Higher Level Cognition: What's Missing

Higher Level Cognition: What's Missing

- Planning, problem solving, reasoning, complex decision-making
- What do all of these have in common?
- Top-down control of behavior: Instead of reacting in a bottom-up fashion to stimuli, behavior is driven (controlled) by an *actively maintained representation* of what we are supposed to be doing...
- Allows us to behave in contextually appropriate fashion instead of just giving the strongest, most dominant response
- Also gives us the ability to link events across time points, and to carry out behaviors that are extended across time...

Why does this happen?

A-not-B

Kai A-not-B

Max Card Sort

Higher Level Cognition: What We Know

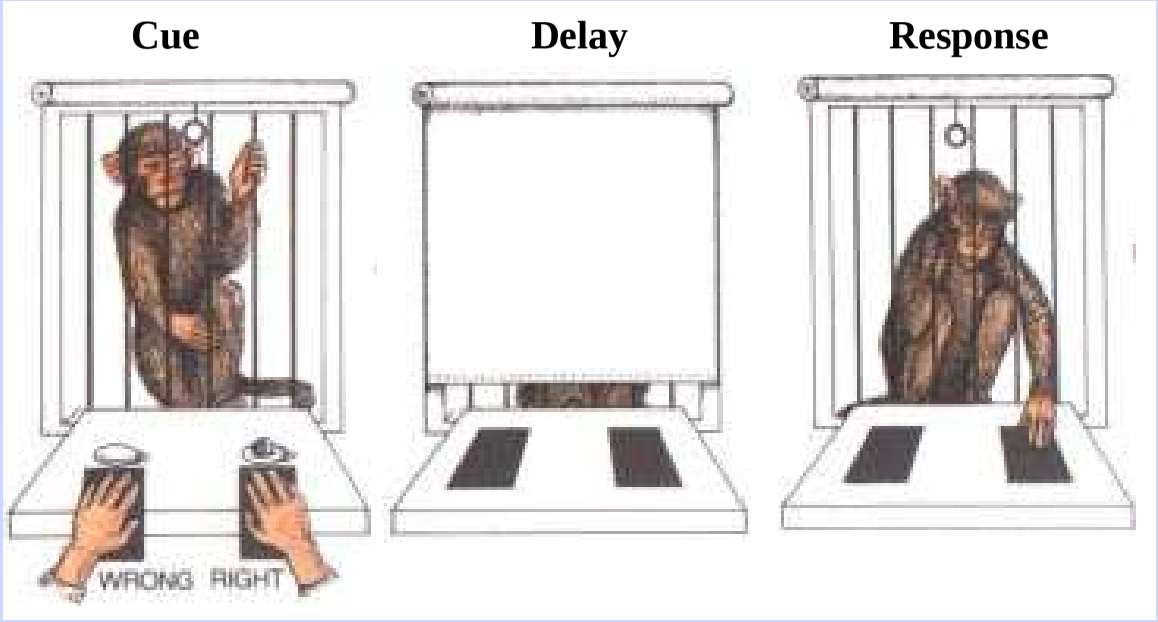
Frontal (and BG) damage impairs planning, reasoning, decision-making, self-initiated actions, self-awareness, social interaction...

The Range of Frontal Functions

Activation-based working memory

Activation-based Working Memory

Monkey electrophysiology

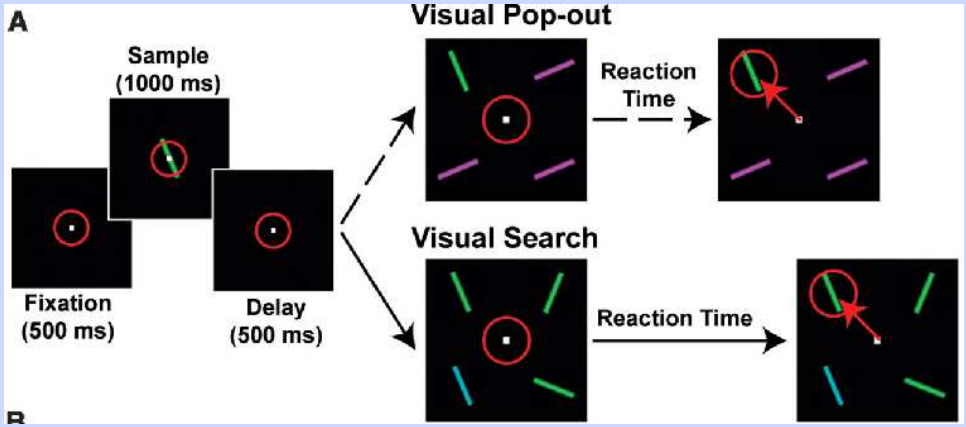


The PFC can maintain information (neural firing) over time (activation-based memory).

$\rightarrow$ This can be used to guide attention in posterior regions
("guided activation" or "biased competition").

Top-down vs bottom-up PFC

Buschman & Miller, 2007, *Science*



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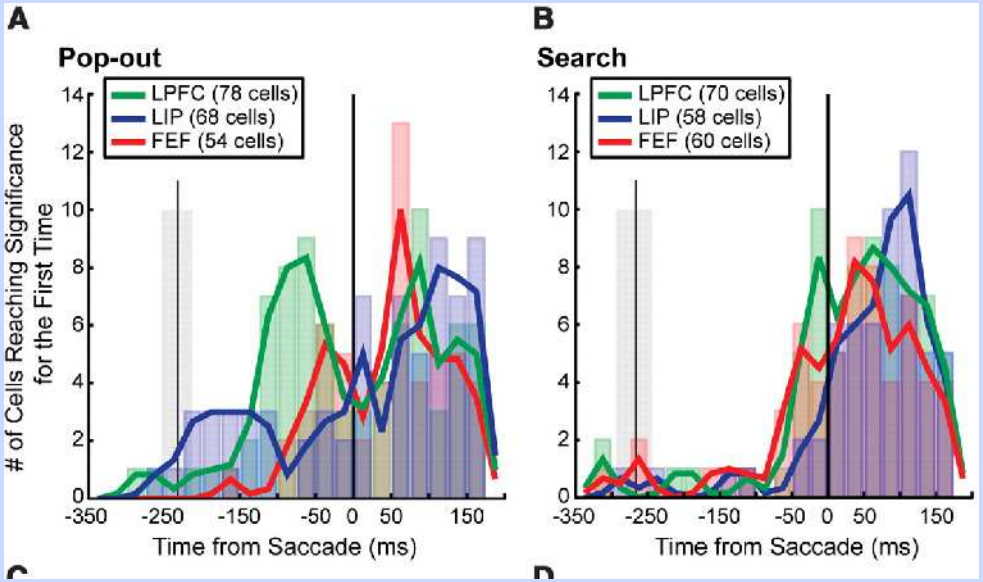

- parietal act for target location precedes pfc act for pop-out
- pfc act precedes parietal for search

Top-down vs bottom-up PFC

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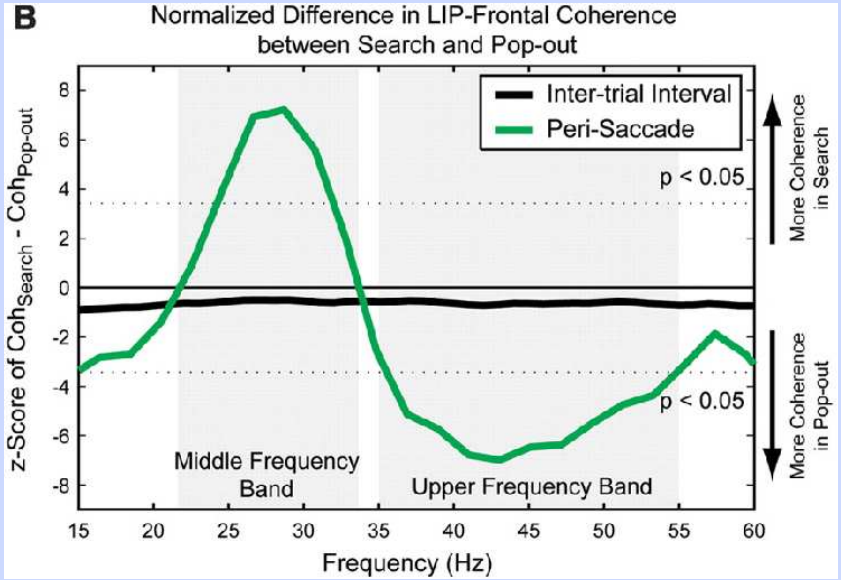

- greater low freq pfc-parietal synchronization for top-down
- greater high freq synchrony for bottom-up

The Range of Frontal Functions

Activation-based working memory

Inhibition Stroop: Difficulty inhibiting prepotent response.

The Stroop Task

The Stroop Task

Pink

The Stroop Task

Pink

Yellow

The Stroop Task

Pink

Yellow

Green

The Stroop Task

Pink

Yellow

Green

Red

The Range of Frontal Functions

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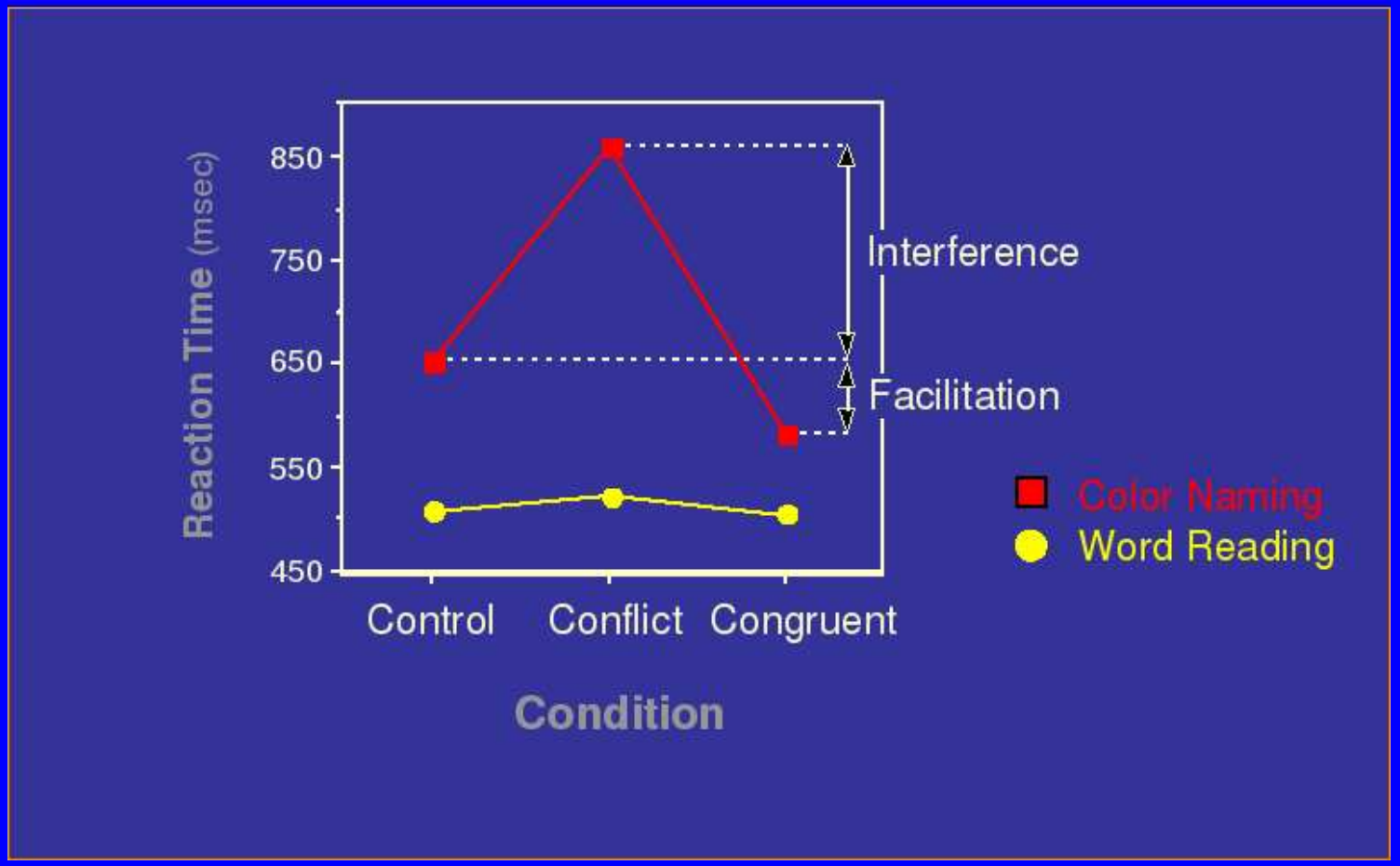
The Stroop Effect



Stroop Effect: *GREEN*

Possible explanation: **differential pathway strength**

- two pathways: word reading and color naming
- These **compete** to generate response
- Word reading pathway is much stronger than color naming
- When word identity information doesn't match color, it **interferes strongly** with color naming

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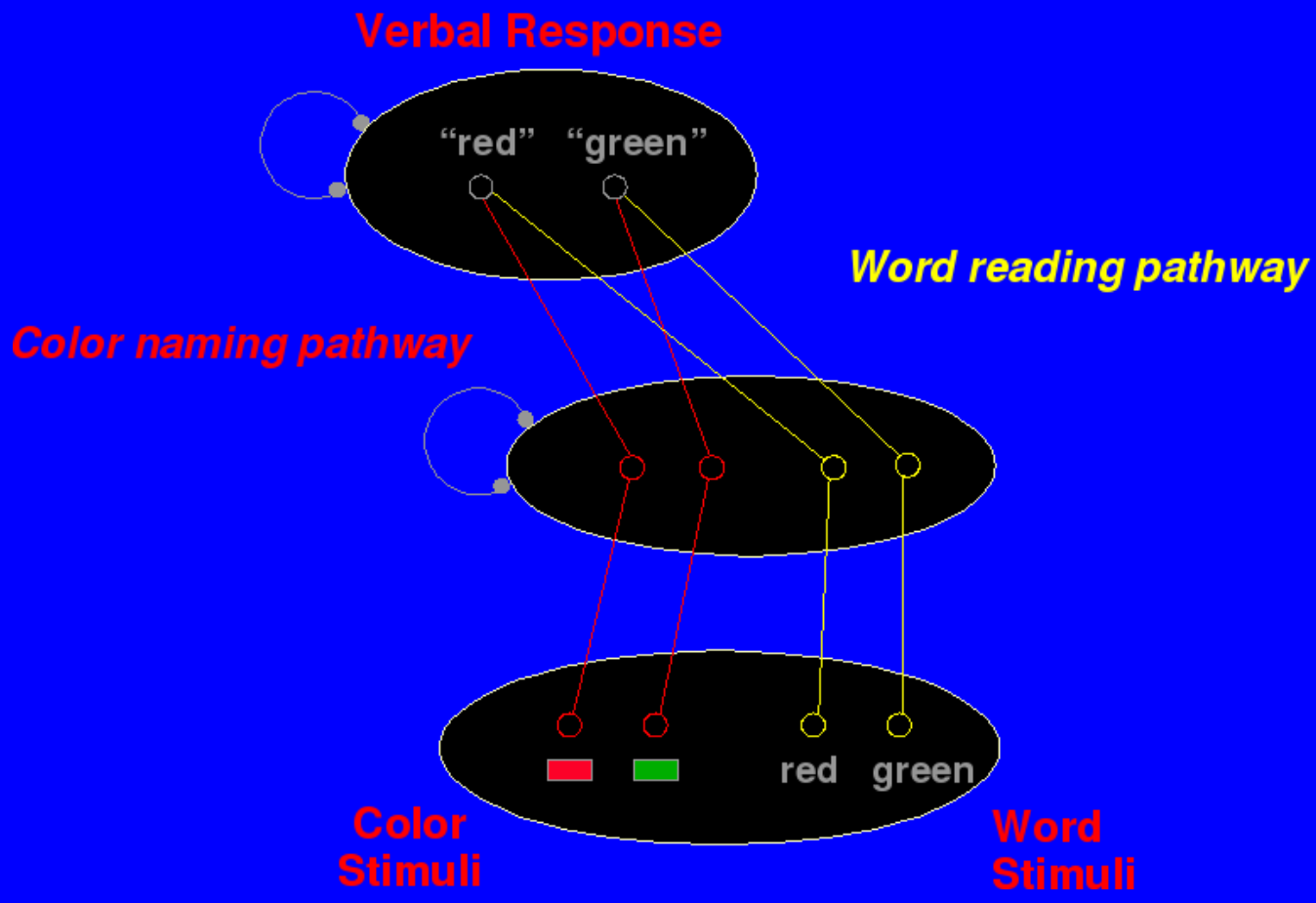
- two pathways: word reading and color naming
- These **compete** to generate response
- Word reading pathway is much stronger than color naming
- When word identity information doesn't match color, it **interferes strongly** with color naming
- Because color pathway is relatively weak, incongruent color info does not interfere with word reading

Stroop Effect: *GREEN*

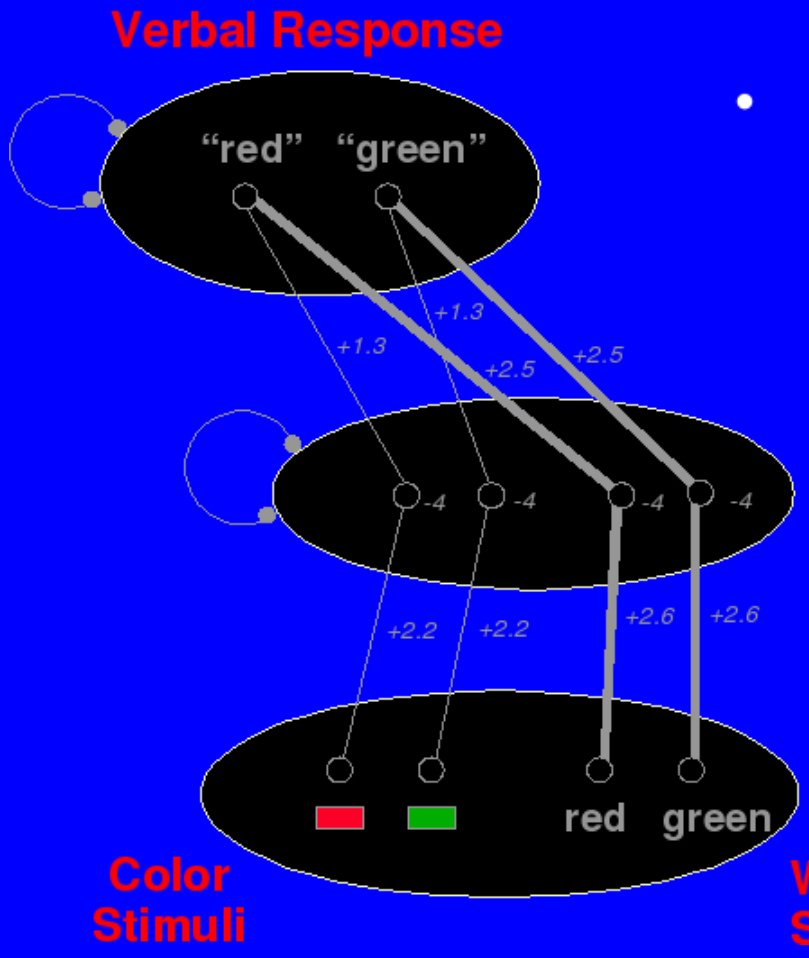
- Puzzle: If the color naming pathway is weaker than word reading, how do we manage to name color of the word "green" above?
- Solution: Prefrontal cortex *actively maintains* a representation of the task that you are supposed to be doing (color naming or word reading)
- This actively maintained task representation **biases processing** in posterior cortex by activating units in appropriate pathway
- e.g.,color naming task rep in PFC sends activation to the units in color naming pathway...

Model of the Stroop Task

(Cohen, Dunbar & McClelland (1990)



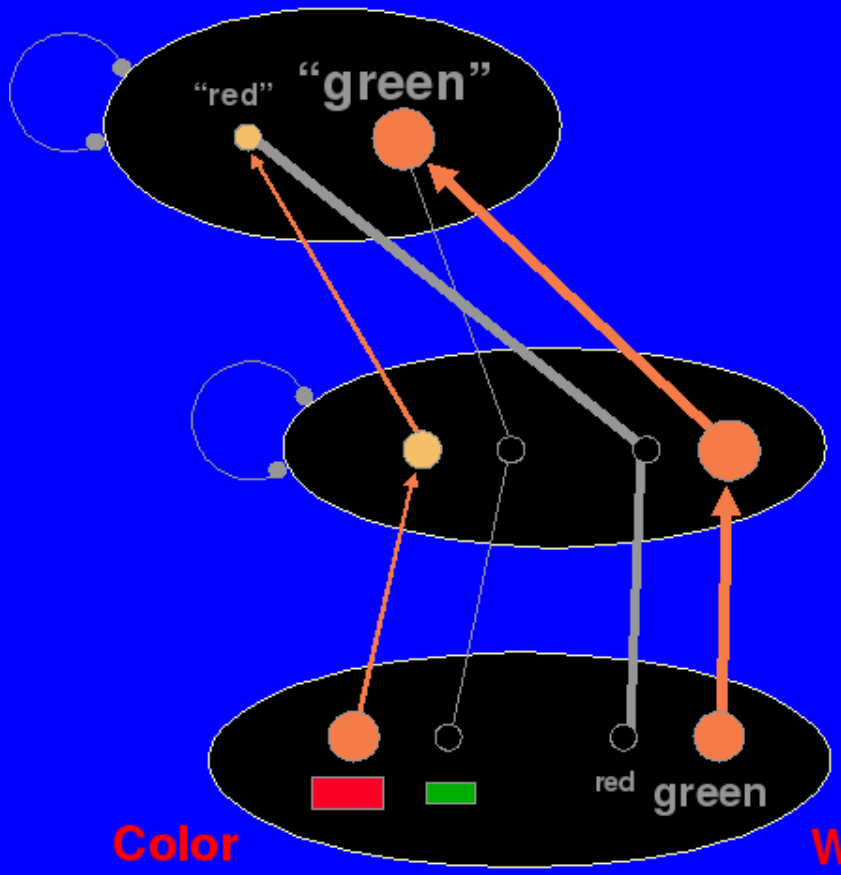
Effects of Training



- Word pathway:

  More training = stronger weights

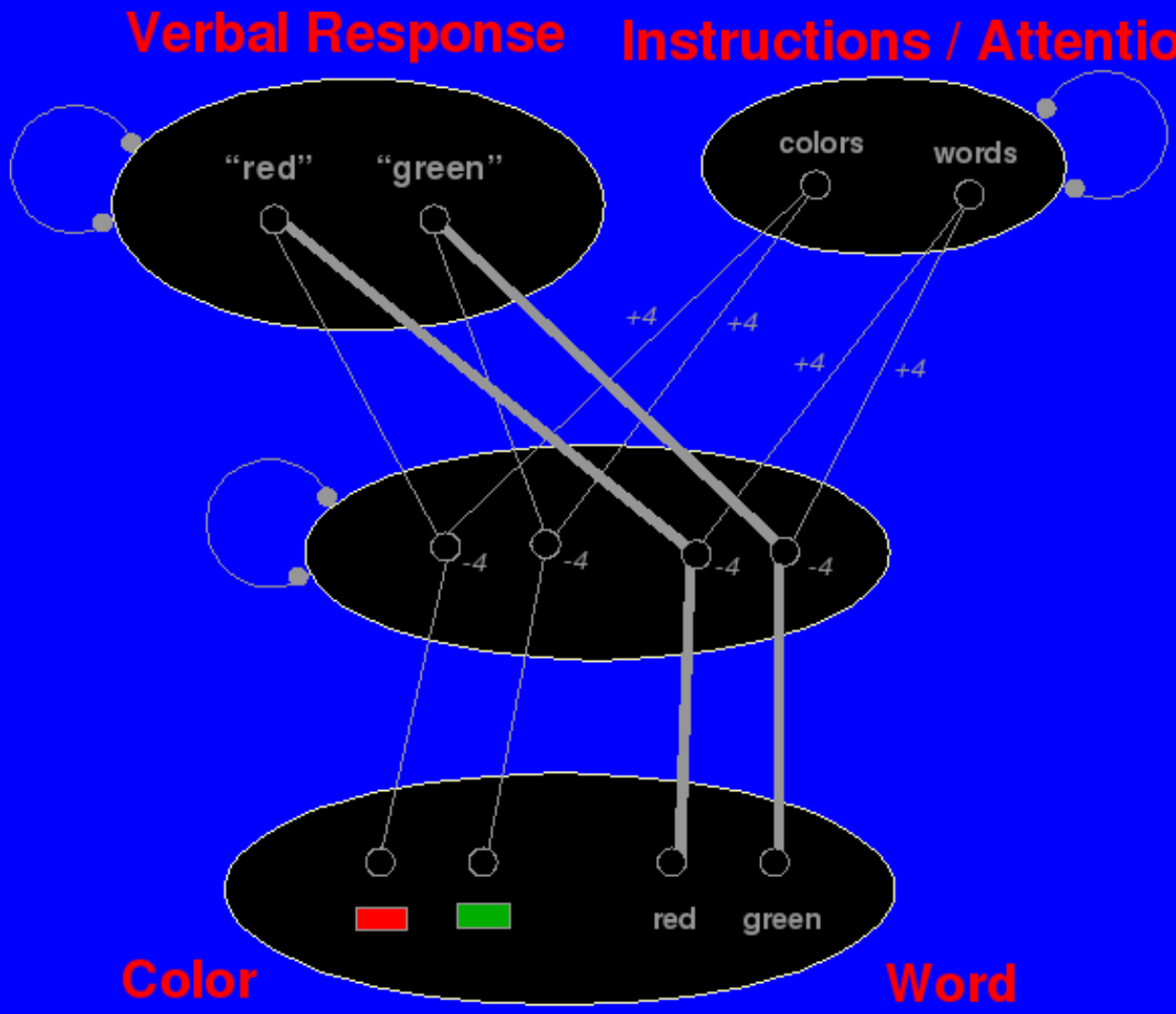
Verbal Response

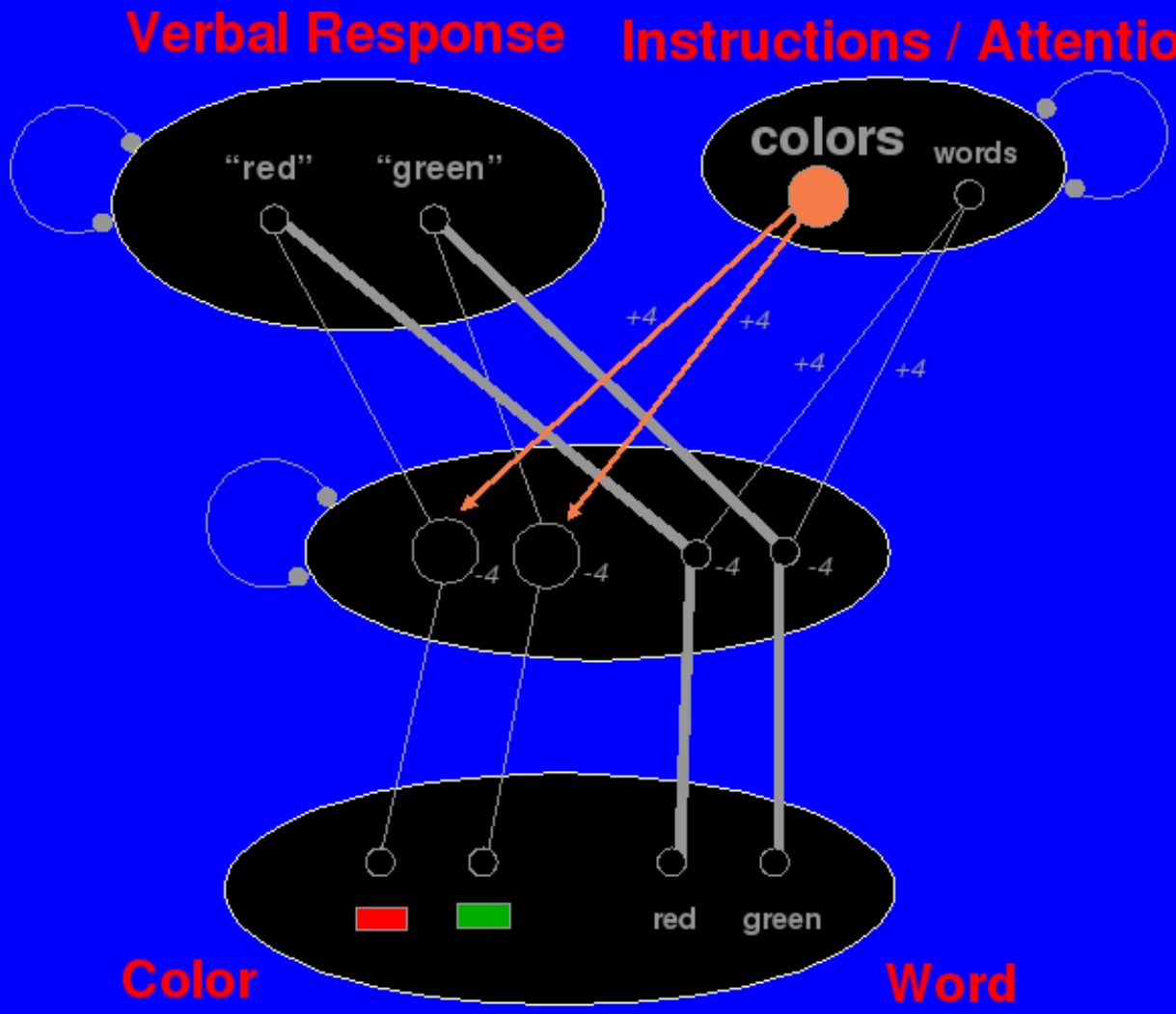


Color Stimuli

Word Stimuli

GREEN


Verbal Response
Instructions / Attention
"red"
"green"
colors
words
+4
+4
+4
+4
-4
-4
-4
-4
red
green
Color Stimuli
Word Stimuli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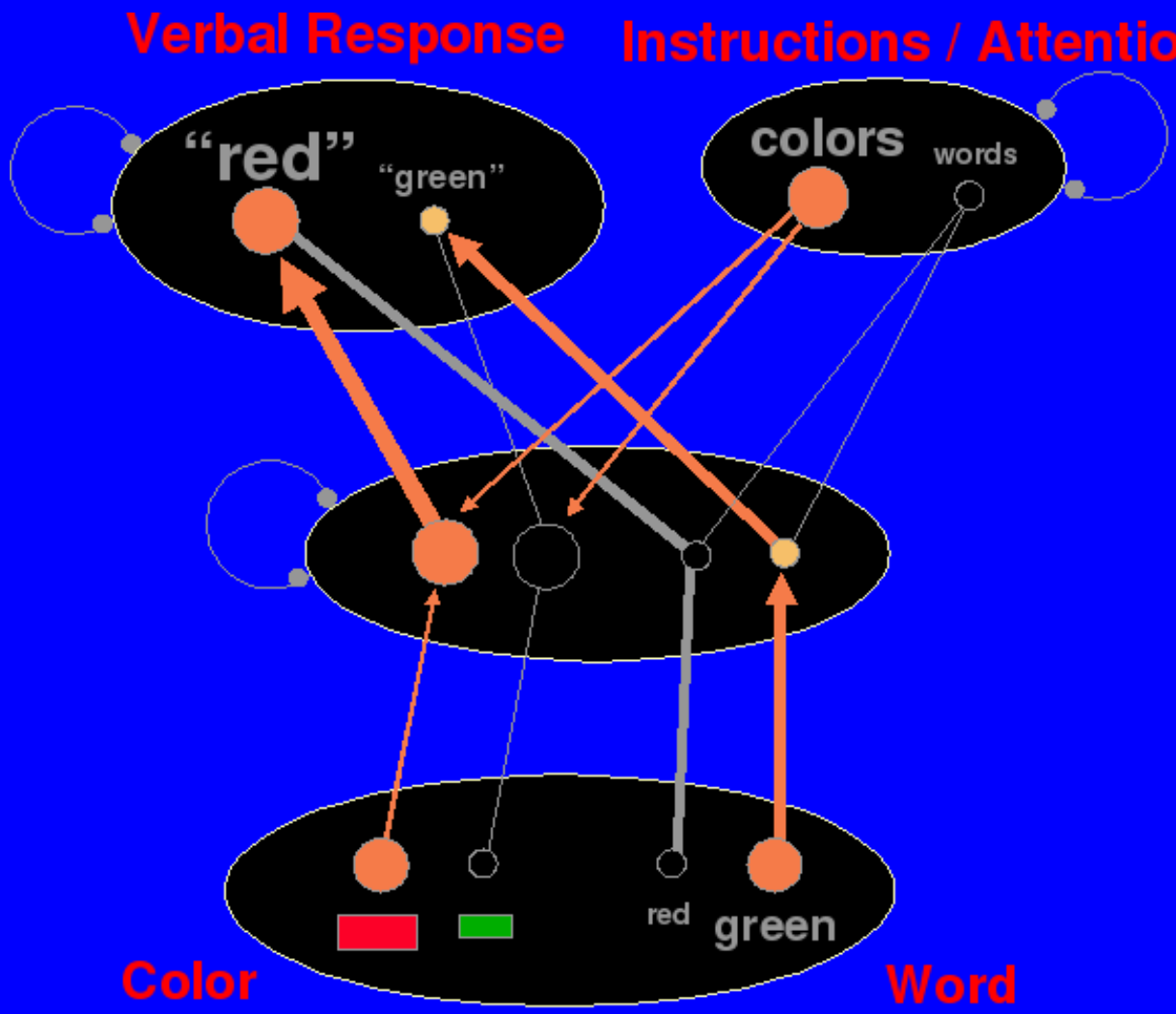
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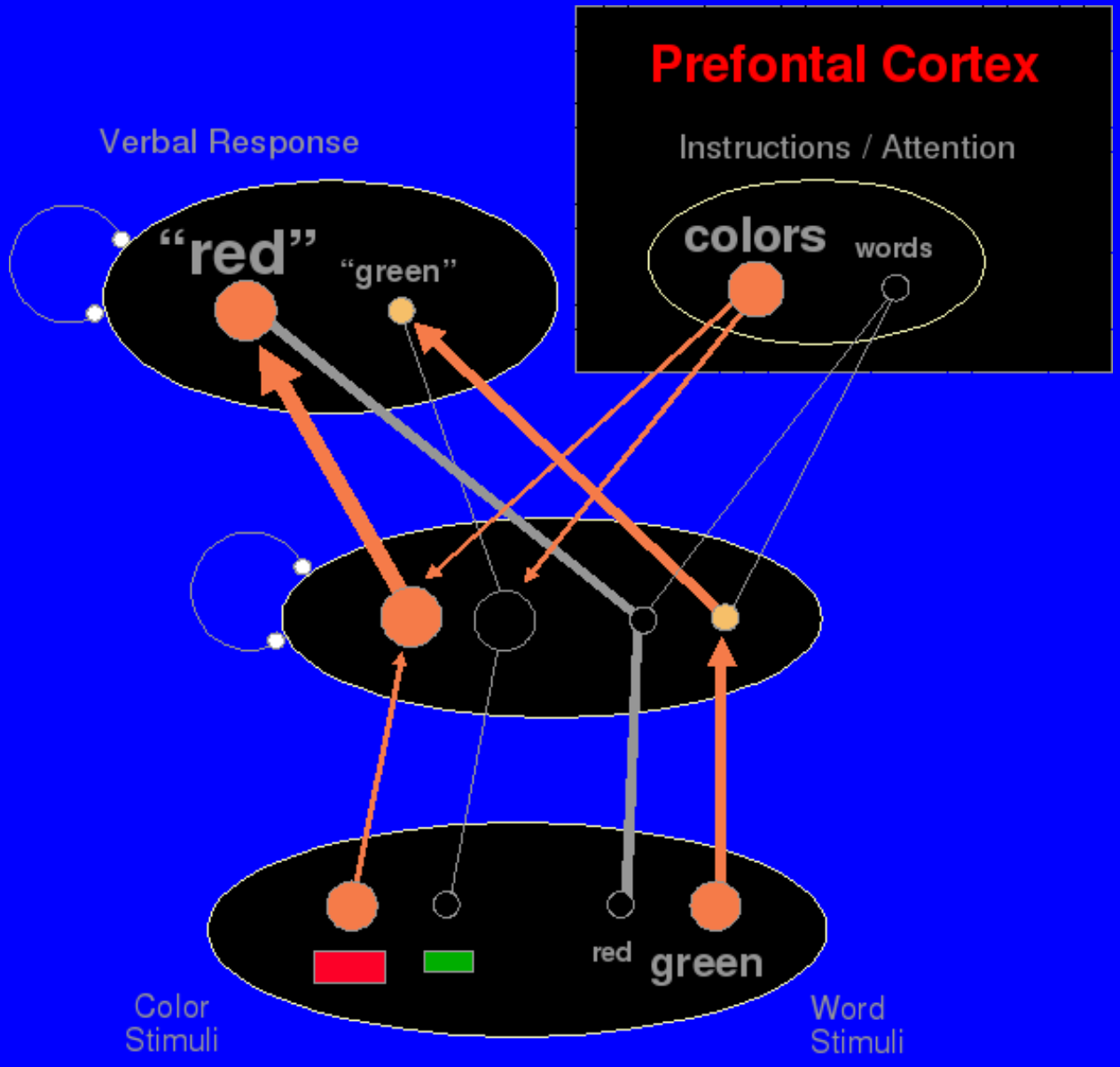
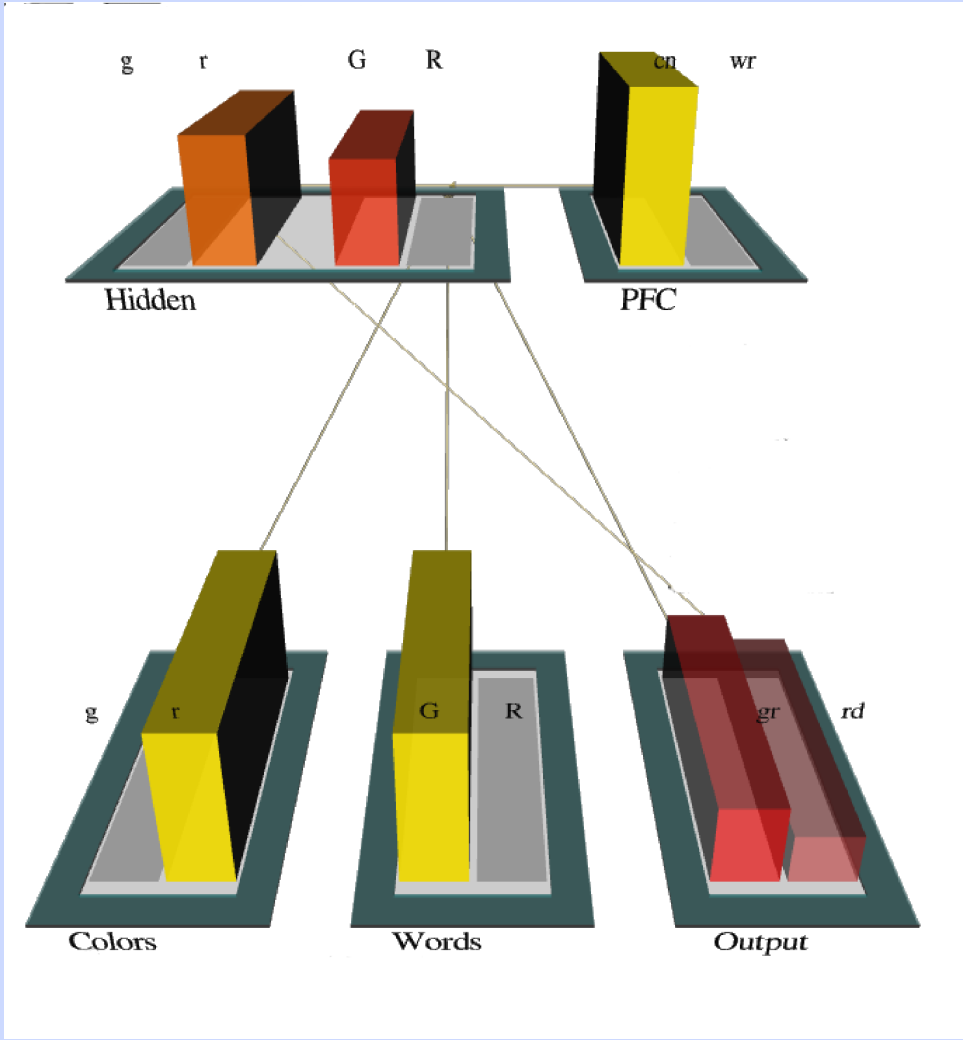


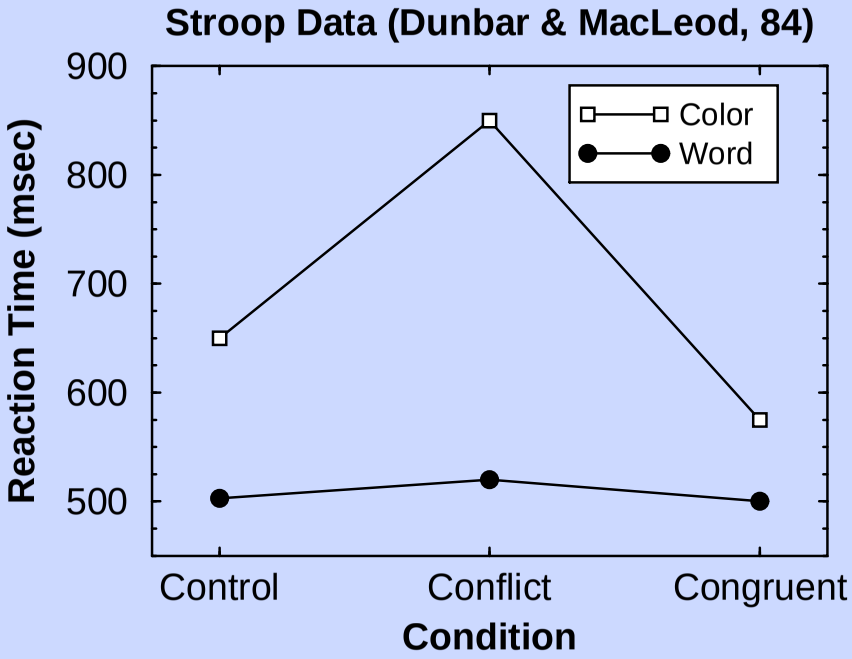
Stimulus: GREEN

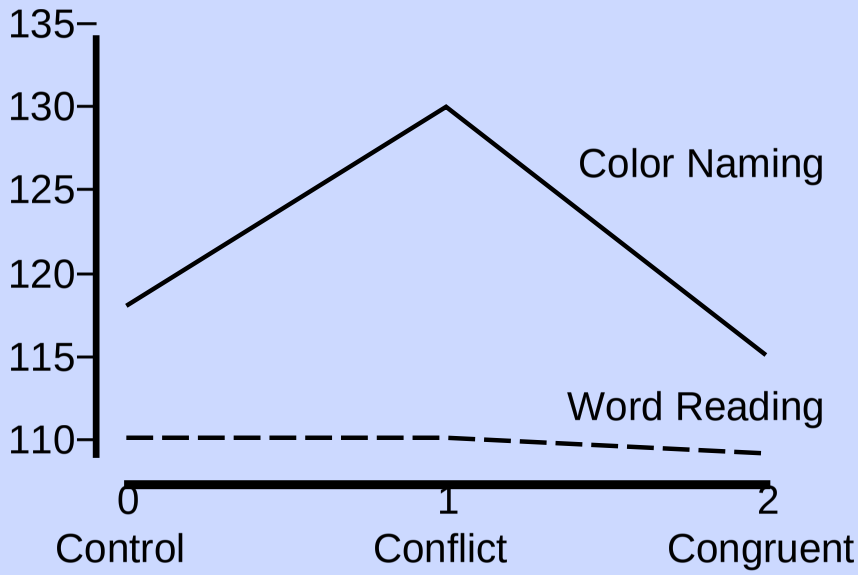
Stroop Model



The Stroop Task: Model Data

Control: Red. Conflict: Red. Congruent: Red.





Pathway Strength vs Processing Speed Theories

- Model: the key difference between word reading and color naming is **pathway strength** (reading $>$ color naming). This results in:
  - Word reading being faster than color naming
  - Asymmetric interference effects
- Other (verbal) theories posit Stroop effects resulting from a **horse race** rather than direct **competition**

Horse Race Theories

- Color does not affect word reading because the word reading process runs to completion before color is processed
- Conversely, word identity **does** affect color naming because word reading process completes before color response is generated
- This theory, stated as such, implies that it should be possible to get color to interfere with word info if the color naming process has a *head start*

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Stroop Accounts: Not a Horse Race

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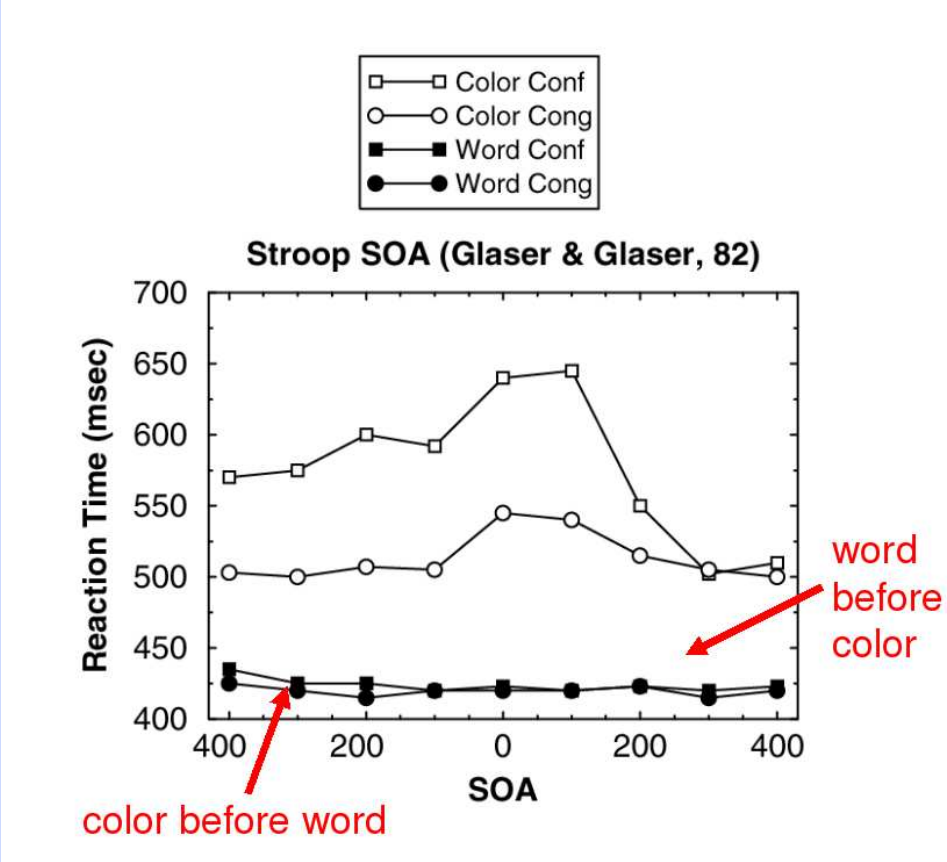
$\Rightarrow$ *GREEN*

Stroop Accounts: Not a Horse Race



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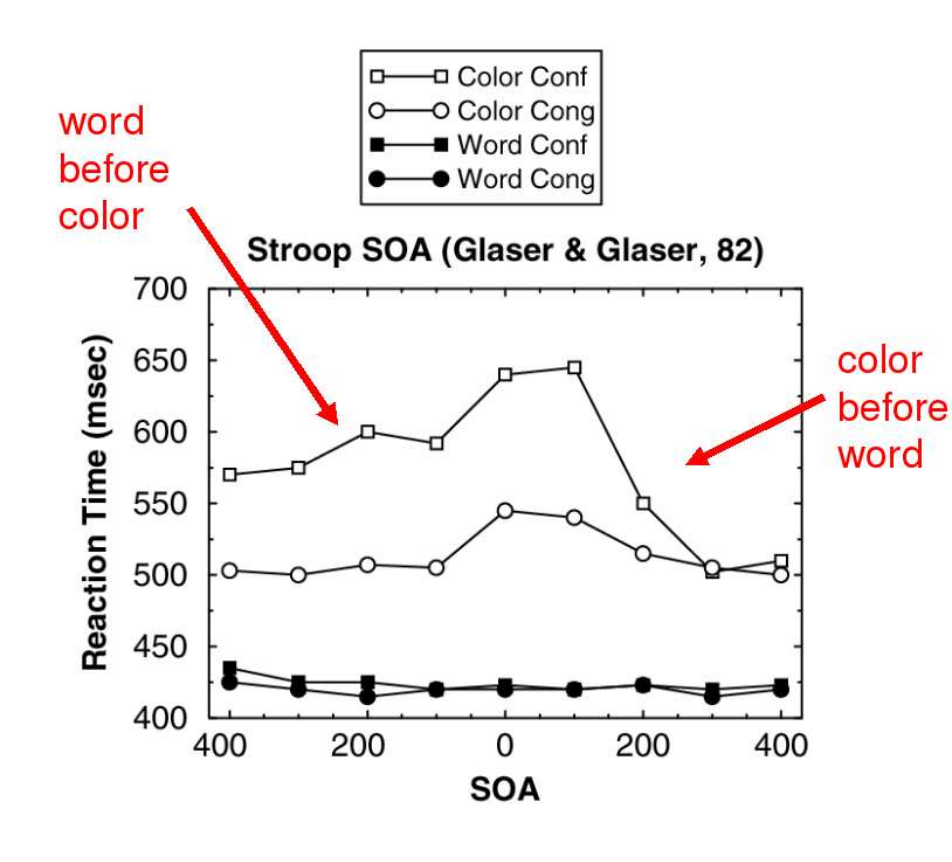

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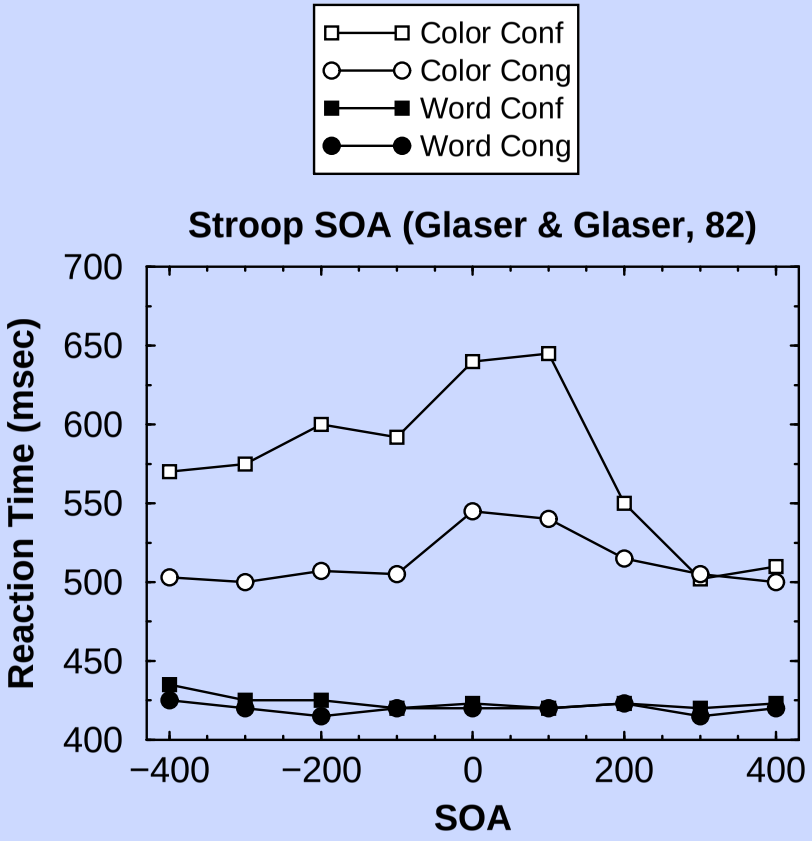

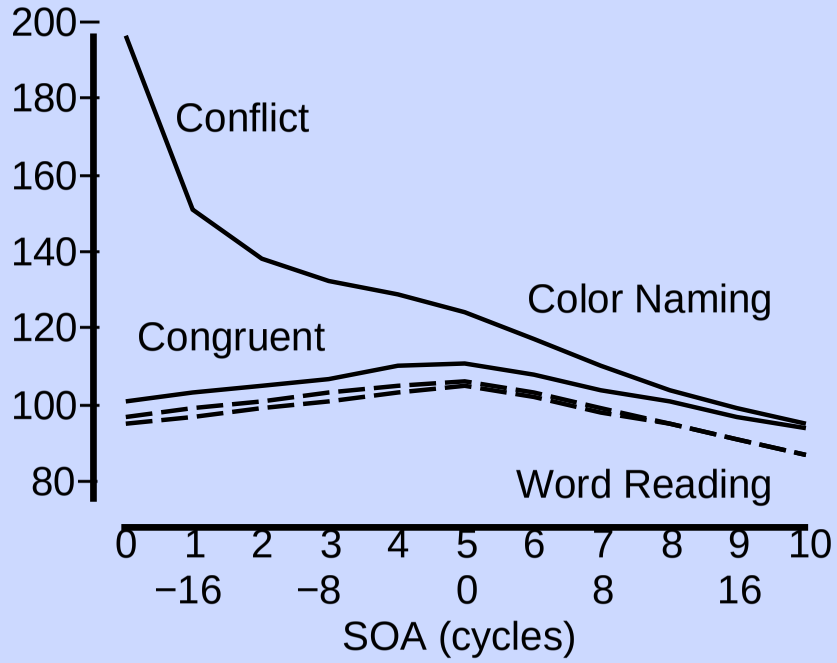

Stroop Accounts: Automaticity

- Early accounts of Stroop focused on automatic vs controlled processing
- According to these theories, word reading is **automatic** and color naming is a **controlled** process.
- Automatic processes don't suffer from interference (they proceed "automatically") but controlled processes do.
- categorical distinction

Stroop Accounts: Automaticity

- Status (whether a process is controlled or automatic) depends on **absolute** pathway strength

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- In contrast, model focuses on **relative** pathway strength - stronger pathway interferes with less strong pathway (but not vice-versa)
- *Prediction*: If we could come up with a task that is **even less** well-learned than color naming, we will find that:
- New task will have no effect on color naming
- Color naming will interfere with new task

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- *Prediction*: If we could come up with a task that is **even less** well-learned than color naming, we will find that:
- New task will have no effect on color naming
- Color naming will interfere with new task
- As new task is practiced repeatedly, effects should reverse

Stroop Accounts: Continuum, not a Dichotomy

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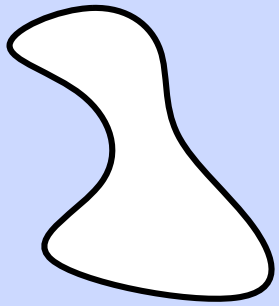
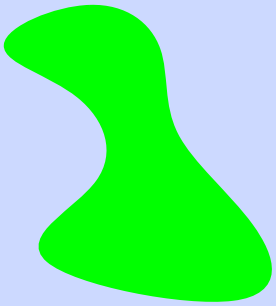
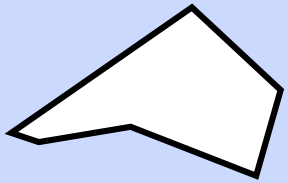
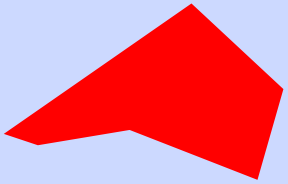


"blue"



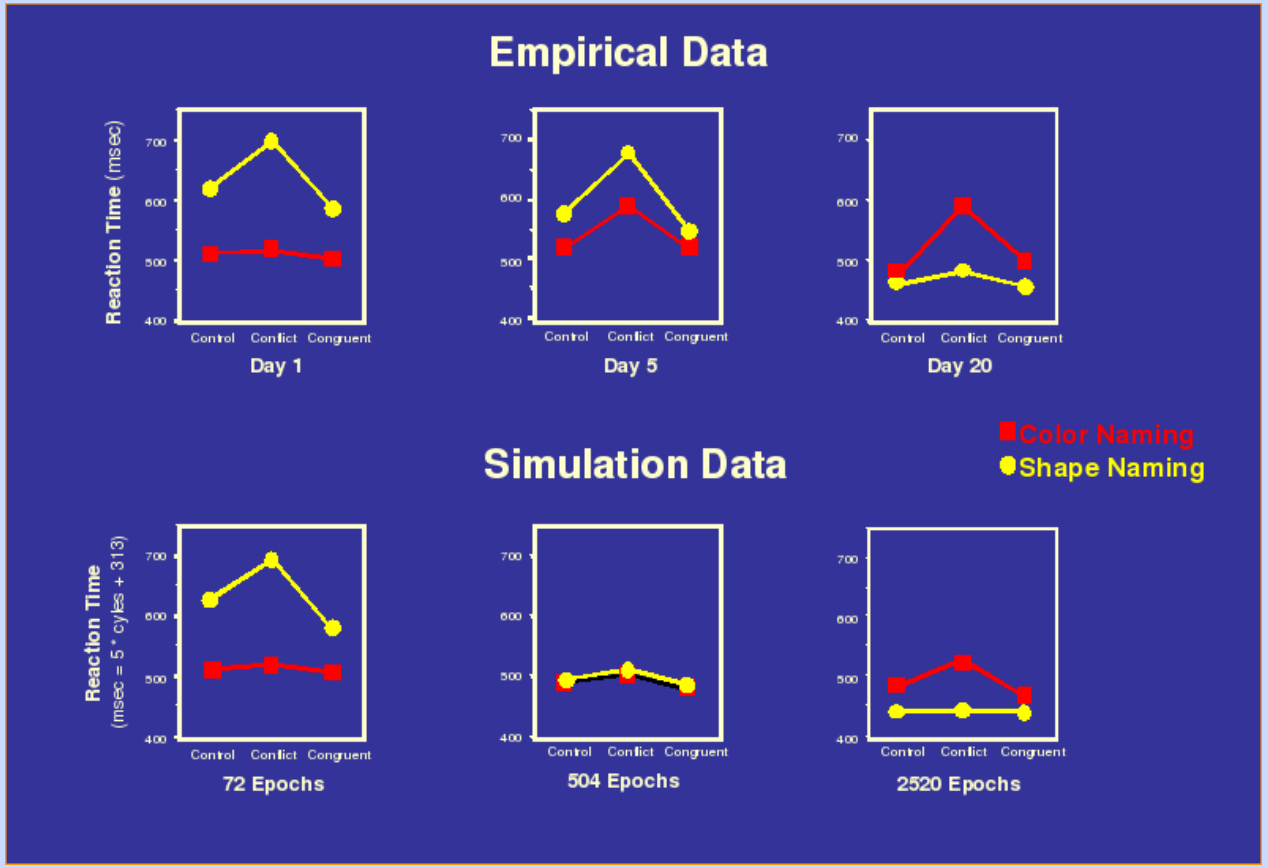


"red"



Shape-naming first like color-naming in standard Stroop,
then like-word reading.

Stroop Accounts: Continuum, not a Dichotomy



MacLeod & Dunbar, 1988

The Stroop task model ... demonstrates the role of a top down influence on activation-based processing mediated by frontal cortex. What I think is the downside of models like this is that the prefrontal cortex is represented by a layer of just two units, meant to condense its function. To me, these units seem sort of like preprogrammed grandmother cells, in the sense that the rules and representations for ”color naming” and ”word reading” aren’t really learned by the network. The user of the model understands how these units are working, but they seem sort of like an unnaturally simplistic way to replace a bigger, more powerful system. I’m wondering if the two-unit PFC layer of this network could be replaced by a hidden layer (or perhaps something else) so that the cn and wr tasks could first be learned by the PFC and then applied to the Stroop task. This would make the PFC in the model more flexible to learn new rules (if say the input had another dimension besides color or word–size or font could be examples). Essentially what I’m asking is, can the PFC in this model be replaced with a layer(s) that would make the network better able to handle more rules and tasks given a set of inputs?

But how do PFC units come to represent task rules??

- Stroop model is a nice simple account of PFC function, but it somehow assumes that PFC 'knows' how to maintain a rule for color naming and to magically bias color-naming hidden units

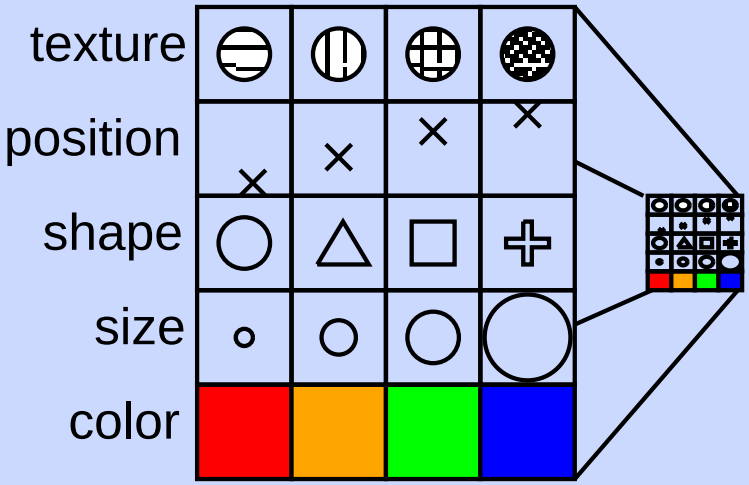
- Interesting question is how these rule-like representations develop in the first place?

- Can PFC *learn* to assign *abstract* rule-like representations that code for *stimulus dimensions* (e.g., color) by experience (with multiple colors)??

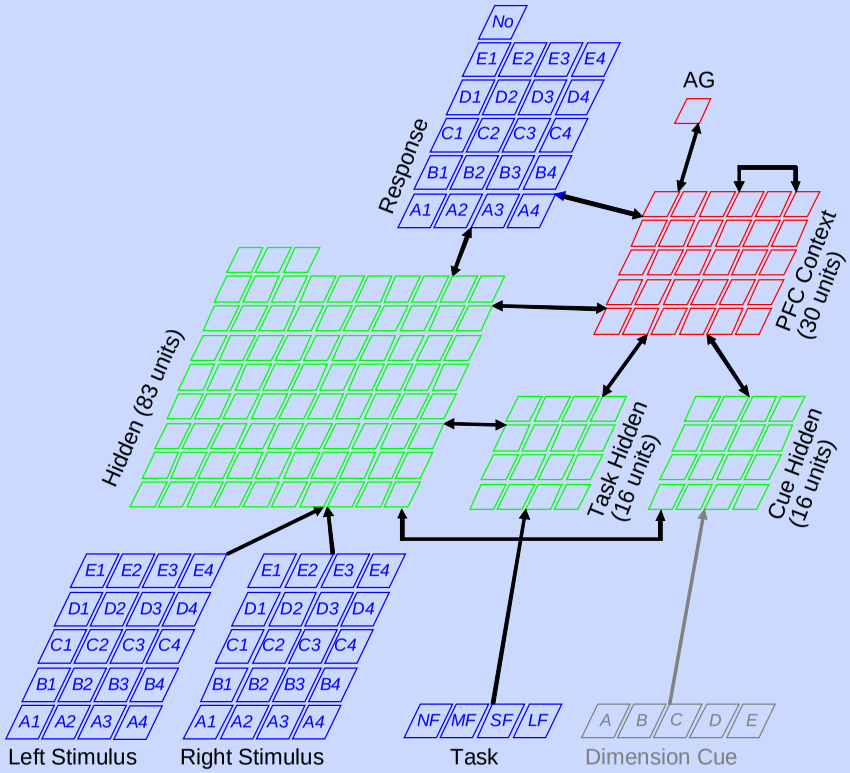
PFC Specializations → Rule-Like Abstract Reps

(Rougier, Noelle, Braver, Cohen & O'Reilly, *PNAS*)

Stimuli

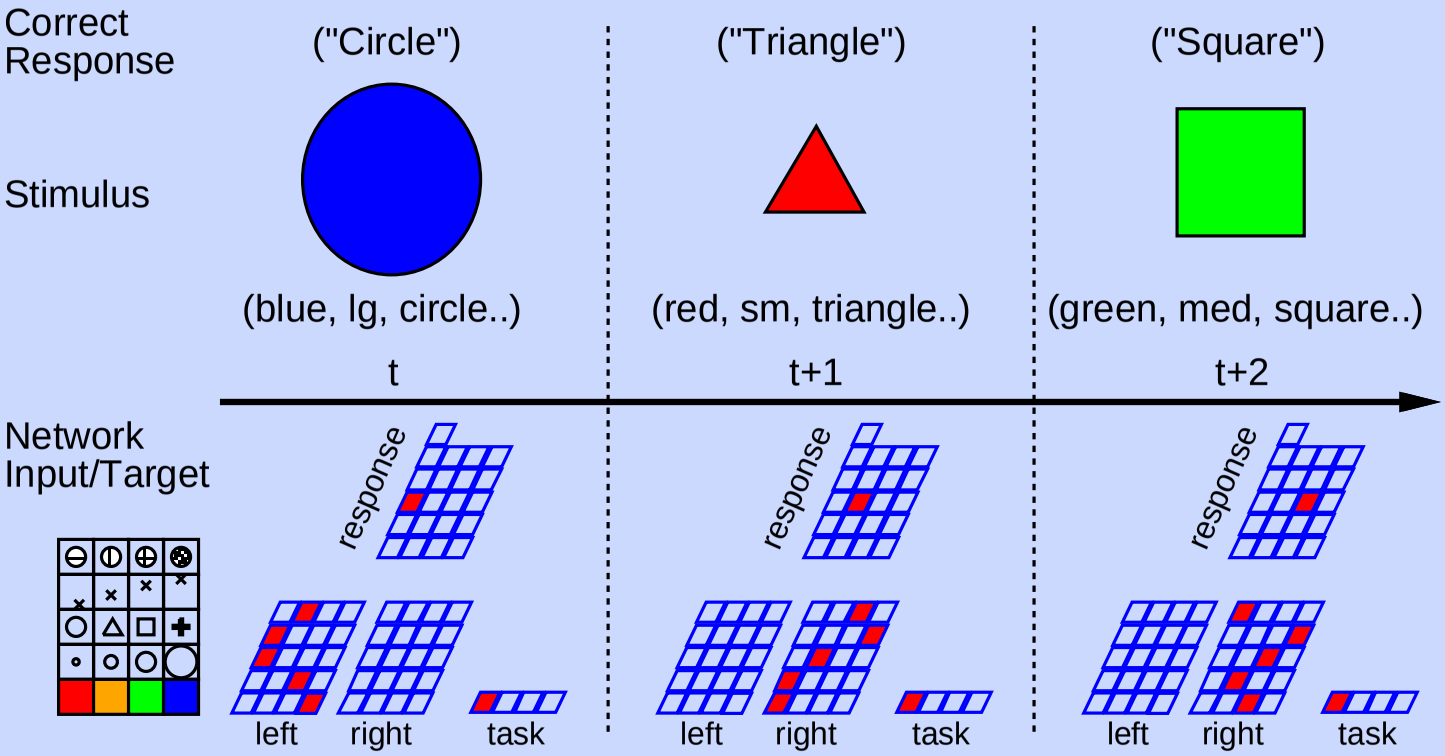


Network



Developing PFC Reps

(Rougier, Noelle, Braver, Cohen & O'Reilly, *PNAS*)



Task 1 = Name the Shape (or color, etc)

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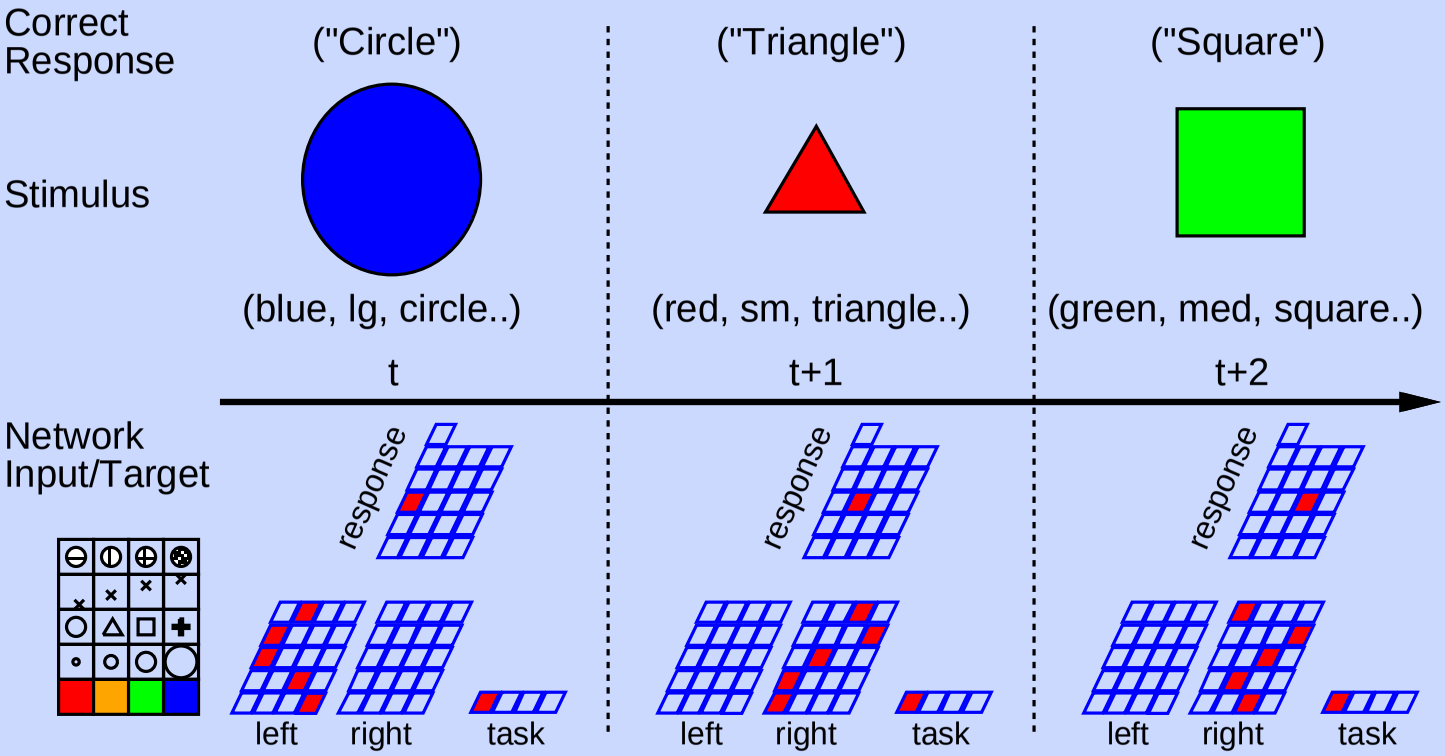

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Task2: Do two stimuli match along some dimension? (yes/no)
Task3: Which object is larger? etc.

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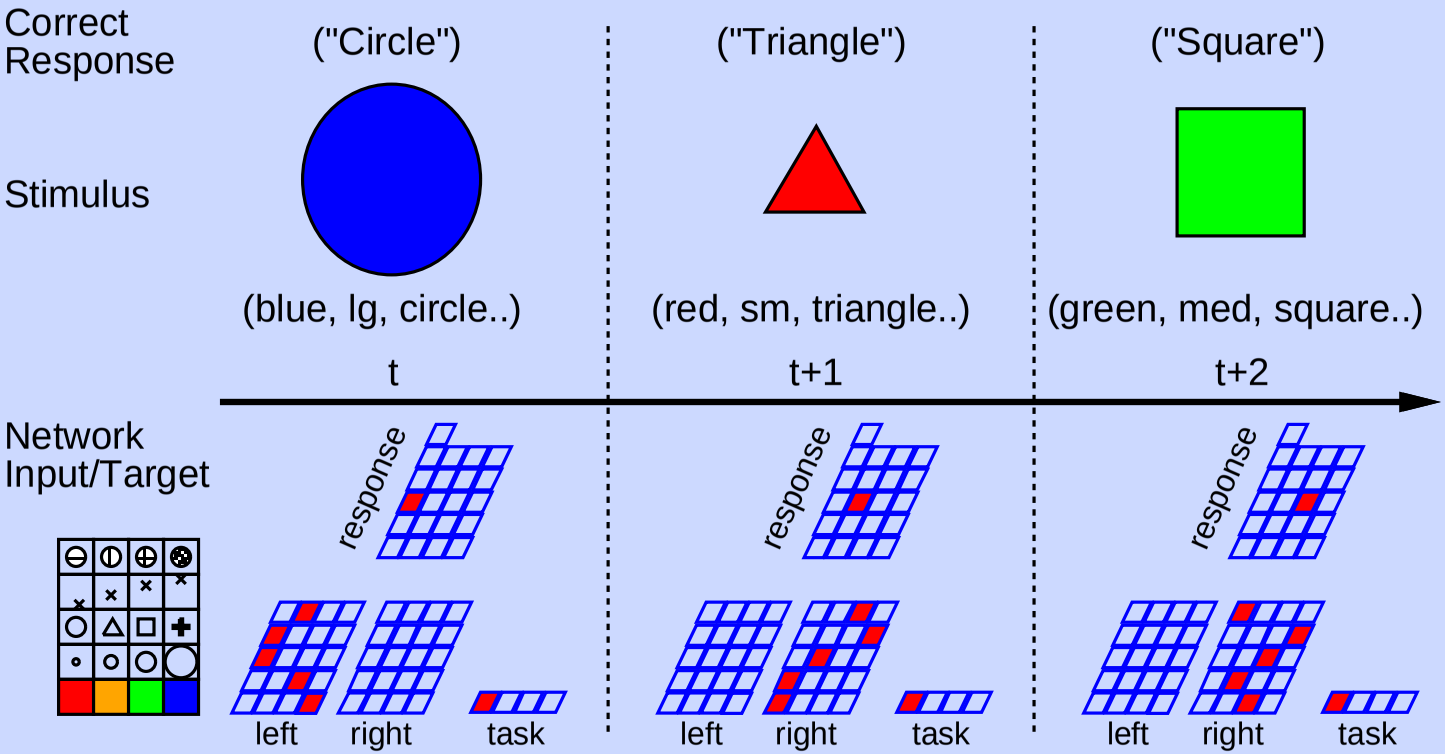

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Task3: Which object is larger? etc.

Key: Do repeated trials of same task – continuous attention to shapes, etc

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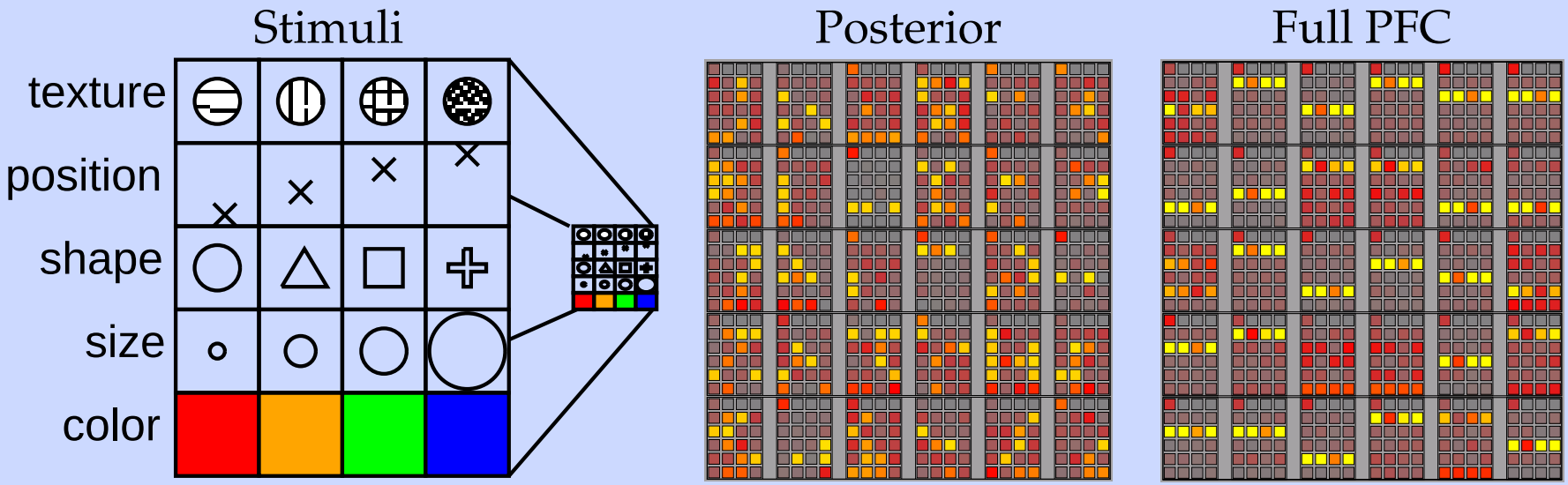
Weights from PFC or Hidden to output response units



Rule = One stimulus dimension (row) relevant at a time. (e.g., card-sorting tasks)

Abstraction derives from sustained maintenance over trials!

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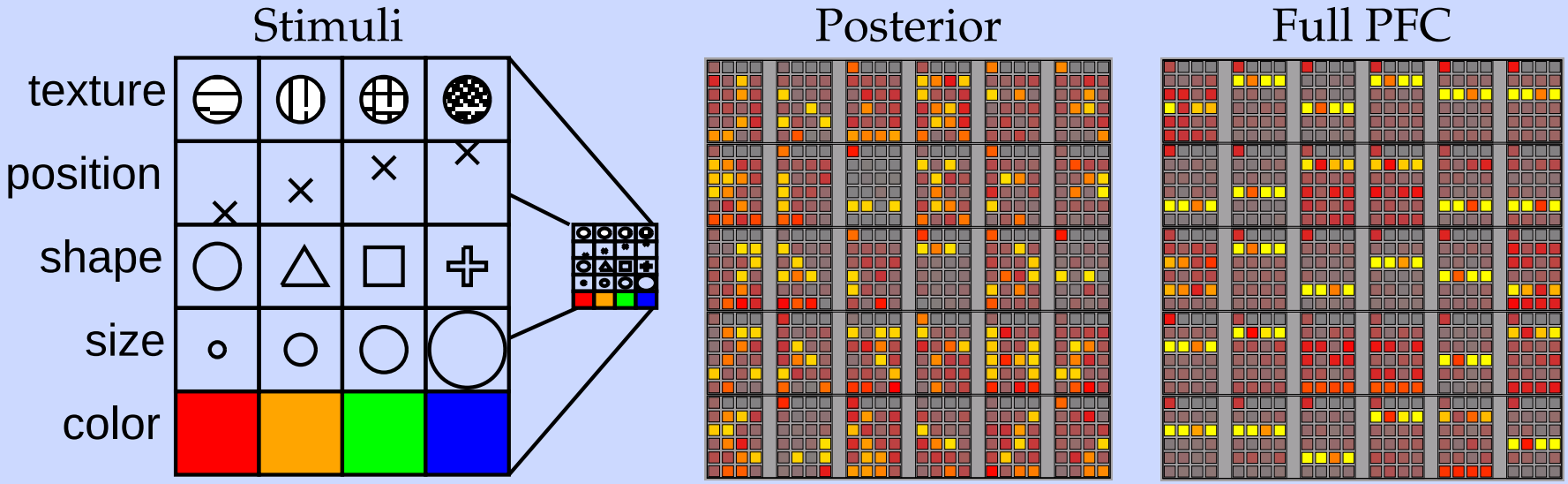

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Posterior net 'memorizes' specific combinations of features/responses for each task, doesn't develop systematic representations

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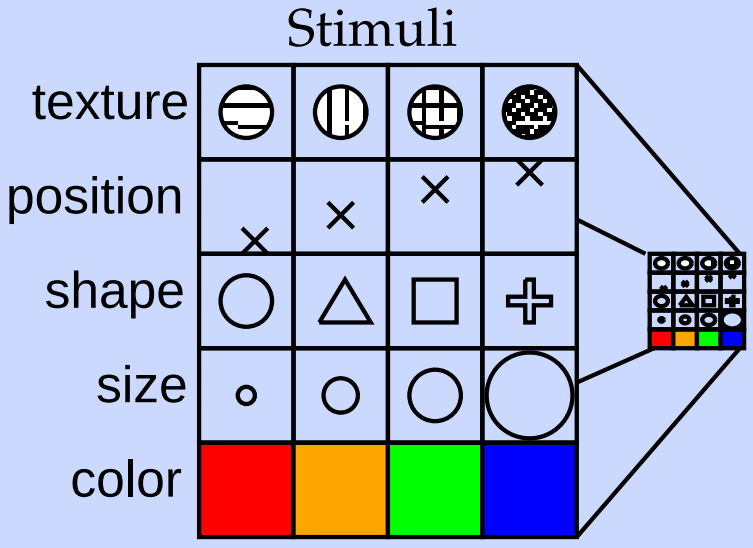

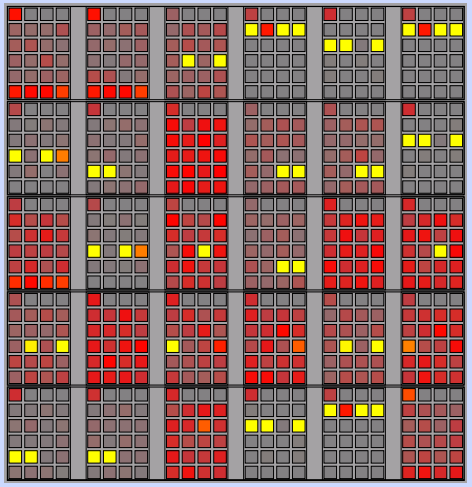

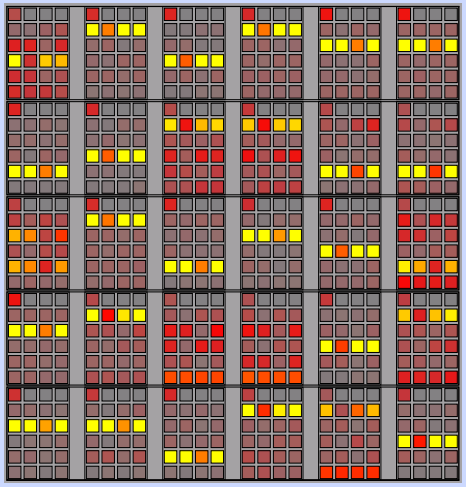

Adaptive gating is key:

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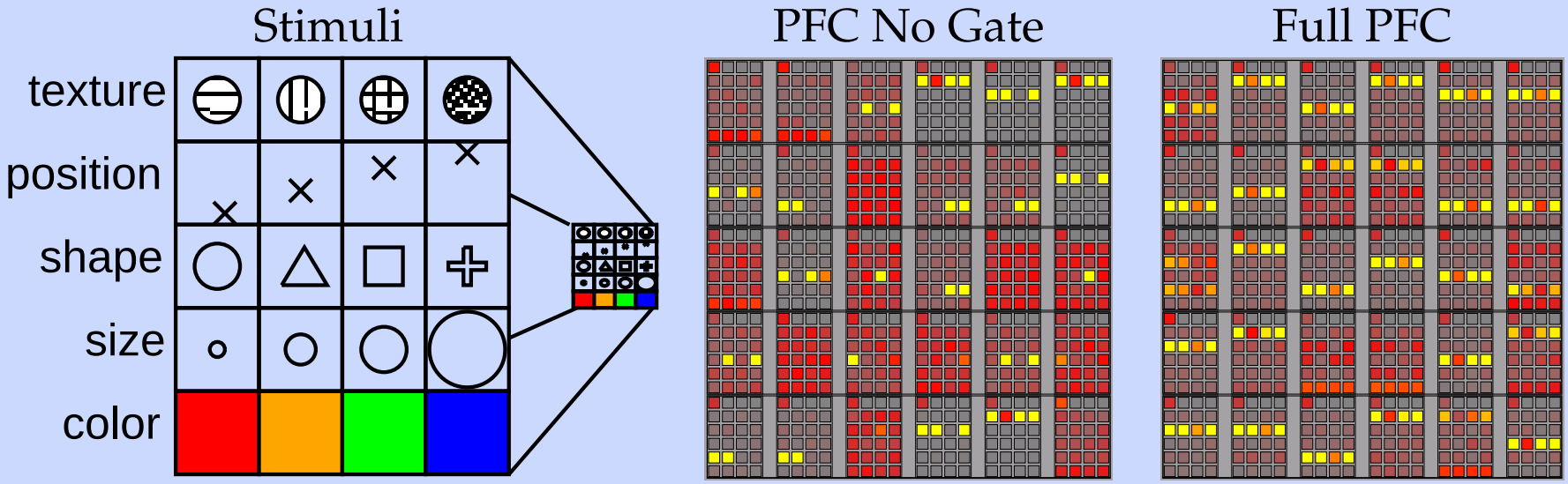

Adaptive gating is key:

within block of trials feature changes but gating mech learns to maintain constant PFC rep (until rule switches, performance goes down → update)

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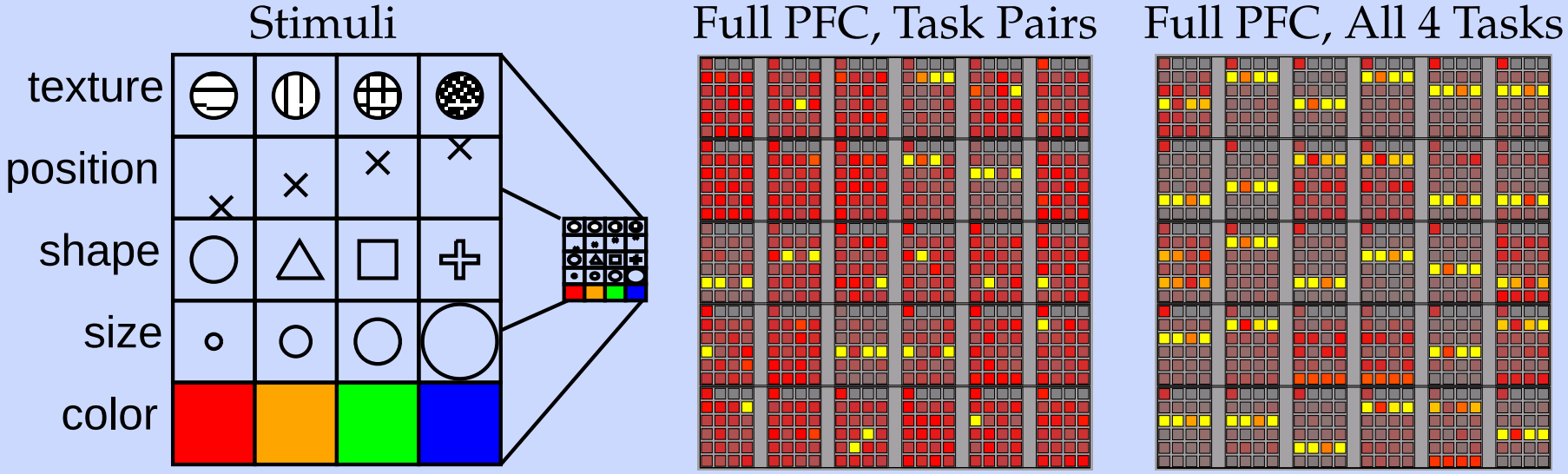
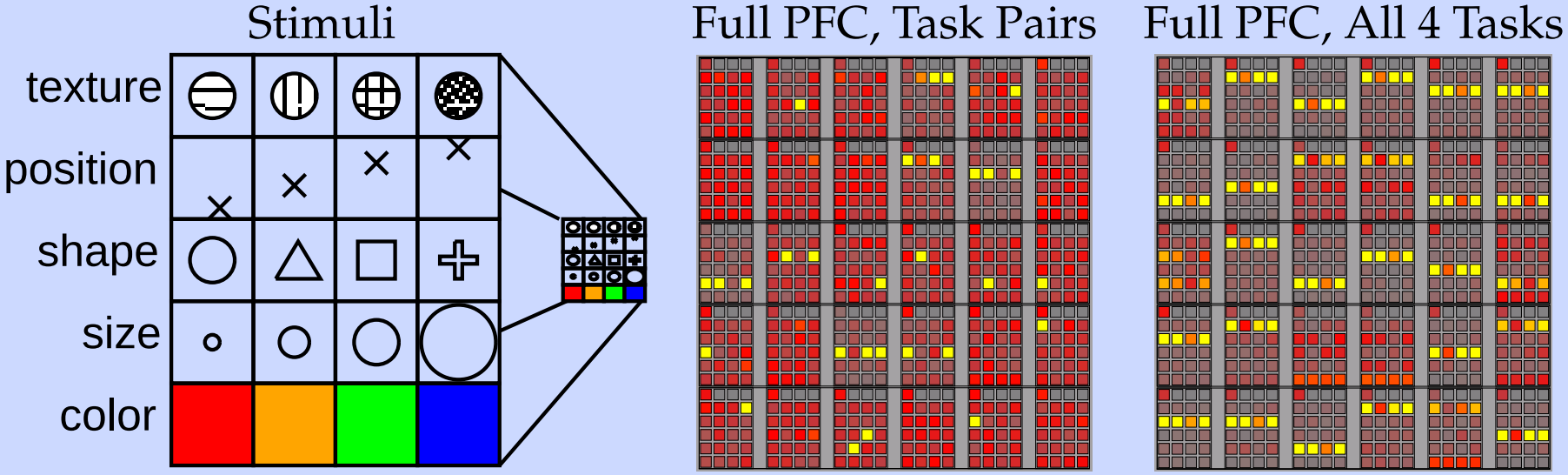


As is breadth of experience (same stimuli across different tasks)

PFC Specializations → Rule-Like Abstract Reps

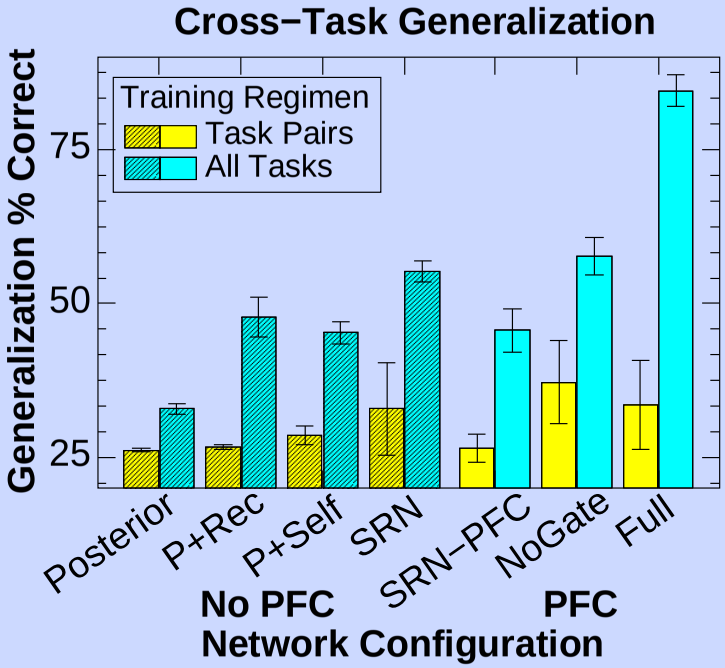
(Rougier, Noelle, Braver, Cohen & O'Reilly, *PNAS*)

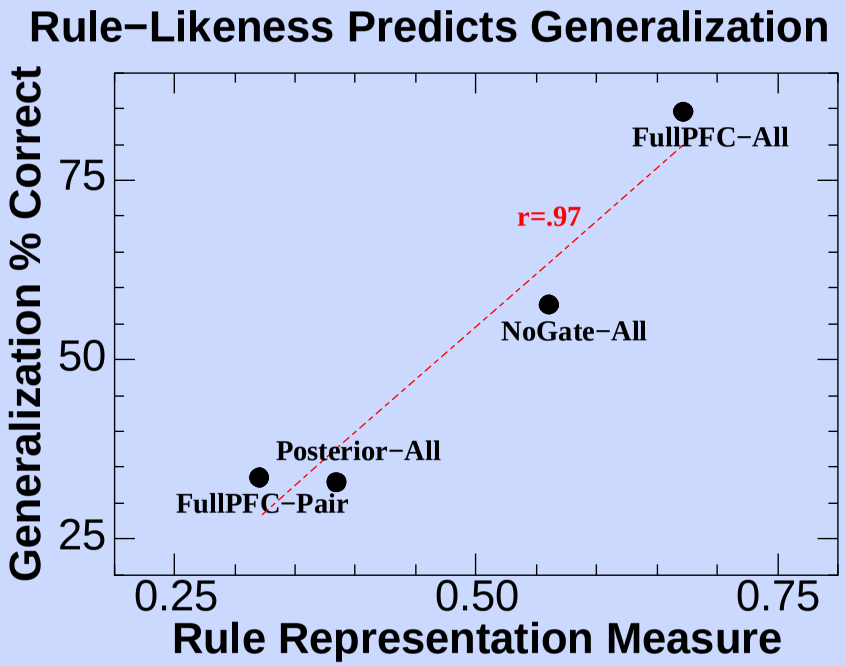


As is breadth of experience (same stimuli across different tasks)

(increasing pressure to use same pfc reps across tasks → systematicity); with small # tasks can get by with memorizing)

Rule-Like Abstract Reps → Generalization

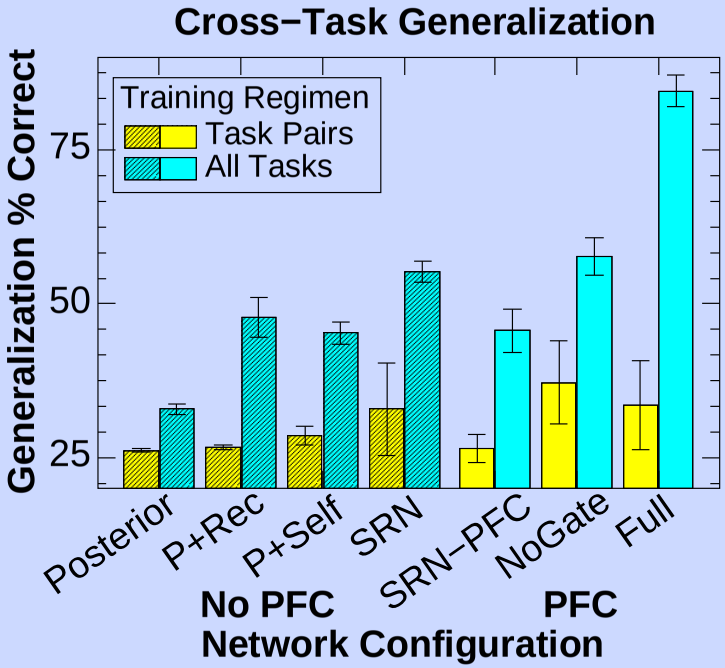


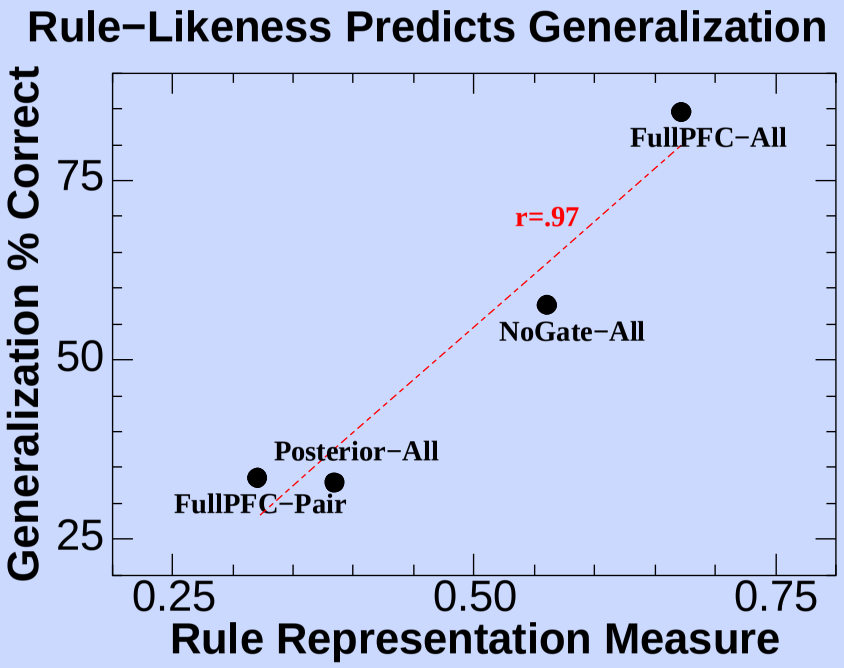


Abstraction → better generalization across tasks

(accuracy on stims not seen in particular task).

Rule-Like Abstract Reps → Generalization





Abstraction → better generalization across tasks
(accuracy on stims not seen in particular task).

Interaction of nature (PFC mechanisms) and nurture (breadth of experience).

Stroop Performance

(Rougier et al, *PNAS*)

Stroop Performance

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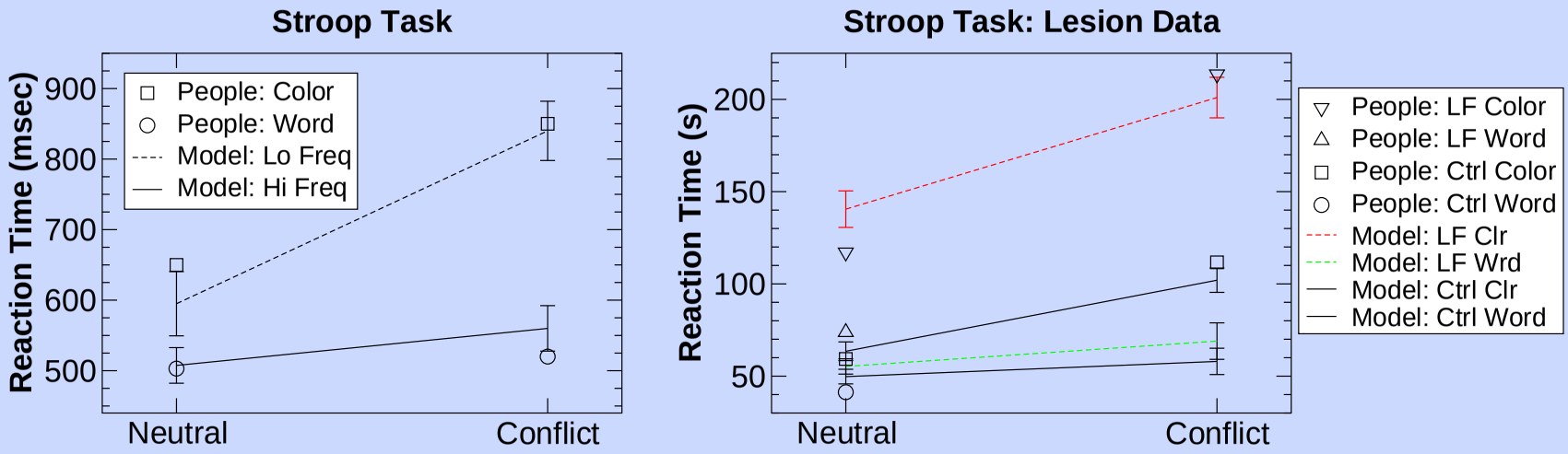
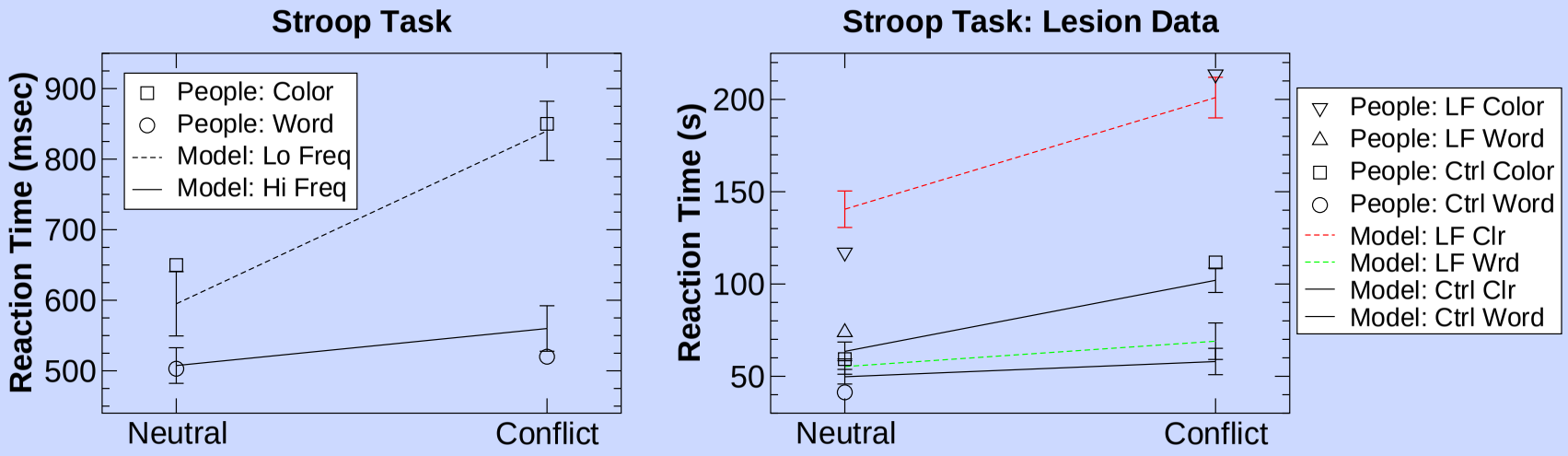


Same network & parameters: PFC control representations developed entirely through learning from random initial weights!

Stroop Performance

(Rougier et al, *PNAS*)



Same network & parameters: PFC control representations developed entirely through learning from random initial weights!

LF = left frontal (DLPFC) lesions in people and model (posttraining, 30% damage)

The Range of Frontal Functions

Activation-based working memory Monkey electrophysiology.

Inhibition Stroop: Difficulty inhibiting prepotent response.

Flexibility Continue with same response after task changes, *perseveration*.

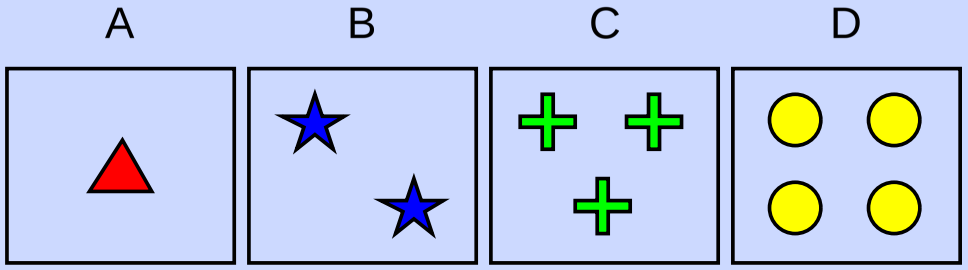
Fluency Difficulty generating variety of responses.

Executive control Probs w/ goal-directed planning, coordinating.

Monitoring/evaluation e.g., Error-monitoring.

Dynamic Categorization Tasks

Wisconsin Card Sort



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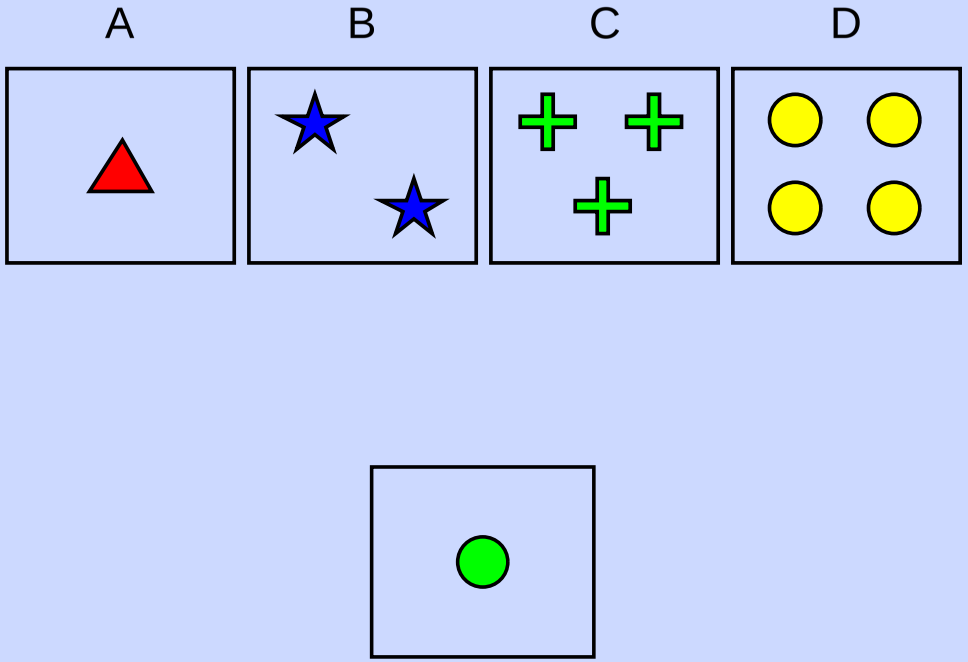

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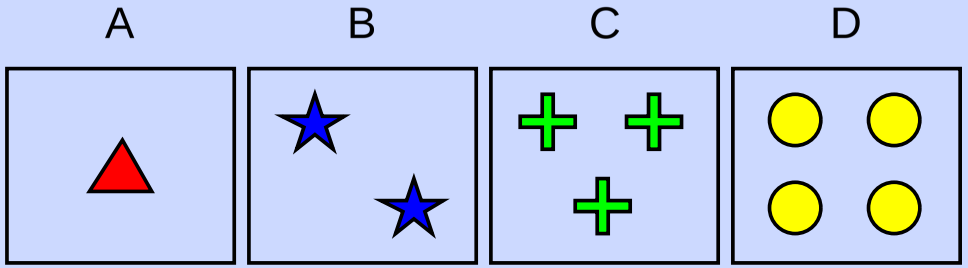

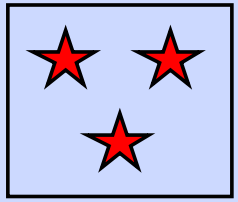

Dynamic Categorization Tasks

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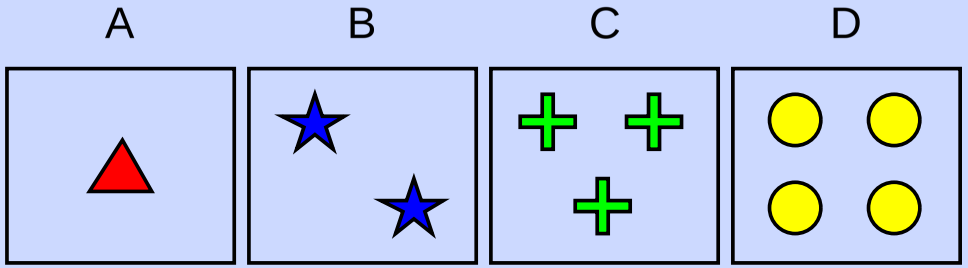

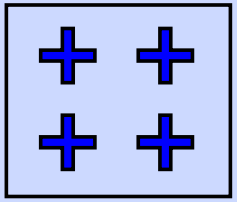

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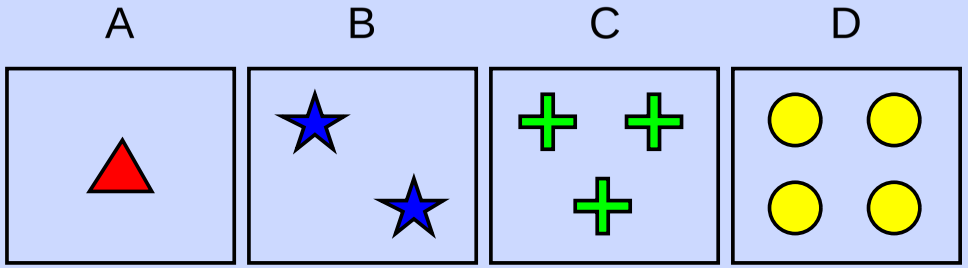

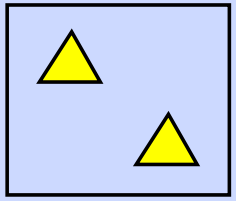

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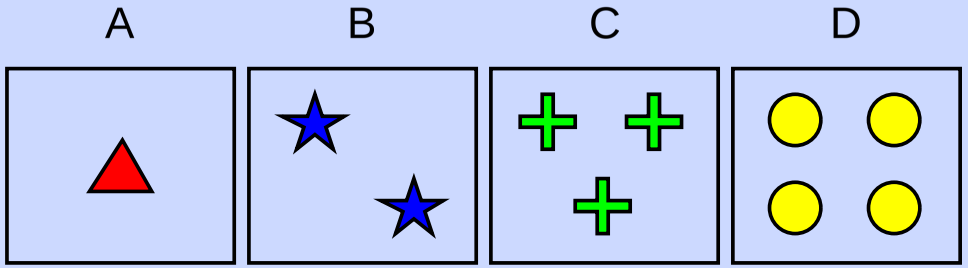

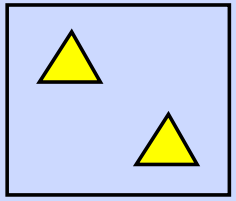

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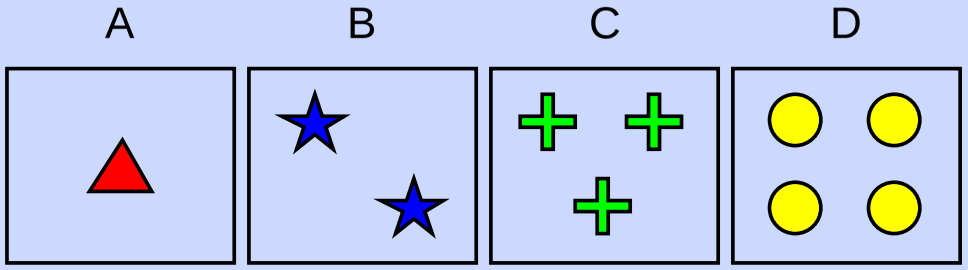

Experimental task (like Stroop), but captures some essential aspects of higher level cognition.

Dynamic Categorization Tasks

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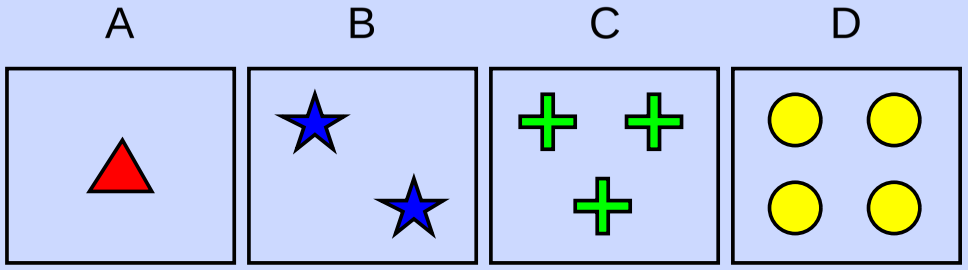


Experimental task (like Stroop), but captures some essential aspects of higher level cognition.

Frontal patients perseverate with the first rule.
$\rightarrow$ weight-based tendencies build up when categorizing according to first rule, and you need to *actively maintain* the new rule to counteract these weight-based tendencies

"Frontal Tasks"

- Stroop: Ability to override prepotent response (word reading) in favor of currently relevant task (color naming) – requires top-down control.

- Activation based directing of attention.

”Frontal Tasks”

- Stroop: Ability to override prepotent response (word reading) in favor of currently relevant task (color naming) – requires top-down control.
- Activation based directing of attention.
- ”Prefrontal control” not just for overriding long term associations like word reading, but also for the ability to quickly change attention in an online fashion in response to changing task demands: UPDATING.

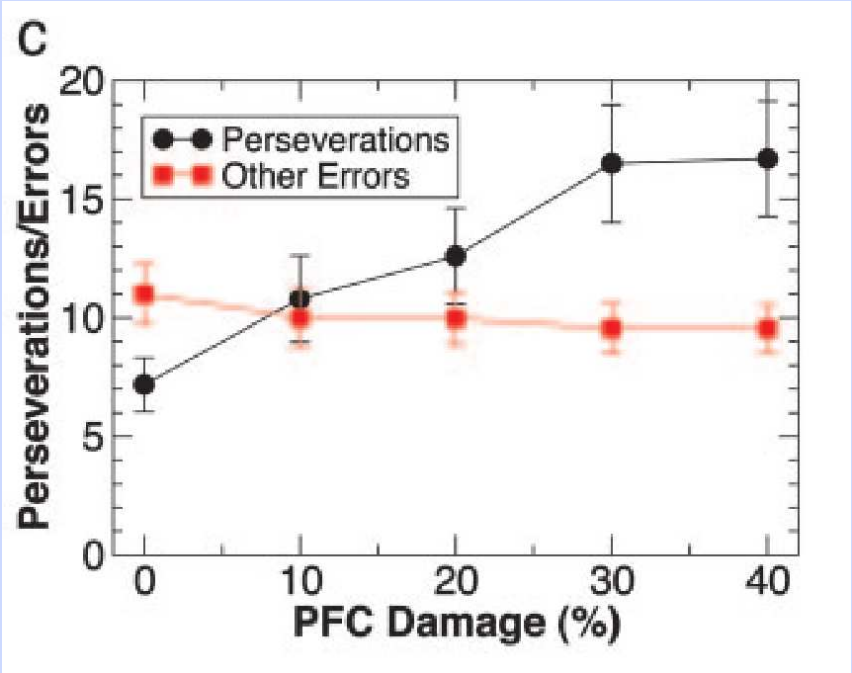
Revenge of the Donuts...

Revenge of the Donuts...

Two strategies for solving donut categorization task:

- Adjust weights to different donut types
- Actively maintain a representation of your current strategy; deactivate this rep and activate another if you get negative feedback
- Active maintenance does not strongly benefit initial learning of the rule
- However it does greatly facilitate performance when the rule switches

WCST in PFC model (Rougier et al)

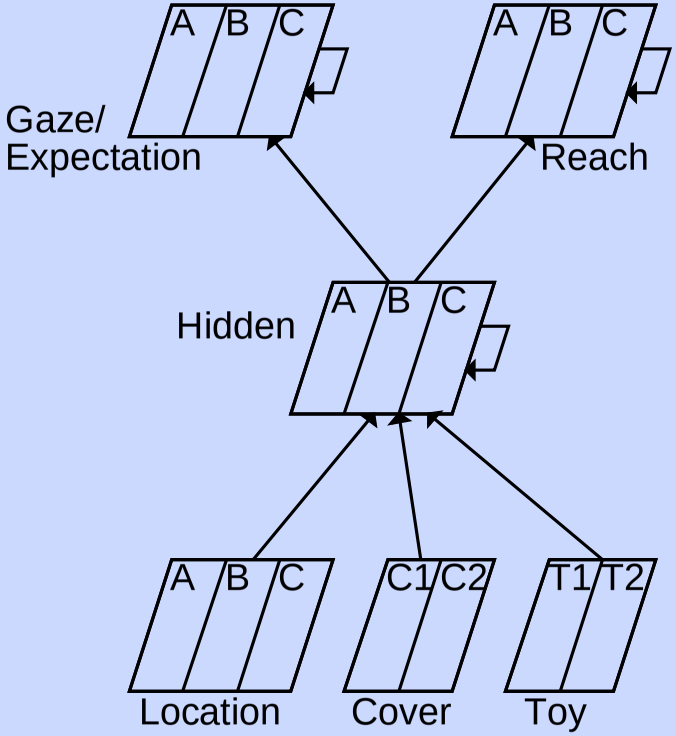


Weight- and Activation-Based Memory Interactions

A-not-B task

- Perseverative searching at A – also seen in patients with PFC damage
- Better peformance in gaze/expectation
- Inhibition problem?
- Model demonstrates maintenance problem.
- Same model accounts for various effects in different versions of A-not-B task not explained by any other unified theory (Munakata, 1998).

A-not-B Model


A B C
A B C
Gaze/
Expectation
Reach
A B C
Hidden
A B C
C1 C2
T1 T2
Location
Cover
Toy

Knowledge-action dissociations in card-sort task

- Kids can tell you where trucks go in the shape game, even after sorting according to color!
- But if you ask "where do red trucks go in the shape game" they still fail! (Morton & Munakata, 2002)
- Explained by different levels of conflict experienced when faced with multiple stimuli-response associations..

Card Sorting Tasks

- Relevant to everyday life, or just to this peculiar task?

Card Sorting Tasks

- Relevant to everyday life, or just to this peculiar task?
- Good measure of online thinking & problem solving: The ability to flexibly consider different possibilities to guide thinking and behavior.

Card Sorting Tasks

- In what situations do we need to to consider/represent different rules in mind and have the ability to flexibly update/maintain them until one works well?

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- If yes, maintain info further processing; if not, update.

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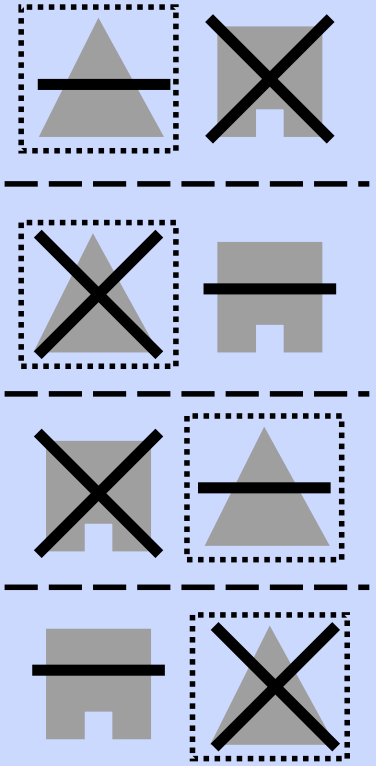
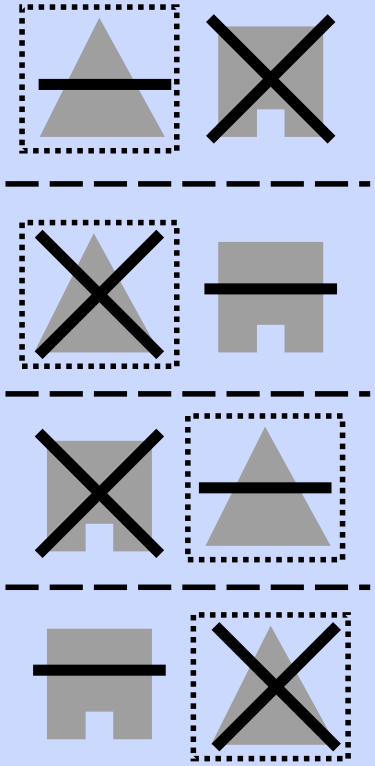
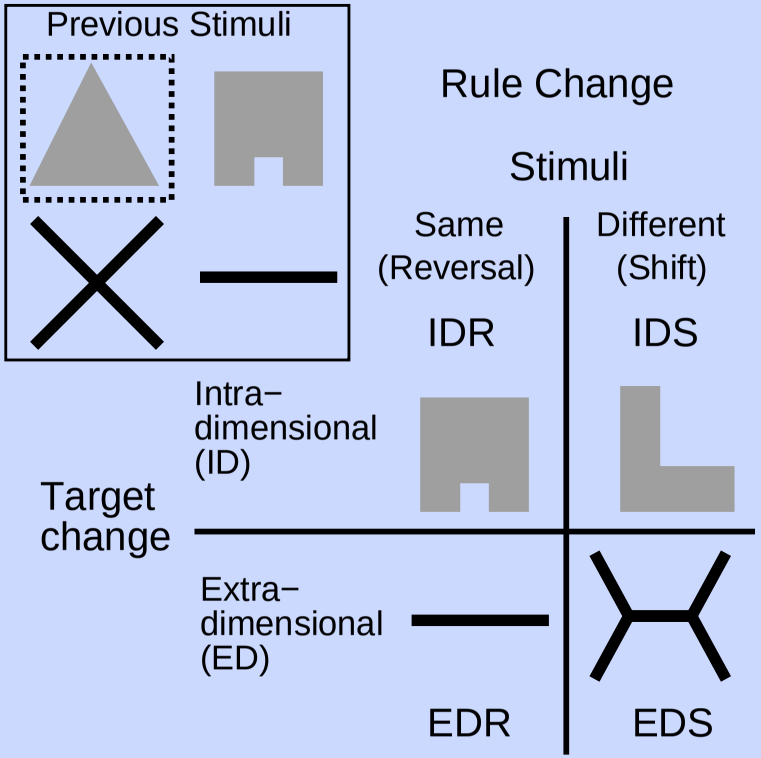
- Science: hypothesis formulation from experimental data.

Dynamic Categorization Tasks: ID/ED task



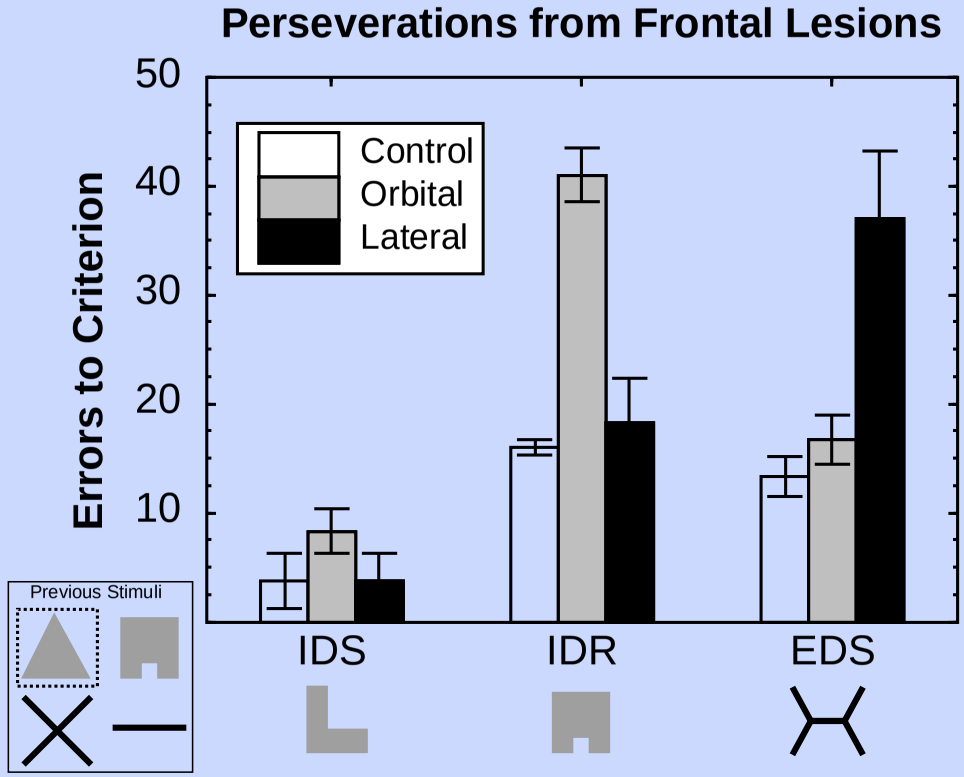
Dynamic Categorization Tasks: ID/ED task





ID/ED and Frontal Damage

(Dias, Robbins & Roberts (1997), *J Neurosci*)



Original interpretation: Orbital = affective inhibition,
Lateral = attentional selection.

Alternative Account

(O'Reilly, Noelle, Braver & Cohen (2002), *Cerebral Cortex*)

Orbital PFC represents detailed features.

Lateral PFC represents abstract dimensions.

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Activation-based PFC processing facilitates rule switch:
Orbital = switch to new features (IDR).
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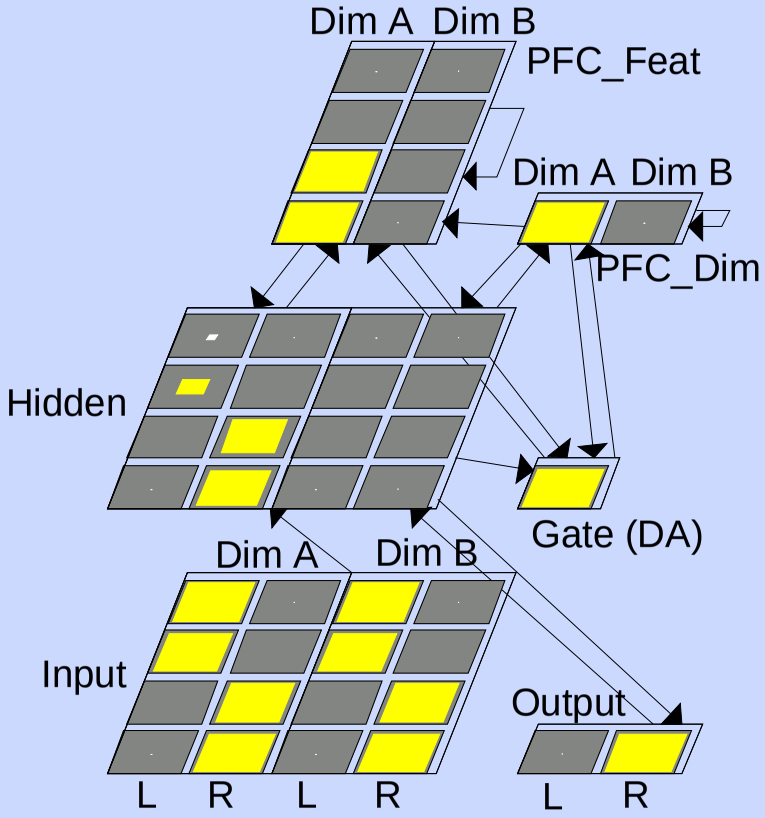
Orbital = switch to new features (IDR).
Lateral = switch to new dimension (EDS).

Perseverations = weight-based processing in absence of PFC.

ID/ED Model

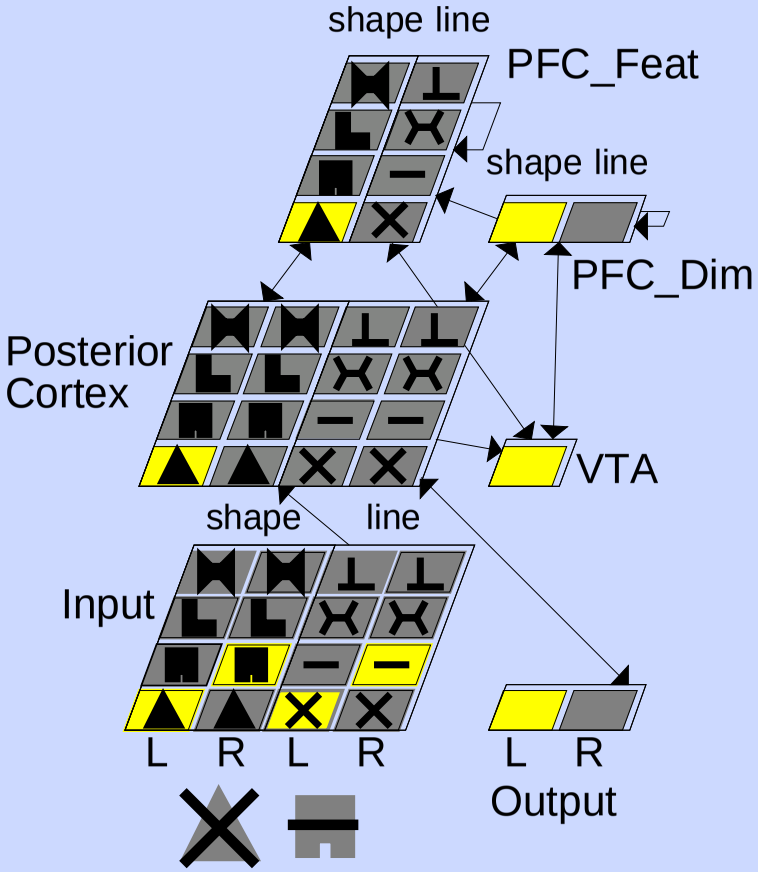


Two dimensions, A and B (shapes & lines)

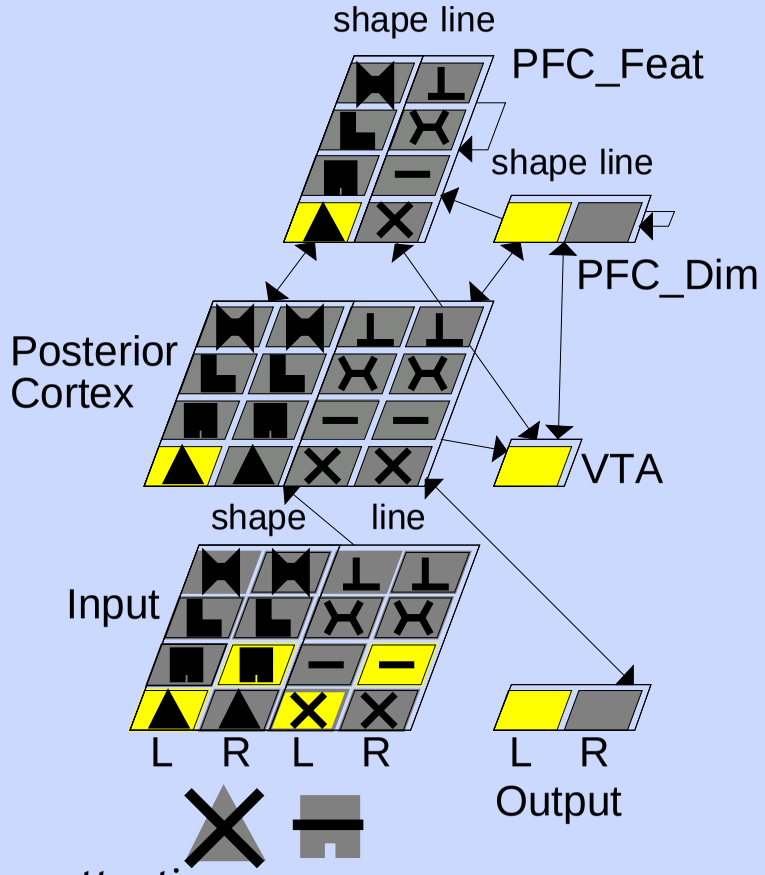
On each trial, four stims are presented:

Dim A left, Dim A right, Dim B left, Dim B right...

ID/ED Model


shape line
PFC_Feat
shape line
PFC_Dim
Posterior
Cortex
VTA
shape
line
Input
L
R
L
R
L
R
Output

ID/ED Model



Activation limited in cortex: attention.
PFC provides top-down bias, with DA/updating unit.
PFC_Feat = stim features indep of location
PFC_Dim = abstract dimensions

PFC updating based on unexpected rewards and errors

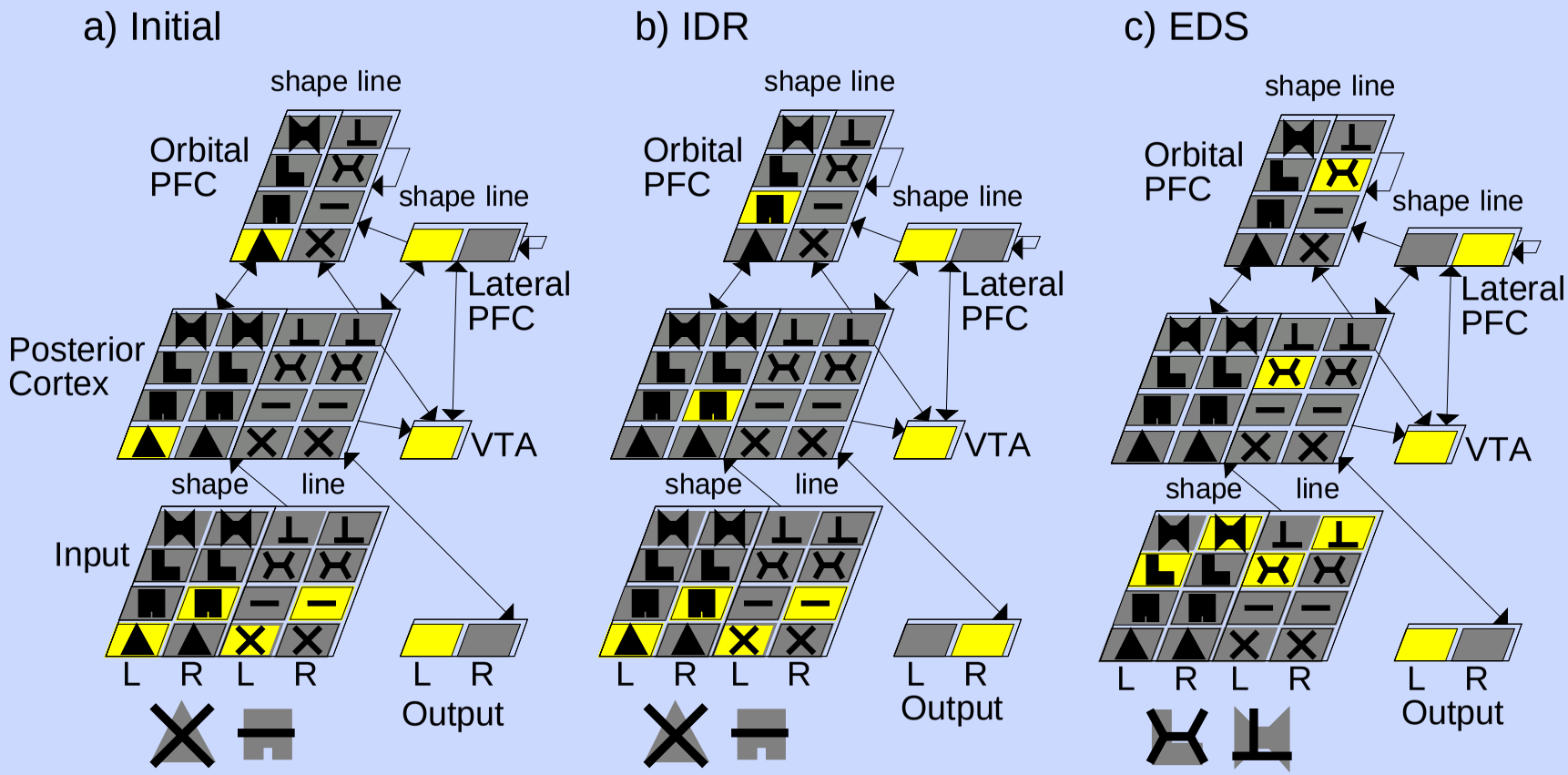
- When there is an increase in DA activity (e.g. the model got the answer right but wasn't expecting a reward):
  - hidden unit activity is gated into PFC
  - connections from hidden units to DA are increased
  - PFC serves to *amplify the influence of hidden units associated with correct responding*
- When there is a decrease in DA activity (the model was expecting a reward but gave the wrong response):
  - PFC activity is wiped clean
  - connections from hidden units to DA are decreased
- Also, there is some "gating noise": trial and error search

Similarities/Differences with Store-Ignore-Recall

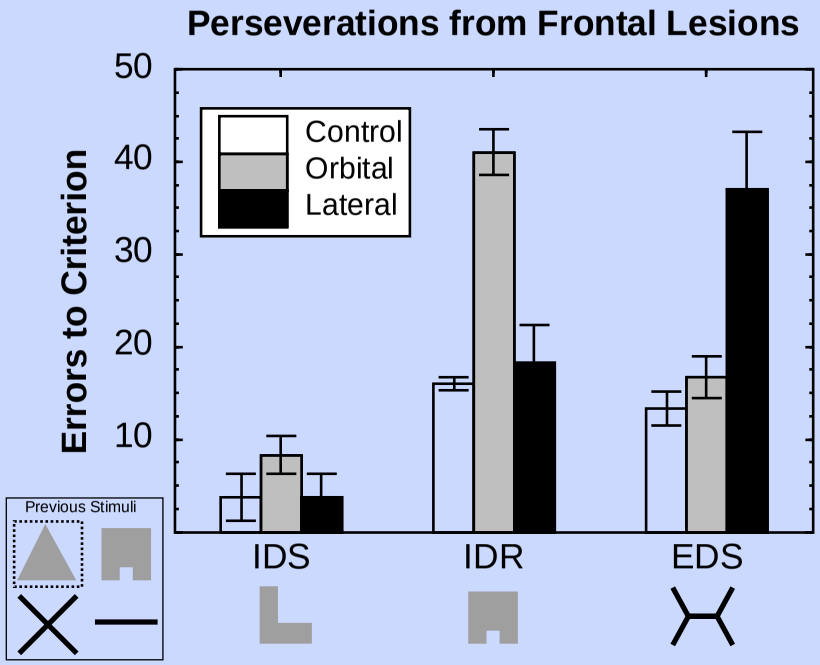
- With S-I-R, the model had to gate the "Store" stimulus into PFC (and carry it forward in time) in order to respond correctly; S-I-R can only be solved with the help of active maintenance (working memory)

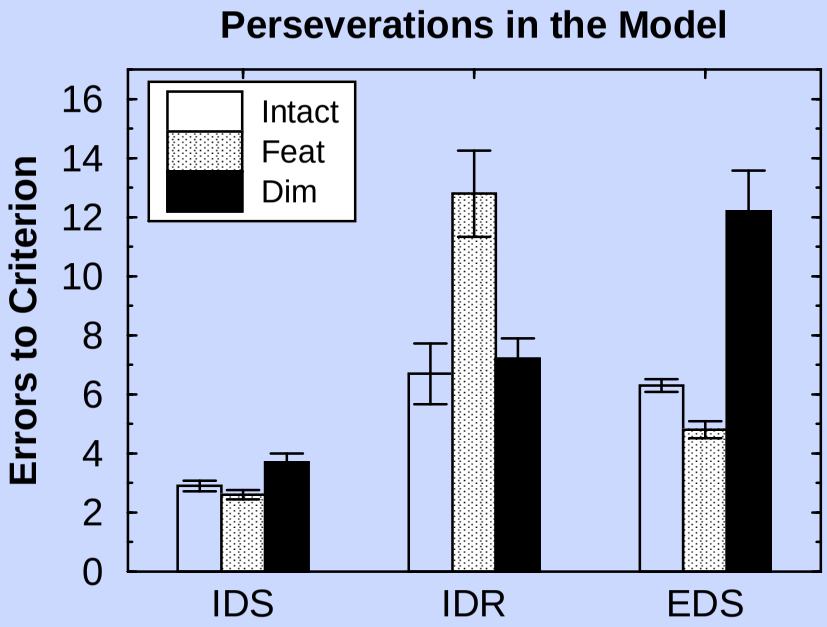
- The ID/ED task **can** be solved without active maintenance; but PFC can **help** by focusing the model's attention on useful parts of the input but it isn't **necessary**..

IDR, EDS in the Model



Model Data

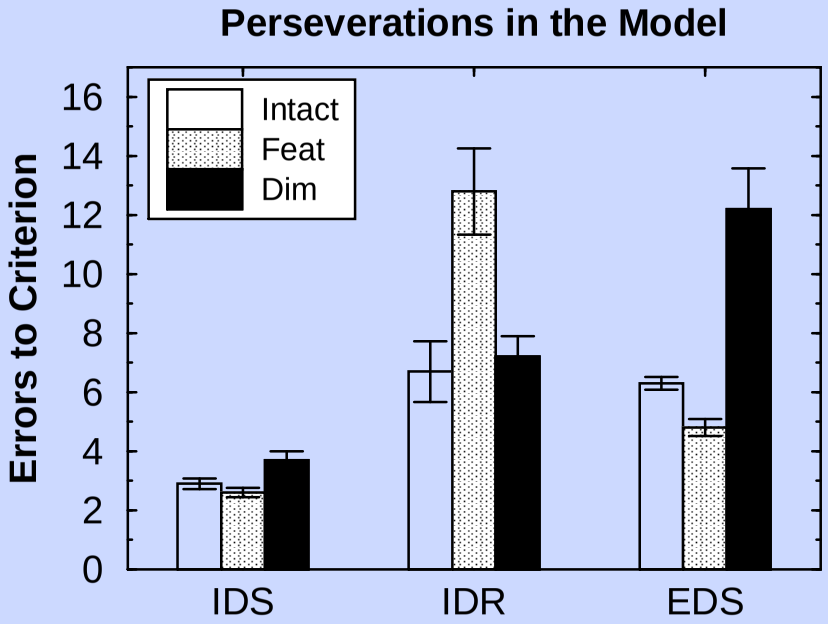

Perseverations from Frontal Lesions
Errors to Criterion
50
40
30
20
10
Control
Orbital
Lateral
IDS
IDR
EDS
Previous Stimuli


Perseverations in the Model
Errors to Criterion
16
14
12
10
8
6
4
2
0
Intact
Feat
Dim
IDS
IDR
EDS

Explanation of Lesion Data: IDS

- Intradimensional shift (IDS): different stimuli pre and post-shift; the relevant dimension (A) stays the same
- No effect of PFC lesions
- PFC is unnecessary because there are no strong, inappropriate tendencies to overcome (new stimuli)

Model Data


Perseverations in the Model
Errors to Criterion
16
14
12
10
8
6
4
2
0
Intact
Feat
Dim
IDS
IDR
EDS

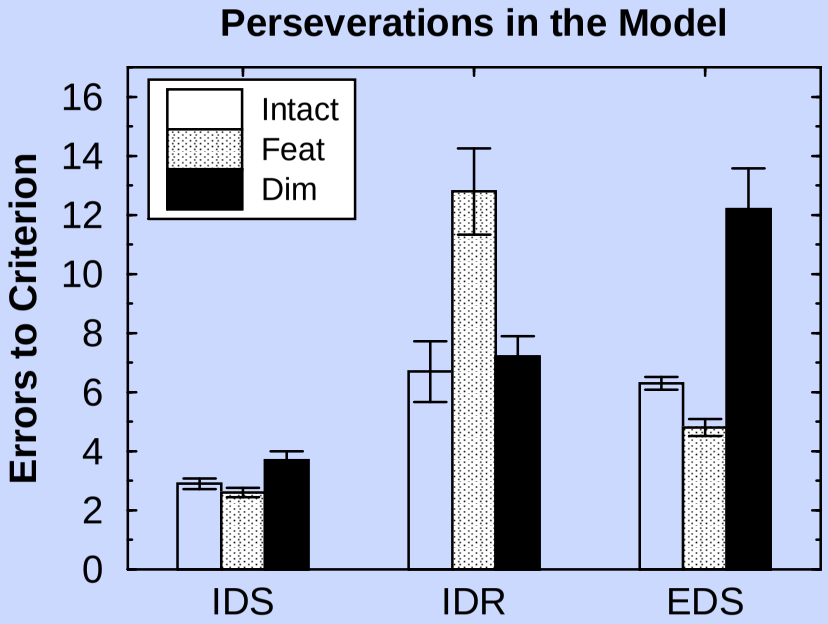
Explanation of Lesion Data: IDR

- Intradimensional reversal (IDR): same stimuli pre and post-shift; initially A1 = target; after the shift A2 = target
- Performance is impaired after PFC_Feat lesions but not PFC_Dim lesions
- It's clear why PFC_Dim is *not* important here: It involves a shift of attention *within* a dimension, not across dimensions..
- How does PFC_Feat help performance?

Explanation of Lesion Data: IDR

- Before shift, some hidden units learn to generate the A1 response
- After shift, these hidden units point to the *wrong* response
- PFC helps the model focus on other hidden units, which can then be associated with the new response
- This way the model avoids having to fully *unlearn* the association between the original hidden units and A1 response

Model Data


Perseverations in the Model
Errors to Criterion
16
14
12
10
8
6
4
2
0
Intact
Feat
Dim
IDS
IDR
EDS

Explanation of Lesion Data: EDS

- Extradimensional shift (EDS): different stimuli pre- and post-shift; initially A1 = target; after the shift, B3 = target
- Performance is impaired after PFC_Dim lesions but not PFC_Feat lesions
- It's clear why PFC_Dim is important: It helps focus attention on the newly relevant dimension
- Why can't PFC_Feat serve the same function? should be able to bias new reps as before...

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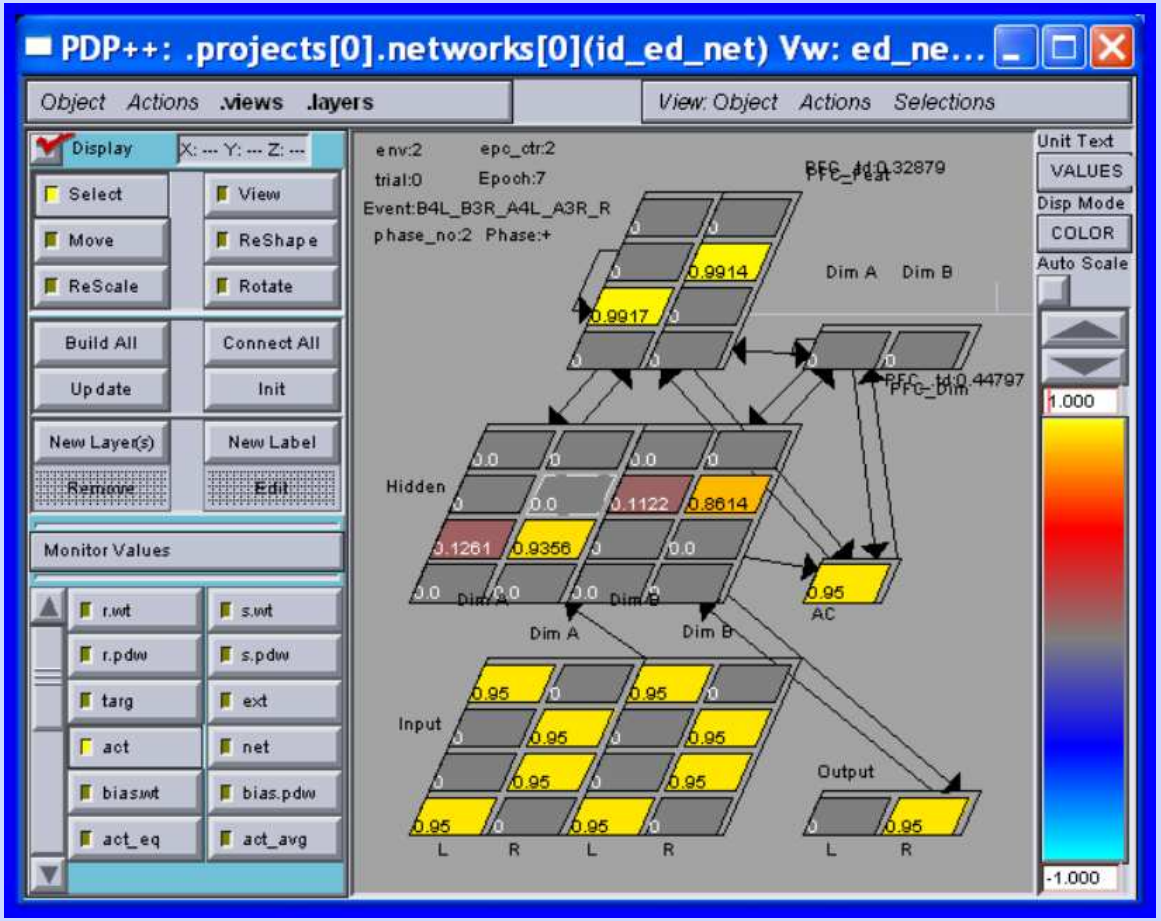
- Why can't PFC_Feat serve the same function? should be able to bias new reps as before...
- *Without PFC_Dim, PFC_Feat has no sense of what constitutes a "dimension", just updates to random new pattern of features from both A and B dimensions...*

After EDS: PFC_Dim lesion



Advantages of ID/ED model

- PFC reps are not clamped as in Stroop – updated in response to changing task demands.
- Nice fit and explanation of complex monkey data.
- Shows how working memory and cognitive control may be two sides of the same coin: activation-based memory is not just memory but also biases activity elsewhere in the brain.
- Shows that ID/ED data can be explained in terms of lateral and orbital PFC carrying out the same *function* (biasing competition in posterior cortex), applied to different kinds of *content* (features vs dimensions)
- Also provides evidence for a hierarchy of PFC representations

Limitations of ID/ED model

- Reps not clamped, but still not learned – one to one connectivity from HL.

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- Reps not clamped, but still not learned – one to one connectivity from HL.

- Distinction between OFC = features, DLPFC = dimensions may be too convenient: observed dissociation; not much evidence of OFC-features (see Frank & Claus, 2006).

- Newer models address the issue of how PFC representations can develop in childhood and lead to higher level *abstraction* and generalization to new tasks (Rougier et al, 2005, *PNAS*)

Limitations of ID/ED model

- Doesn't distinguish b/w updating and maintenance systems.
- Goal/Subgoal requires *selective* updating with concurrent maintenance of task relevant info.
- Updating system thought to involve the BG and DA, damaged in PD,SZ and lead to "frontal-like" impairments in Stroop, WCST, etc.
- Newer BG models address these issues in more complex tasks (eg. O'Reilly & Frank, 2006)

Goal/Subgoal Hierarchical Structure

1. Open fridge.
2. Get food items.
3. Close fridge.
4. Get bread from cupboard

Update these subgoals to guide actions, but to guide the ordering of subgoals themselves, need to maintain overall goal of task (Make sandwich)

A Unified Activation-based Account

Central frontal mechanisms:

Activation-based working memory Frontal neurons maintain actively over delays.

Monitoring/evaluation e.g., Error-monitoring, critical for dopaminergic modulation.

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Inhibition Need to maintain top-down activation for weaker task.

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Flexibility Dynamics of activation-based more rapid than weight-based.

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A Unified Activation-based Account

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Flexibility Dynamics of activation-based more rapid than weight-based.

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Executive control Maintain & update plans / goals over time, avoid distraction.

Higher Level Cognition: What's Missing

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- Reasoning
- Decision-making
- Emotion
- Consciousness, sense of self
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Beyond the PFC

Bias & Binding in the PFC and Hippocampus: