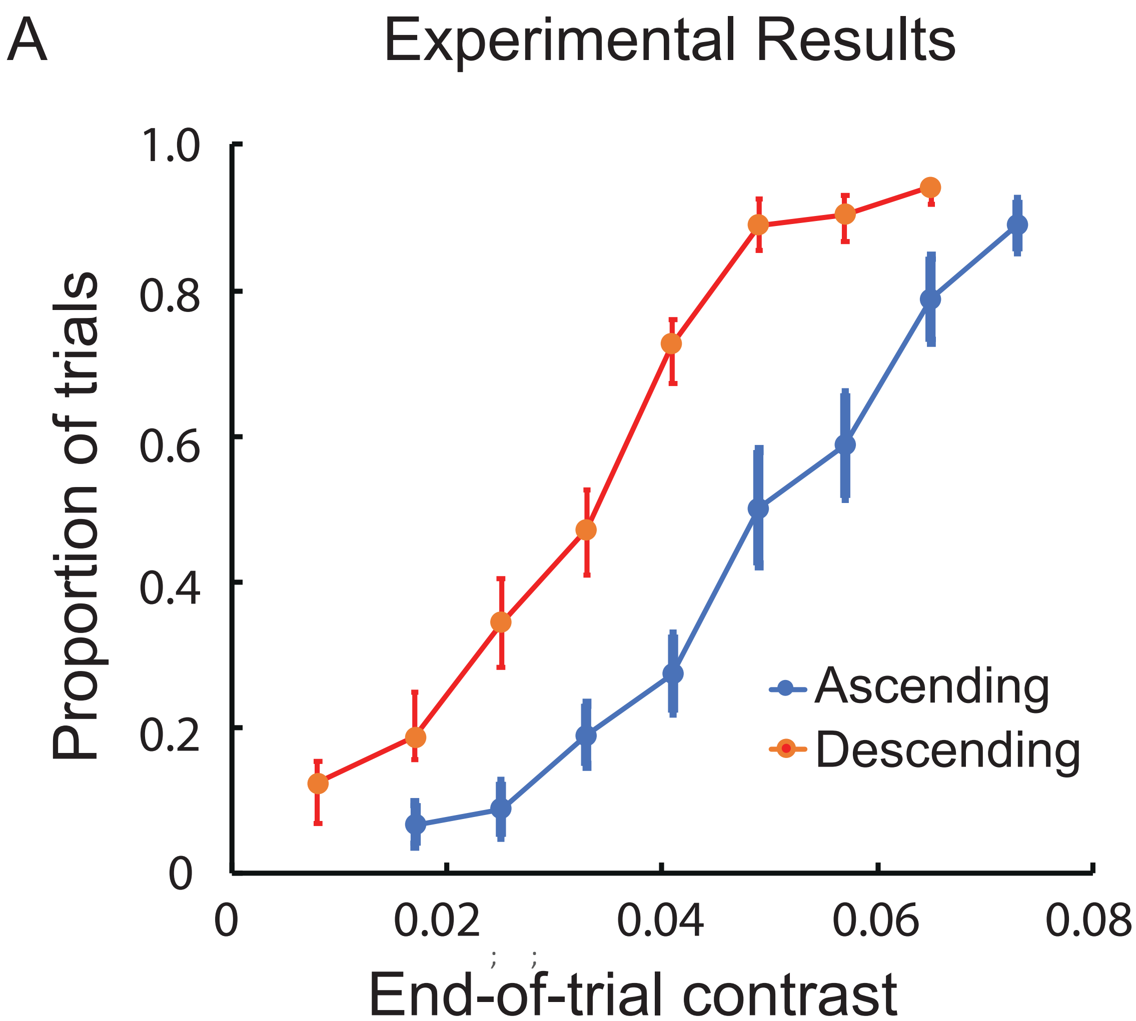
Hysteresis

- detection for decreasing vs increasing probe contrast



modified method of limits

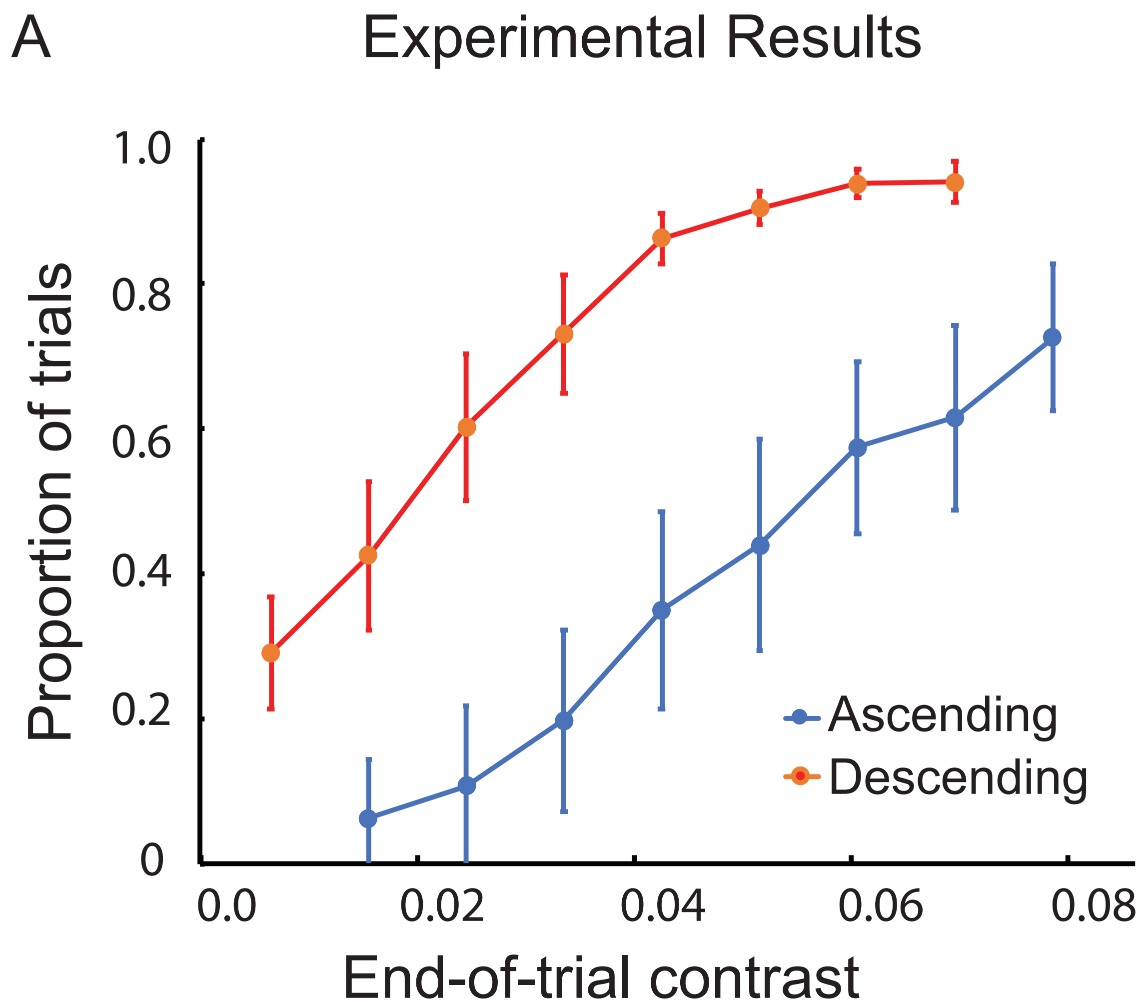
Hysteresis



A
Experimental Results
1.0
0.8
0.6
0.4
0.2
0
Proportion of trials
0
0.02
0.04
0.06
0.08
End-of-trial contrast
Ascending
Descending

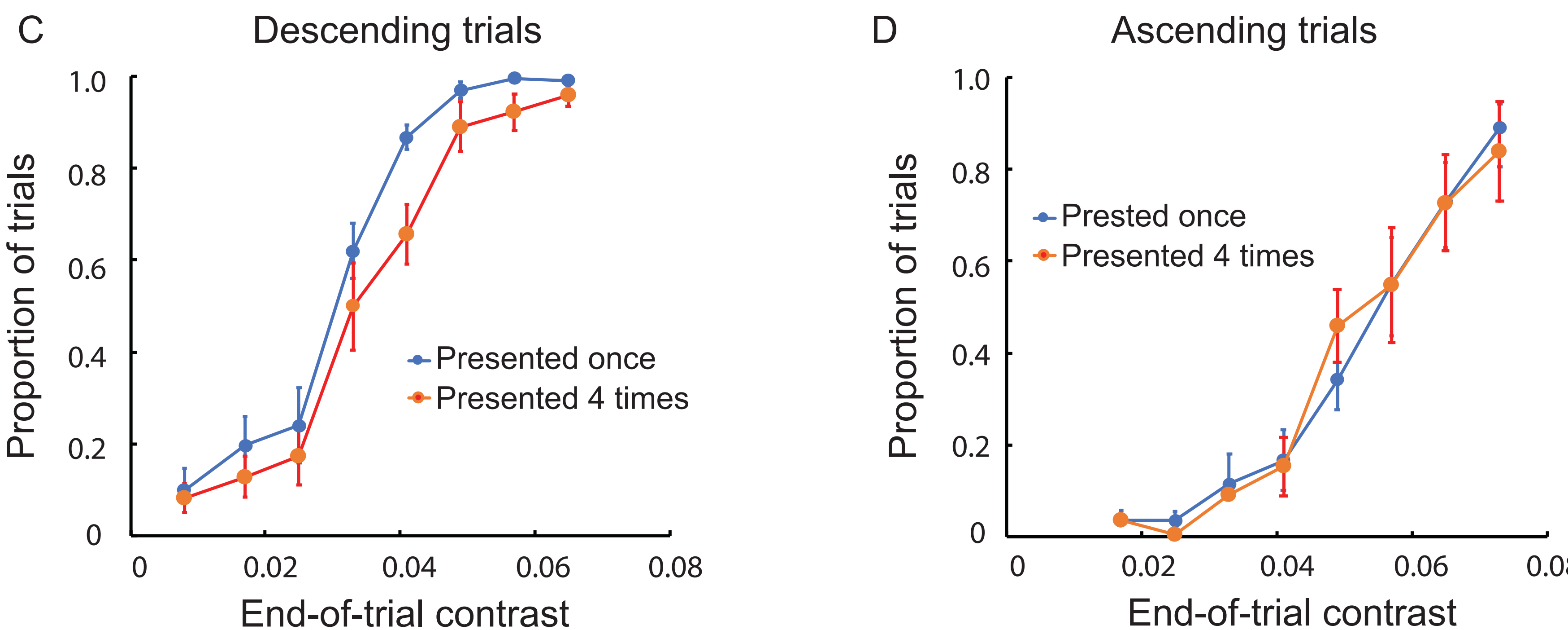
Hysteresis

- even stronger for short presentations (frame duration 104 ms)



Loss of stability

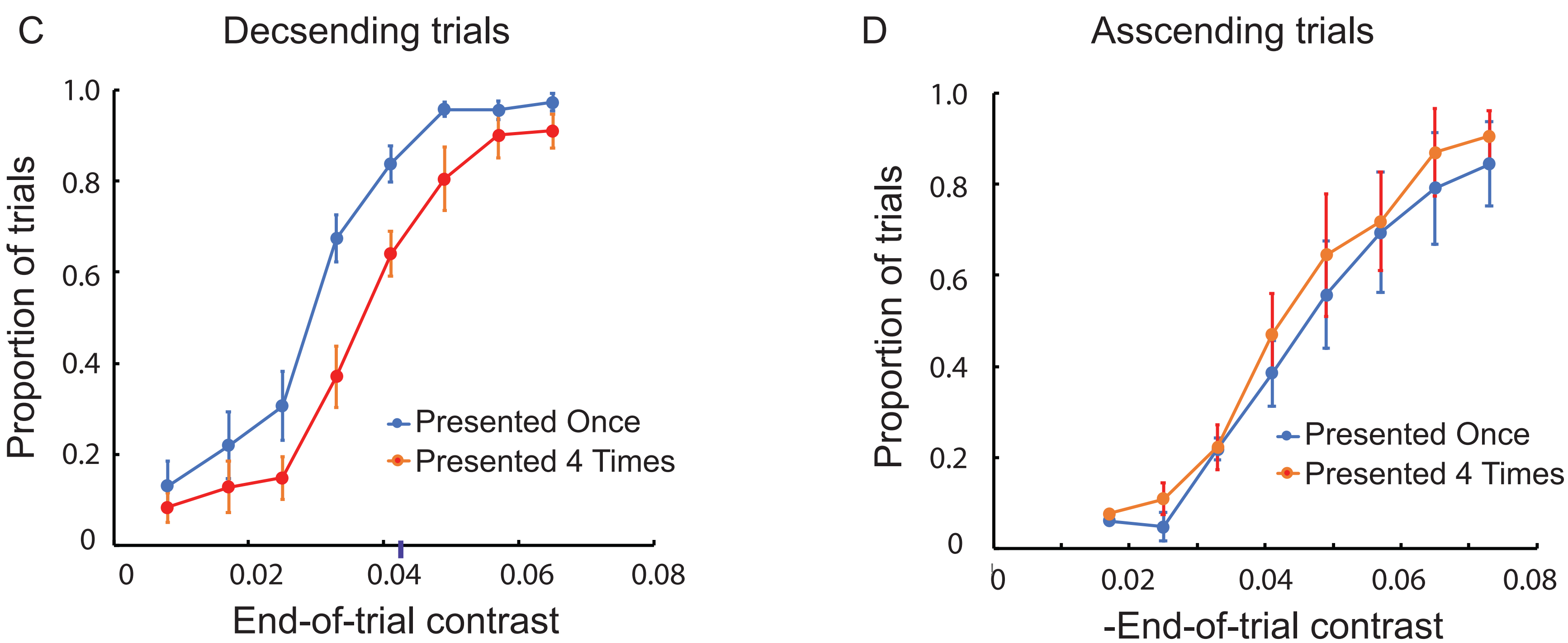
- detection at end of hysteresis is unstable



repeating final probe contrast level 4 times

Adaptation

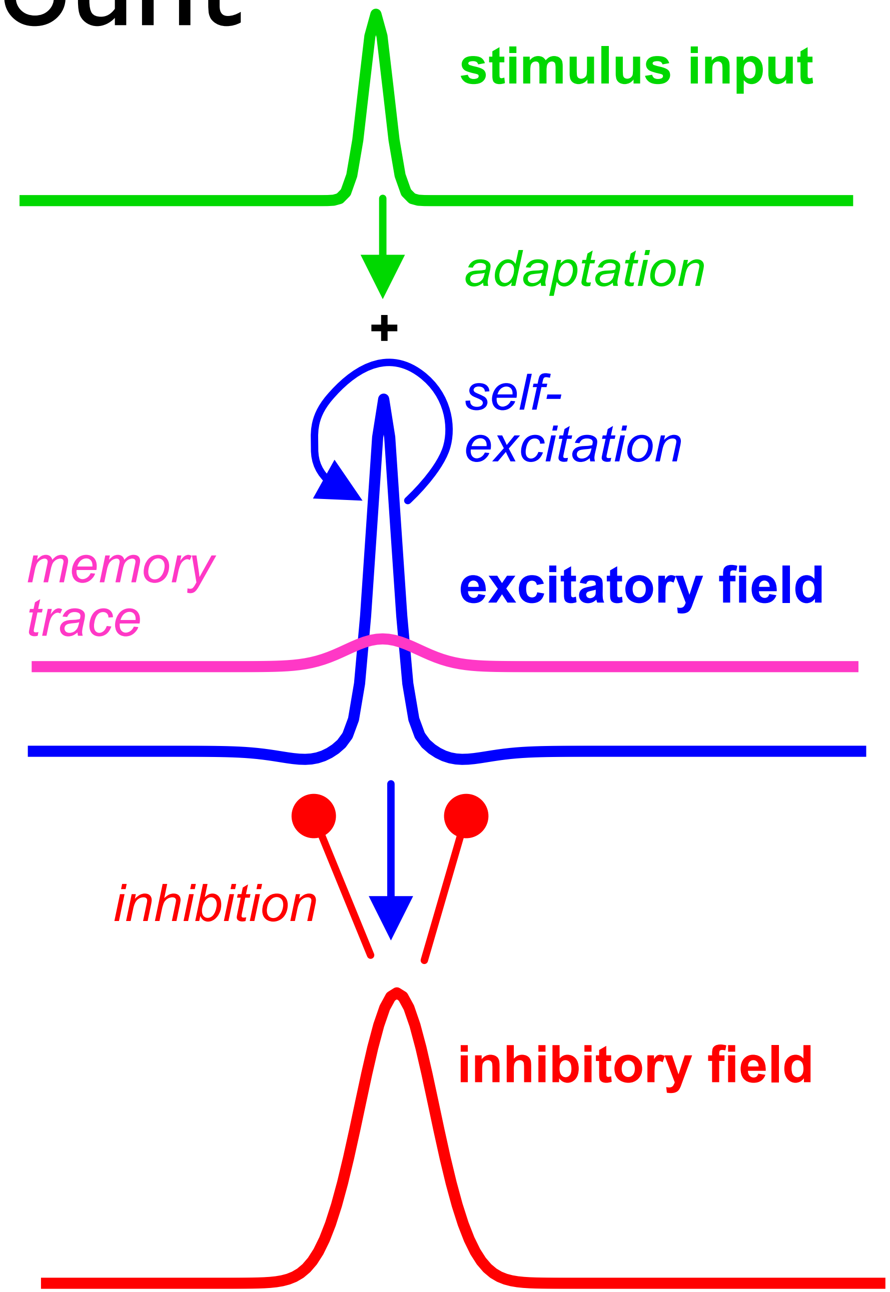
- exposure to contrast before descending arm of hysteresis reduces detection



repeating initial probe contrast level 4 times

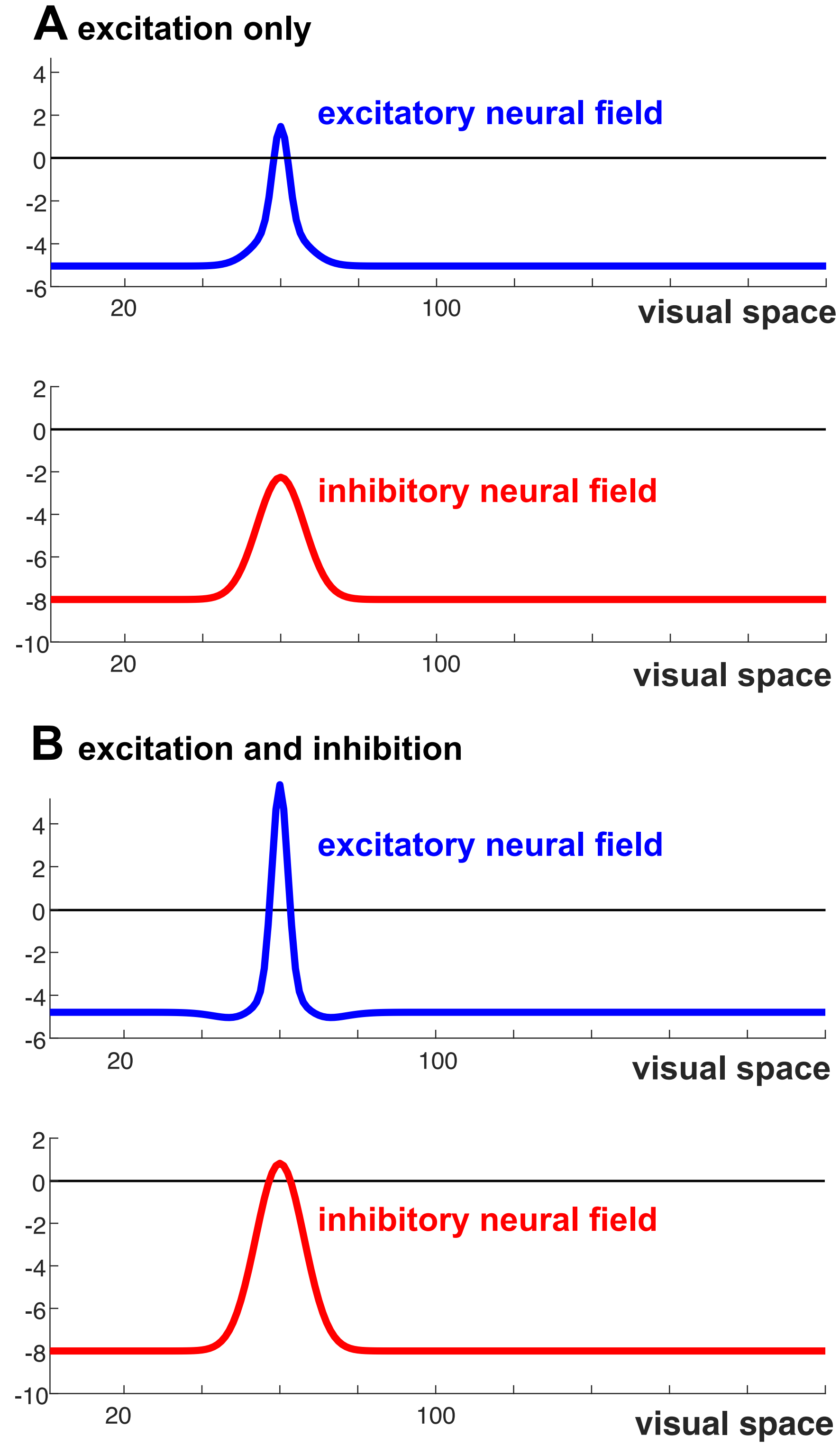
DFT account

- 2-layer neural dynamic field
- input with Hebbian adaptation
- memory trace in excitatory field
- very slow colored noise on resting level
- => fit all experiments form single parameter set

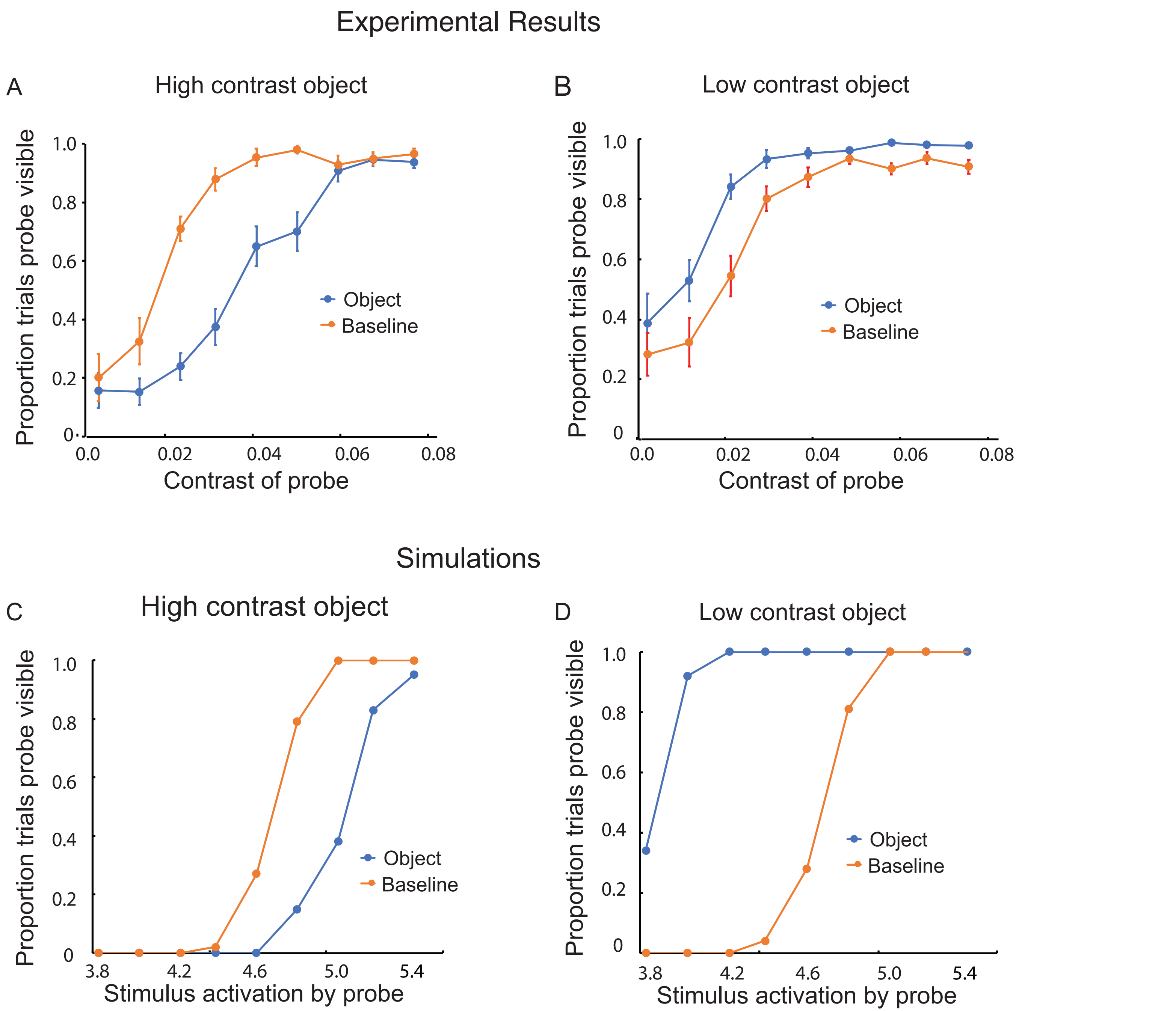


DFT account for base phenomenon

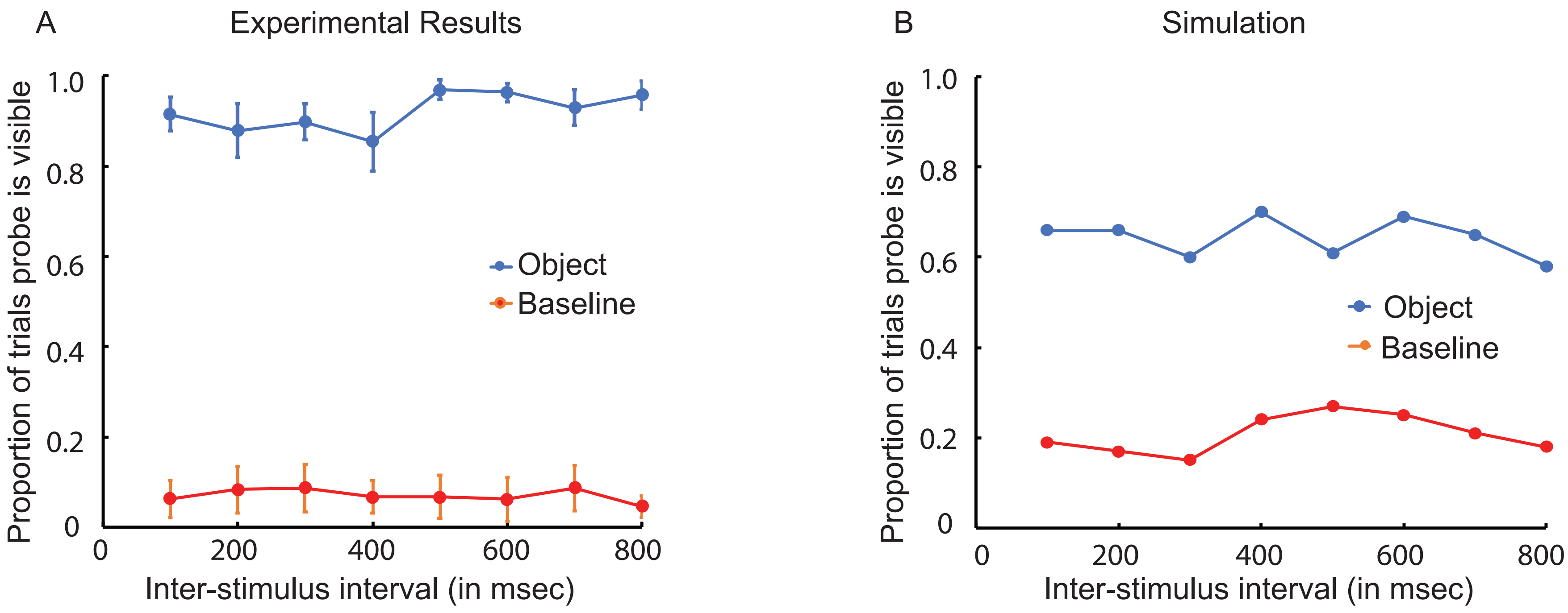
- within a neural dynamic field
- at low contrast, only the excitatory is above threshold, leading to excitatory interaction=facilitation
- at hight contrast, the inhibitory layer is above threshold, leading to inhibitory interaction=suppression



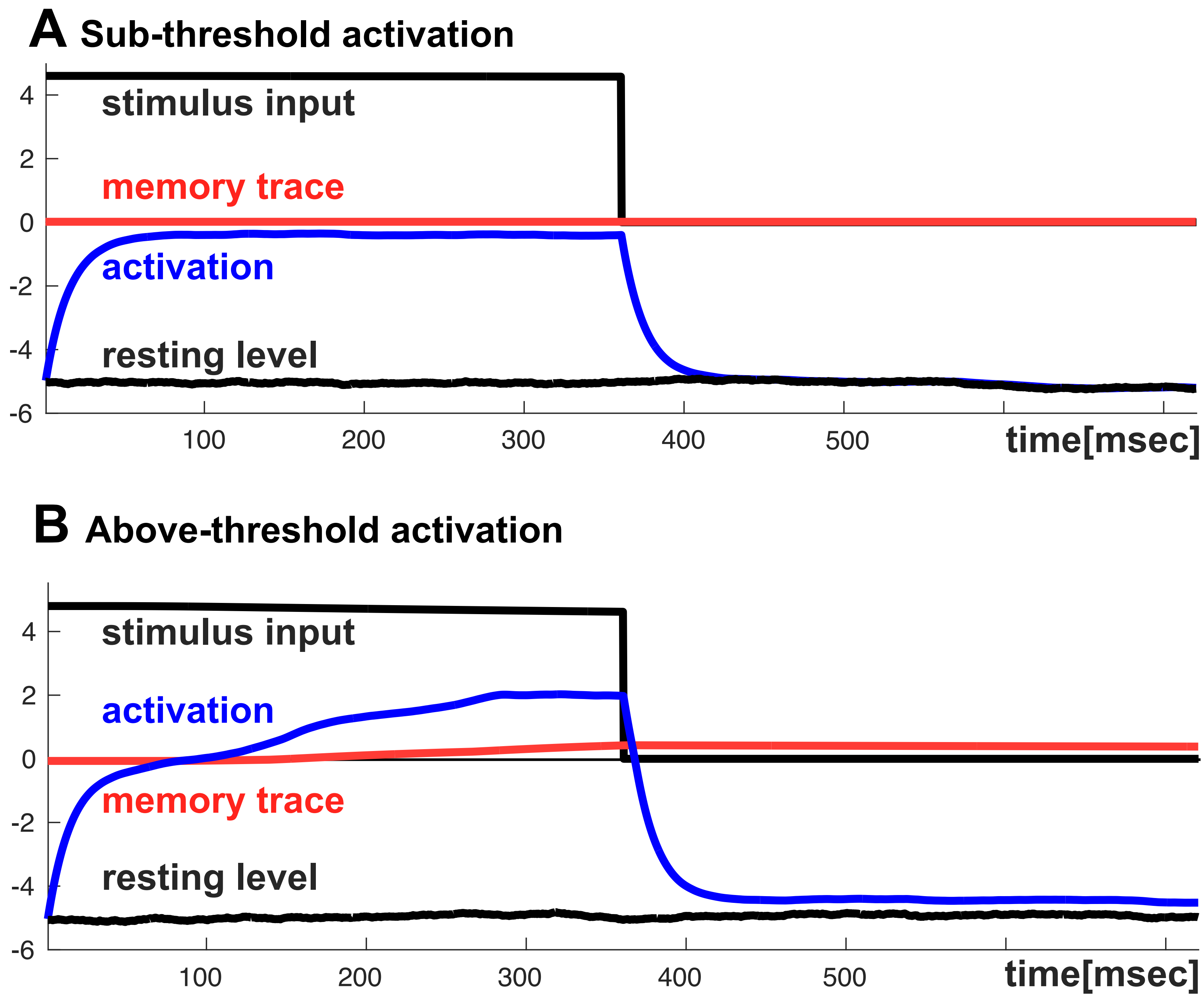
Base phenomenon



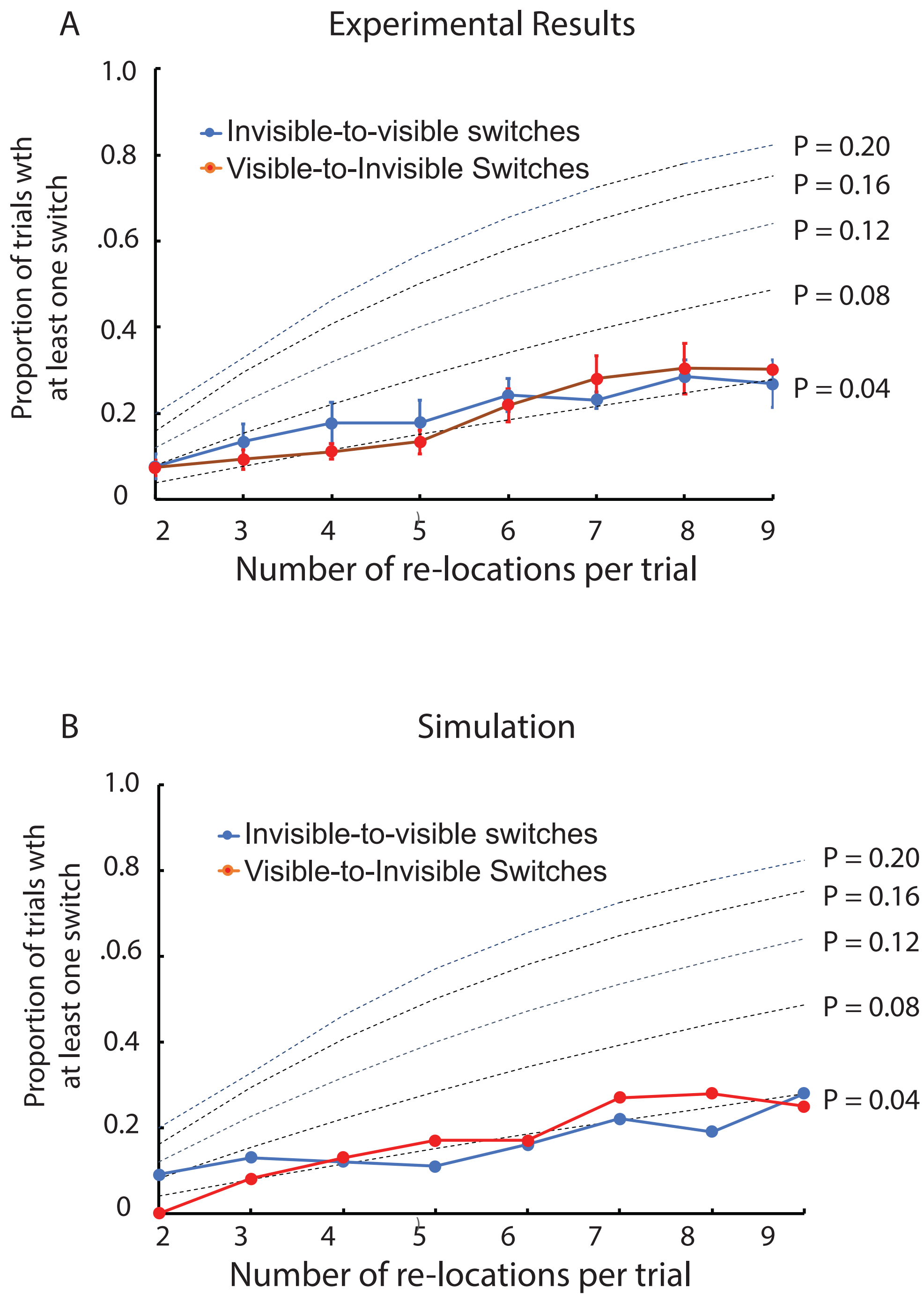
ISI


A
Experimental Results
Proportion of trials probe is visible
1.0
0.8
0.6
0.4
0.2
0
0
200
400
600
800
Inter-stimulus interval (in msec)
Object
Baseline
B
Simulation
Proportion of trials probe is visible
1.0
0.8
0.6
0.4
0.2
0
0
200
400
600
800
Inter-stimulus interval (in msec)
Object
Baseline

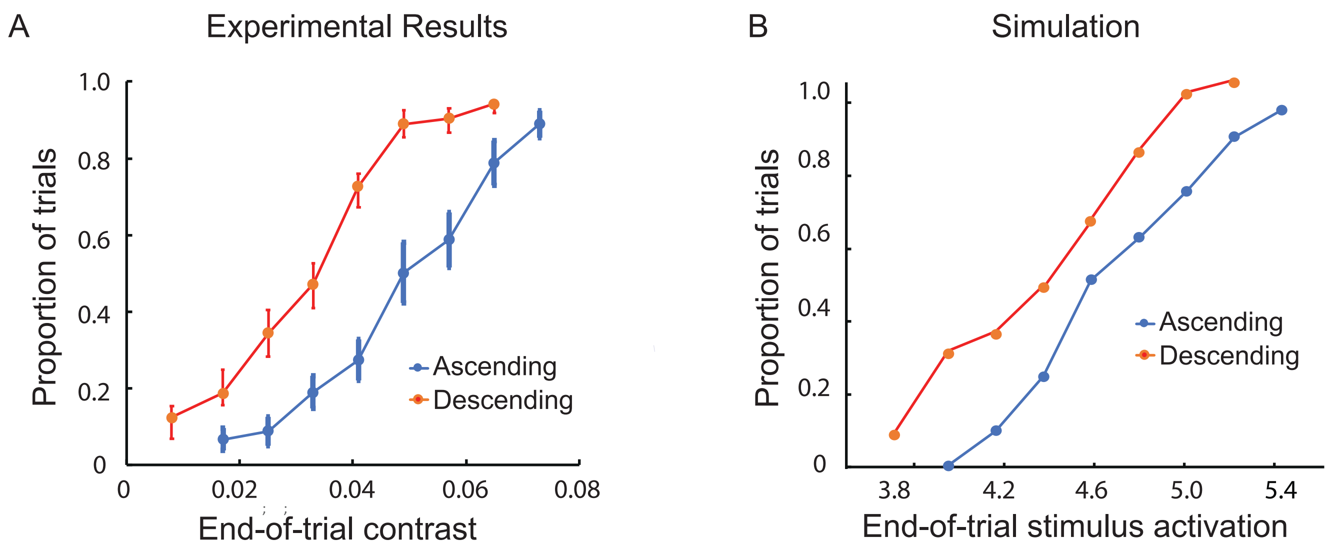
Detection in DFT



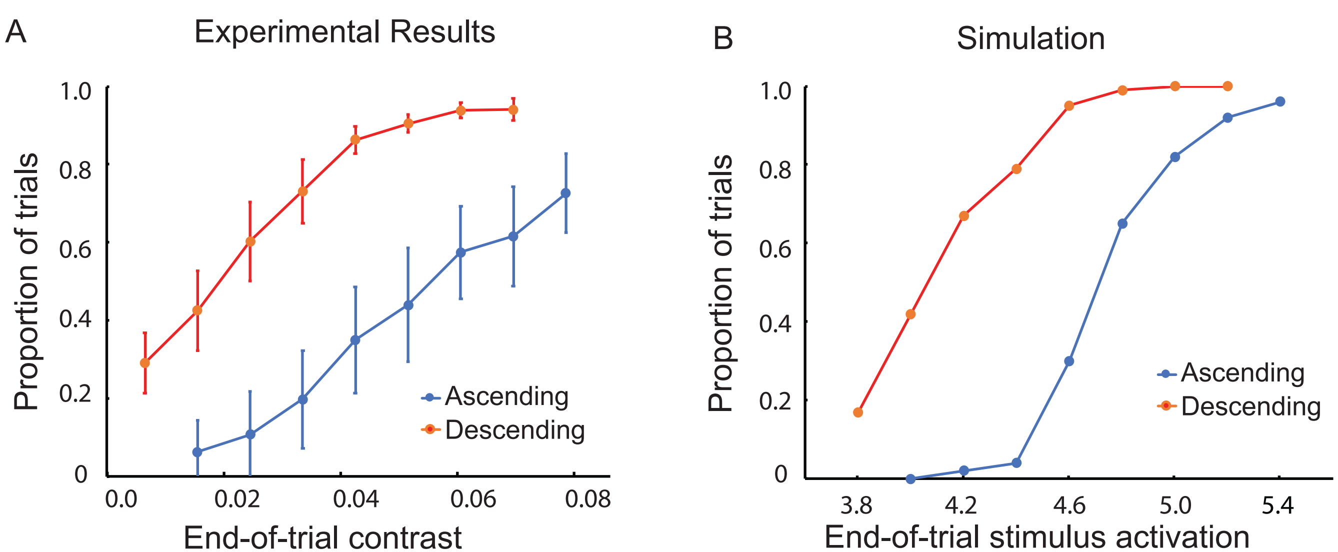
Bistability



Hysteresis

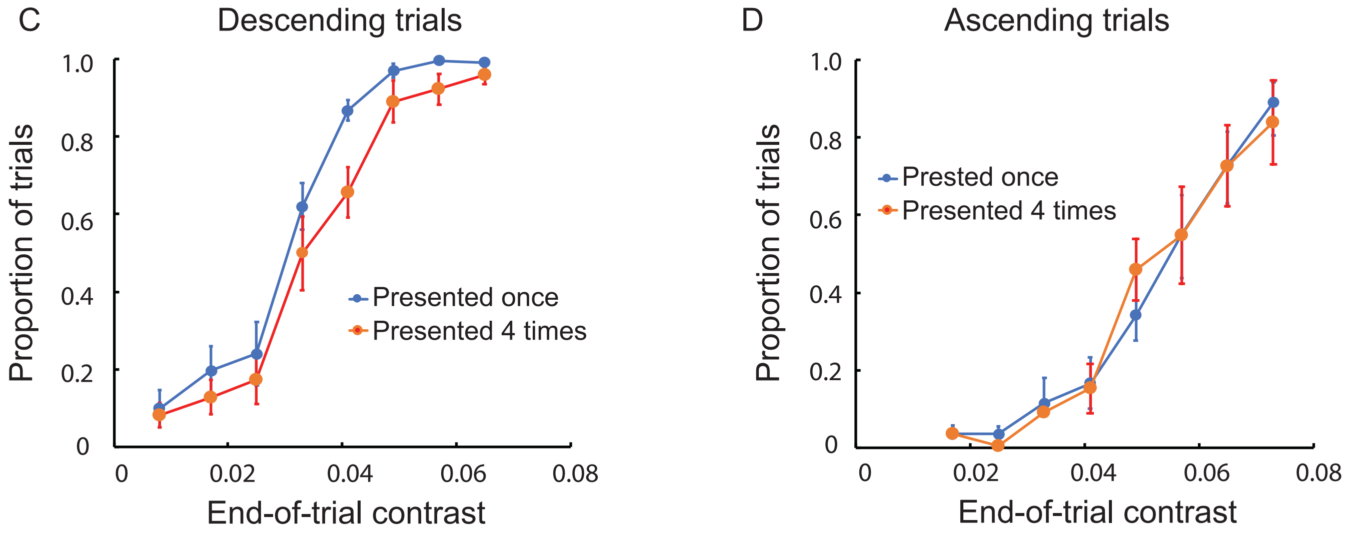


frame duration
360 ms

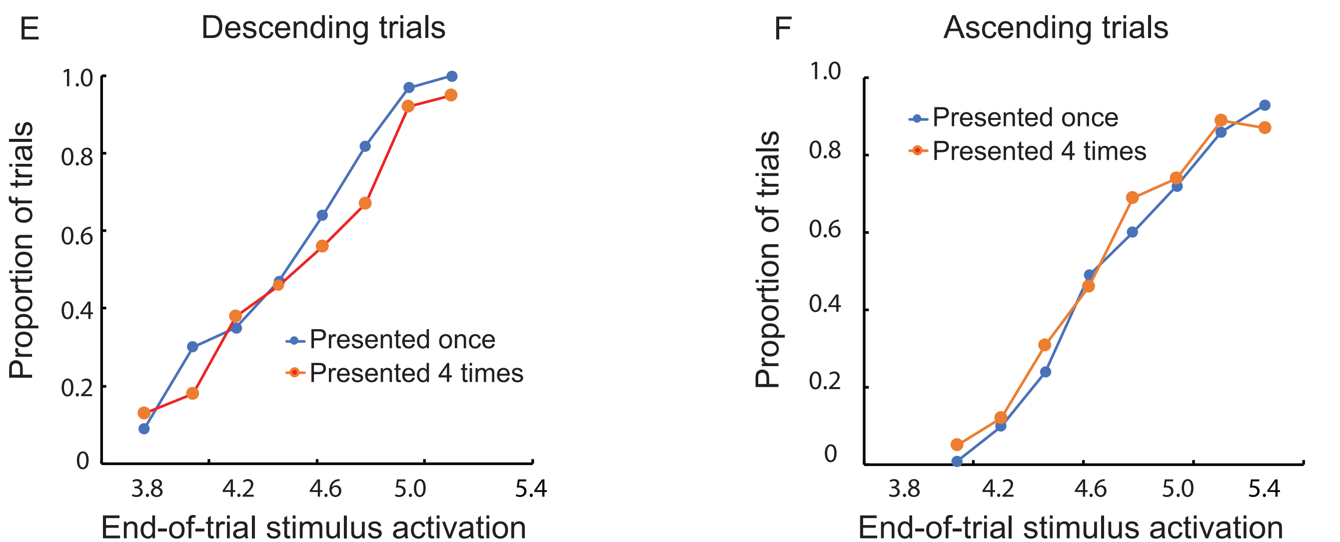


frame duration
104 ms

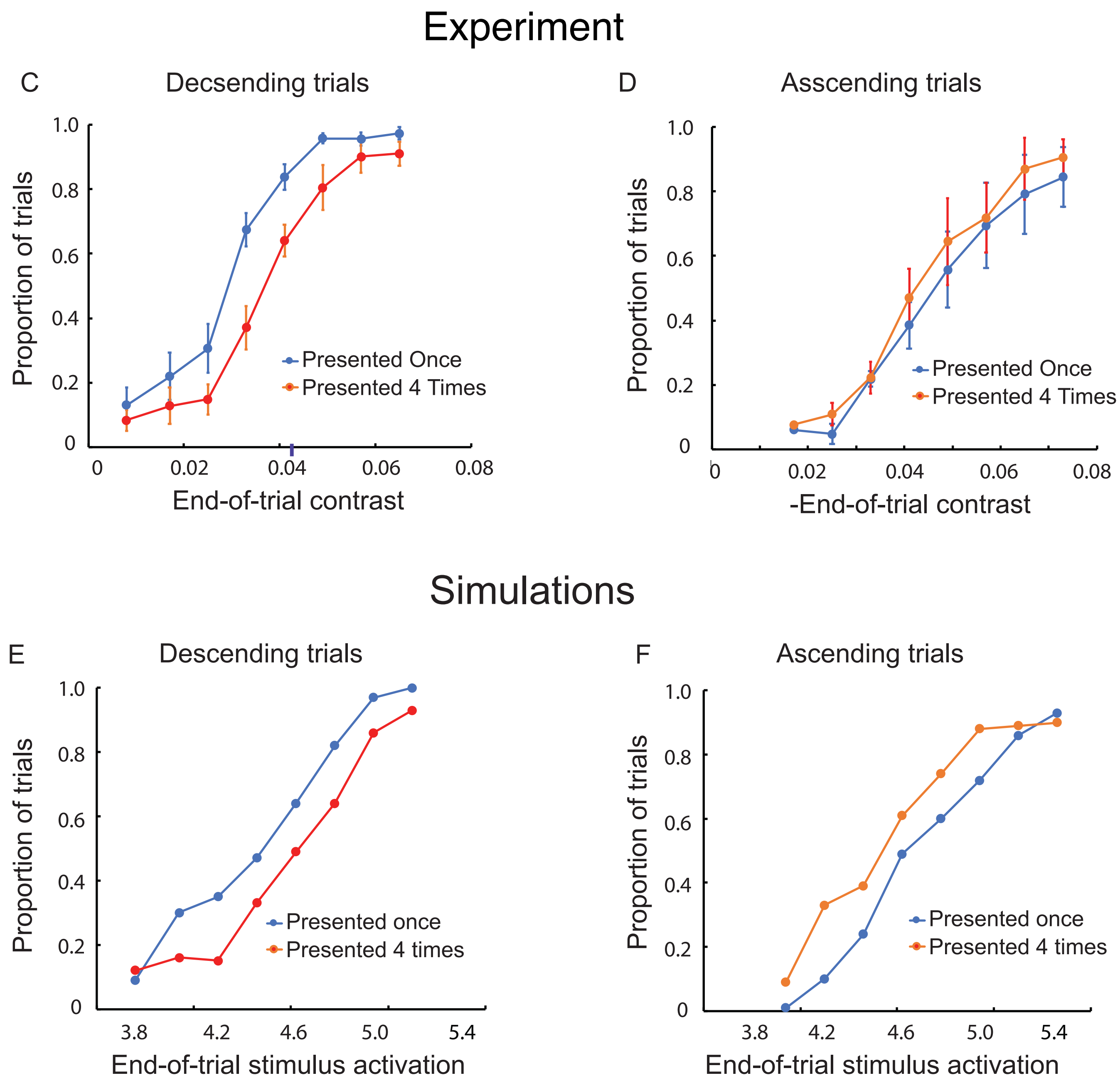
Experiment



Simulations

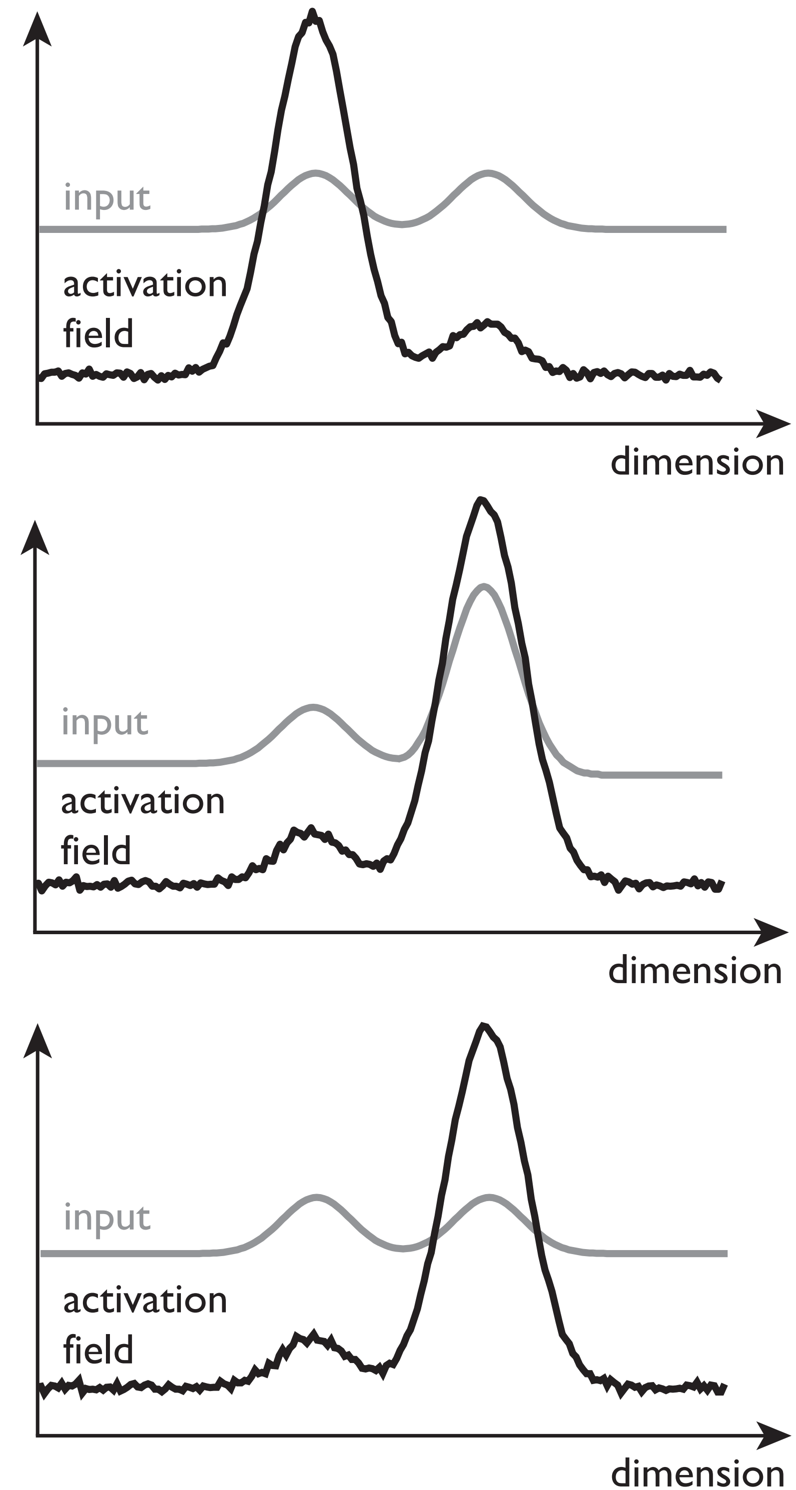


repeating final probe contrast level 4 times

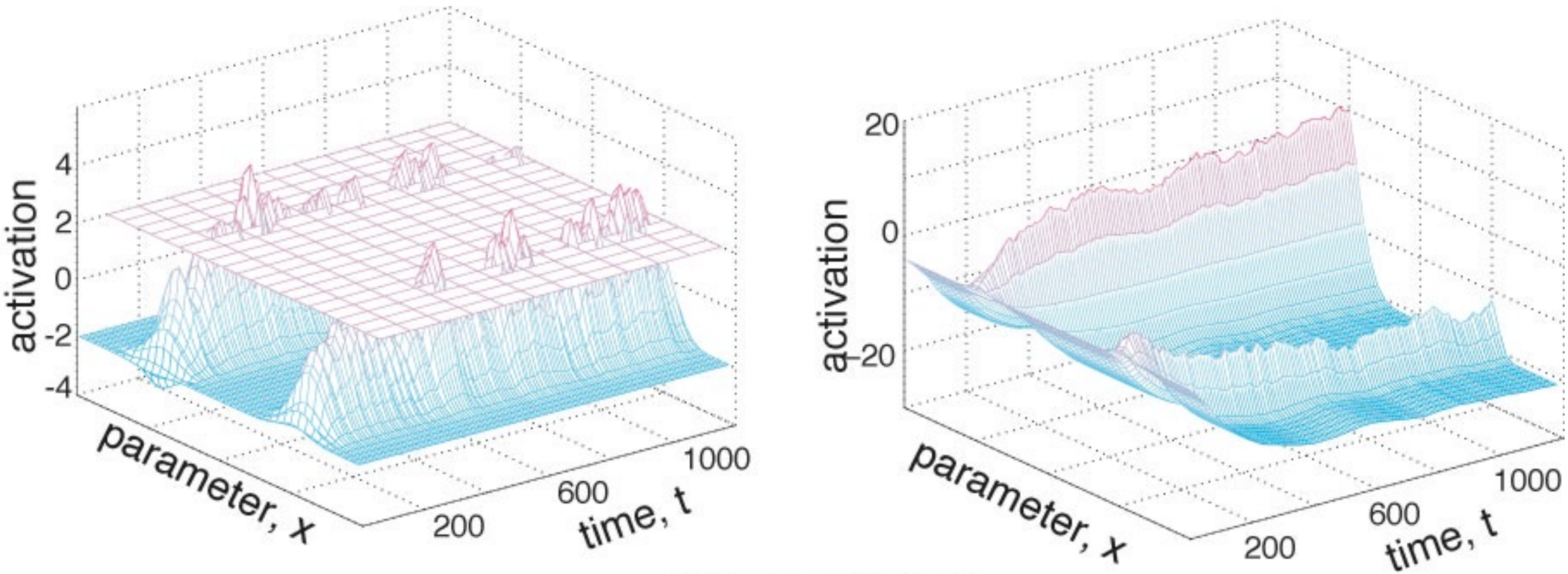


repeating initial probe contrast level 4 times

(2) Selection decisions



Selection decisions are stabilized by bistability



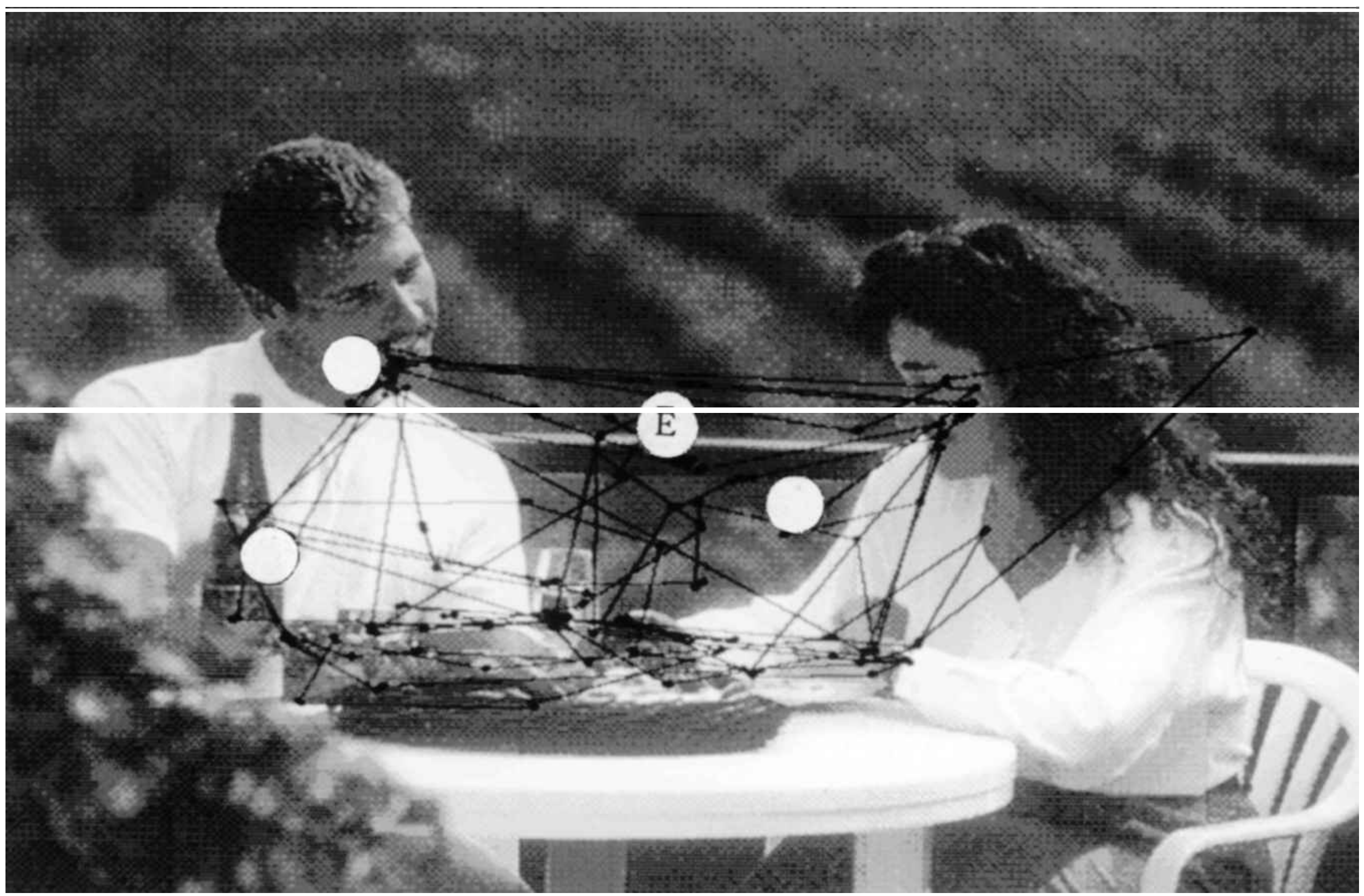
[Wilimzig, Schöner, 2006]

Behavioral signatures of selection decisions

- in most experimental situations, the correct selection decision is cued by an *imperative signal* leaving no actual freedom of choice to the participant (only the freedom of *error*)
- when performance approaches chance level, this approximates *free choice*
  - reasons are experimental (uncertainty, strategies…)

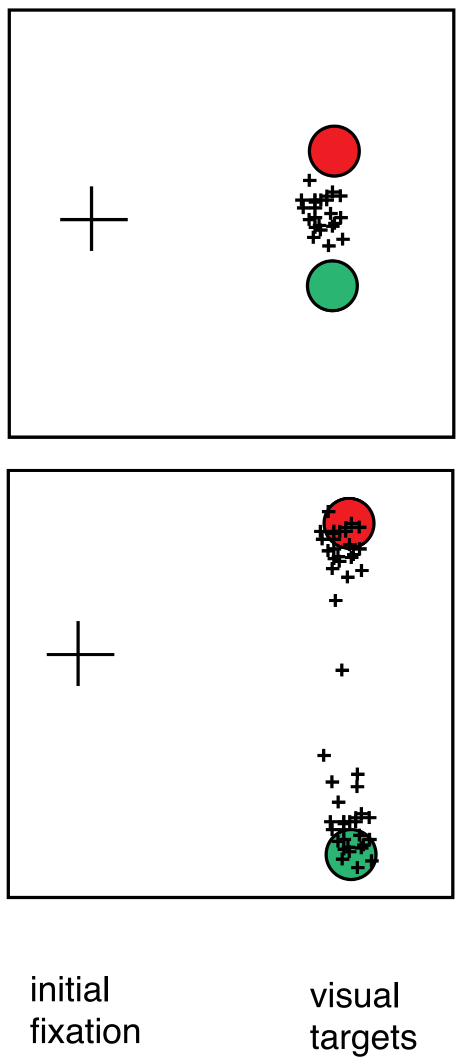
“free” choice without imperative signal

- selecting a new saccadic location

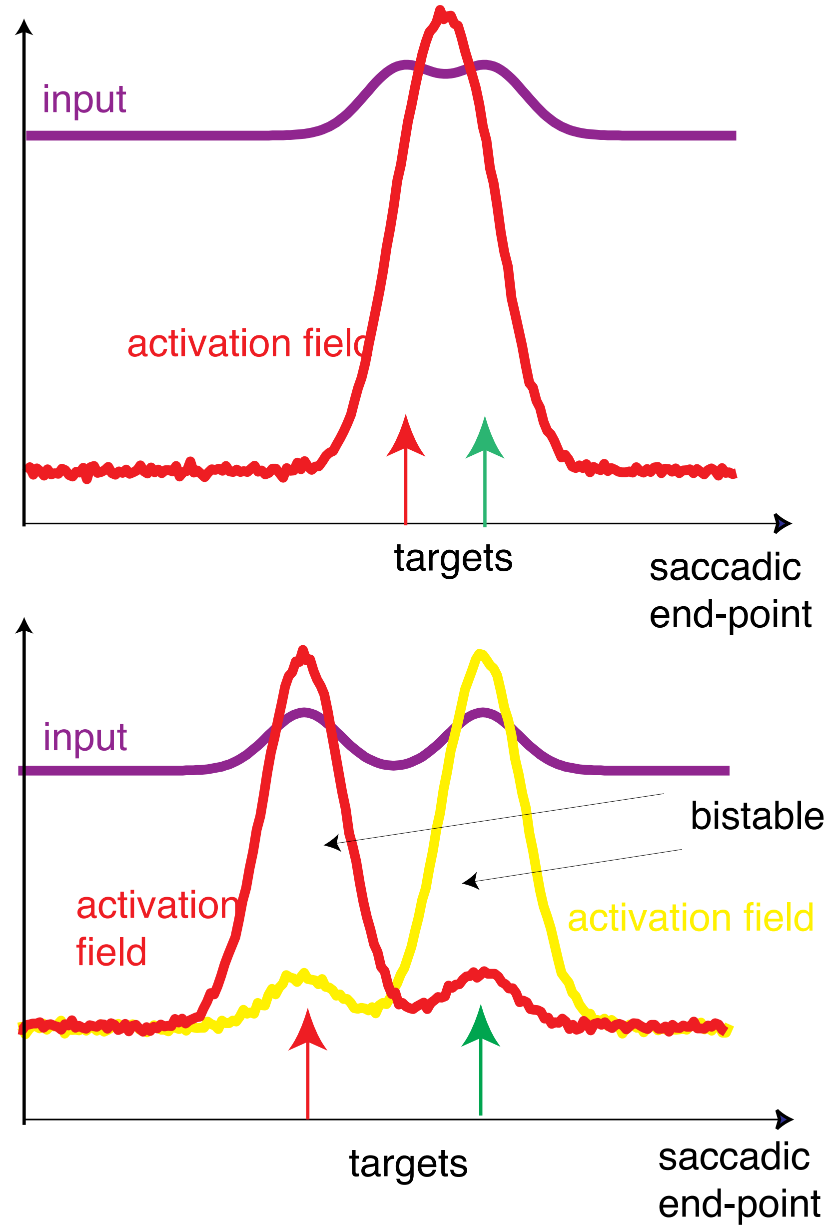


[O’Reagan et al., 2000]

saccadic selection



[after: Ottes et al., Vis. Res. 25:825 (85)]



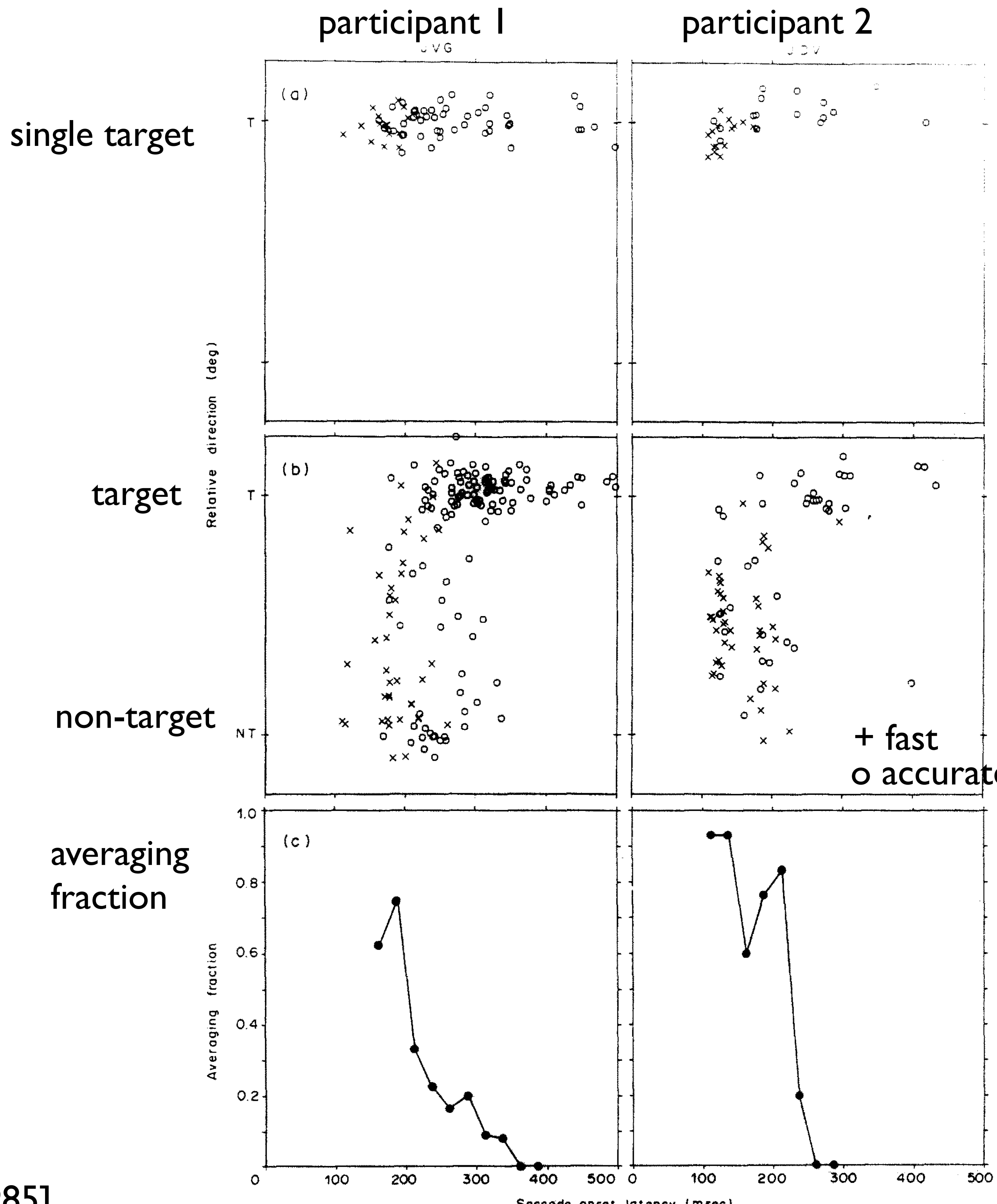
[after Kopecz, Schöner: Biol Cybern 73:49 (95)]

saccadic selection

- in reduced visual environment, selections become relatively reproducible…
- selection decisions depend on metrics of visual stimuli
  - averaging vs. selection

saccadic selection

- time course of saccadic selection:
- transition from averaging to selection



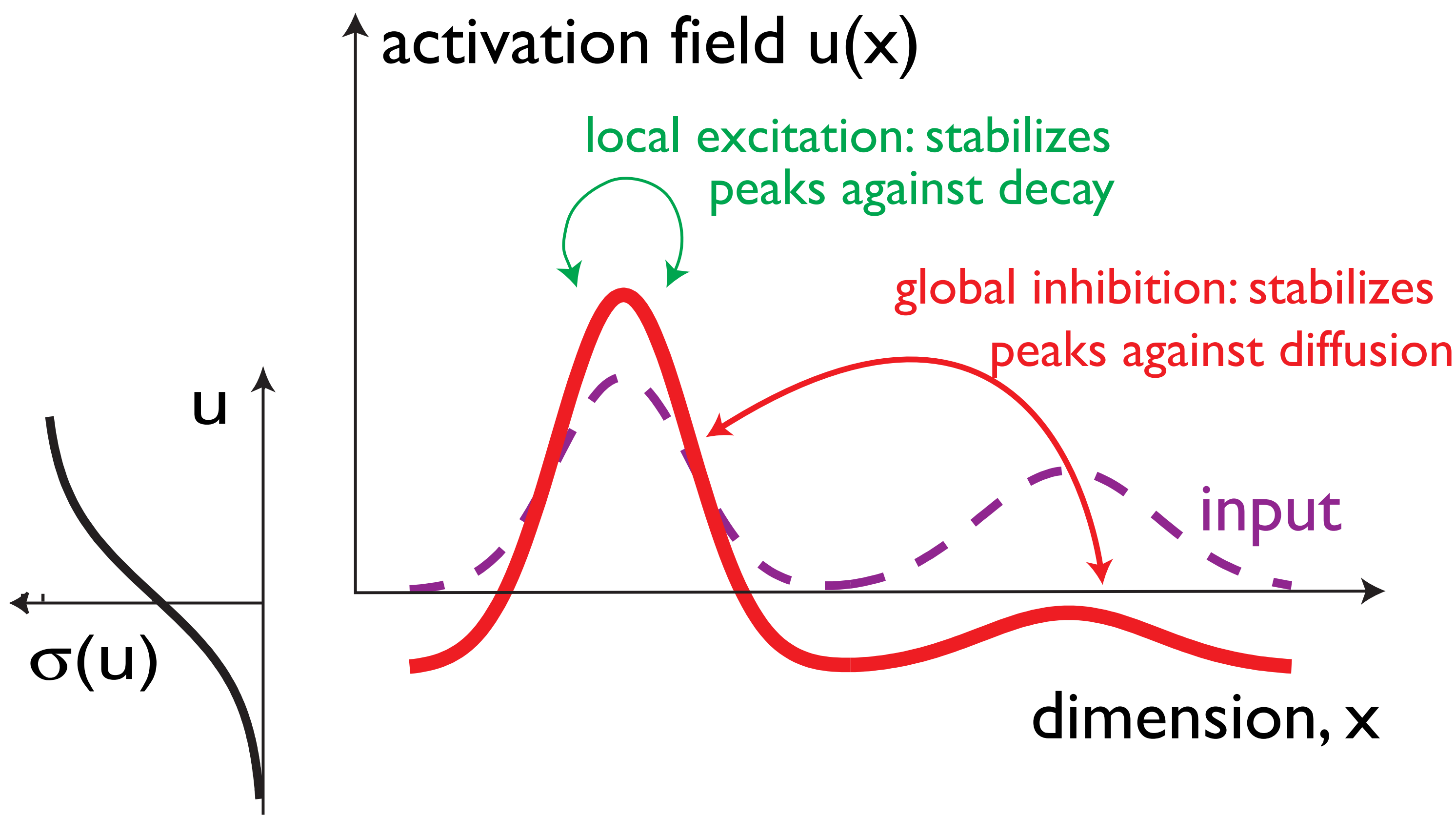
[Ottes, Van Gisbergen, Eggermont, 1985]

saccadic selection

- understanding the time course of selection requires a re-examination of the theory

… so far we assumed

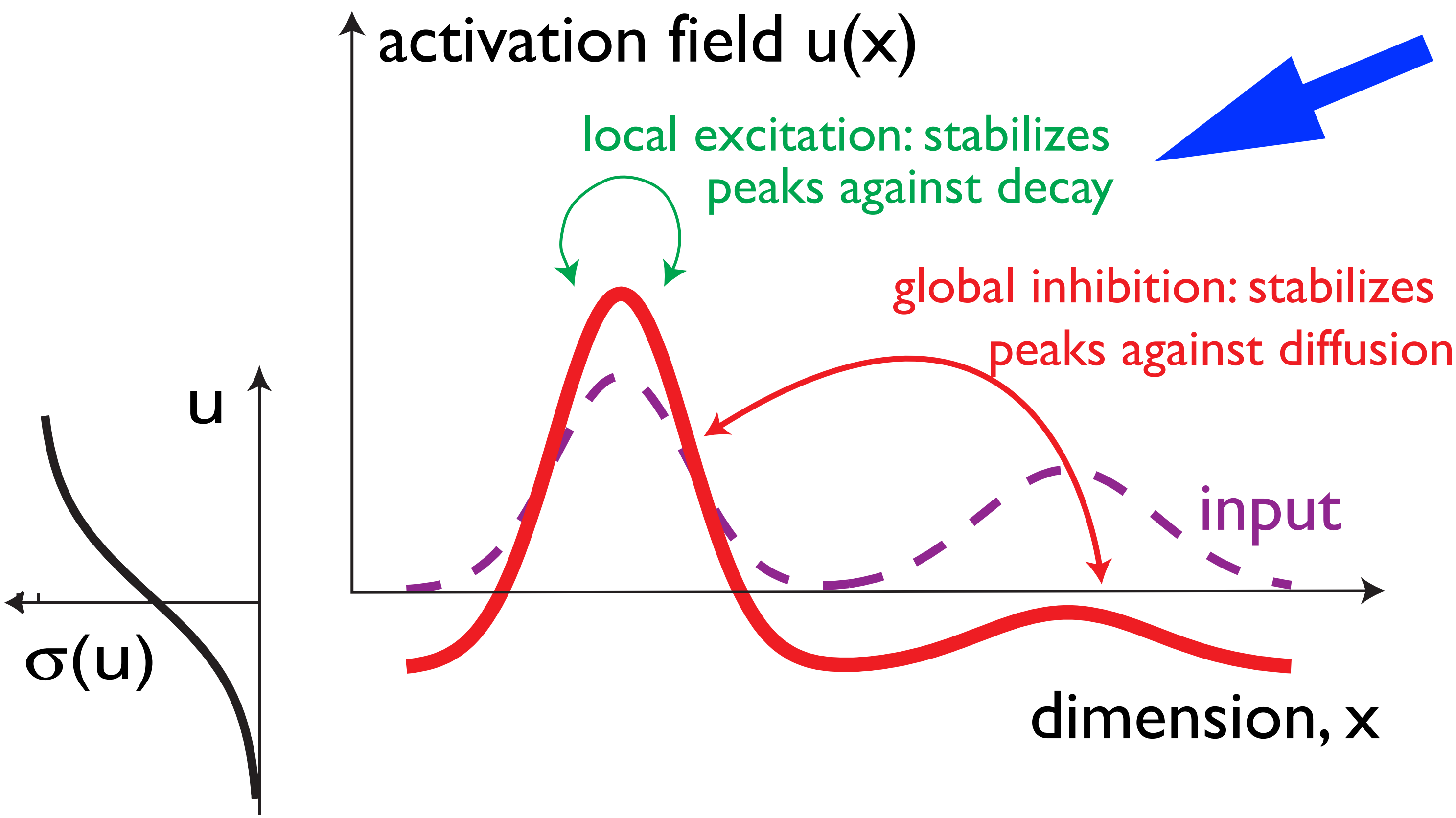
- that a single population of activation variable mediates both the excitatory and the inhibitory coupling required to make peaks attractors



But: Dale's law

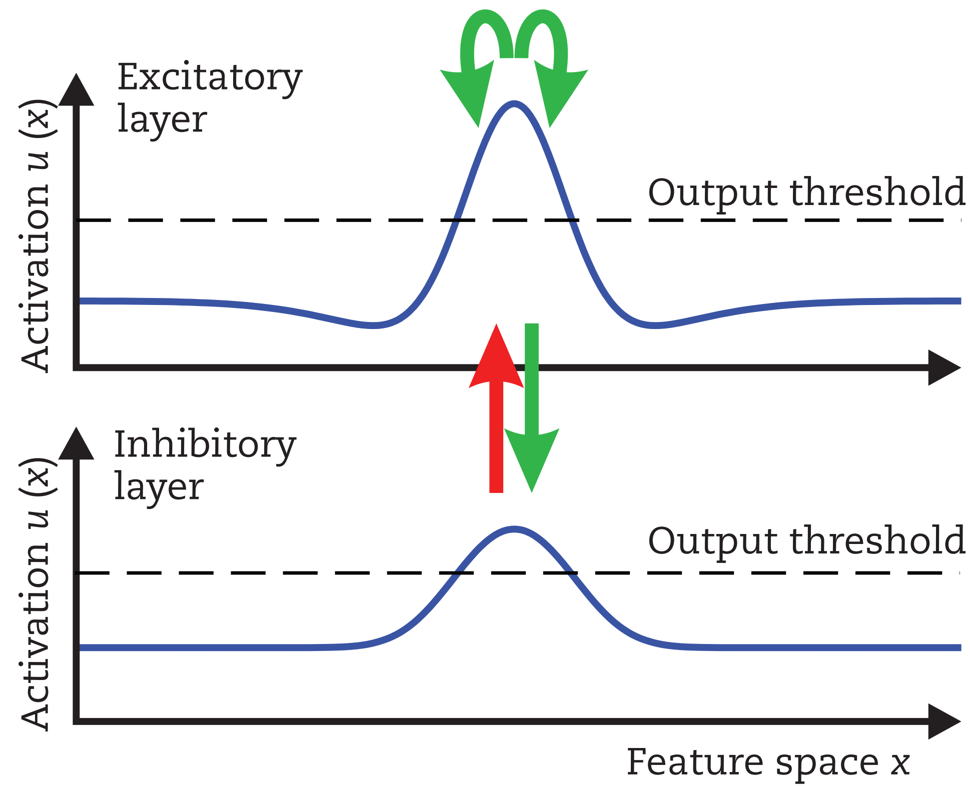
- says: every neuron forms with its axon only one type of synapse on the neurons it projects onto
- and that is either excitatory or inhibitory

this is not actually possible!



2 layer neural fields

- inhibitory coupling is mediated by inhibitory interneurons that
  - are excited by the excitatory layer
  - and in turn inhibit the inhibitory layer



[chapter 3 of the book]

2 layer Amari fields

$$\tau_u \dot{u}(x,t) = -u(x,t) + h_u + s(x,t) + \int k_{uu}(x-x')\, g(u(x',t))\, dx' - \int k_{uv}(x-x')\, g(v(x',t))\, dx'$$

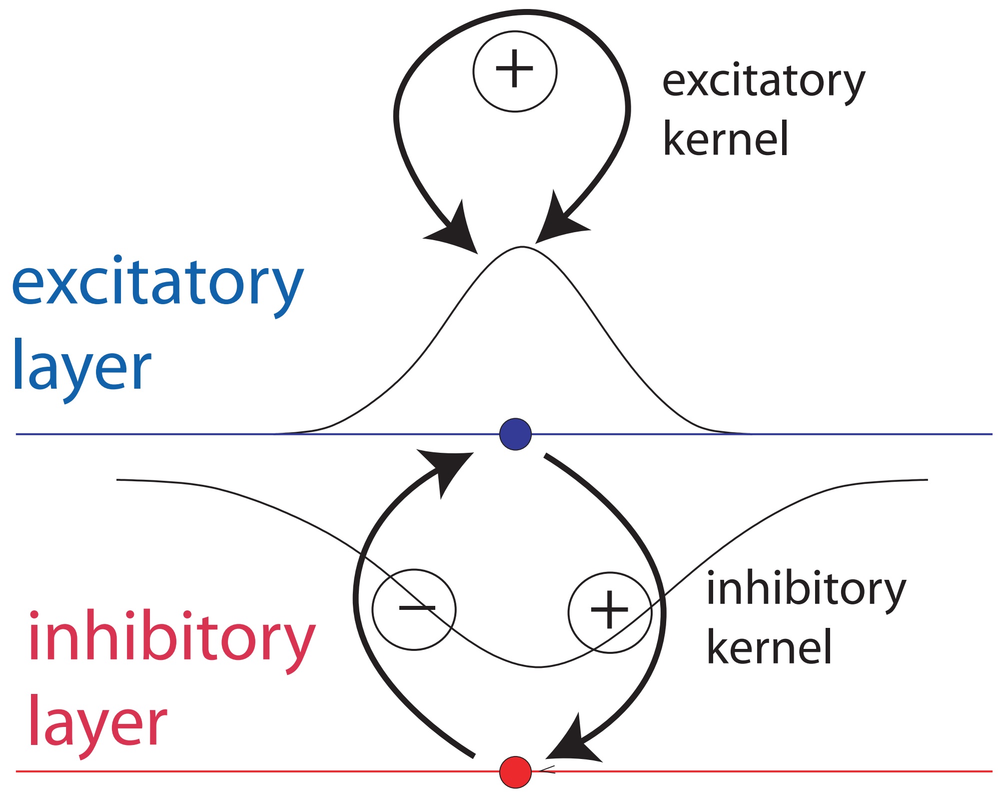
$$\tau_v \dot{v}(x,t) = -v(x,t) + h_v + \int k_{vu}(x-x')\, g(u(x',t))\, dx'$$

with projection kernels

$$k_{uu}(x-x') = c_{uu} \cdot \exp\left(-\frac{(x-x')^2}{2\sigma_{uu}^2} \right)$$

Implications

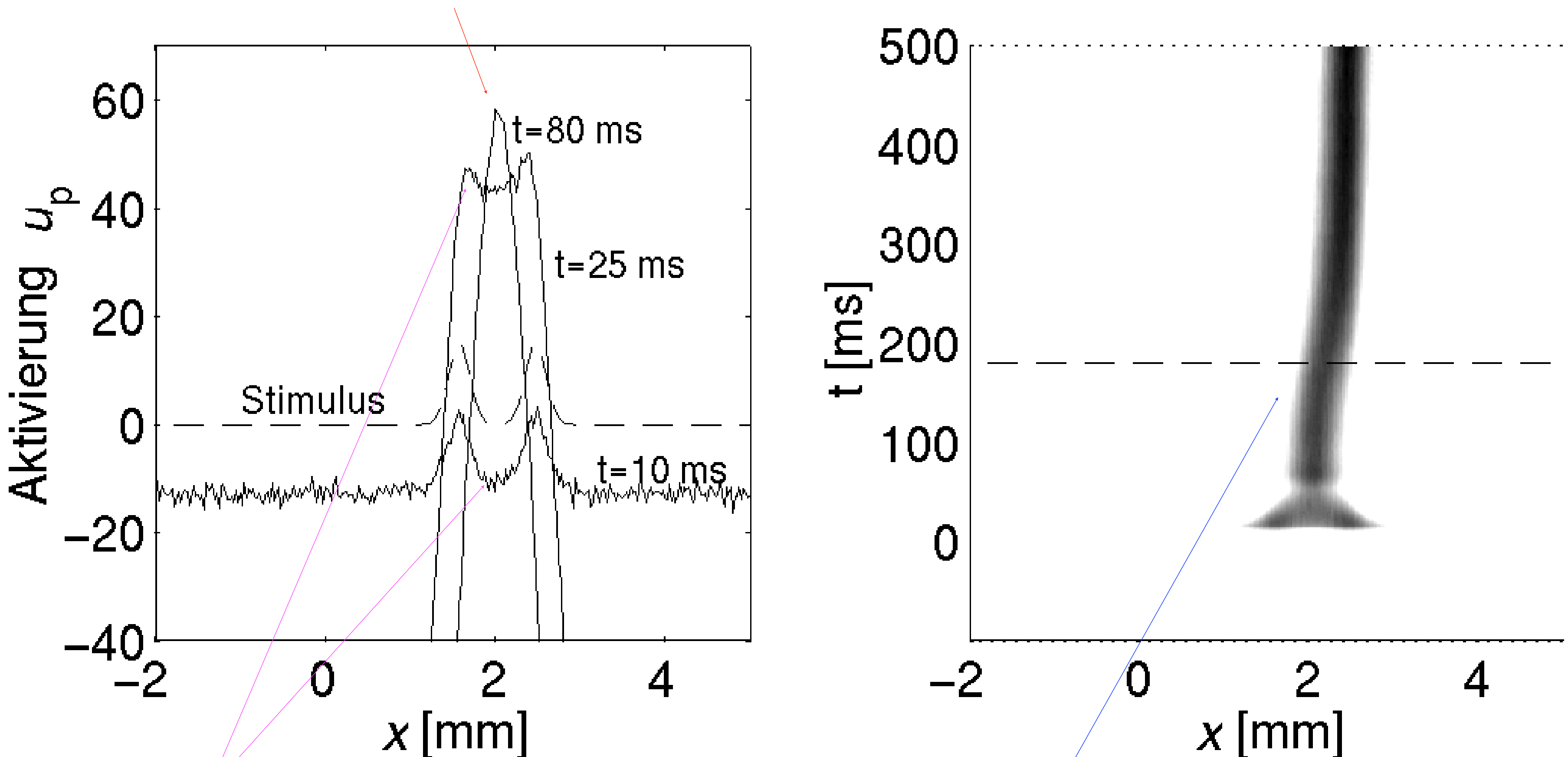
- the fact that inhibition arises only after excitation has been induced has observable consequences in the time course of decision making:
  - initially input-dominated
  - early excitatory interaction
  - late inhibitory interaction



[figure: Wilimzig, Schneider, Schöner, Neural Networks, 2006]

time course of selection

intermediate: dominated by excitatory interaction

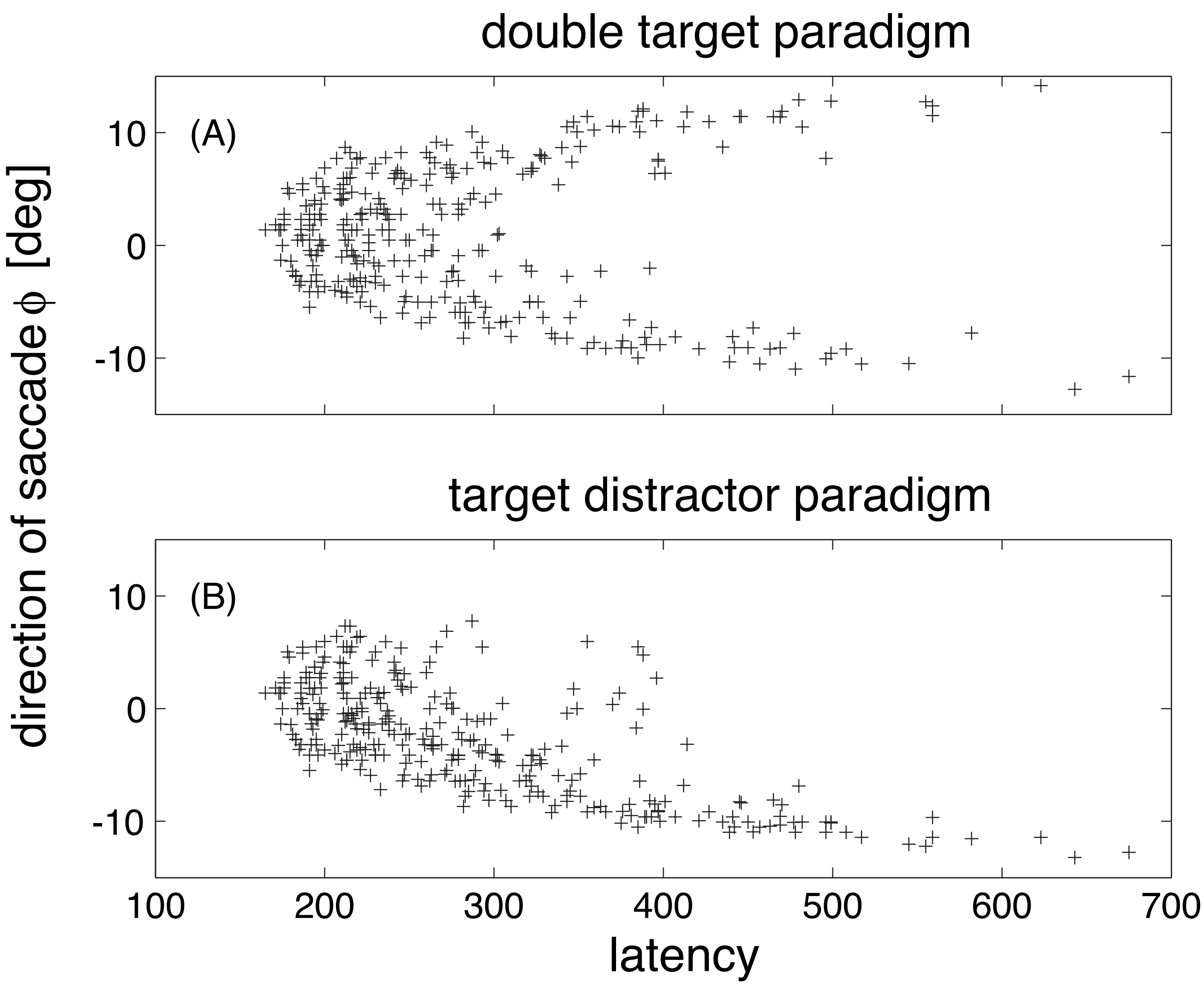


early: input driven

late: inhibitory interaction drives selection

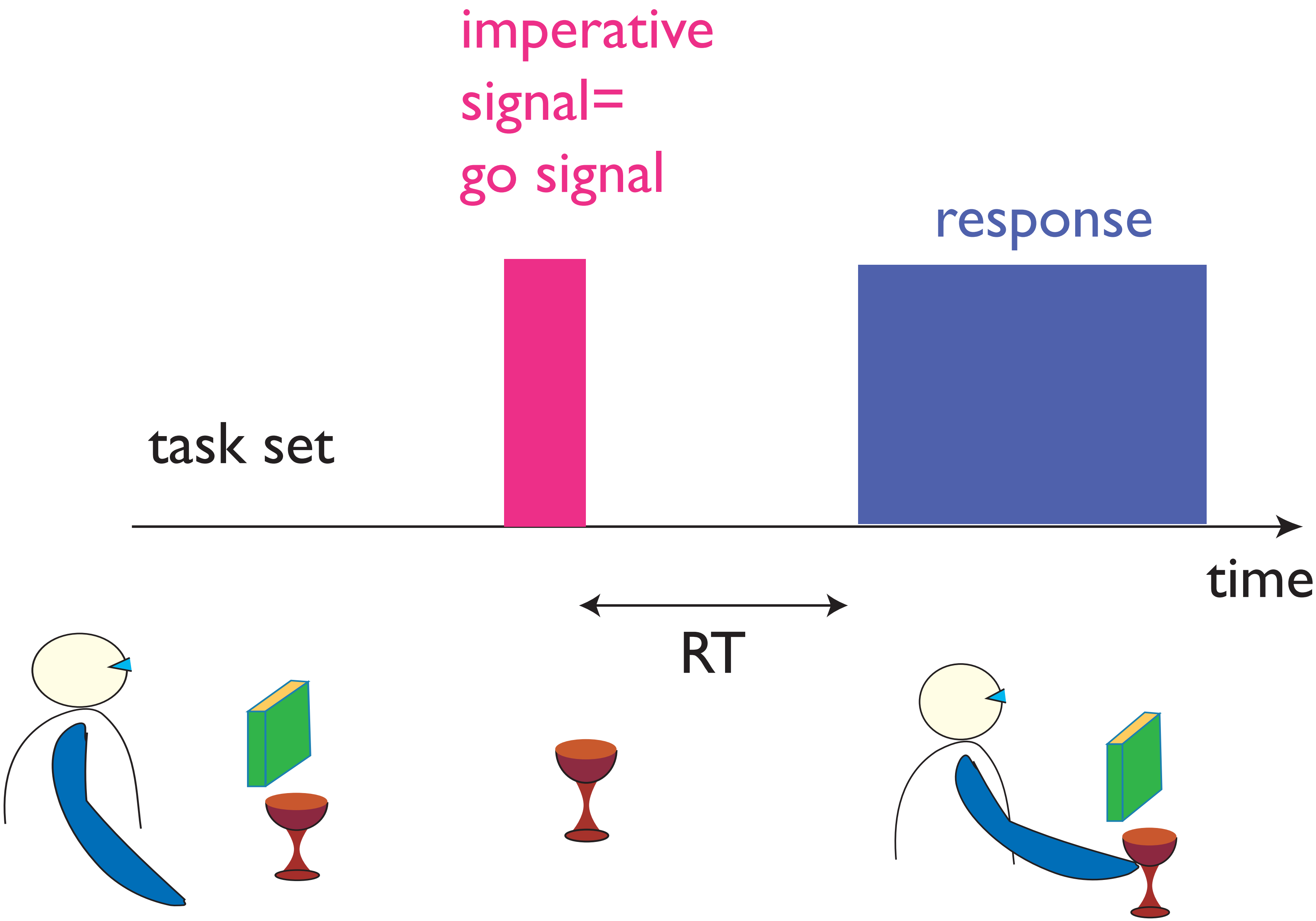
[figure: Wilimzig, Schneider, Schöner, Neural Networks, 2006]

=> early fusion, late selection



[figure: Wilimzig, Schneider, Schöner, Neural Networks, 2006]

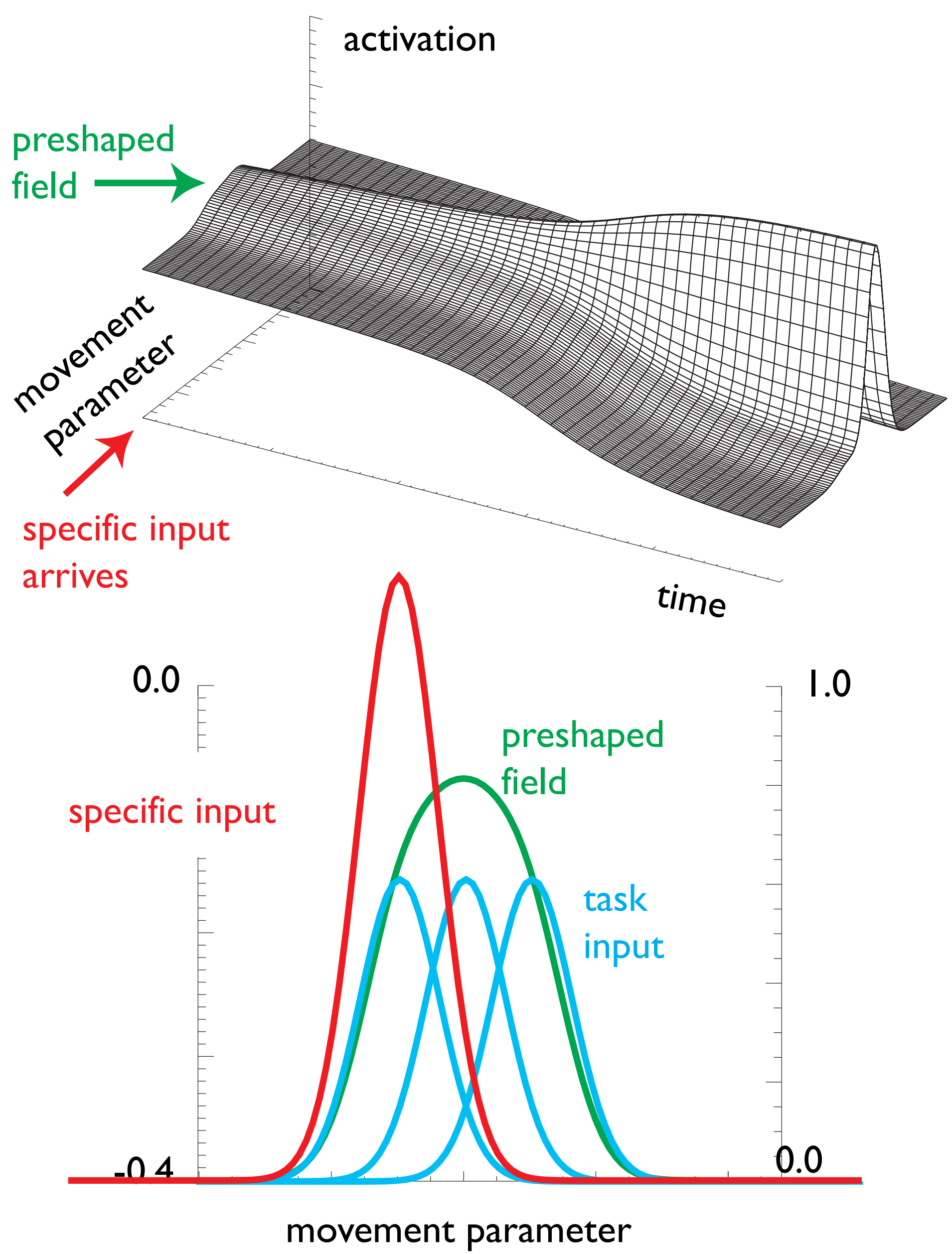
Selection decisions in the reaction time (RT) paradigm



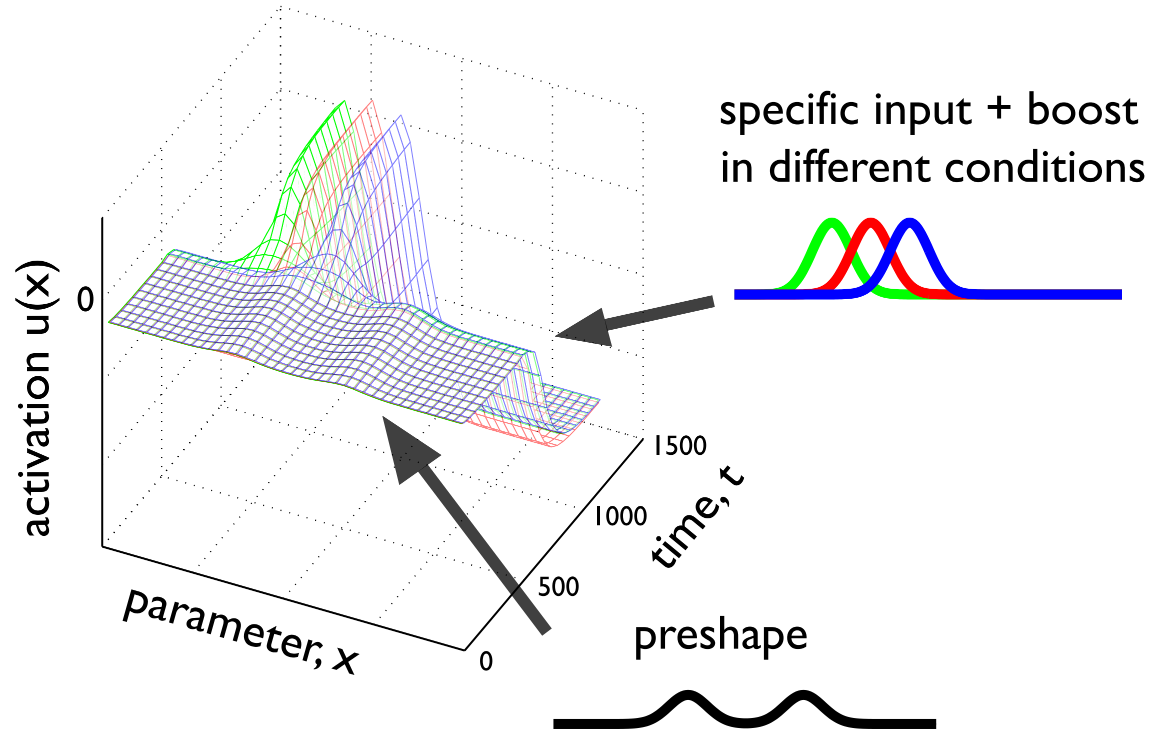
The task set

- is the critical factor in such studies of selection: which perceptual/action alternative/choices are available…
  - e.g., how many choices
  - e.g., how likely is each choice
  - e.g., how "easy" are the choices to recognize/perform
- because the task set is known to the participant prior to the presentation of the imperative signal, one may think of the task set as a "preshaping" of the underlying representation (pre=before the decision)

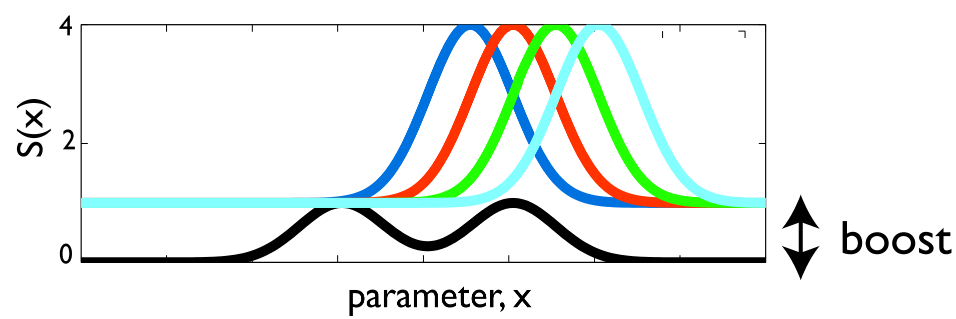
notion of preshape

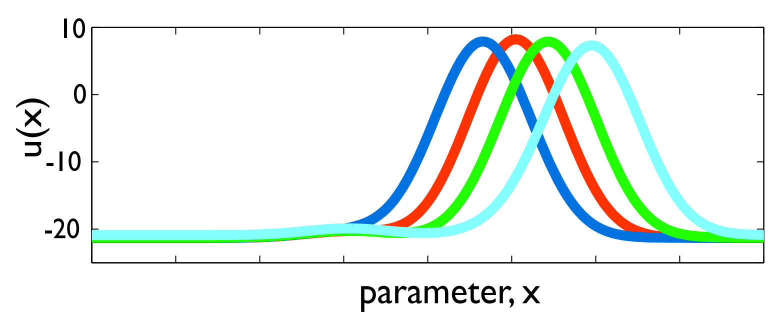


weak preshape in selection



- specific (imperative) input dominates and drives detection instability

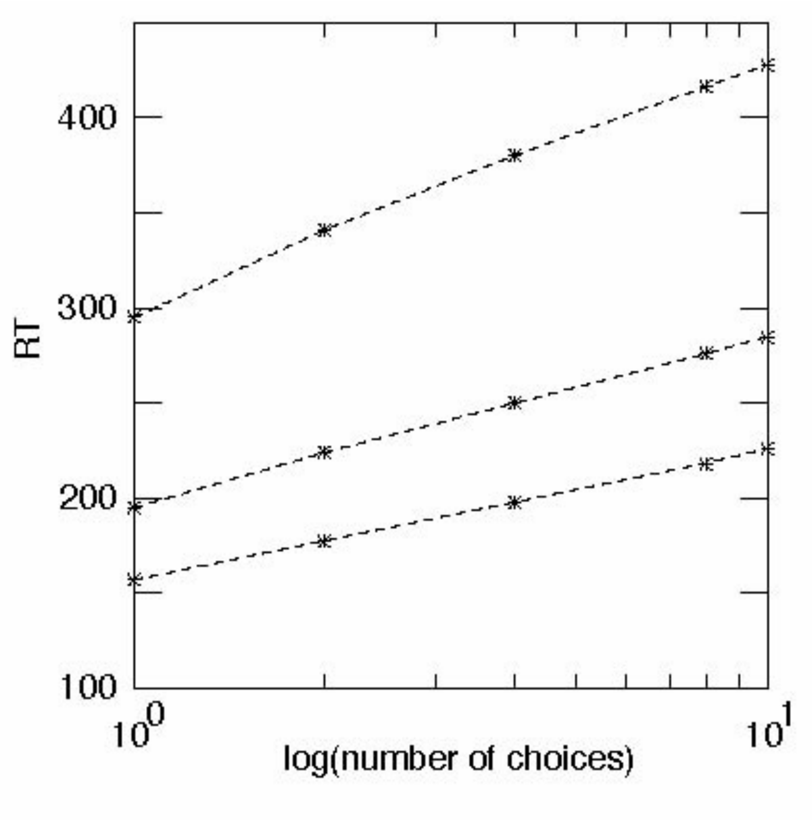


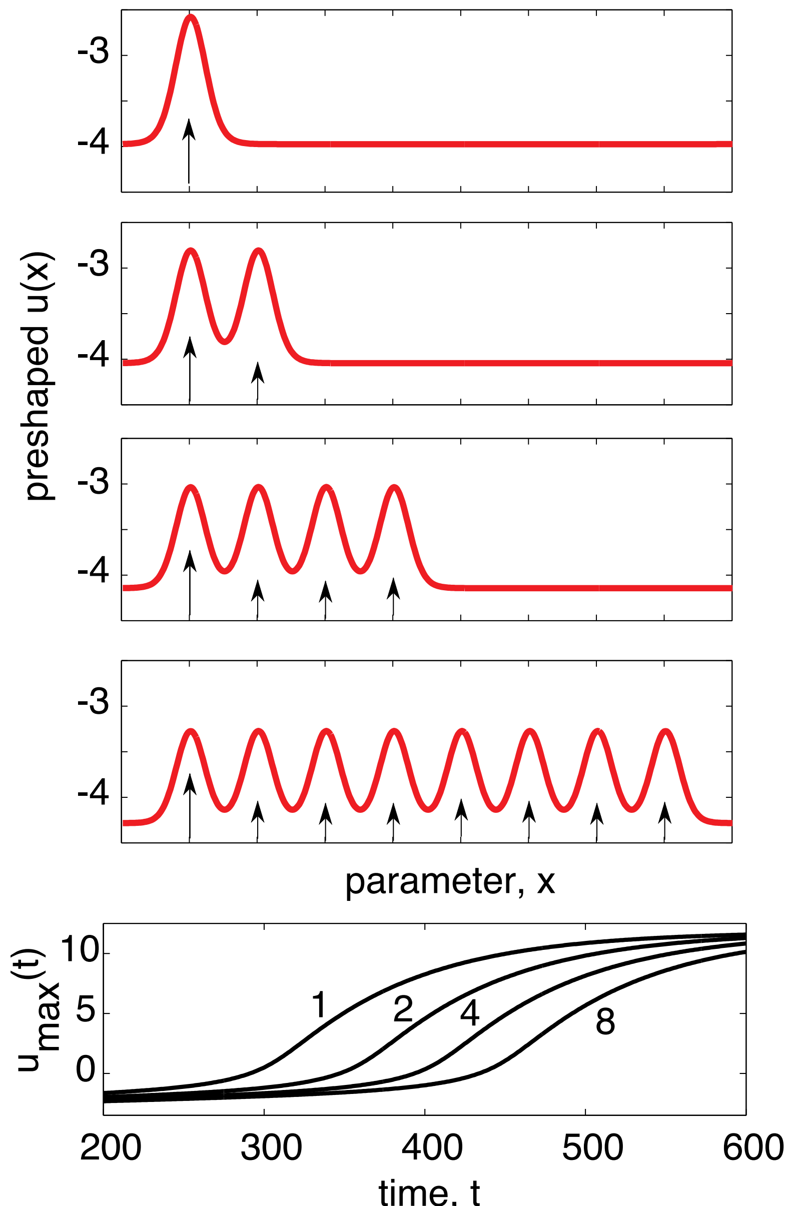


[Wilimzig, Schöner, 2006]

using preshape to account for classical RT data

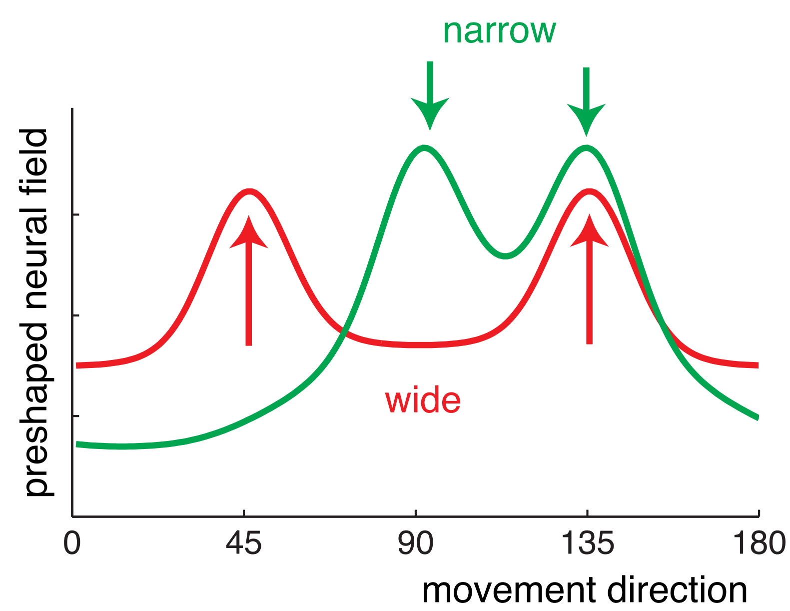
- Hick's law: RT increases with the number of choices



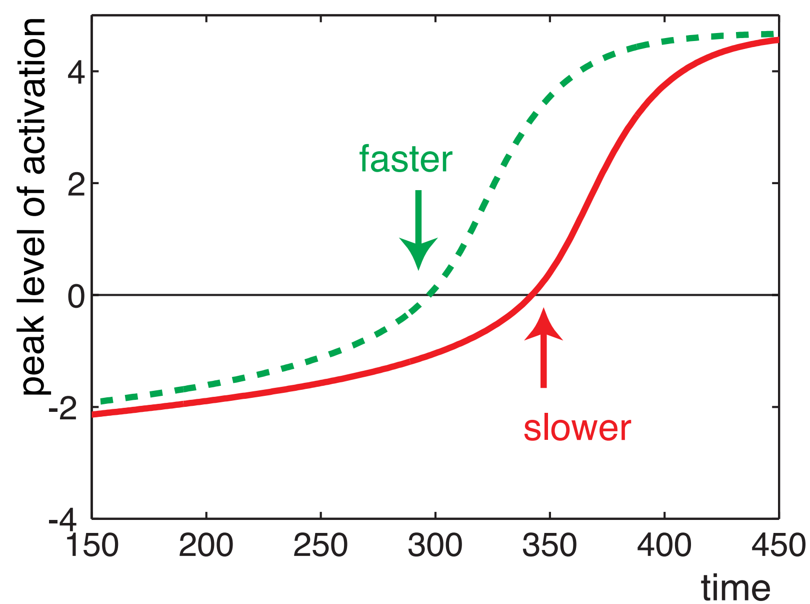


[Erlhagen, Schöner, Psych Rev 2002]

metric effect

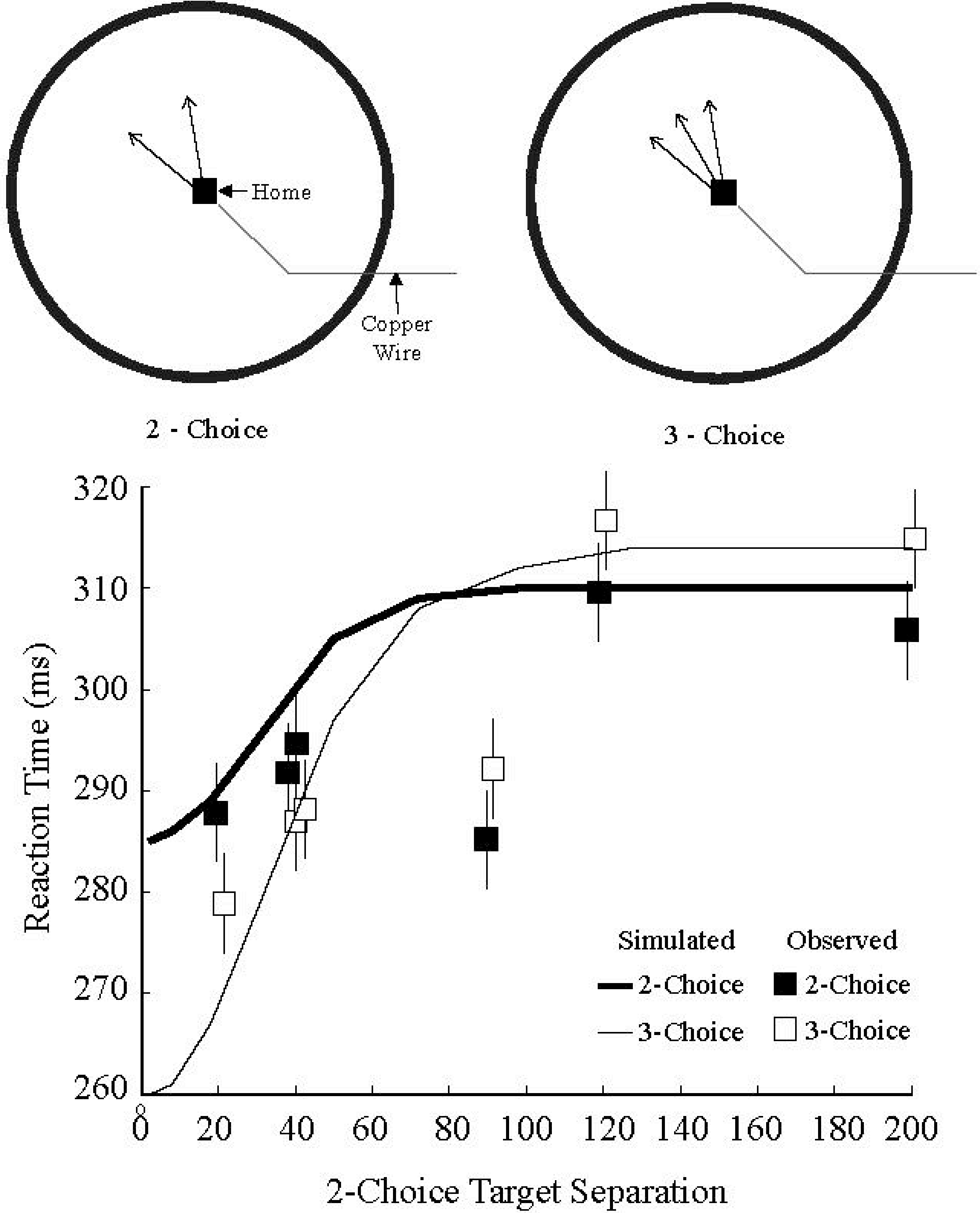


- predict faster response times for metrically close than for metrically far choices

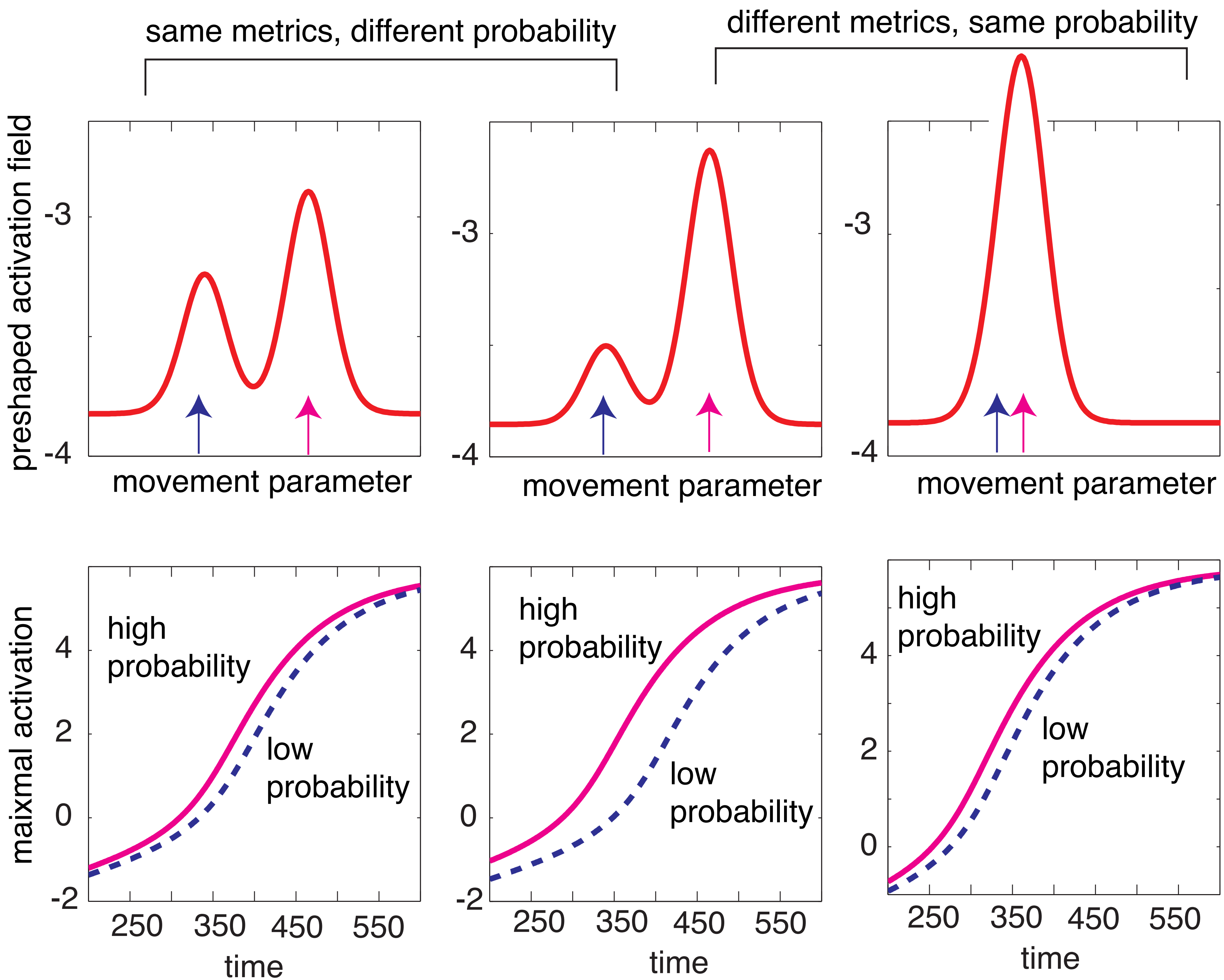


[from Schöner, Kopecz, Erlhagen, 1997]

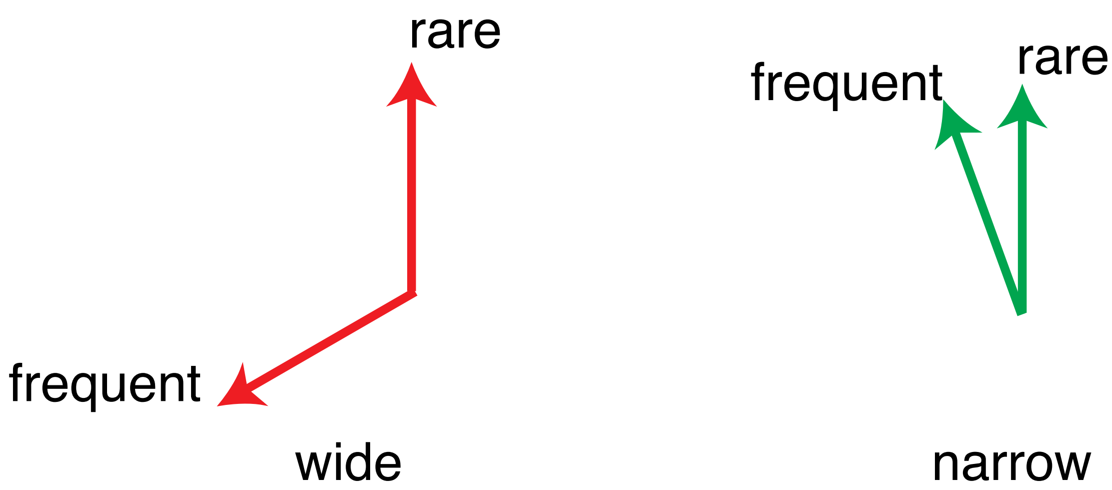
experiment: metric effect

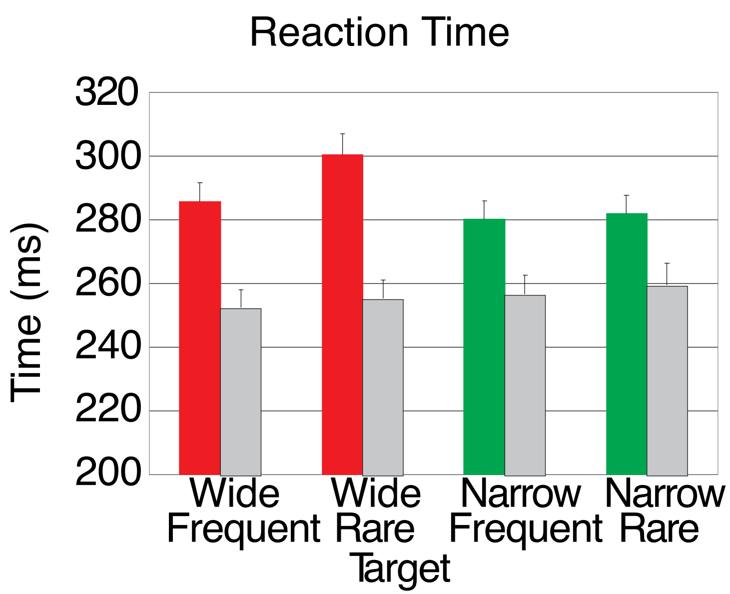


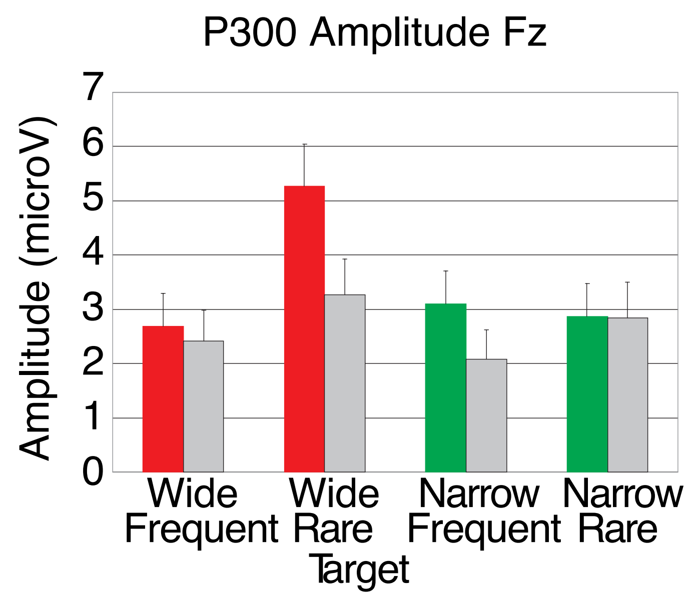
[McDowell, Jeka, Schöner]



[from Erlhagen, Schöner: Psych. Rev. 2002]



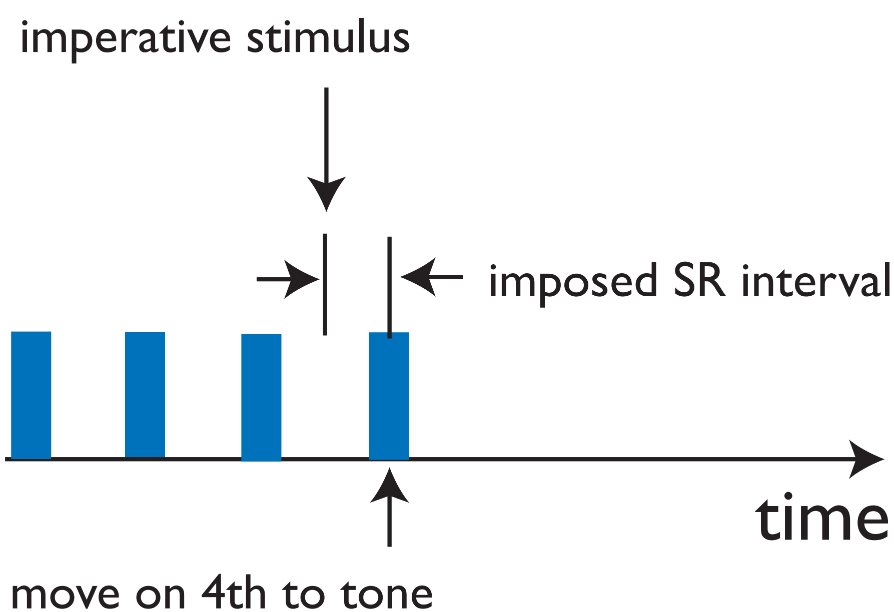




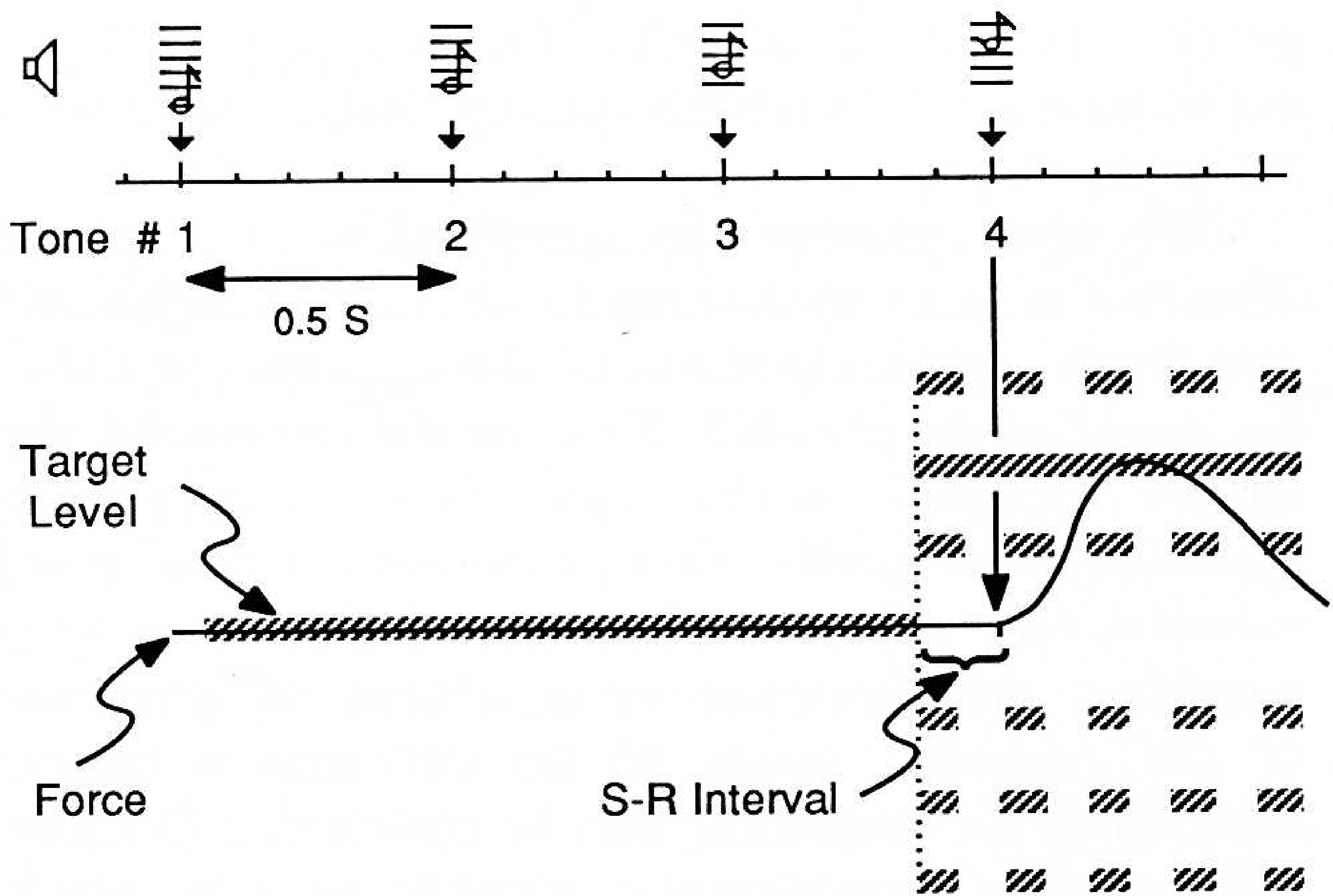
[from McDowell, Jeka, Schöner, Hatfield, 2002]

Time course of selection decisions: Behavioral evidence for the graded and continuous evolution of decision

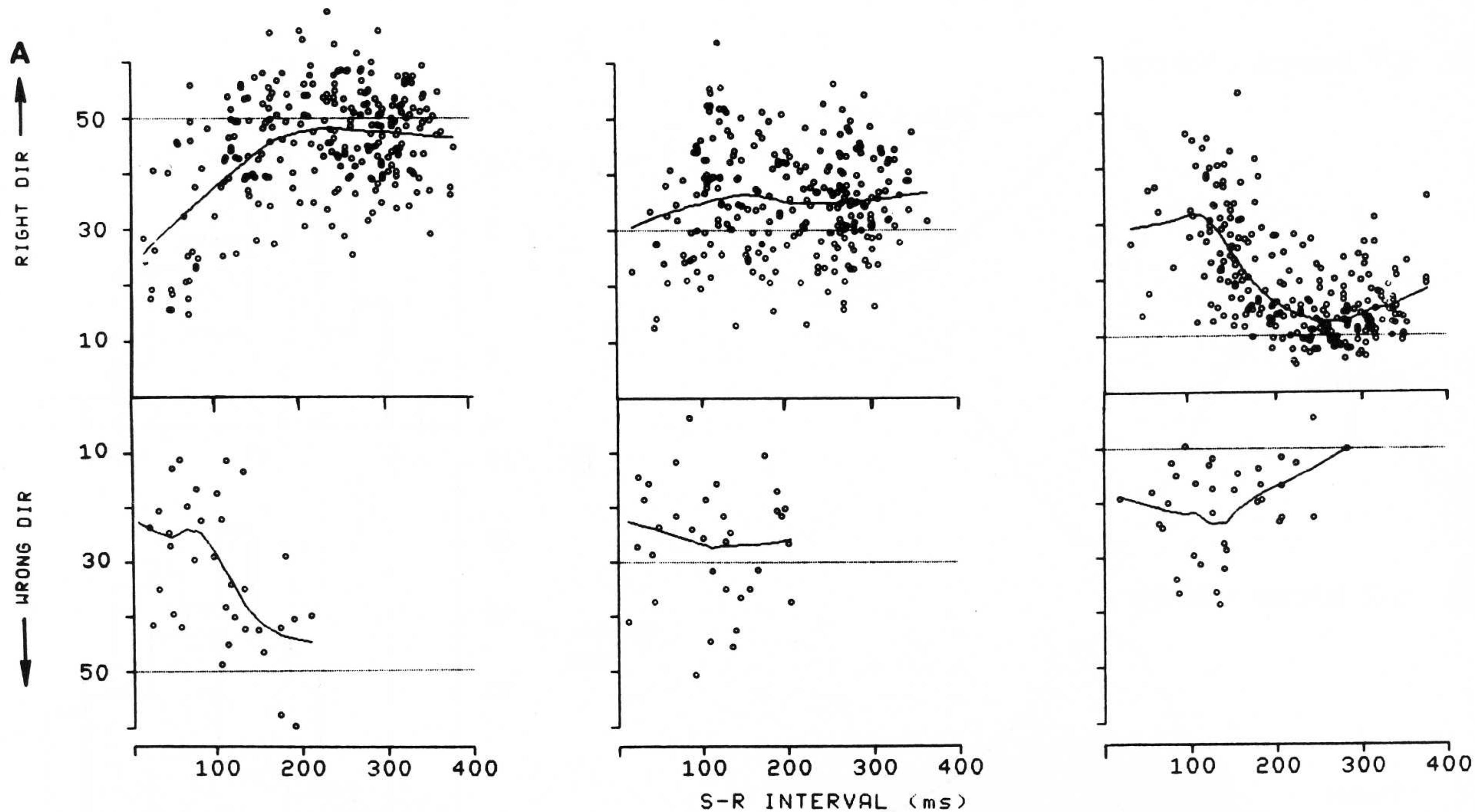
timed movement
initiation paradigm



[Ghez and colleagues, 1988 to 1990's]

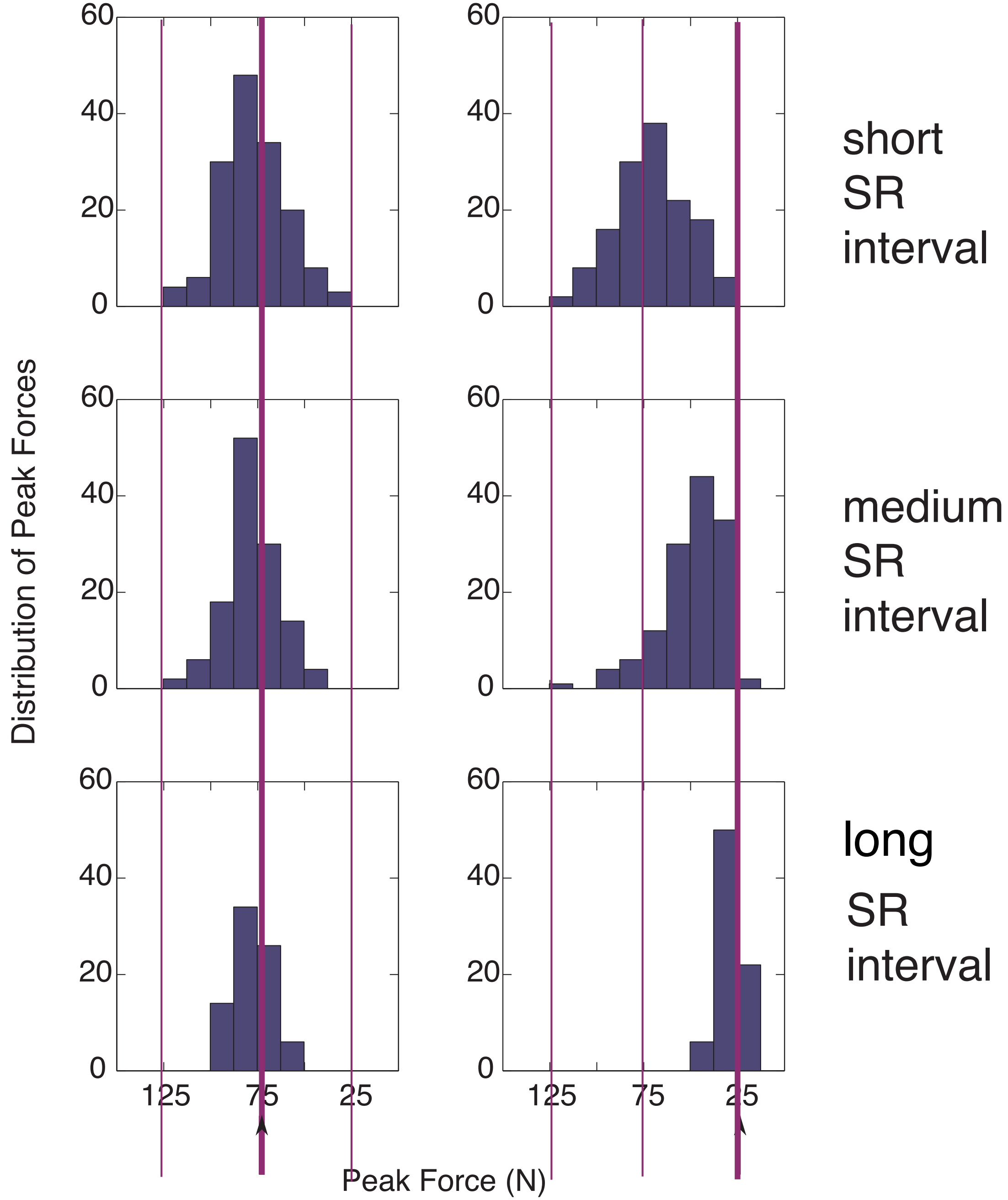


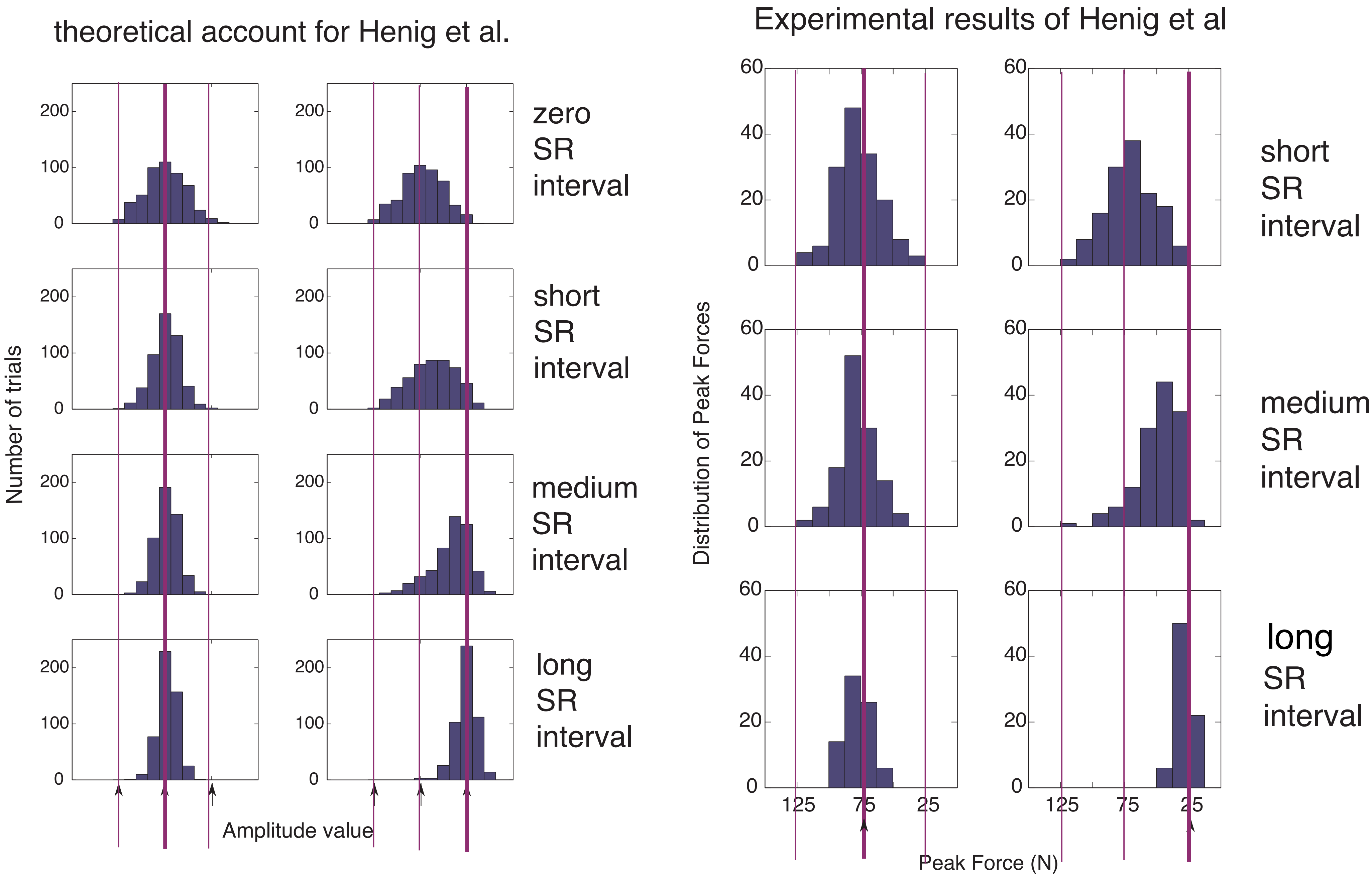
[Favilla et al. 1989]



[Favilla et al. 1989]

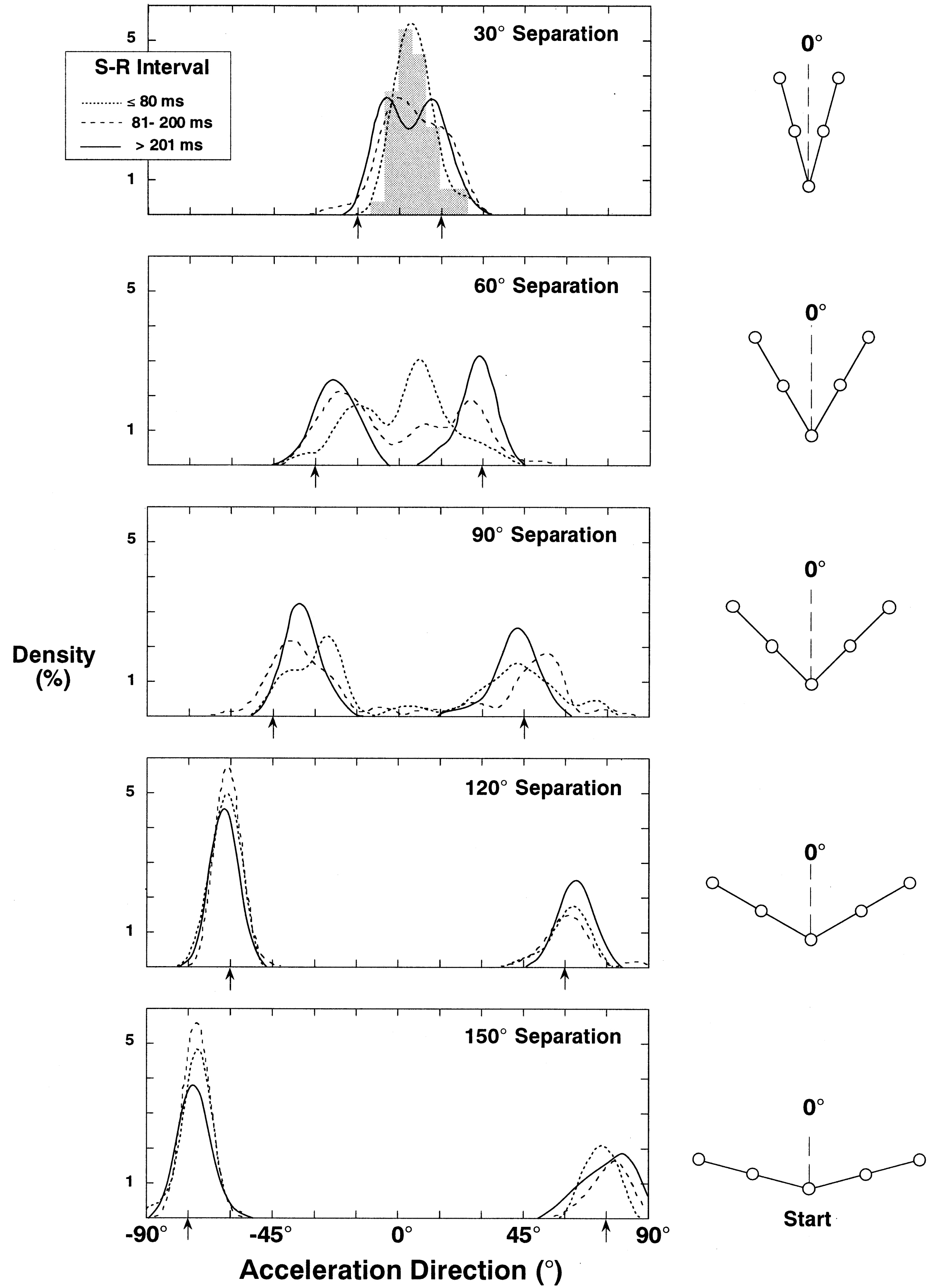
Experimental results of Henig et al



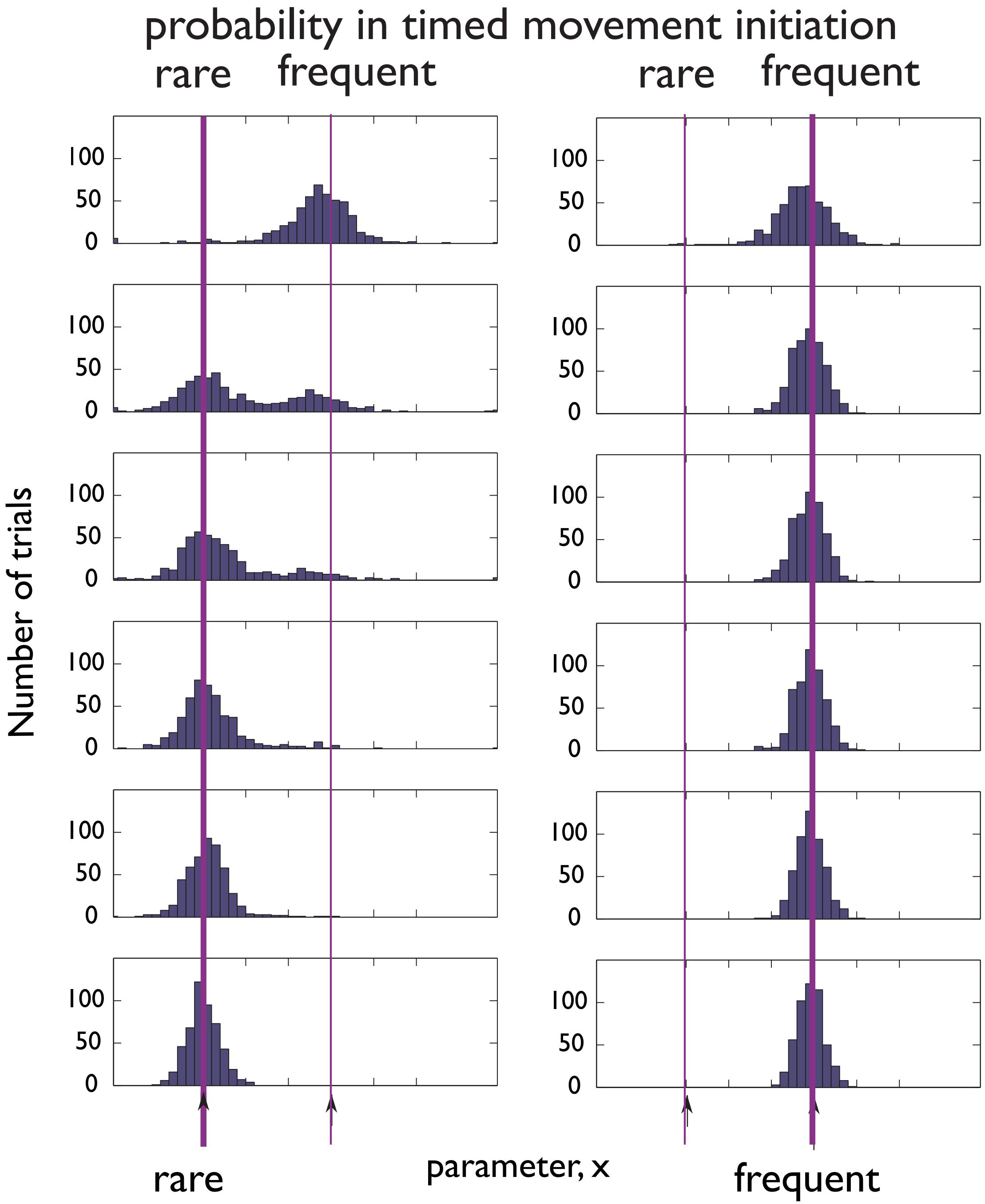


[Erlhagen, Schöner. 2002, Psychological Review 109, 545–572 (2002)]

- infer width of preshape peaks in field



[Ghez et al 1997]



short SR interval:
observe preshape

long SR interval:
observe stimulus-defined
movement plan

Ghez et al, 1997

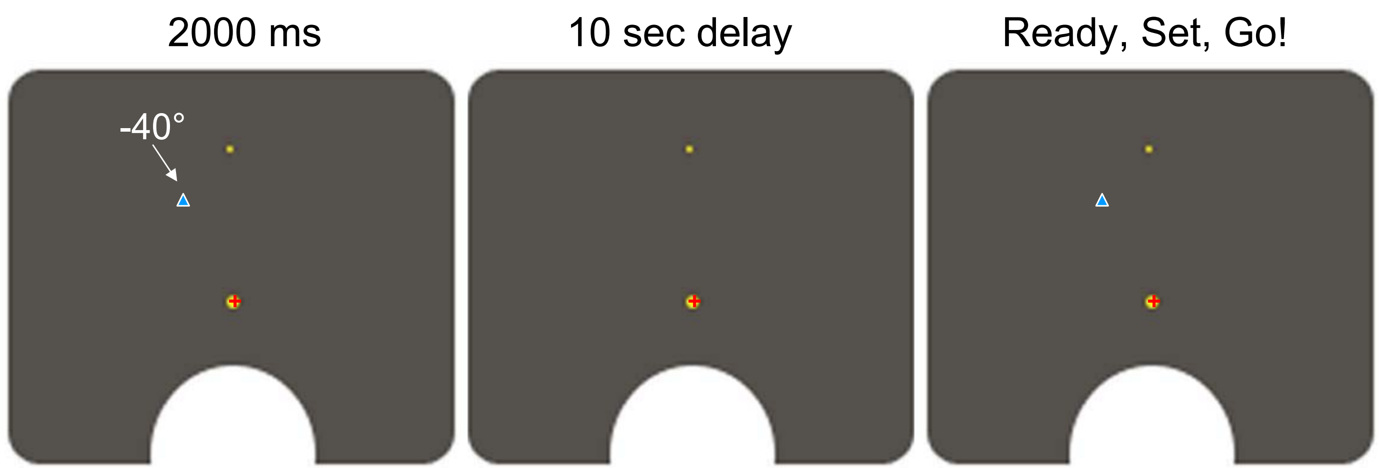
(3) Working memory as sustained activation

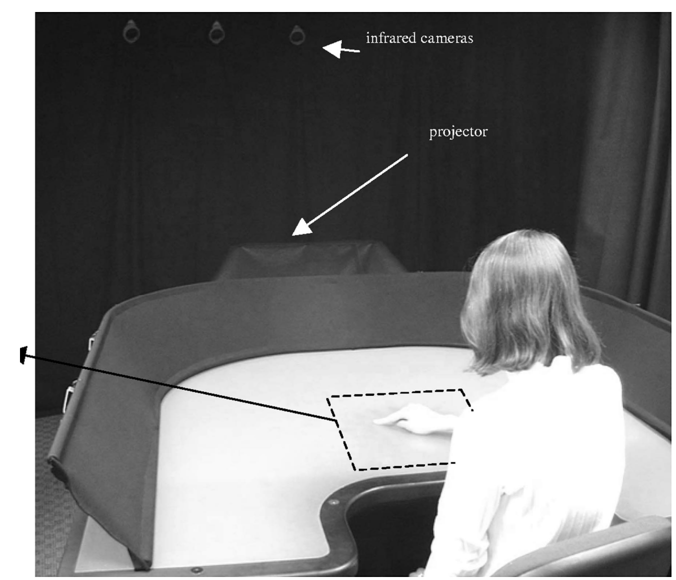
- activation peak induced by input
- remains stable after input is removed

Working memory as sustained peaks

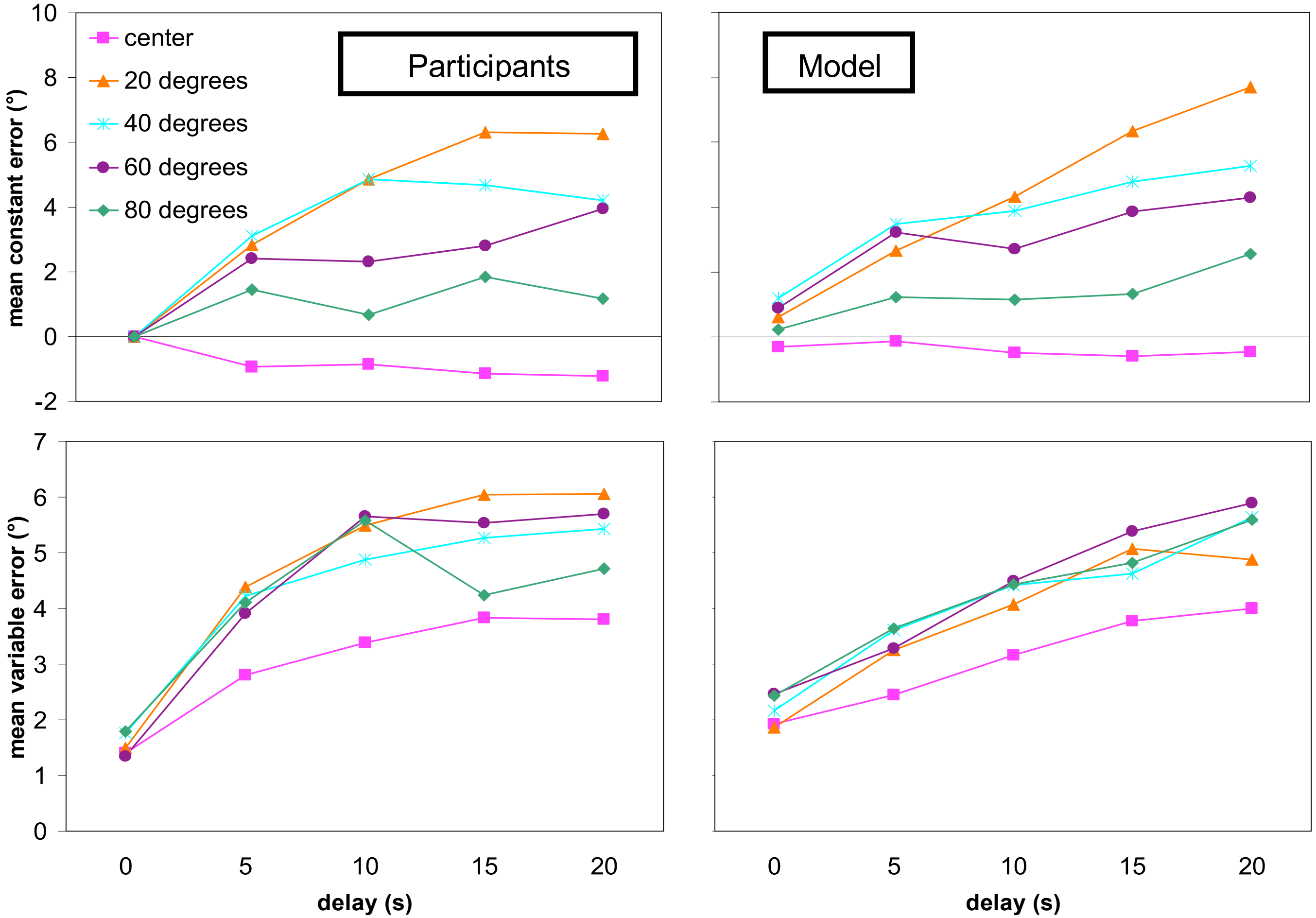
- WM is marginally stable state: it is not asymptotically stable against drift within the low-dimensional space
- => empirically real.. ?

"space ship" task probing spatial working memory

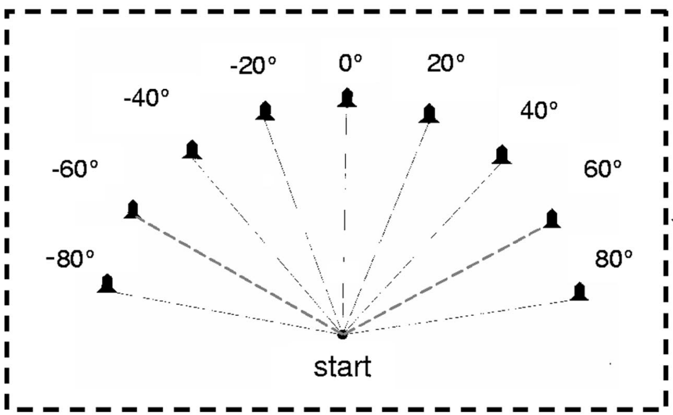


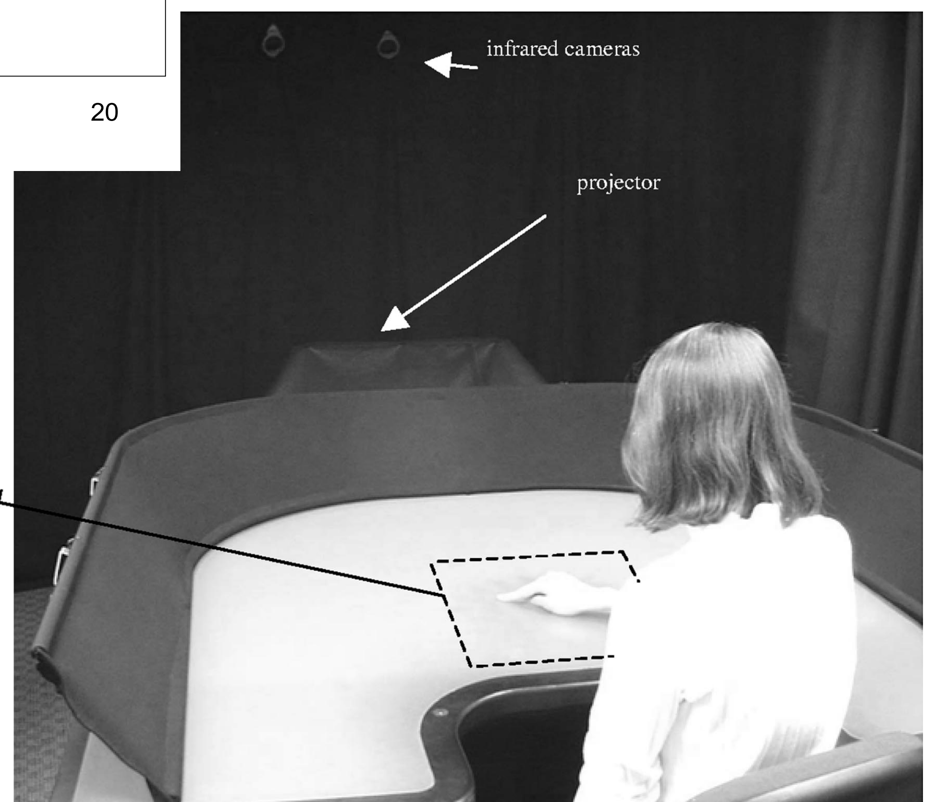


[Schutte, Spencer, JEP:HPP 2009]



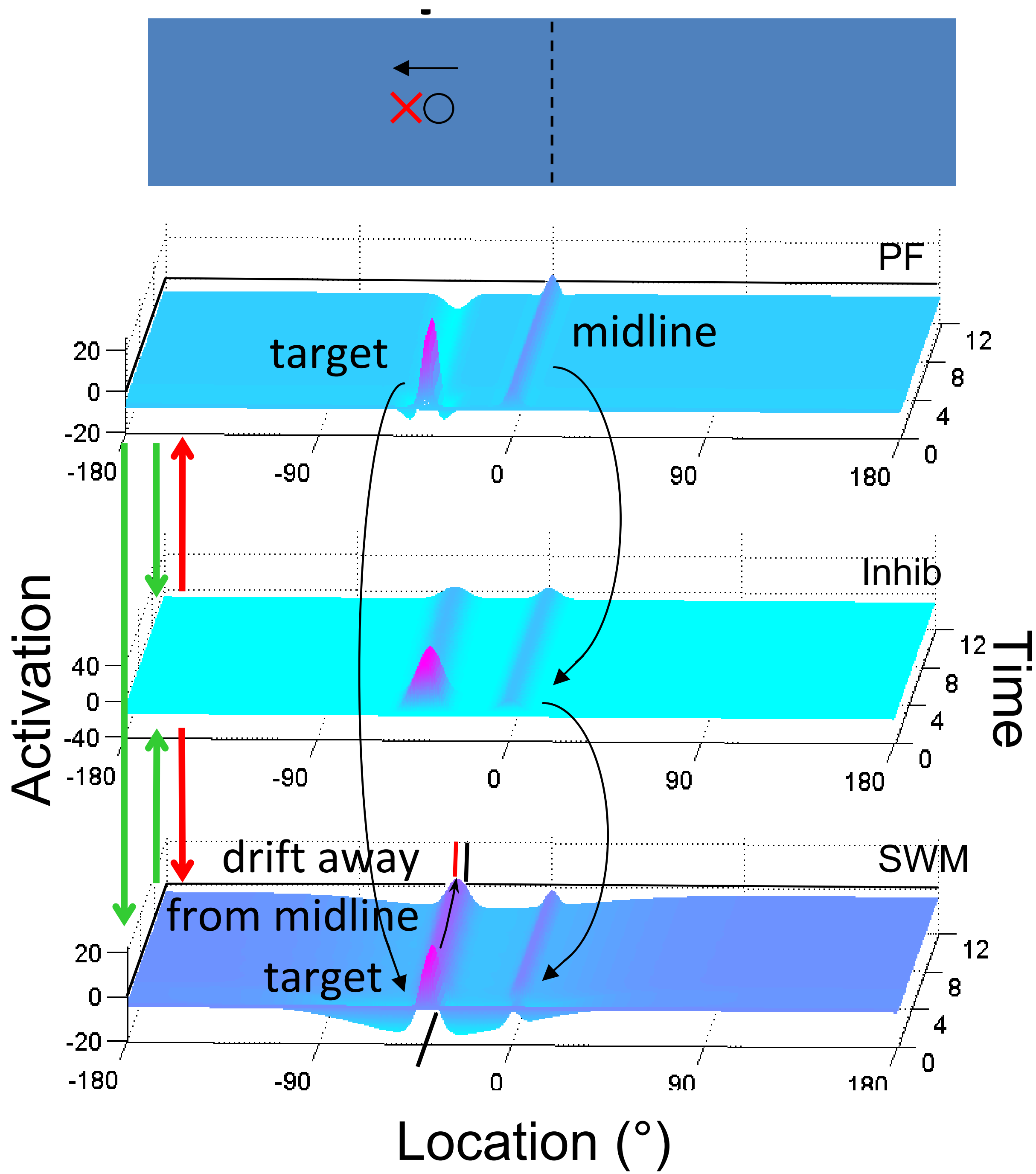
repulsion from mid-line





[Spencer, Schöner, 2006]

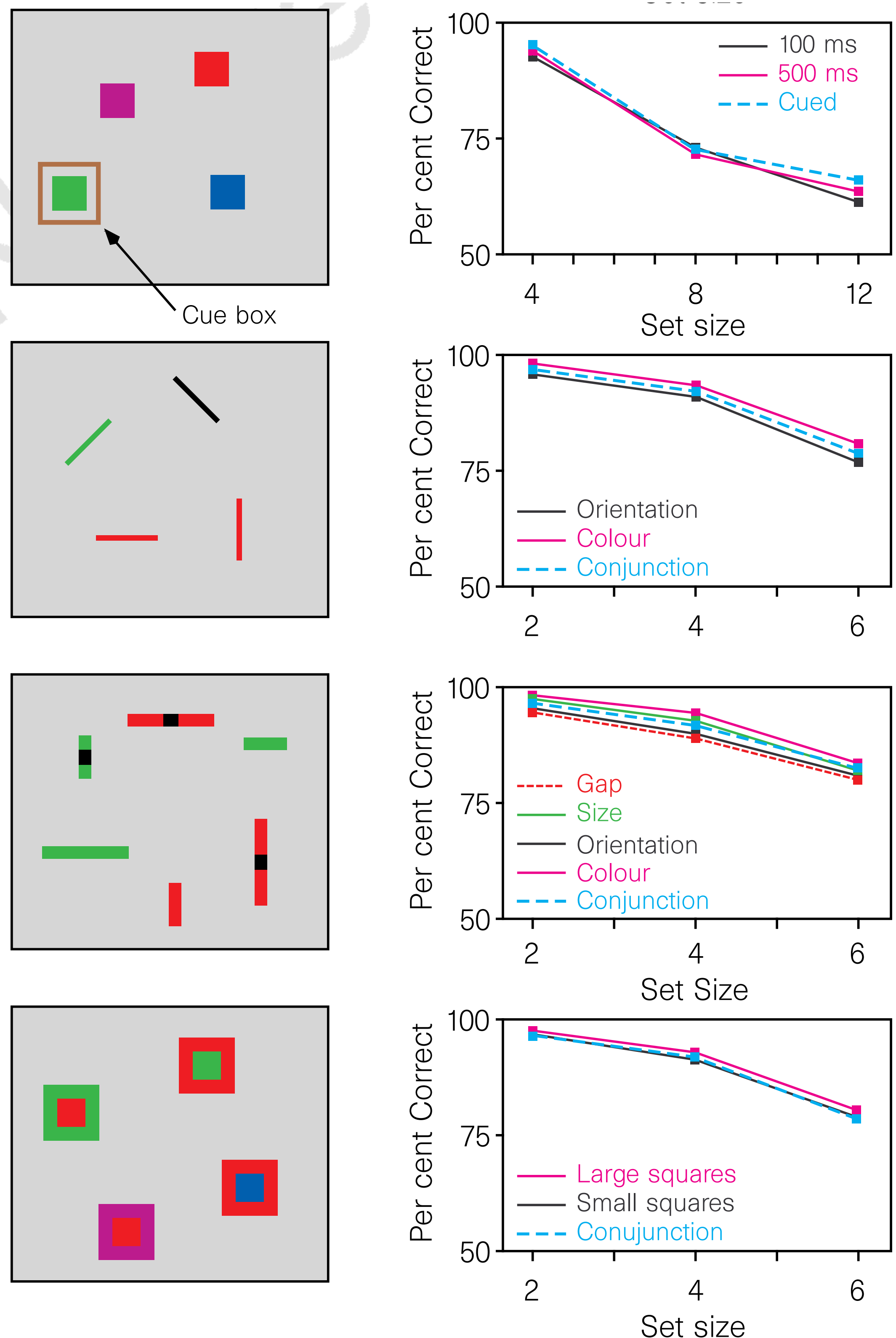
- DFT account of repulsion: inhibitory interaction with peak representing landmark



[Simmering, Schutte, Spencer: Brain Research, 2007]

visual working memory has capacity limits

- capacity based on the number of objects…
  - about 4
- probed by change detection, free recall



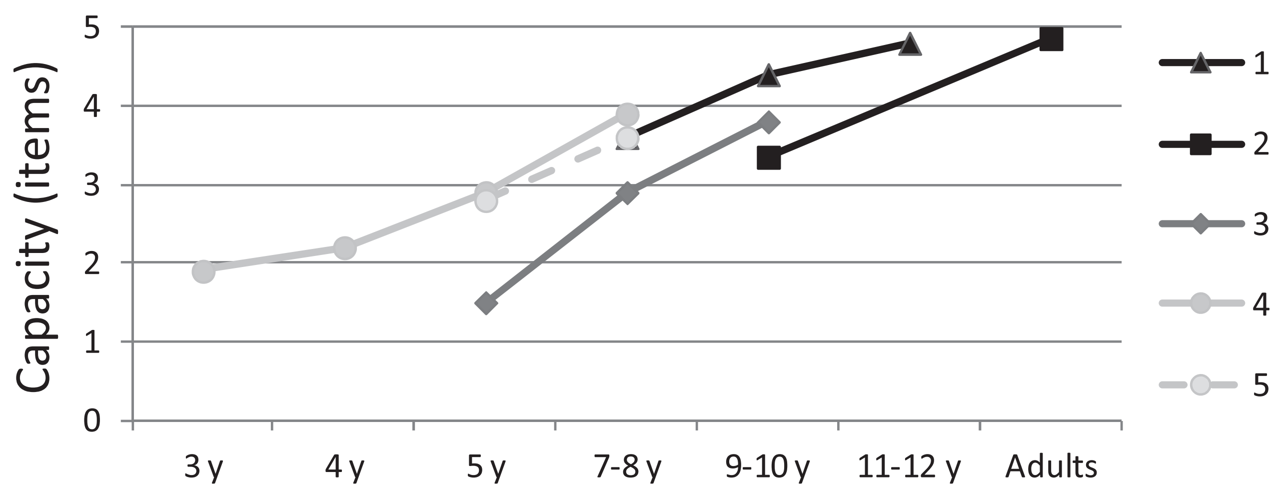
[Luck, Vogel, 1997]

DFT account of WM capacity

- fundamentally caused by accumulation of inhibitory interaction across peaks
- => generic to DFT

WM capacity depends on interaction

- capacity increases across development
- consistent with "spatial precision hypothesis"… interaction becomes more excitatory/local over development



[Simmering 2010]

Change detection

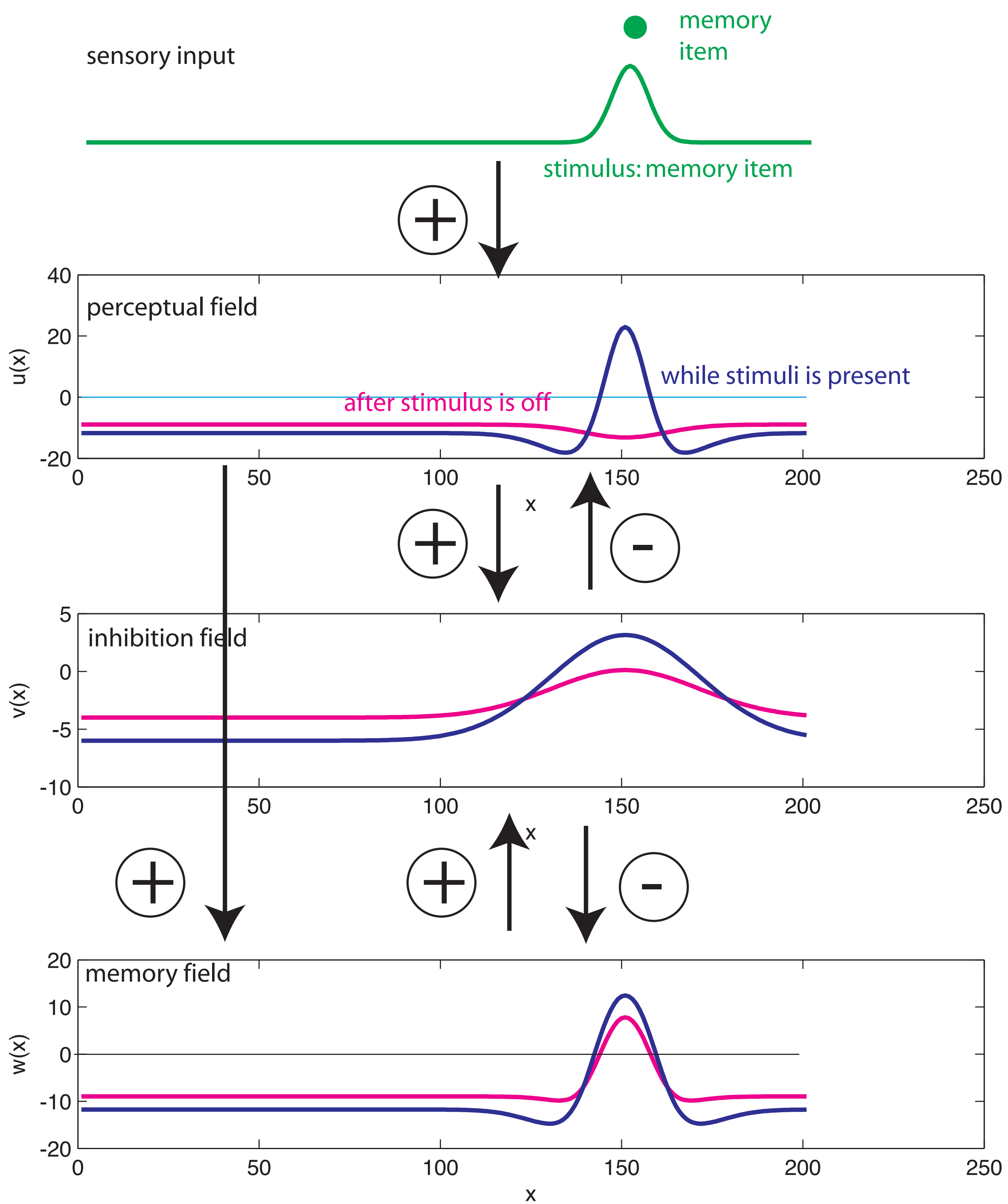
- the standard probe of working memory

[Johnson, et al. 2009]

DFT account for change detection

- separation between perceptual and memory function

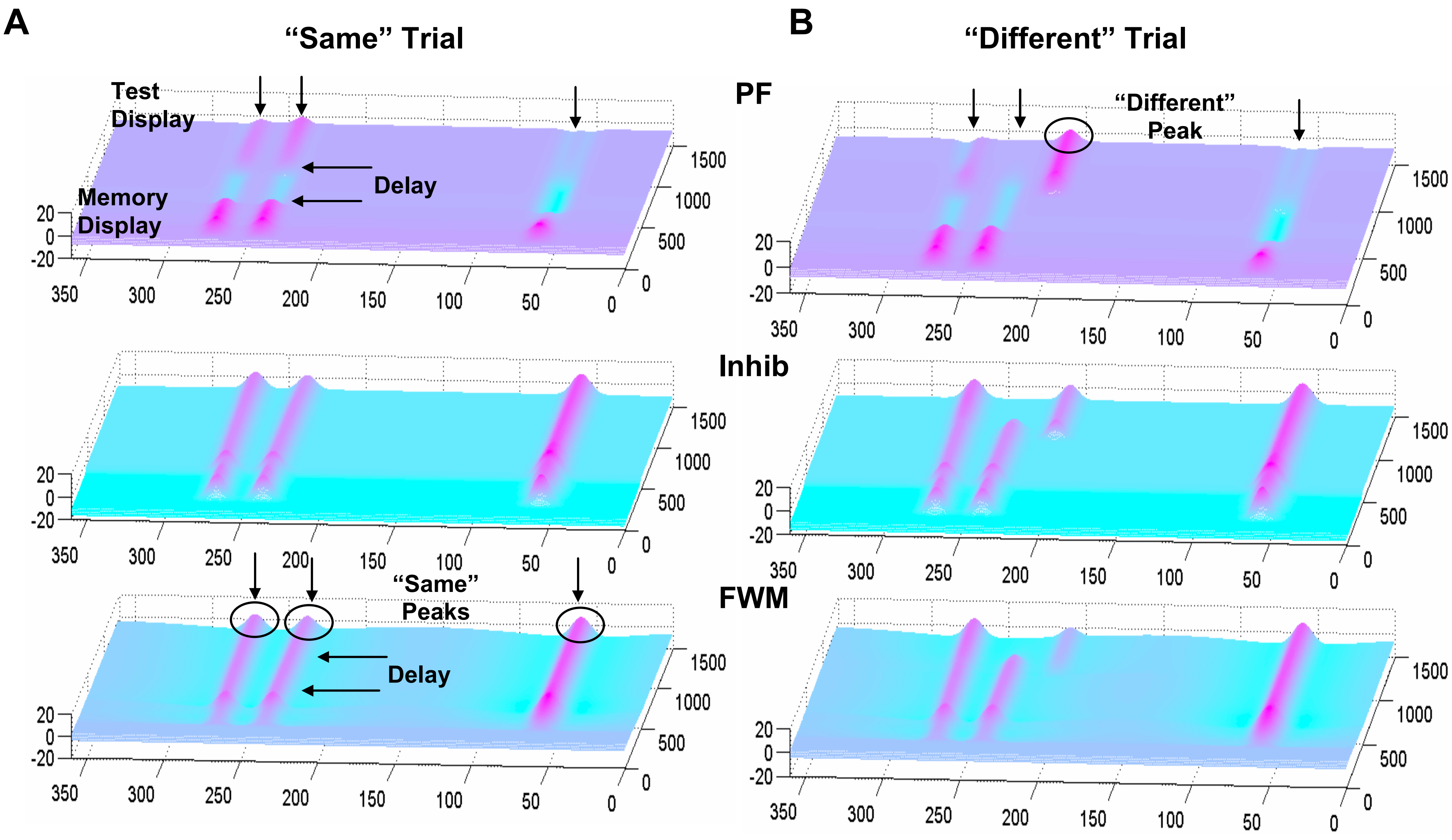
3 layer model



3 layer model

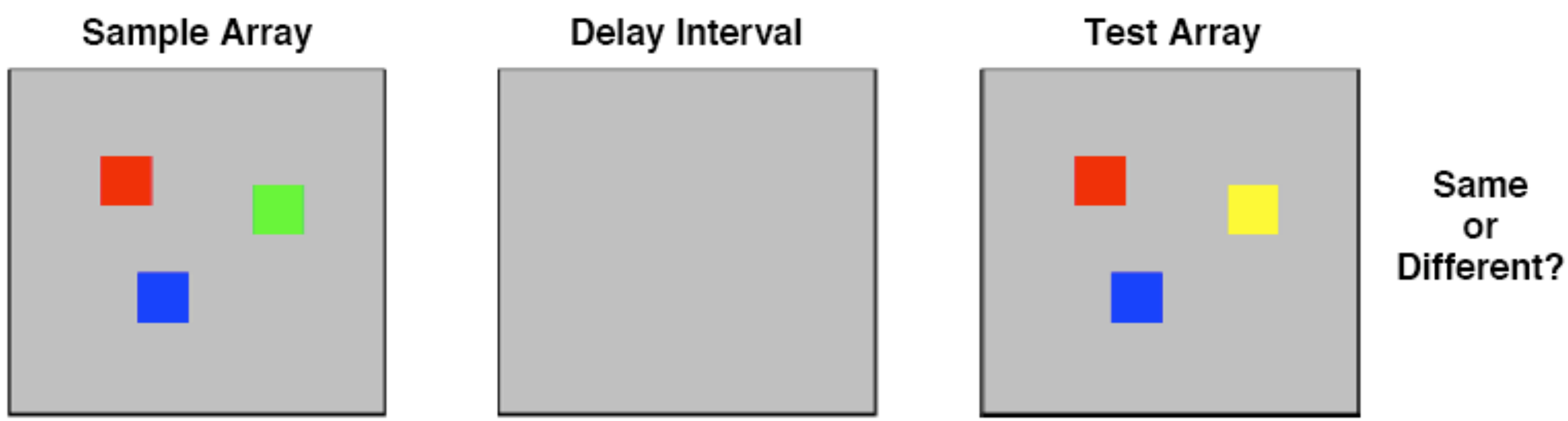
$$
\begin{aligned}
\tau \dot{u}(x,t) &= -u(x,t) + h_u + S(x,t) + \int dx'\ c_{\mathrm{uu}}(x-x')\ \sigma(u(x',t)) \\
&- \int dx'\ c_{\mathrm{uv}}(x-x')\ \sigma(v(x',t)) + \int dx'\ c_{\mathrm{uw}}(x-x')\ \sigma(w(x',t)) \\
\tau \dot{v}(x,t) &= -v(x,t) + h_v \\
&+ \int dx'\ c_{\mathrm{vu}}(x-x')\ \sigma(u(x',t)) + \int dx'\ c_{\mathrm{vw}}(x-x')\ \sigma(w(x',t)) \\
\tau \dot{w}(x,t) &= -w(x,t) + h_w + \int dx'\ c_{\mathrm{ww}}(x-x')\ \sigma(w(x',t)) \\
&- \int dx'\ c_{\mathrm{wv}}(x-x')\ \sigma(v(x',t)) + \int dx'\ c_{\mathrm{wu}}(x-x')\ \sigma(u(x',t))
\end{aligned}
$$

DFT model of change detection



[Johnson, Spencer, Schöner: *New Ideas in Psychology* 2008]

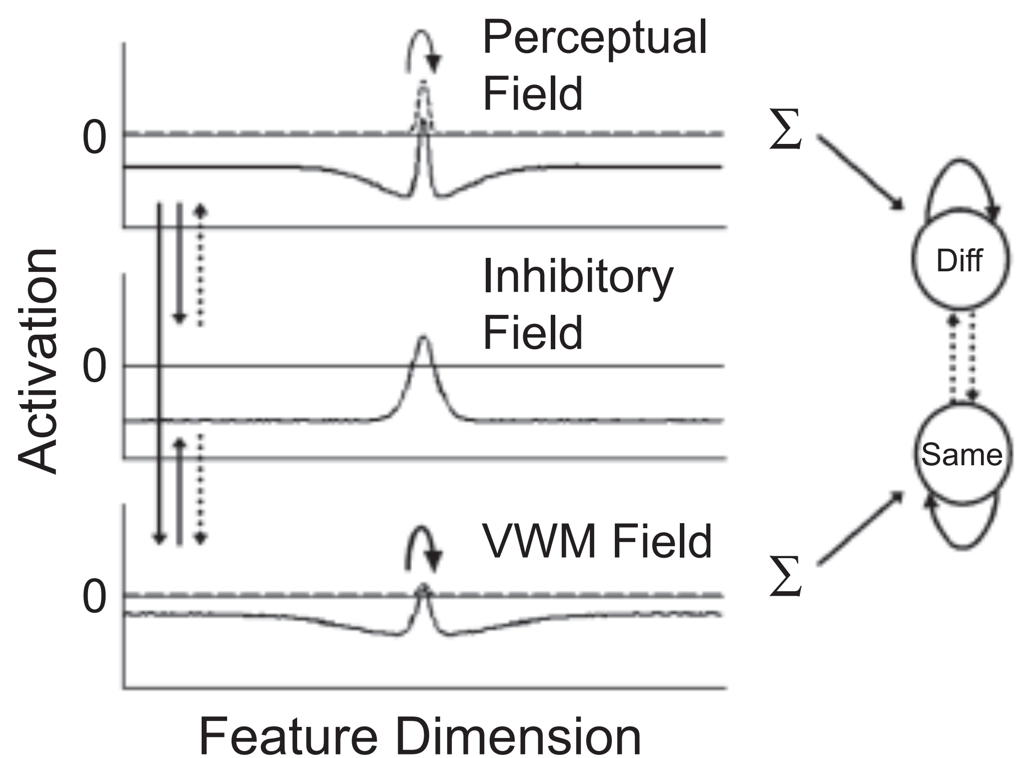
Experiment: metric effects in VWM



[Johnson, Spencer, Luck, Schöner: *Psychological Science* 2008]

DFT account for change detection

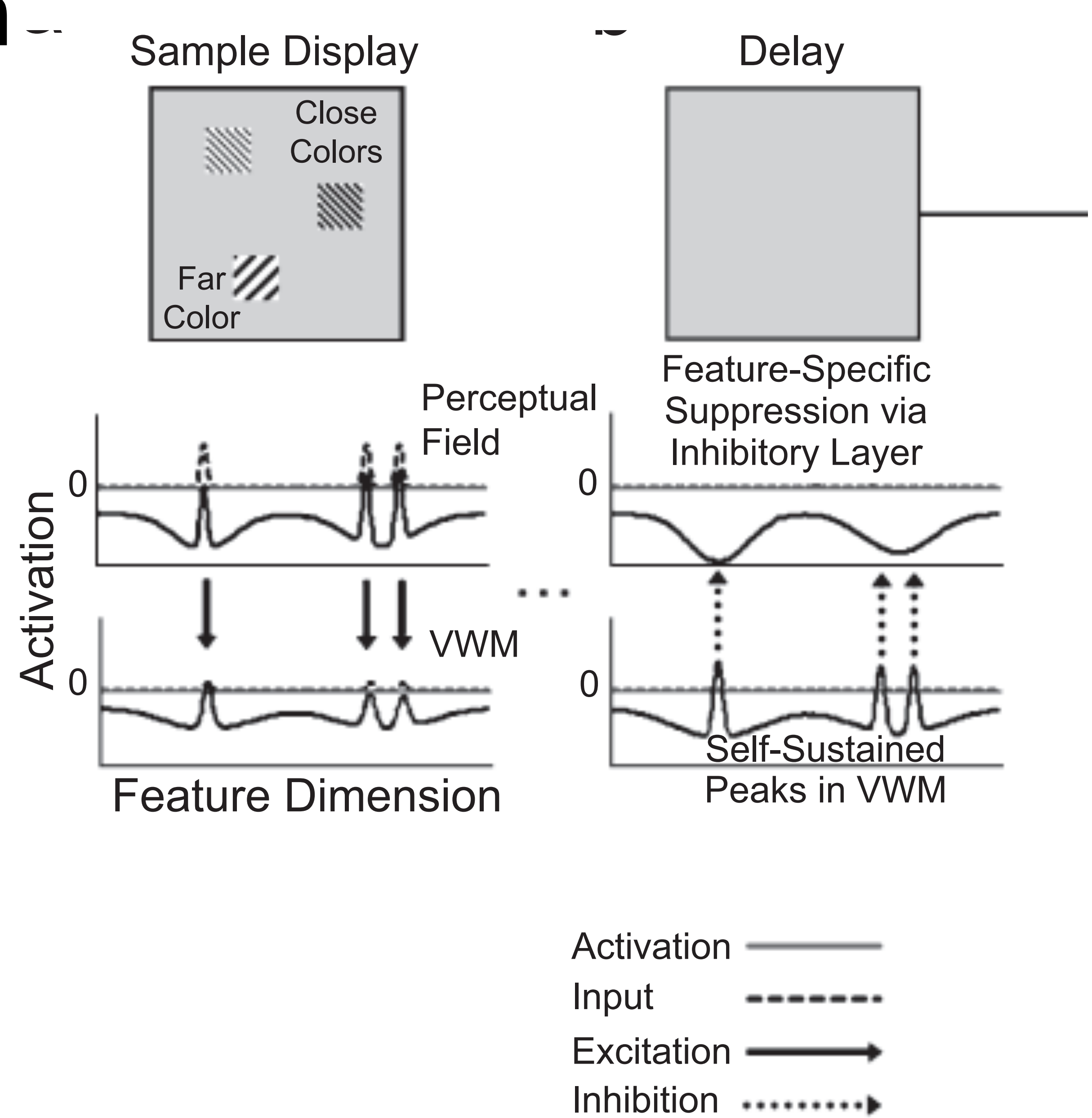
- generate the categorical "answer" by two competing nodes
- based on the "hidden" go-signal in the task



[Johnson, et al. 2009]

DFT account for change detection

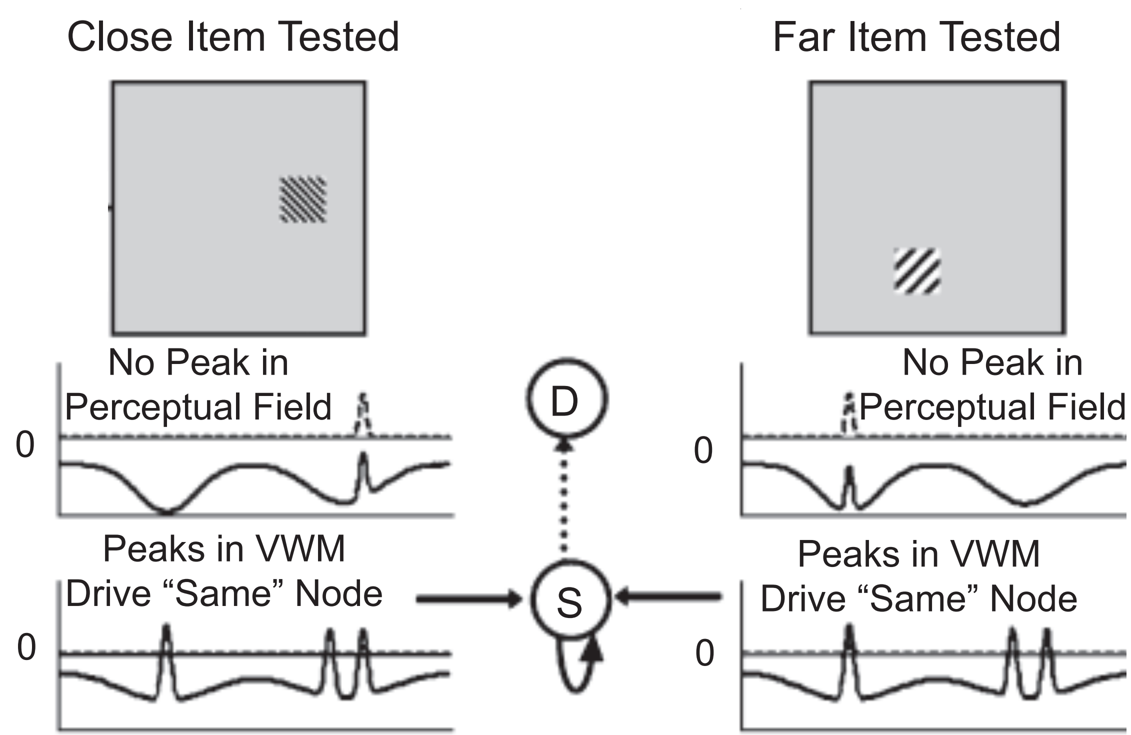
- 1) working memory is created



[Johnson, et al. 2009]

DFT account for change detection

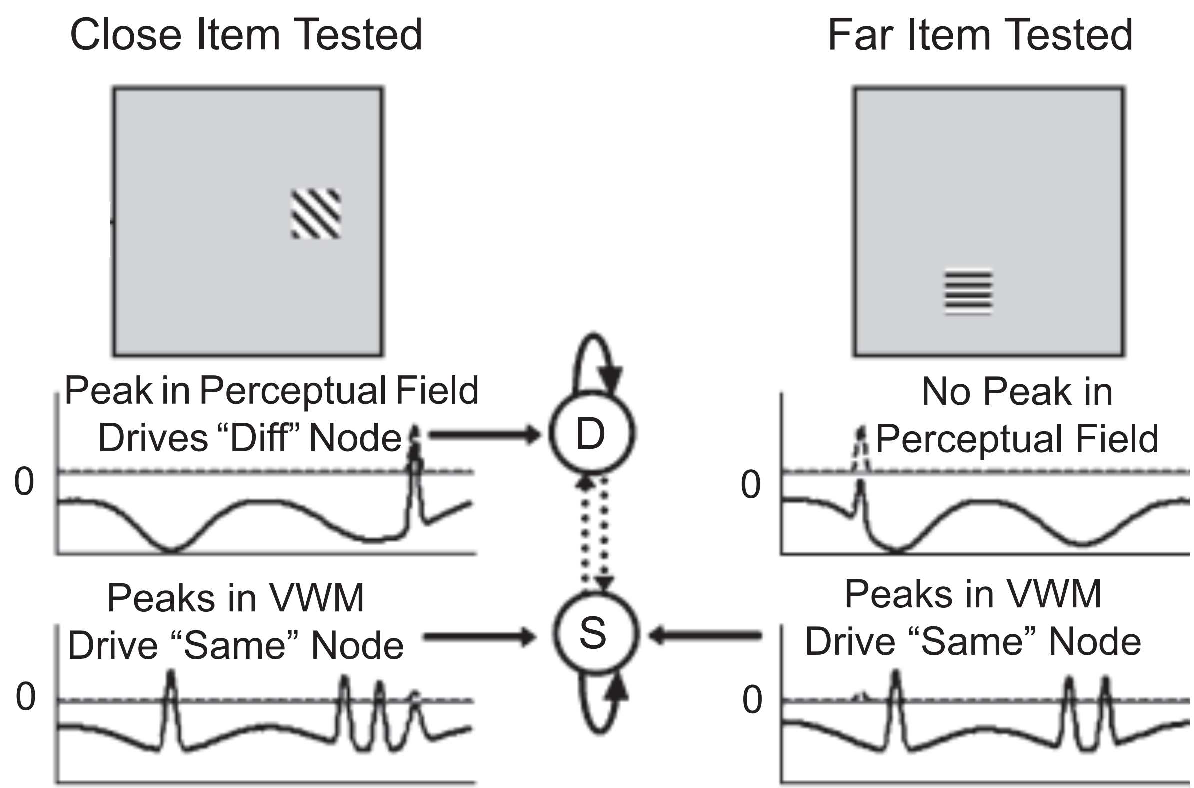
- 2) change detection in "same" trial



[Johnson, et al. 2009]

DFT account for change detection

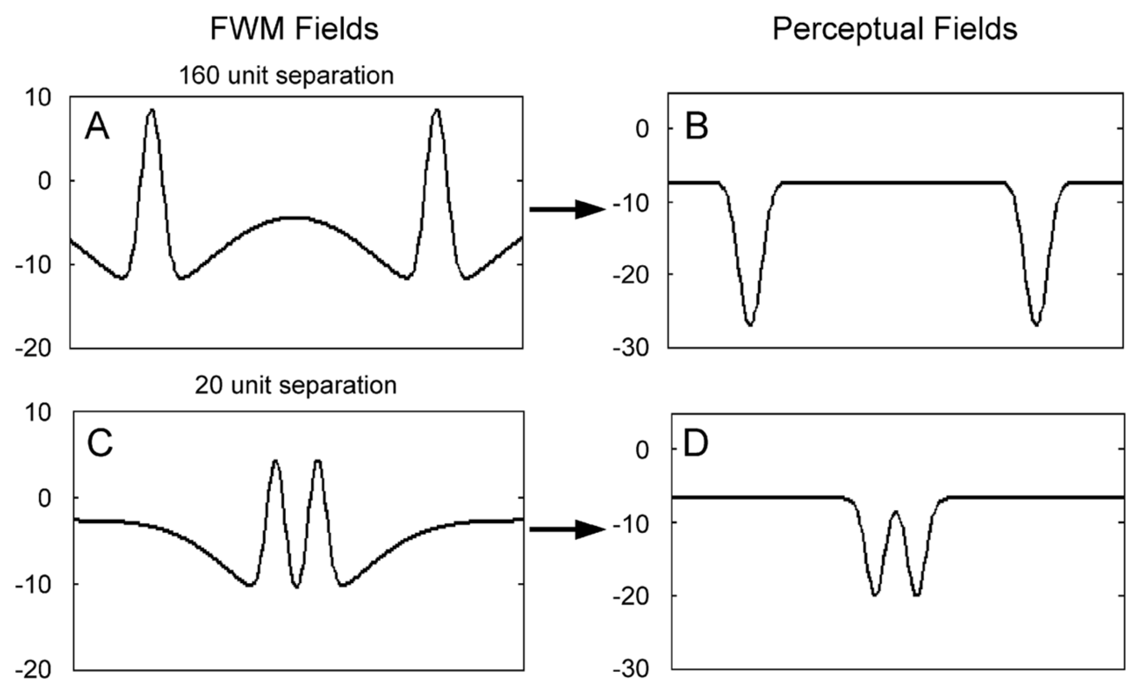
- 2) change detection in “different” trial



[Johnson, et al. 2009]

DFT account for change detection

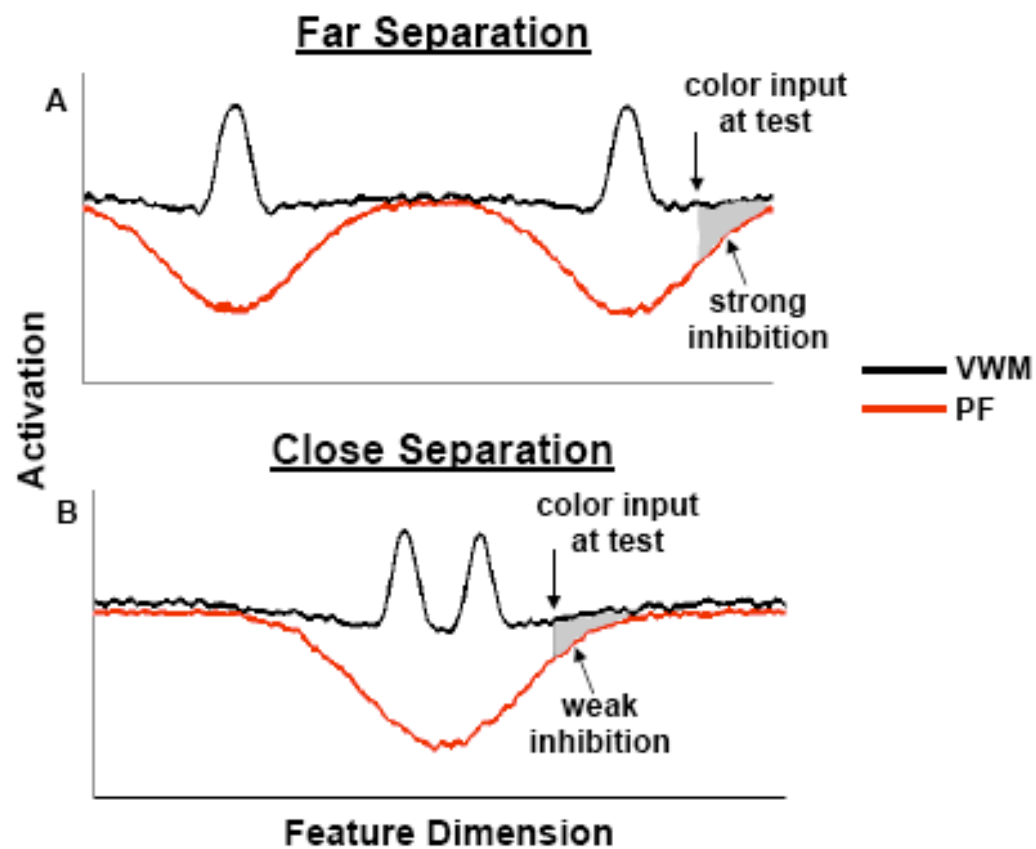
- predict better change detection when items are metrically closer !



[Johnson, et al. 2009]

Metric effect

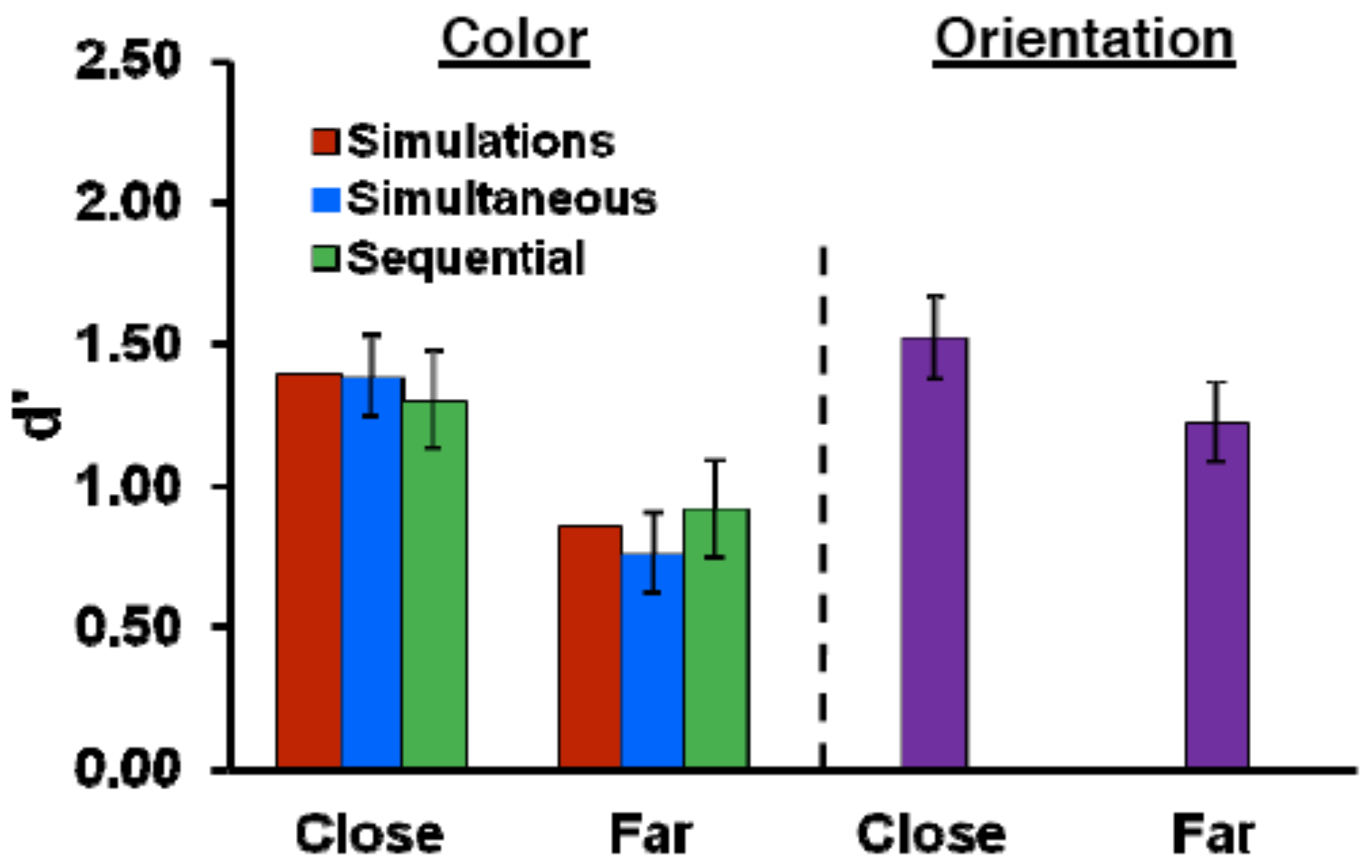
- close metric separation: peaks weakened by overlapping inhibition
- => less inhibition in perceptual layer
- => reduced threshold for change detection



[Johnson, Spencer, Luck, Schöner: *Psychological Science* 2008]

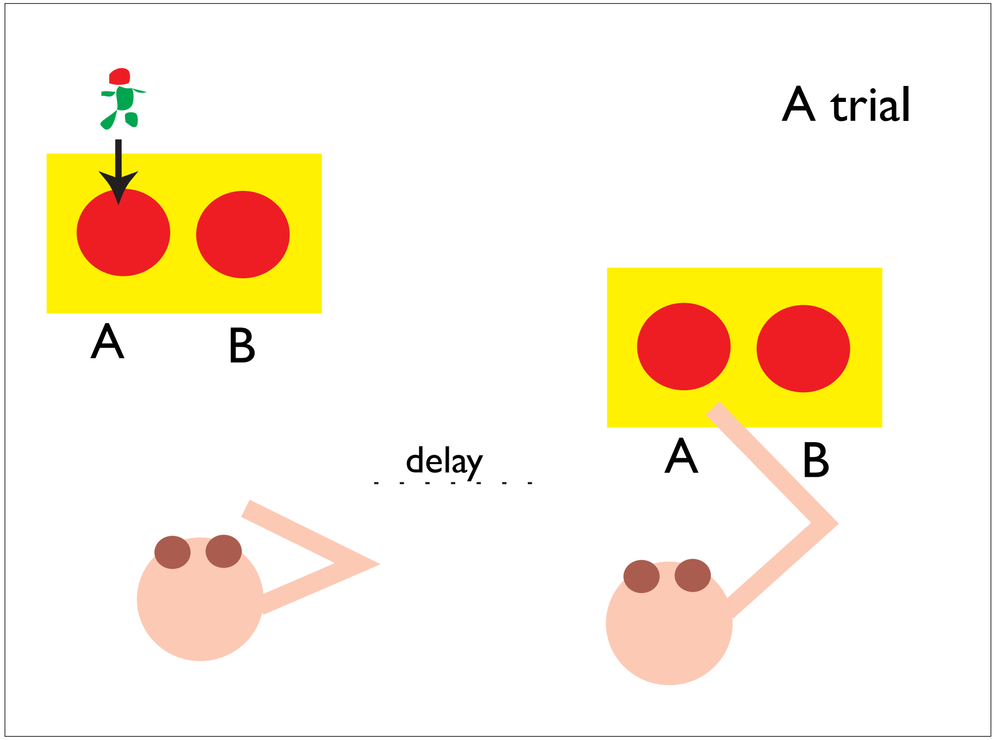
Experimental confirmation

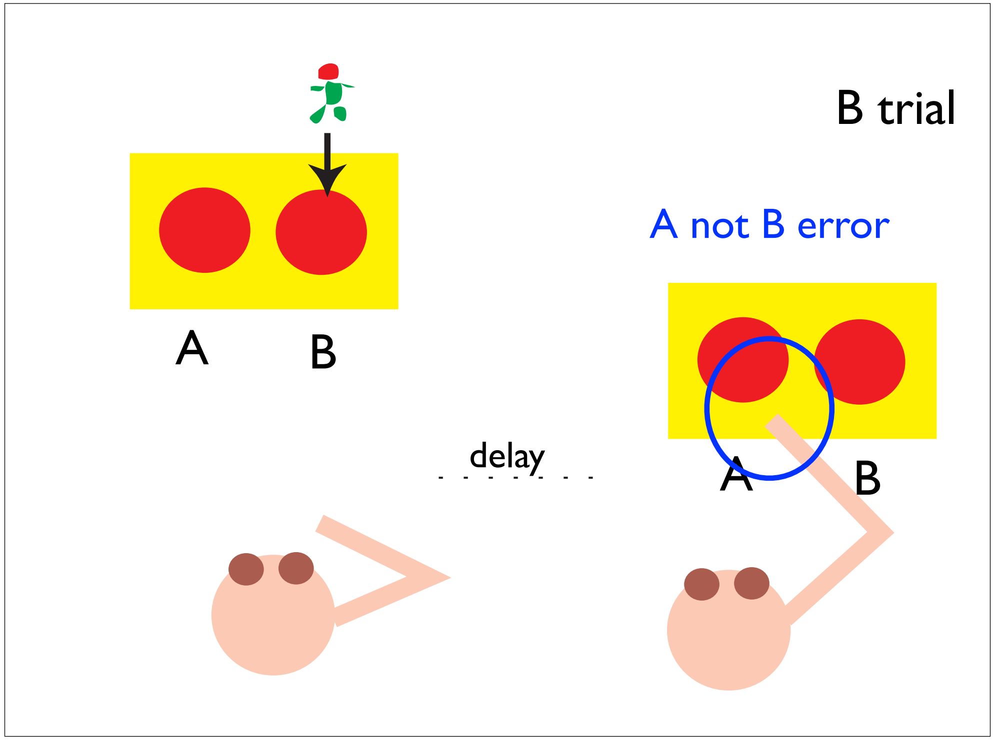
- => predict more sensitive change detection for item that are metrically close!



[Johnson, Spencer, Luck, Schöner: *Psychological Science* 2008]

Piaget's A not B paradigm: "out-of-sight -- out of mind"

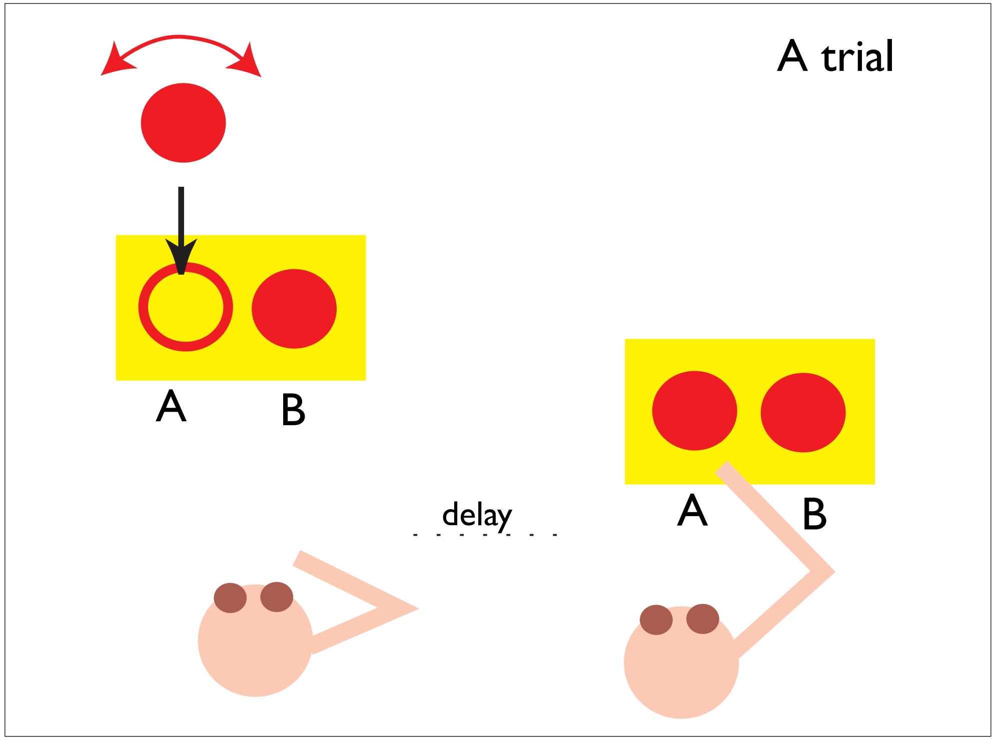


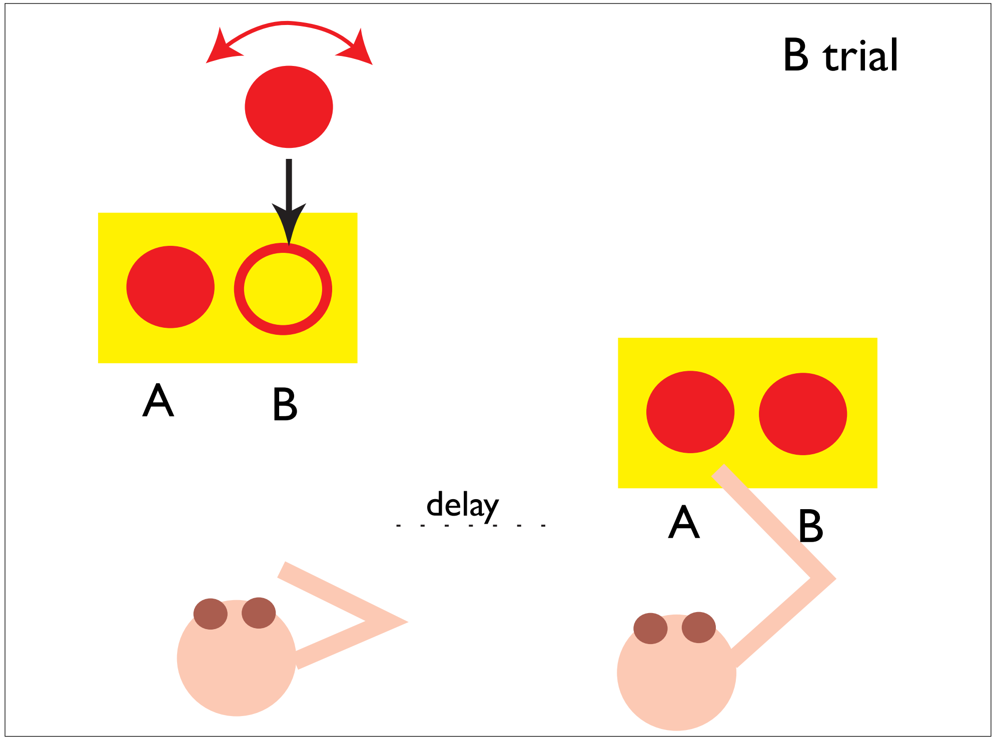


Toyless variant of A not B task

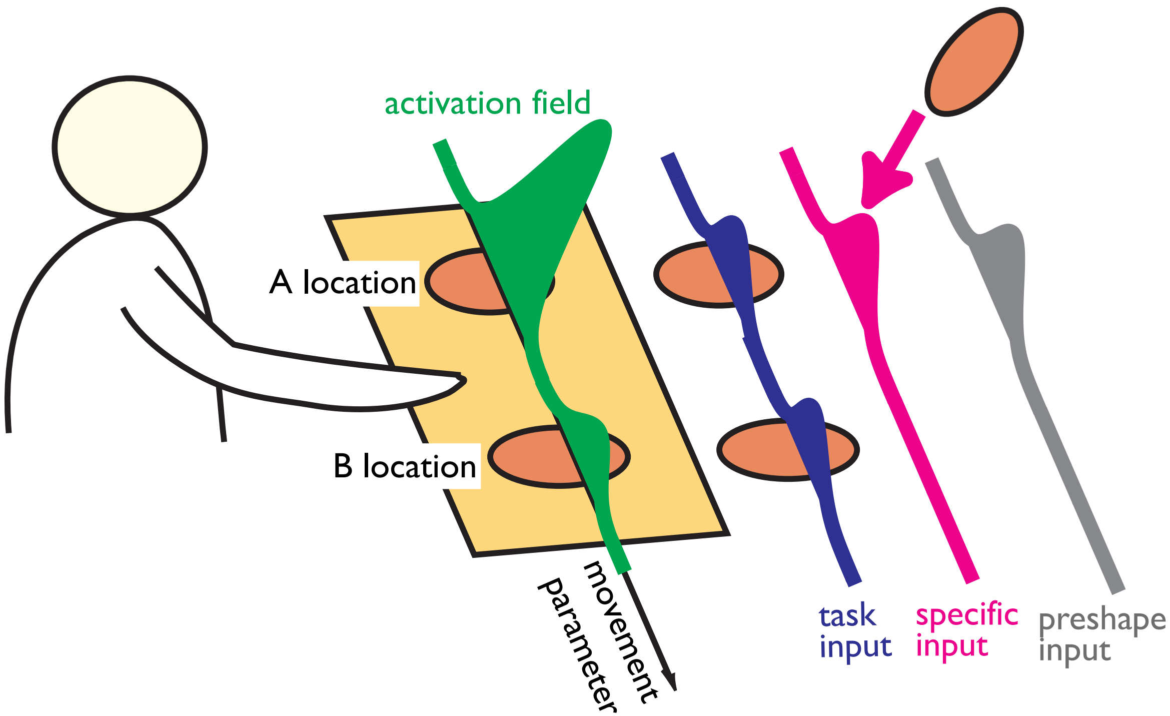
[Smith, Thelen et al.: Psychological Review (1999)]

Toyless variant of A not B: essentially a selection decision task!

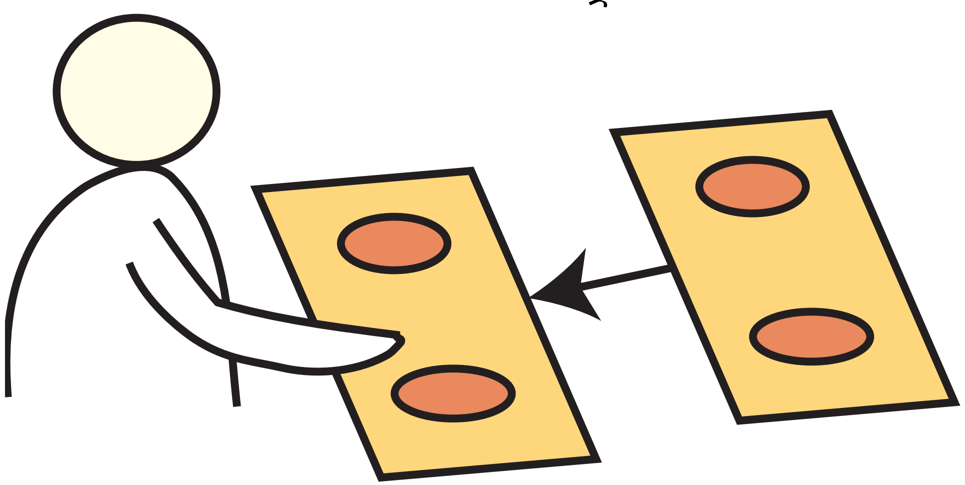




[Smith, Thelen et al.: Psychological Review (1999)]



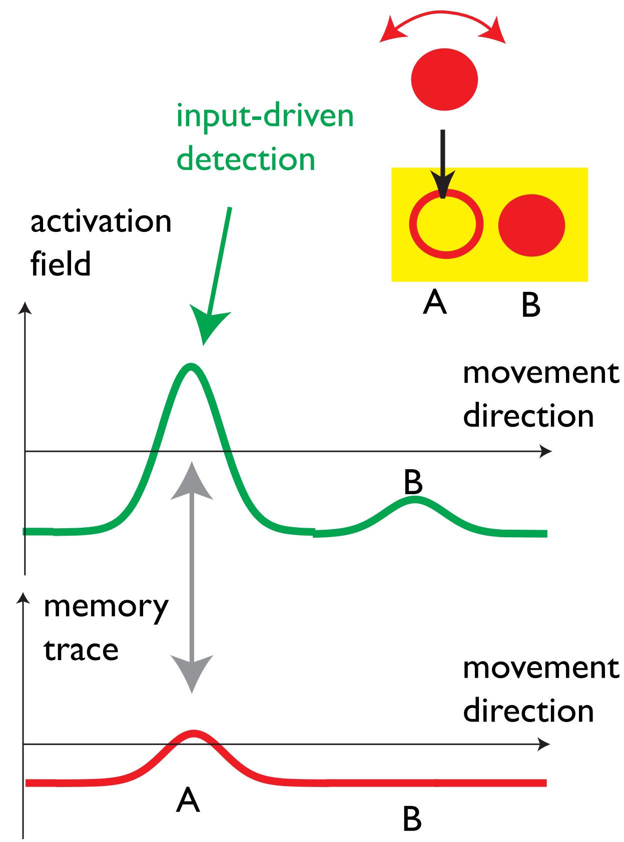
[Thelen, et al., BBS (2001)]



[Dineva, Schöner, Dev. Science 2007]

Instabilities

- detection: forming and initiating a movement goal
- selection: making sensori-motor decisions
- (learning: memory trace)
- boost-driven detection: initiating the action
- memory instability: old infants sustain during the delay, young infants do not



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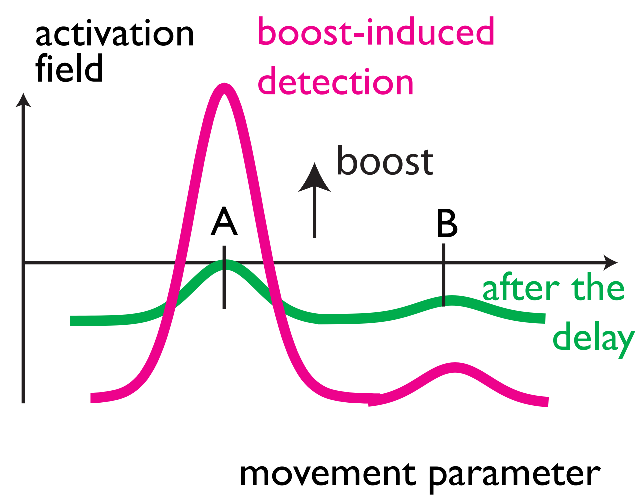

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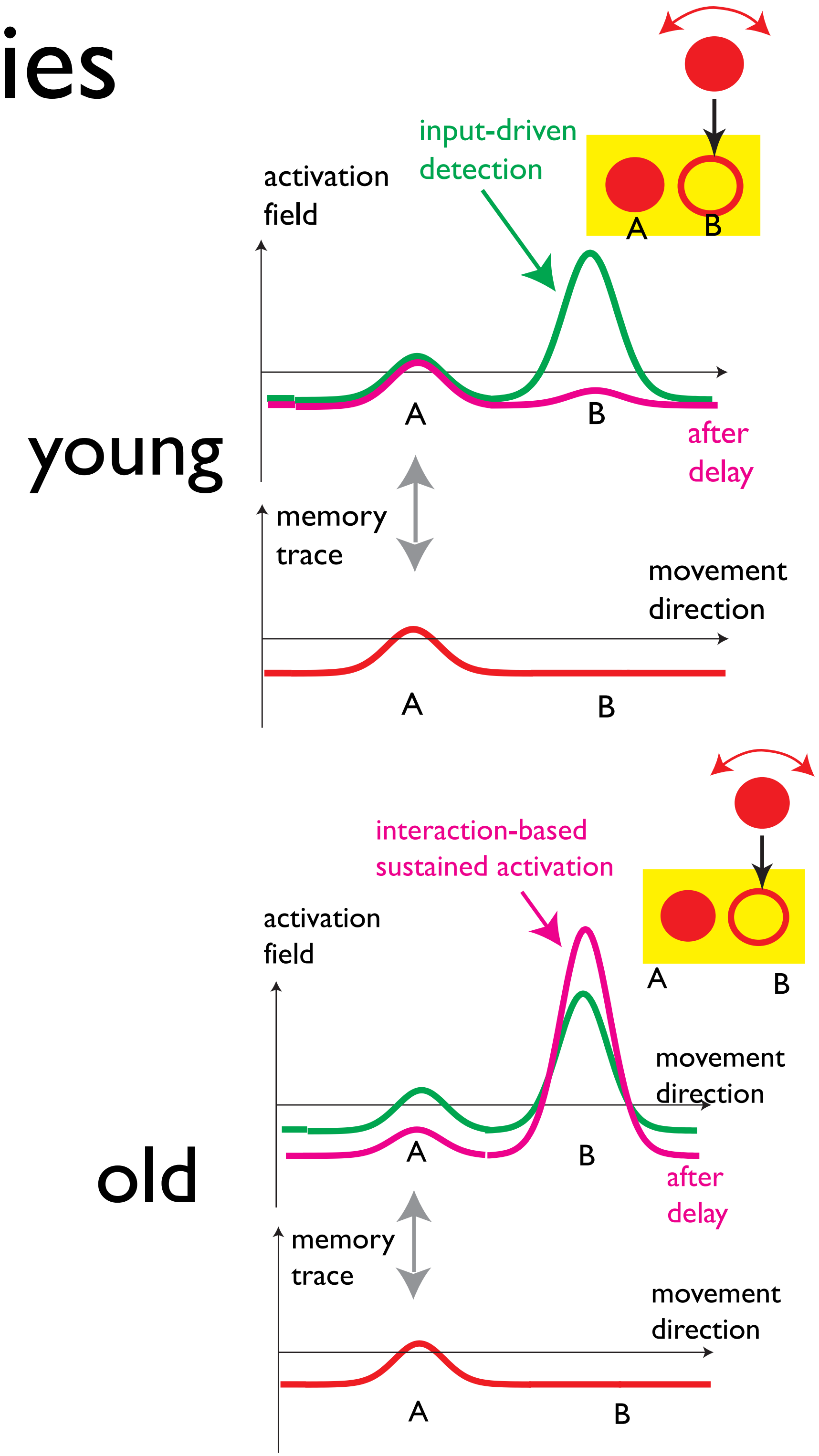
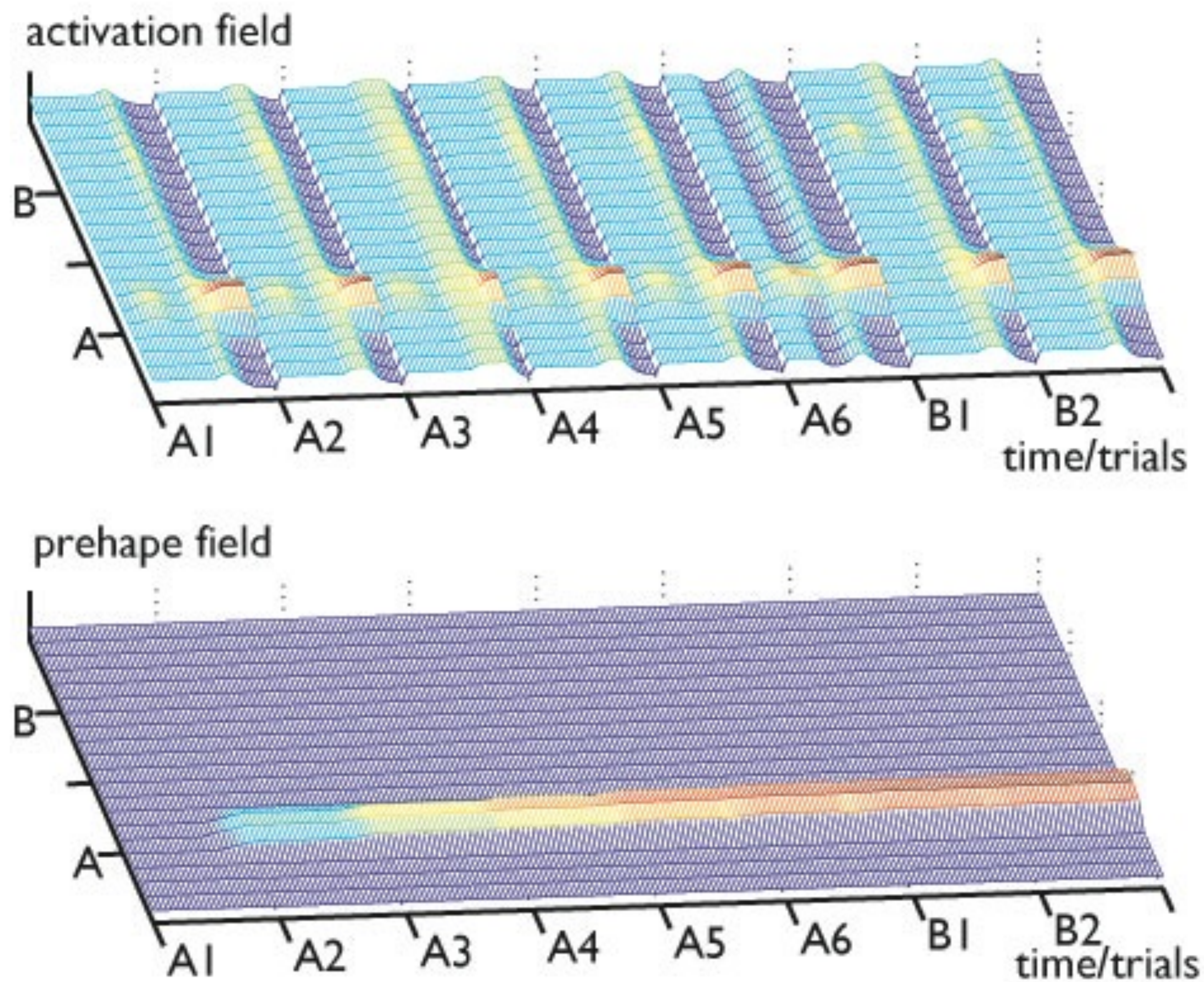
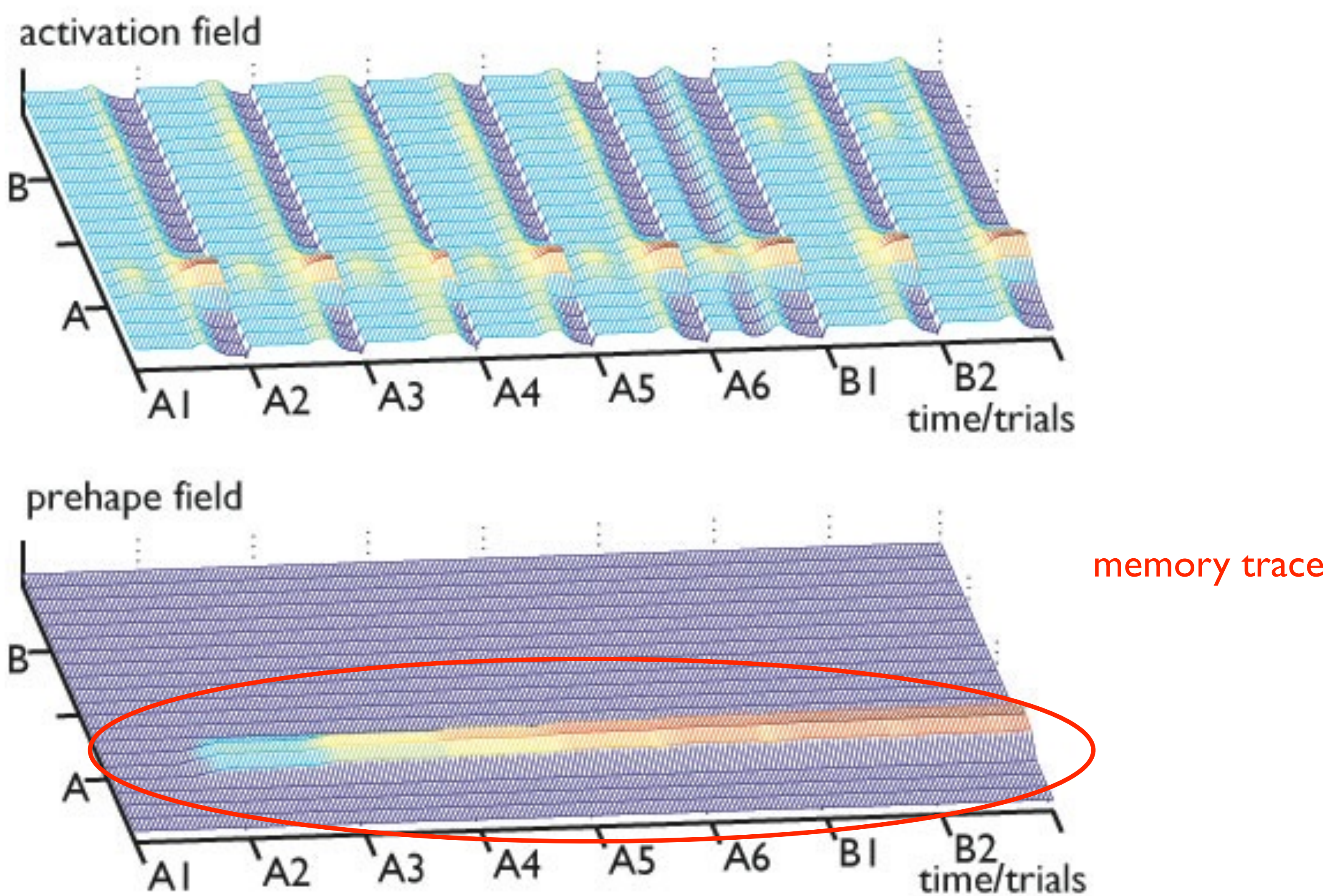


DFT of infant perseverative reaching



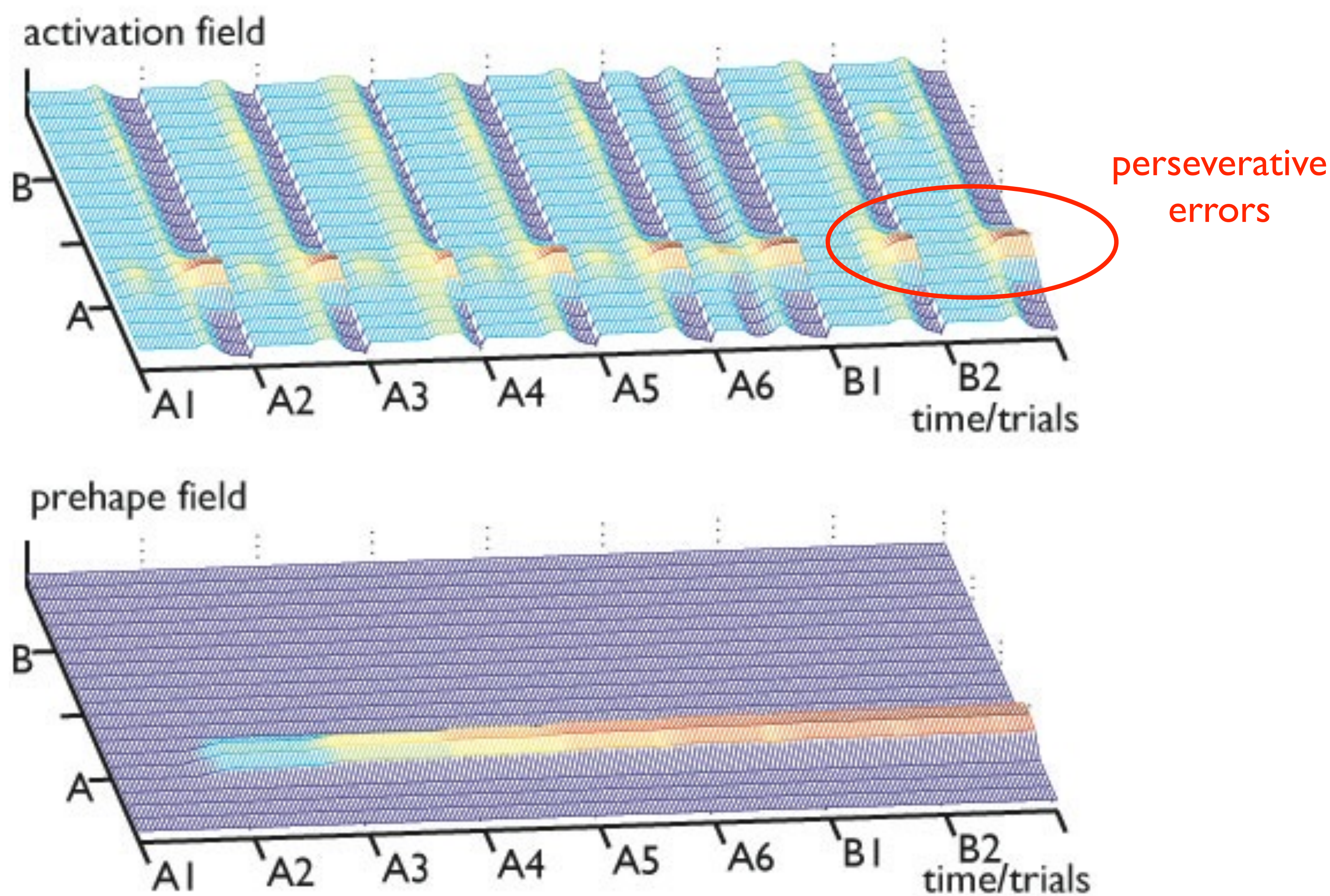
[Dinveva, Schöner, Dev. Science 2007]

DFT of infant perseverative reaching



[Dinveva, Schöner, Dev. Science 2007]

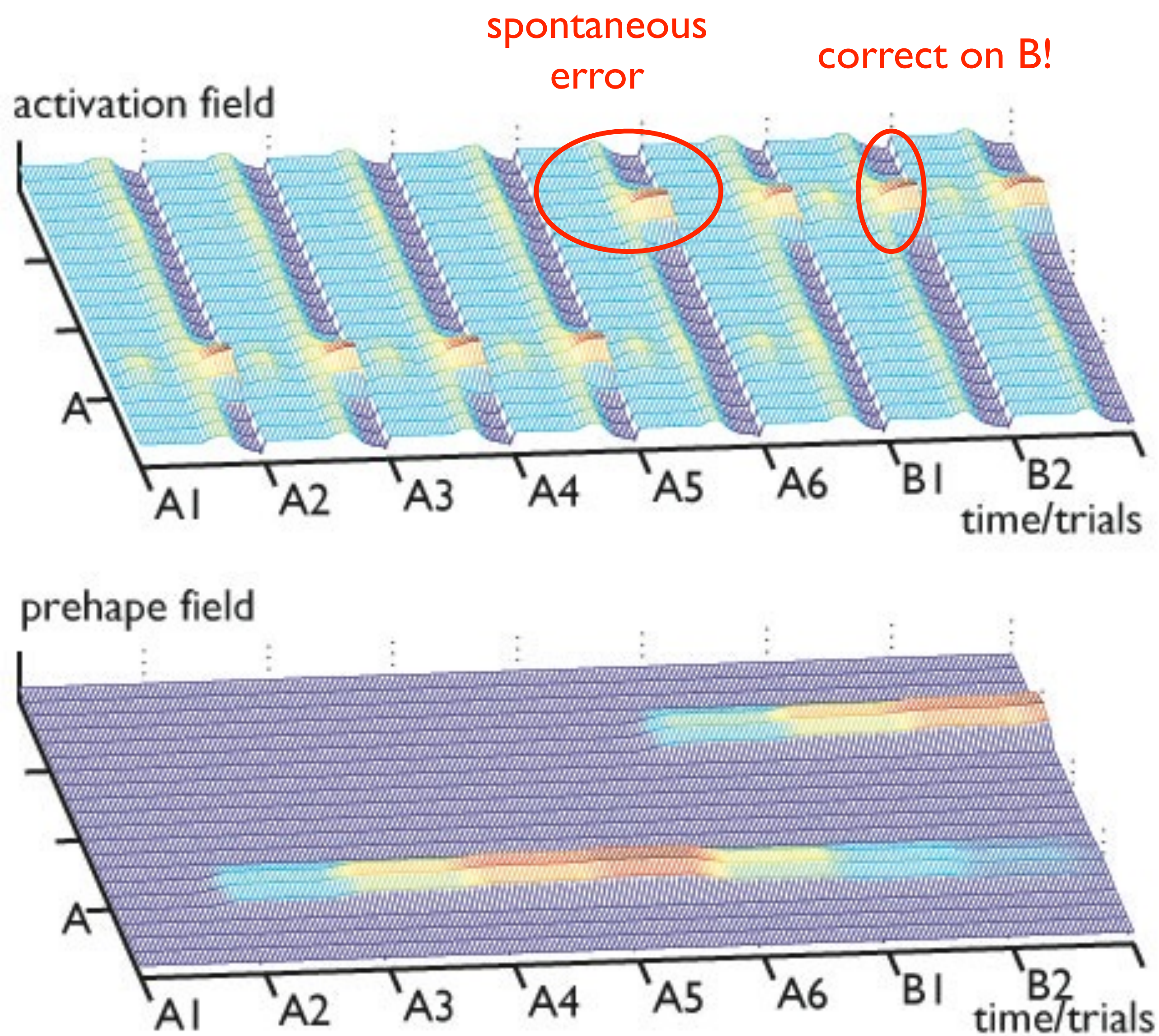
DFT of infant perseverative reaching



[Dinveva, Schöner, Dev. Science 2007]

DFT of infant perseverative reaching

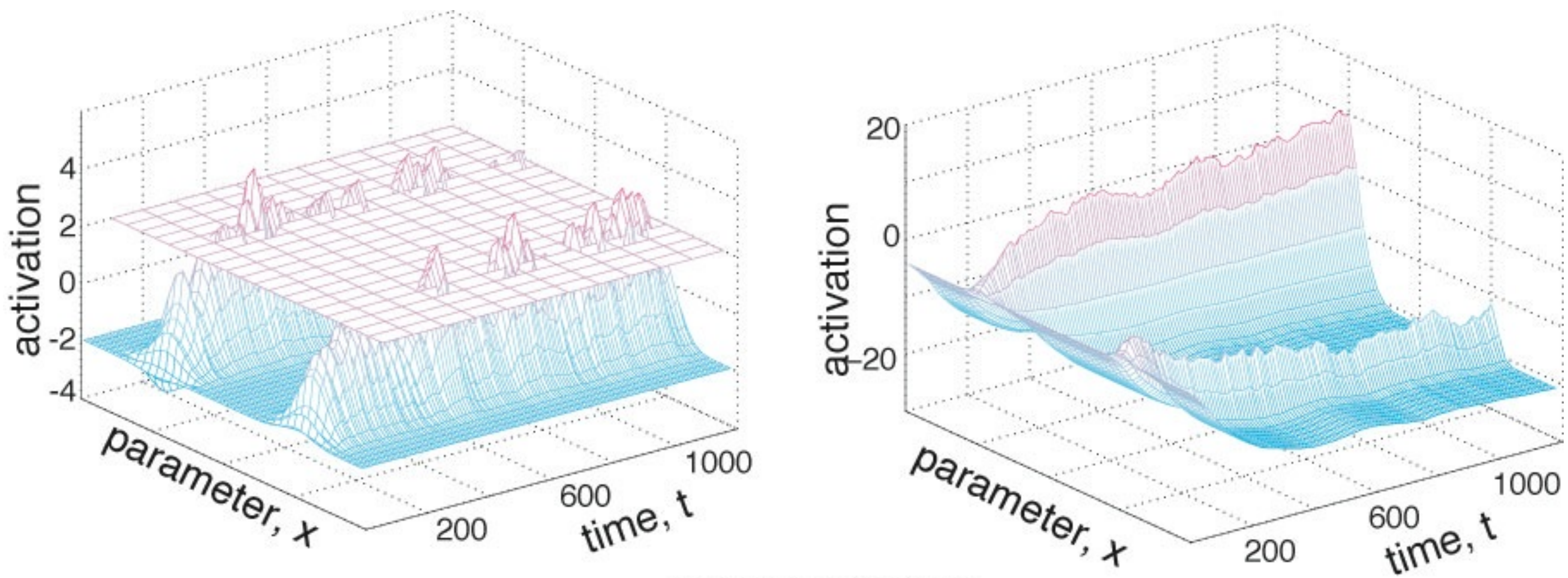
- in spontaneous errors, activation arises at B on an A trial
- which leads to correct reaching on B trial
- because reaches to B on A trials leave memory trace at B



[Dinveva, Schöner, Dev. Science 2007]

=> DFT is a neural process model

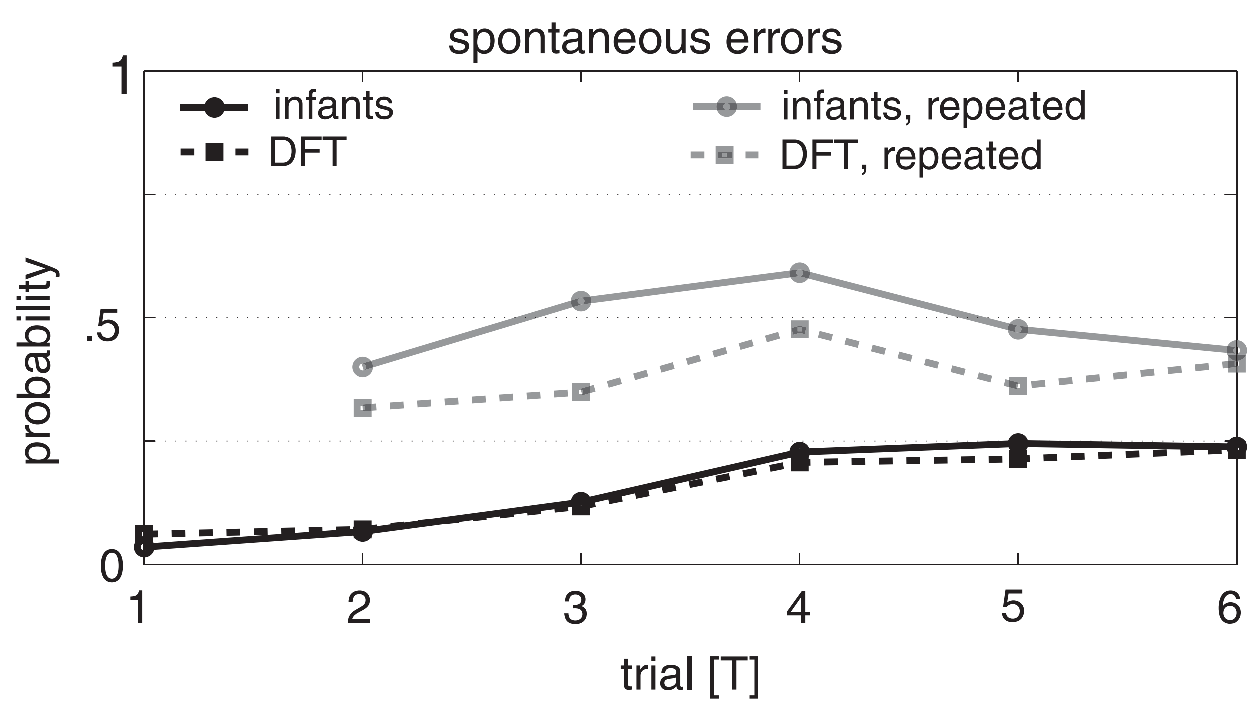
- that makes the decisions in each individual trial, by amplifying small differences into a macroscopic stable state
- and that's how decisions leave traces, have consequences



[Wilimzig, Schöner, 2006]

Decisions have consequences

- a spontaneous error doubles probability to make the spontaneous error again



[Dineva, Schöner: Connection Science 2018]

Experimental signatures of DFT

- metric effects: distances between potential states matter
- effects of timing: time matters, spatio-temporal co-variation
- instabilities: it matters how far a state is from becoming unstable…