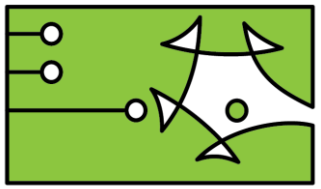
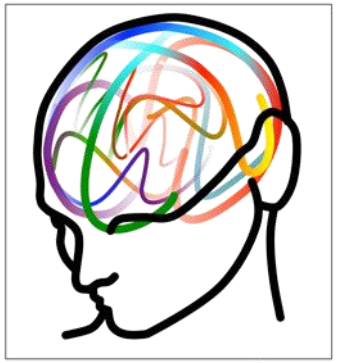
INSTITUTE FOR LEARNING & BRAIN SCIENCES



University of Washington
Institute for Neuroengineering

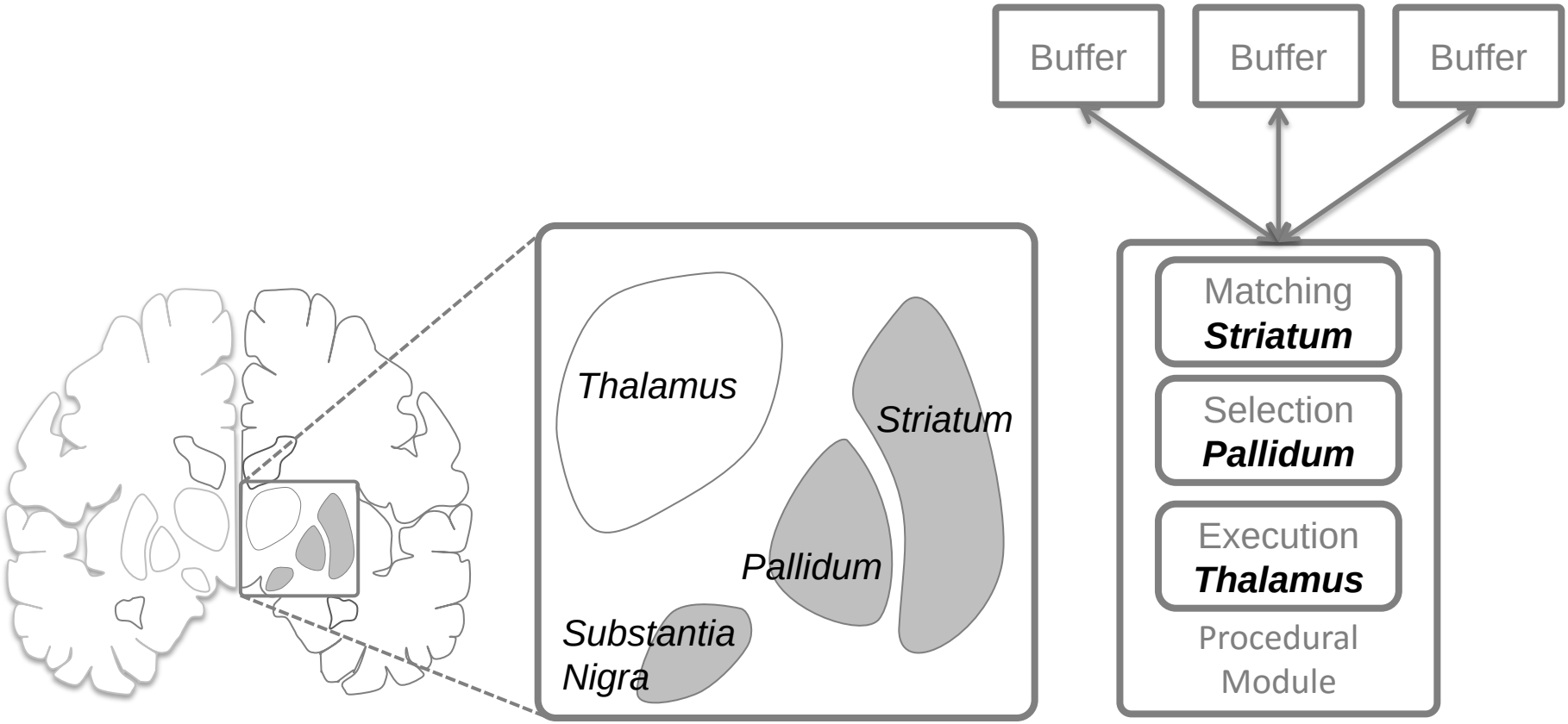


Cognition & Cortical Dynamics Laboratory

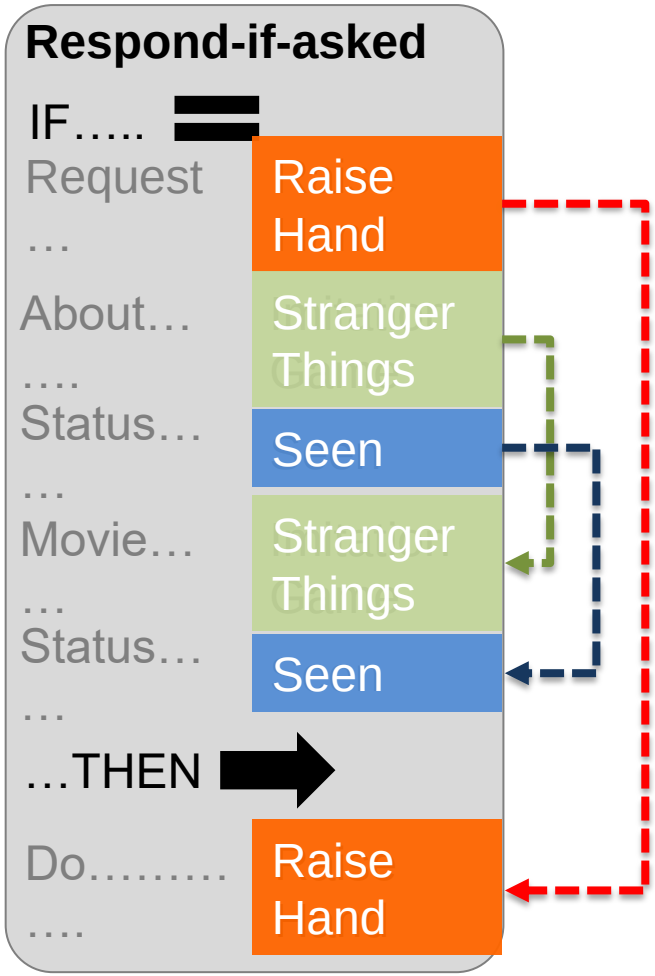
Implications of a Dynamic Causal Modeling Analysis of fMRI Data

Andrea Stocco
University of Washington, Seattle

Production Rules and Basal Ganglia



Production Rules Transfer Variables



Exchanging information across buffers

- Question 1: Can we **experimentally test** it?
- Question 2: Are we **missing** something crucial from basal ganglia anatomy

Exchanging information across buffers

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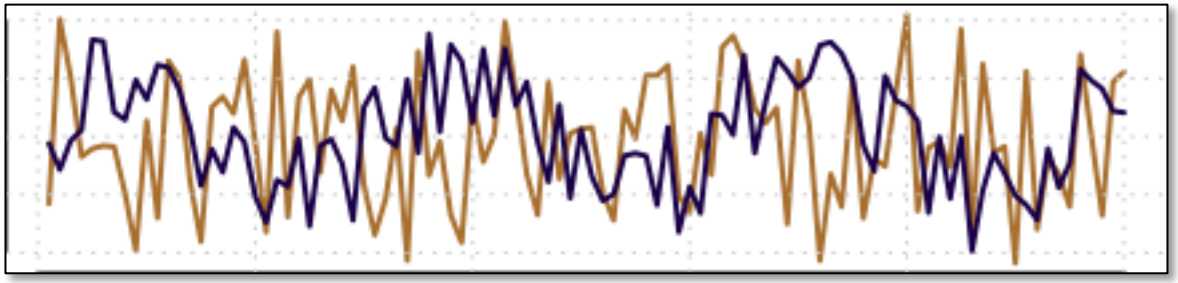
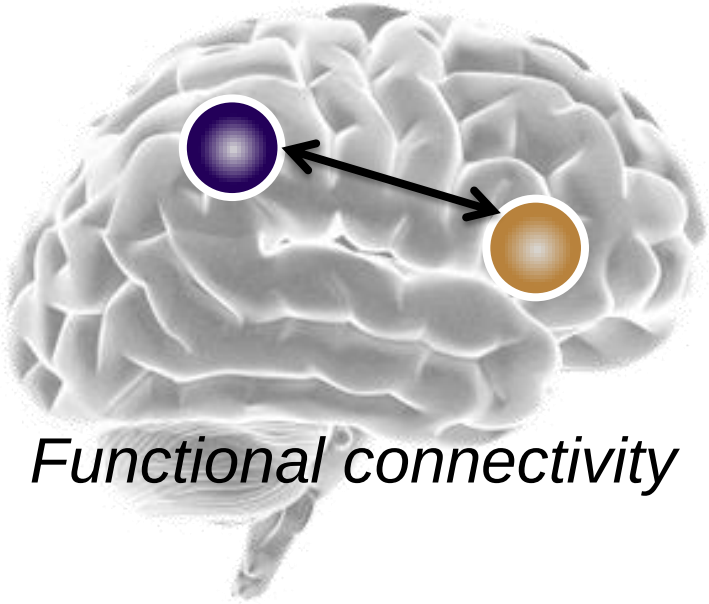
- Question 2: Are we **missing** something crucial from basal ganglia anatomy

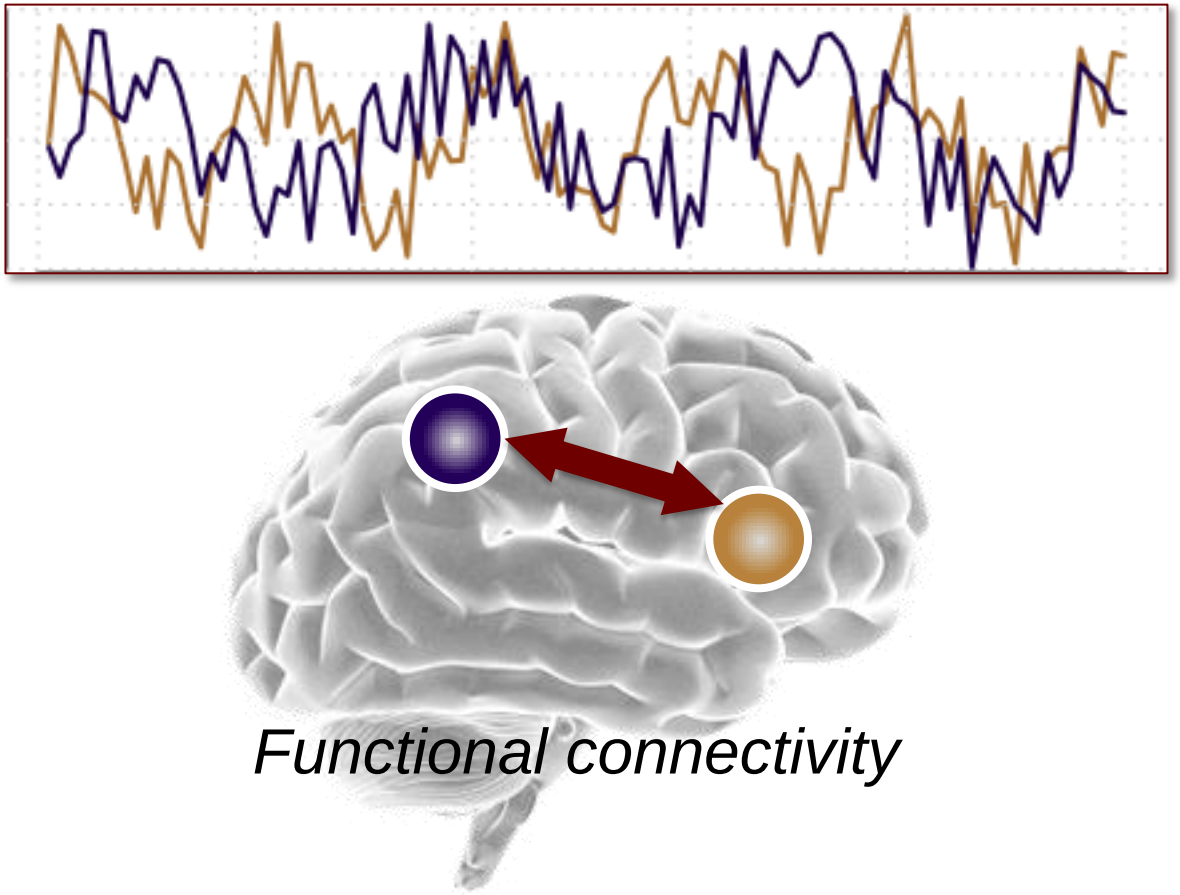
How Do We Measure Information Transfer?





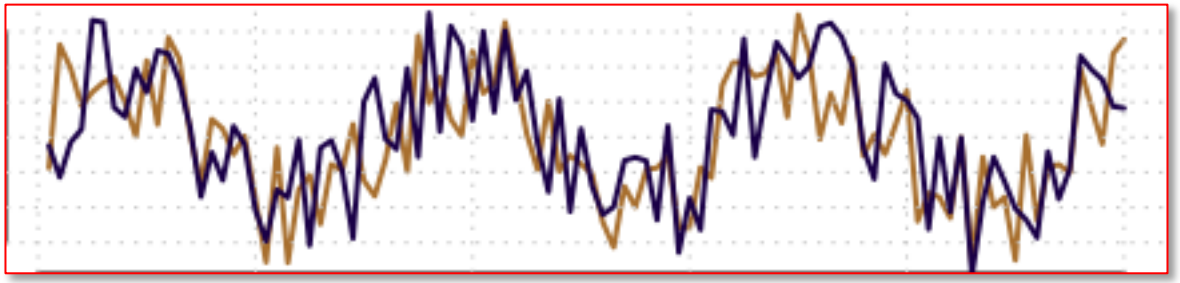
Functional connectivity

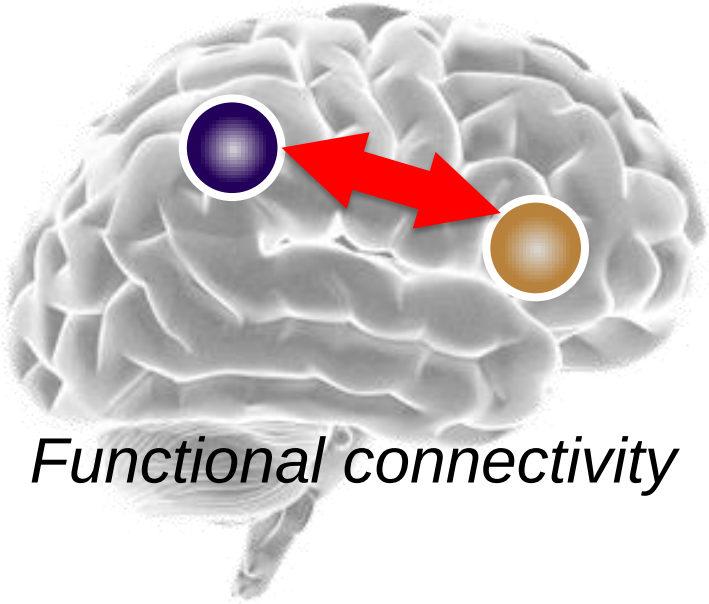
Increased Correlation



Functional connectivity

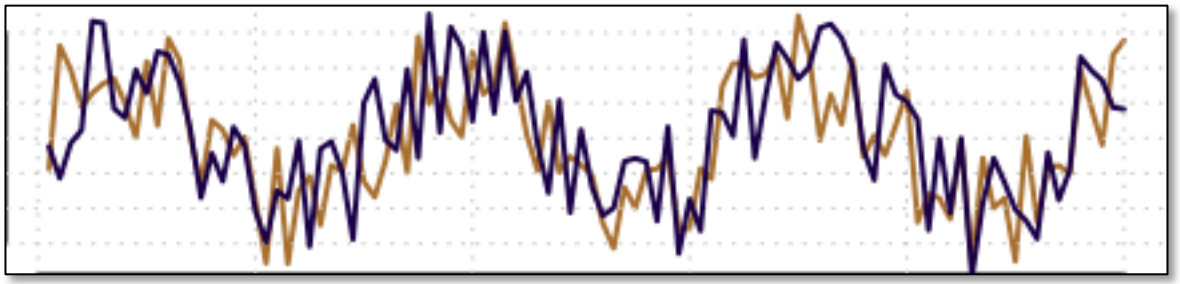
Bidirectional Measures

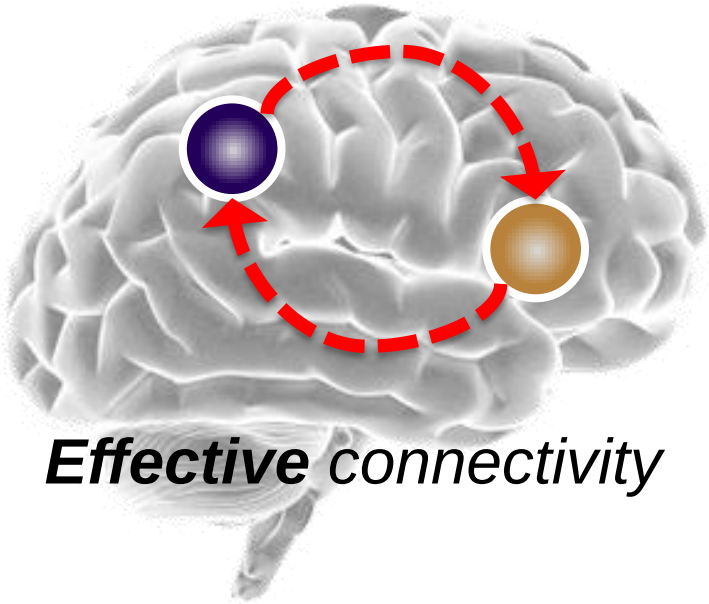




Functional connectivity

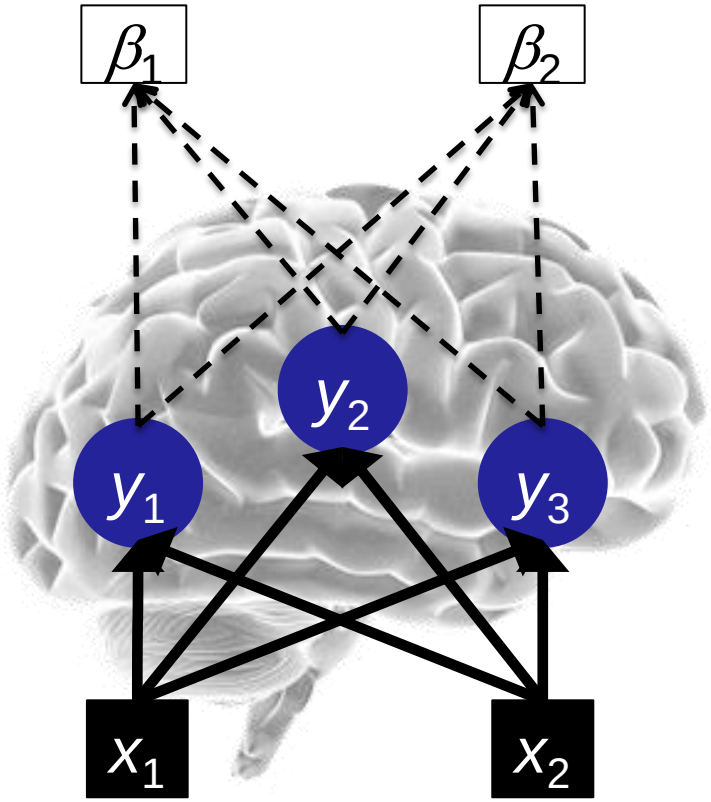
How do we test it?



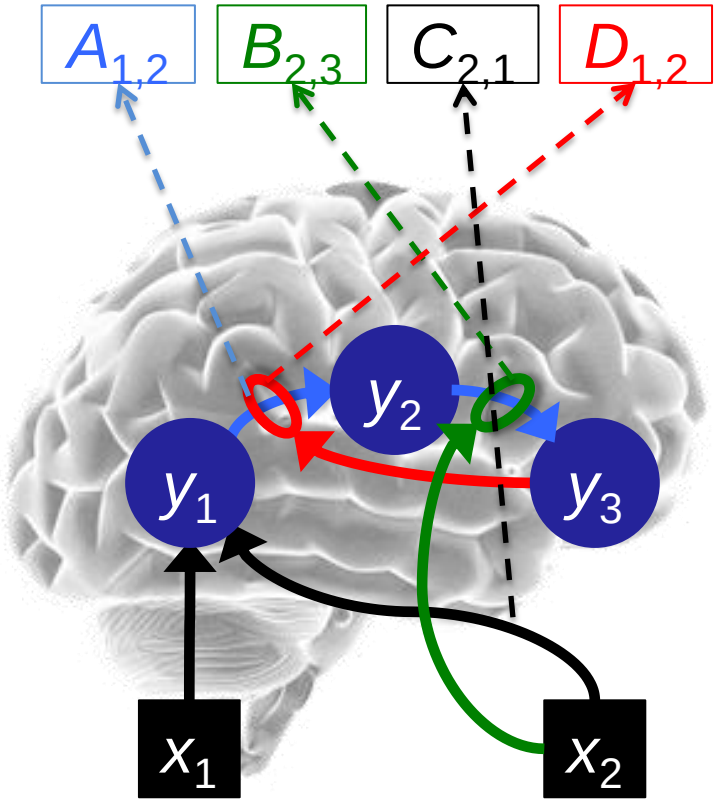


Effective *connectivity*

Dynamic Causal Modeling



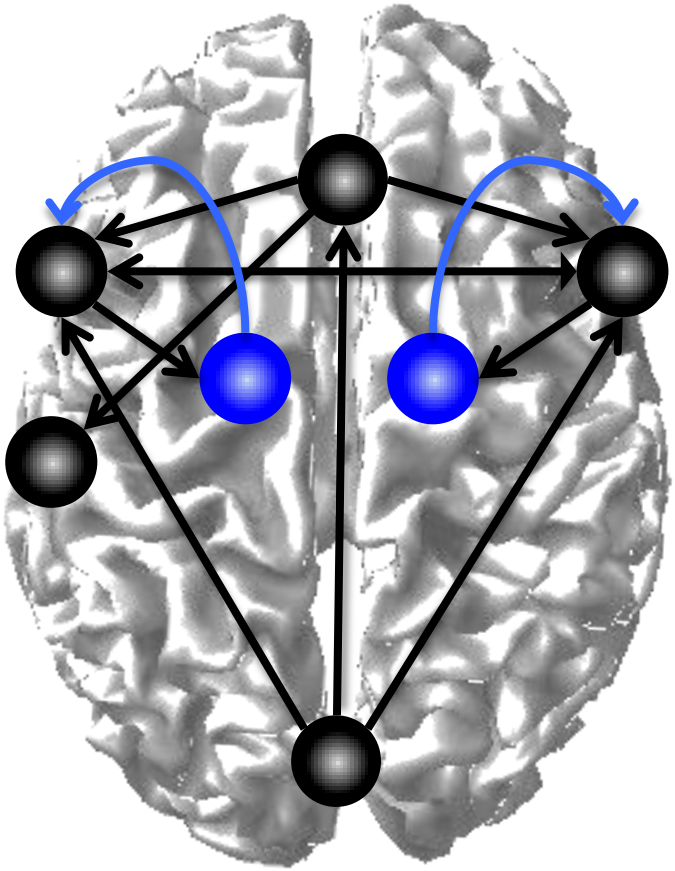
$$\mathbf{y} = \Sigma_i \beta_i * \mathbf{x}_i$$



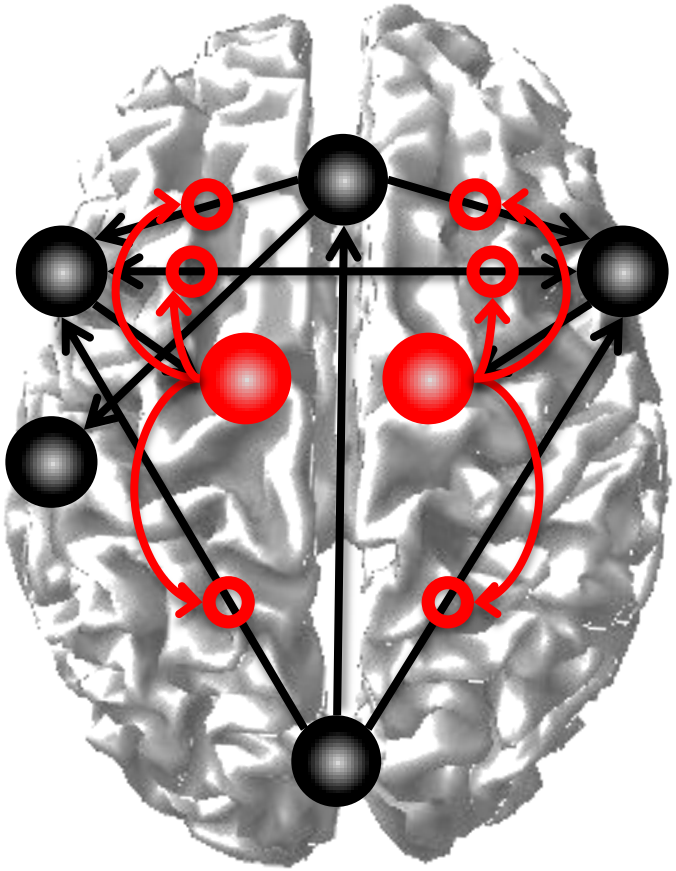
$$d\mathbf{y}/dt = \mathbf{A}y + \Sigma_i x_i \mathbf{B}(i)y + \Sigma_j y_j \mathbf{D}(j)y + \mathbf{C}x$$

Do the Basal Ganglia Modulate Connectivity?

Direct Model

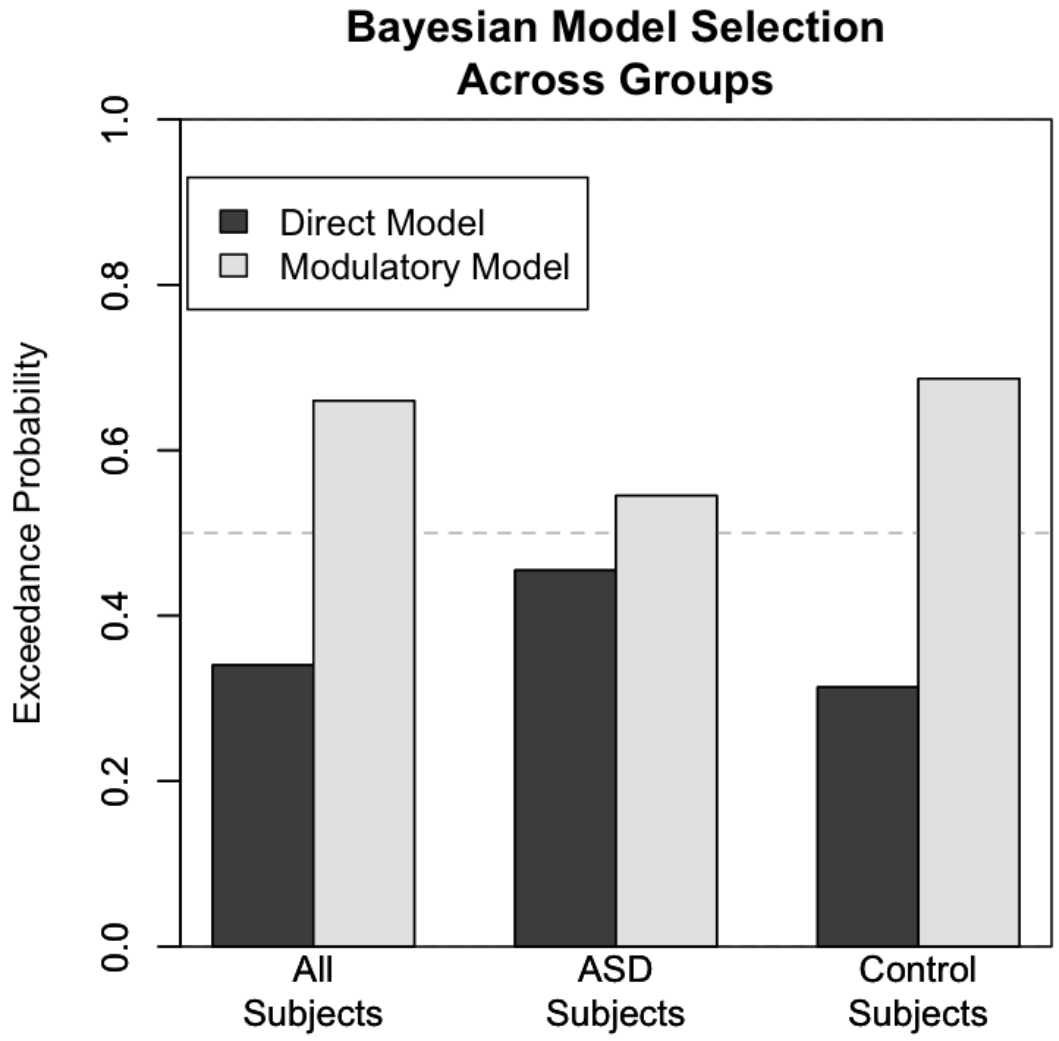


Modulatory Model



Prat, Stocco et al., *submitted*

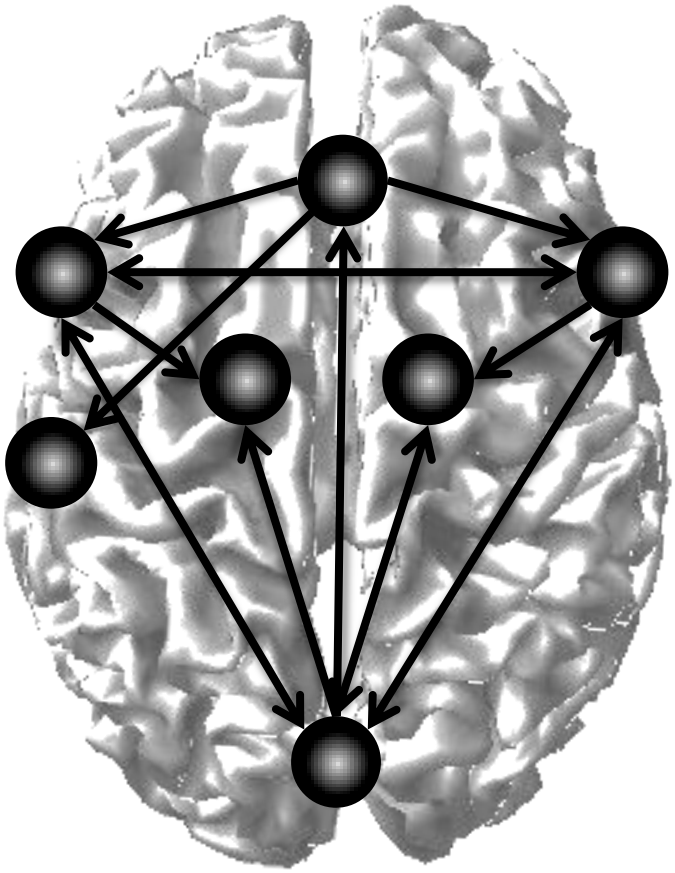
… They Do!



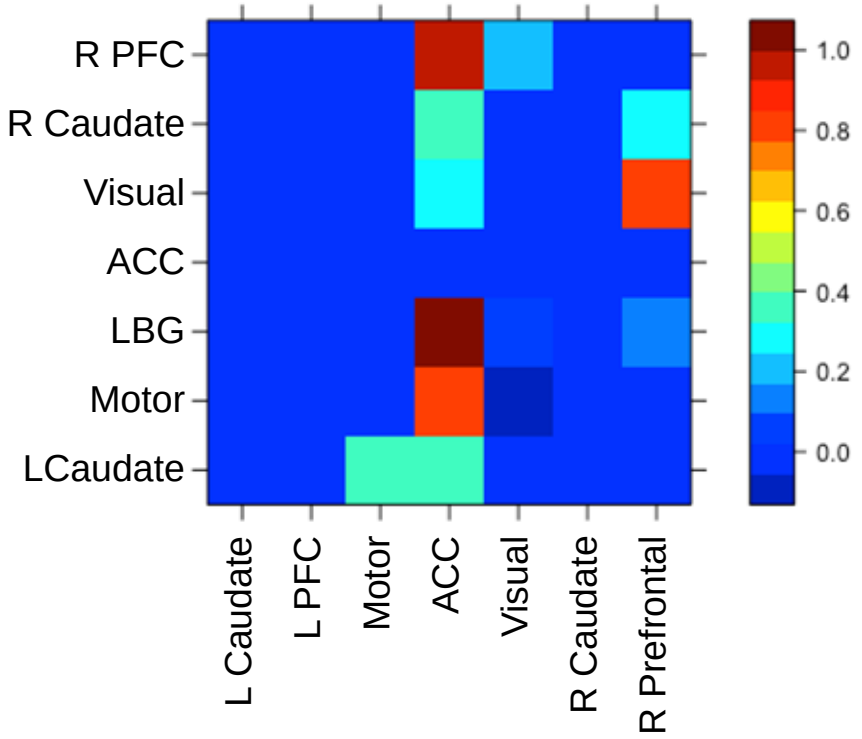
Prat, Stocco et al., *submitted*

Empirical Connectivity Matrix

Modulatory Model



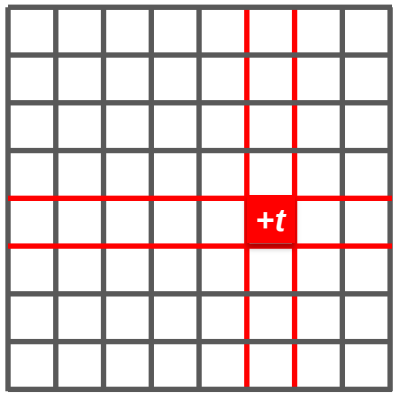
Connectivity Matrix



ACT-R's Connectivity Matrix

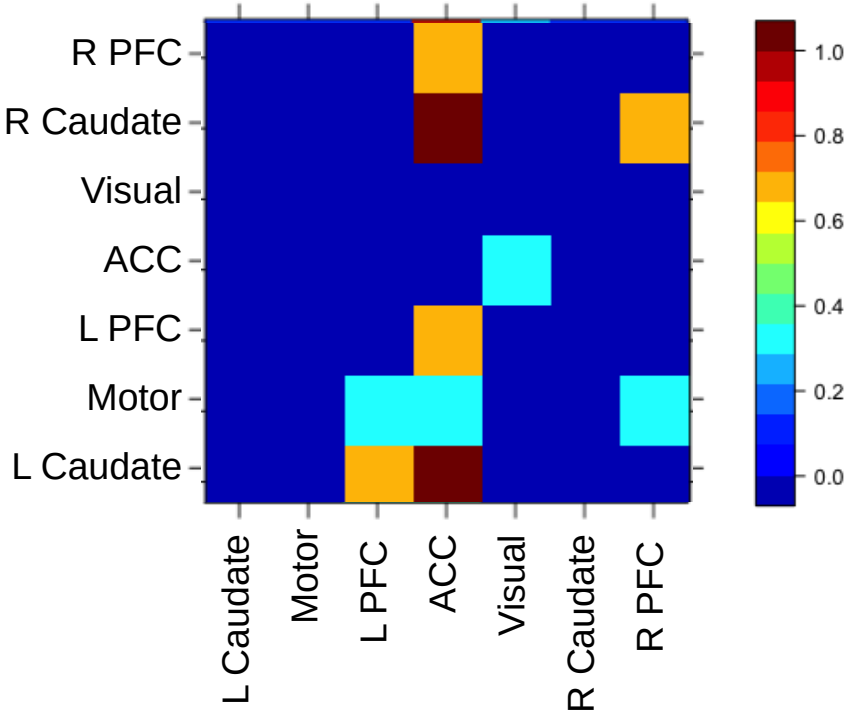
```
....
120.545   PROCEDURAL     CONFLICT-RESOLUTION
120.595   PROCEDURAL     PRODUCTION-FIRED PREPARE-FOR-ENCODING
120.595   PROCEDURAL     CLEAR-BUFFER RETRIEVAL
120.595   PROCEDURAL     CONFLICT-RESOLUTION
120.645   PROCEDURAL     PRODUCTION-FIRED NEXT-POSITION
120.645   PROCEDURAL     CLEAR-BUFFER GOAL
120.645   GOAL           SET-BUFFER-CHUNK GOAL OPERATION34
120.645   PROCEDURAL     CONFLICT-RESOLUTION
120.745   IMAGINAL       MOD-BUFFER-CHUNK IMAGINAL
120.745   PROCEDURAL     CONFLICT-RESOLUTION
120.795   PROCEDURAL     PRODUCTION-FIRED RETRIEVE-O
120.795   PROCEDURAL     CLEAR-BUFFER RETRIEVAL
120.795   DECLARATIVE    START-RETRIEVAL
120.795   PROCEDURAL     CONFLICT-RESOLUTION
121.695   DECLARATIVE    RETRIEVED-CHUNK OPERATION29
121.695   DECLARATIVE    SET-BUFFER-CHUNK RETRIEVAL OPERATION29-0
121.695   PROCEDURAL     CONFLICT-RESOLUTION
...
```

```
...
(p prepare-for-encoding
  =visual>
    =TASK
==>
  +imaginal>
    task  =TASK
  +visual-location>
```

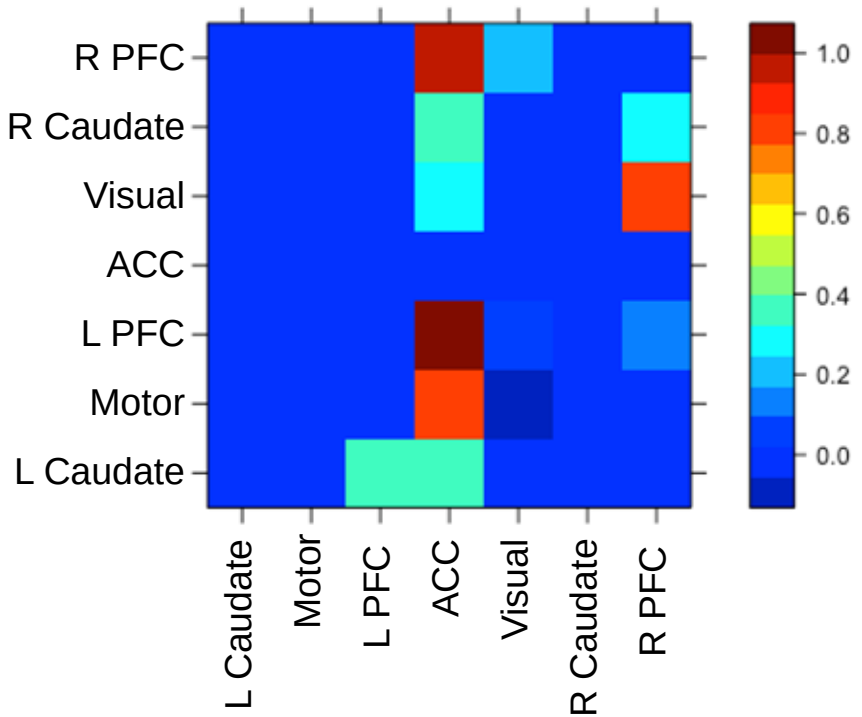


The Connectivity Matrix

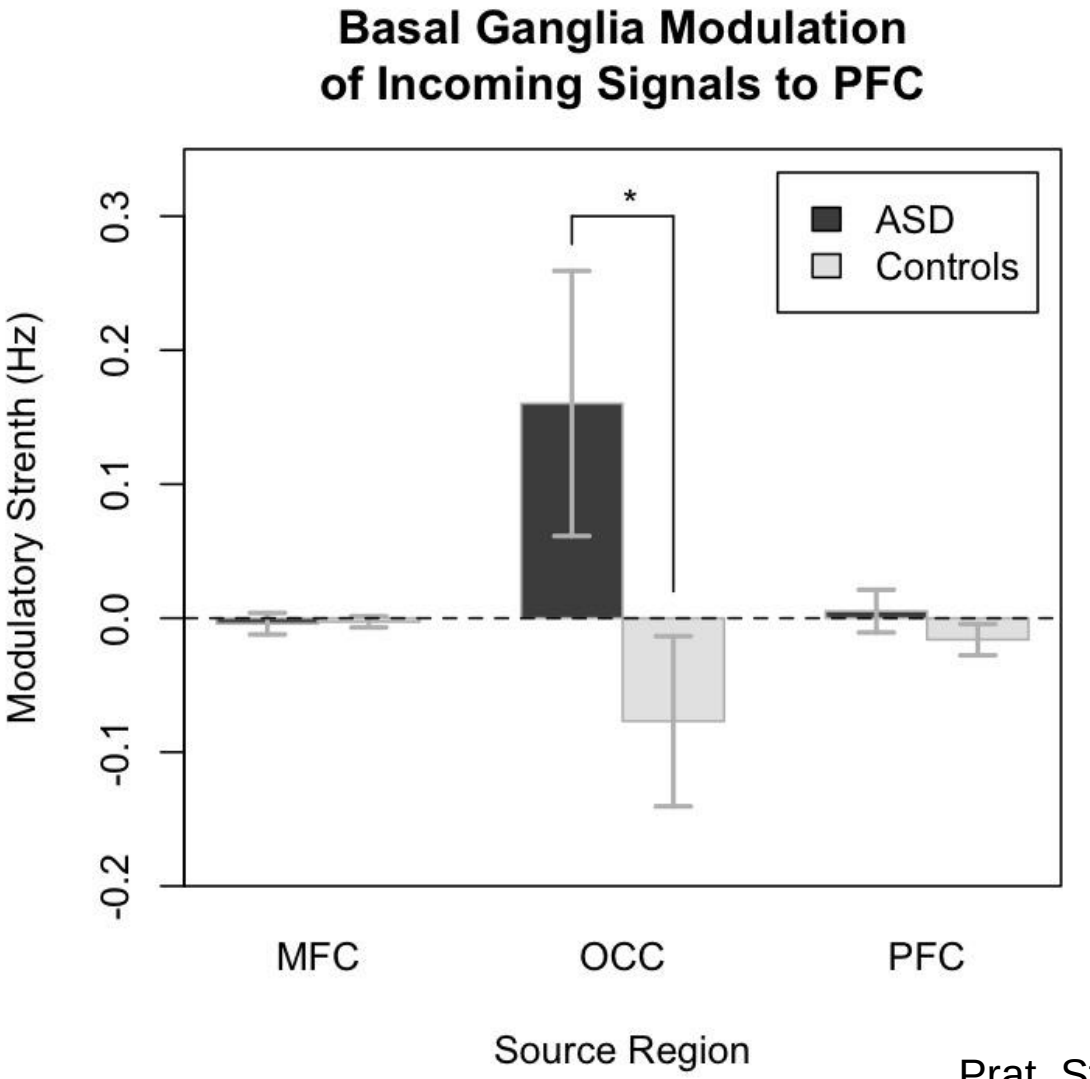
Model



Experimental Data



Negative Values Are Important



Prat, Stocco et al., *submitted*

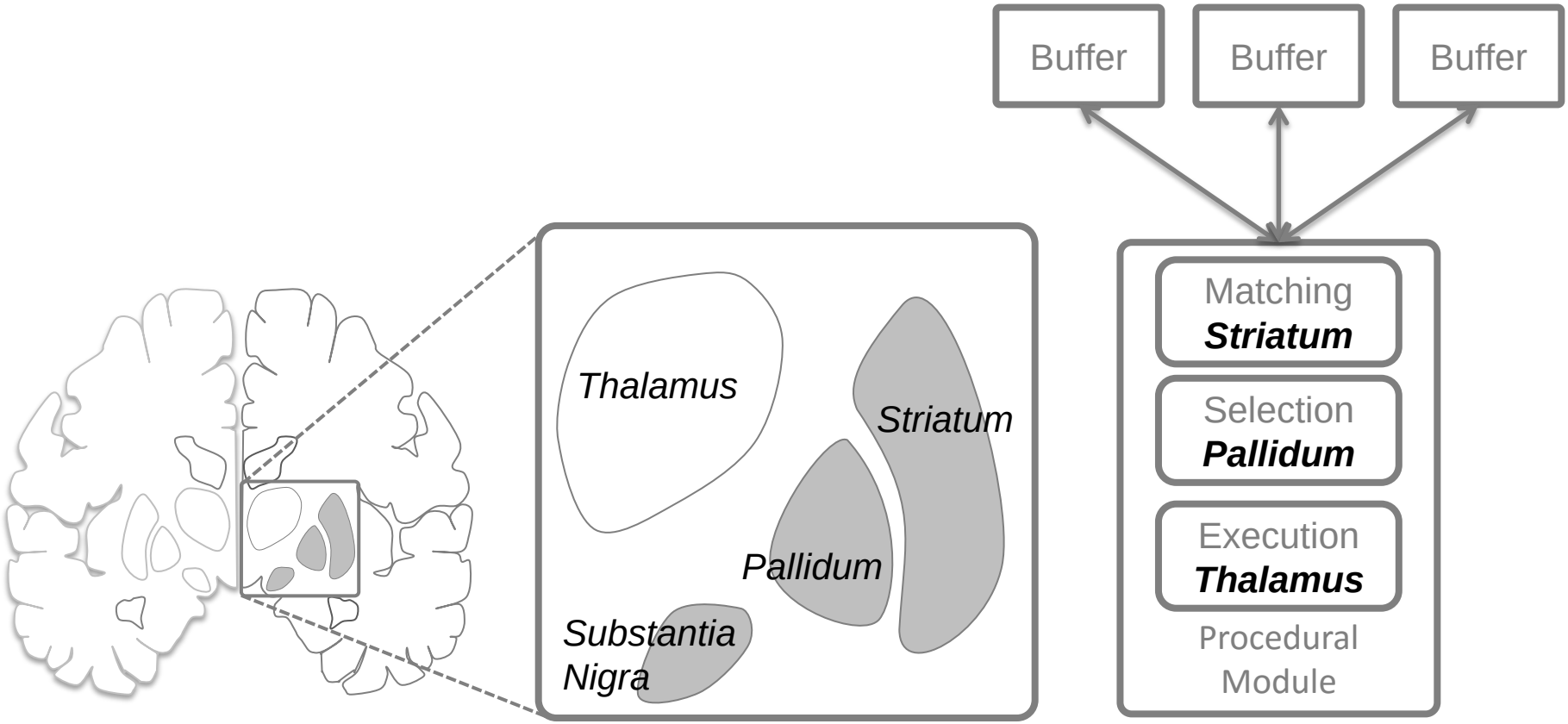
Summary, part 1

- The effect of production rules can be measured through **effective connectivity**
- Effective connectivity patterns can be used to **test ACT-R models**
- However:
  - Negative values pose a problem
  - Suggest **inhibitory** production rules

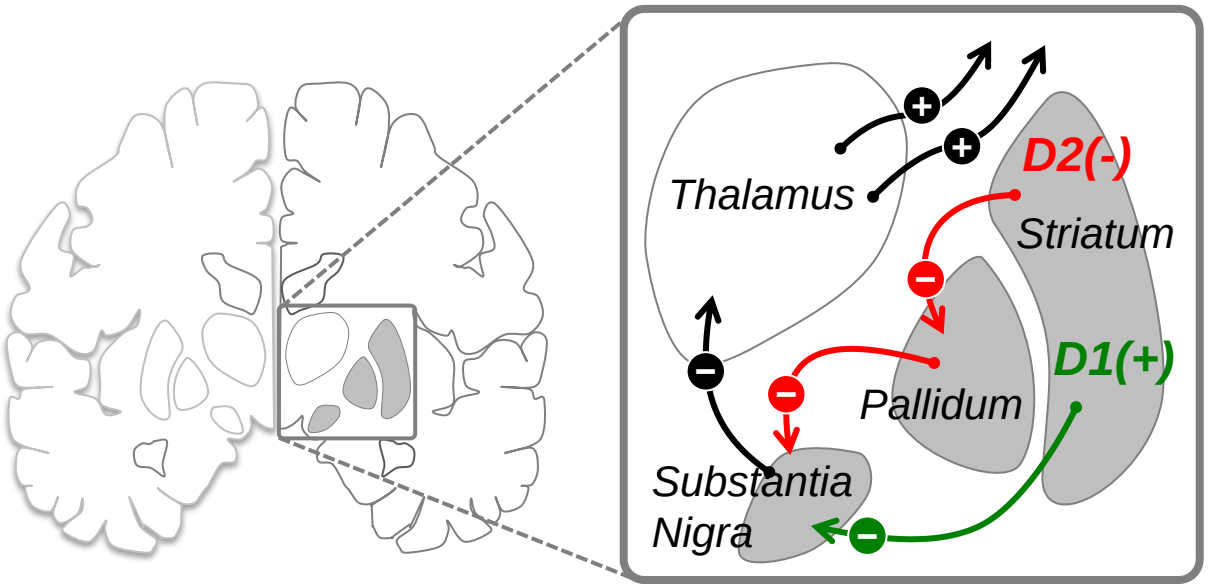
Exchanging information across buffers

- Question 1: Is it **compatible** with basal ganglia anatomy?
- Question 2: Are we **missing** something crucial from basal ganglia anatomy

Basal Ganglia physiology and ACT-R



Basal Ganglia physiology and ACT-R

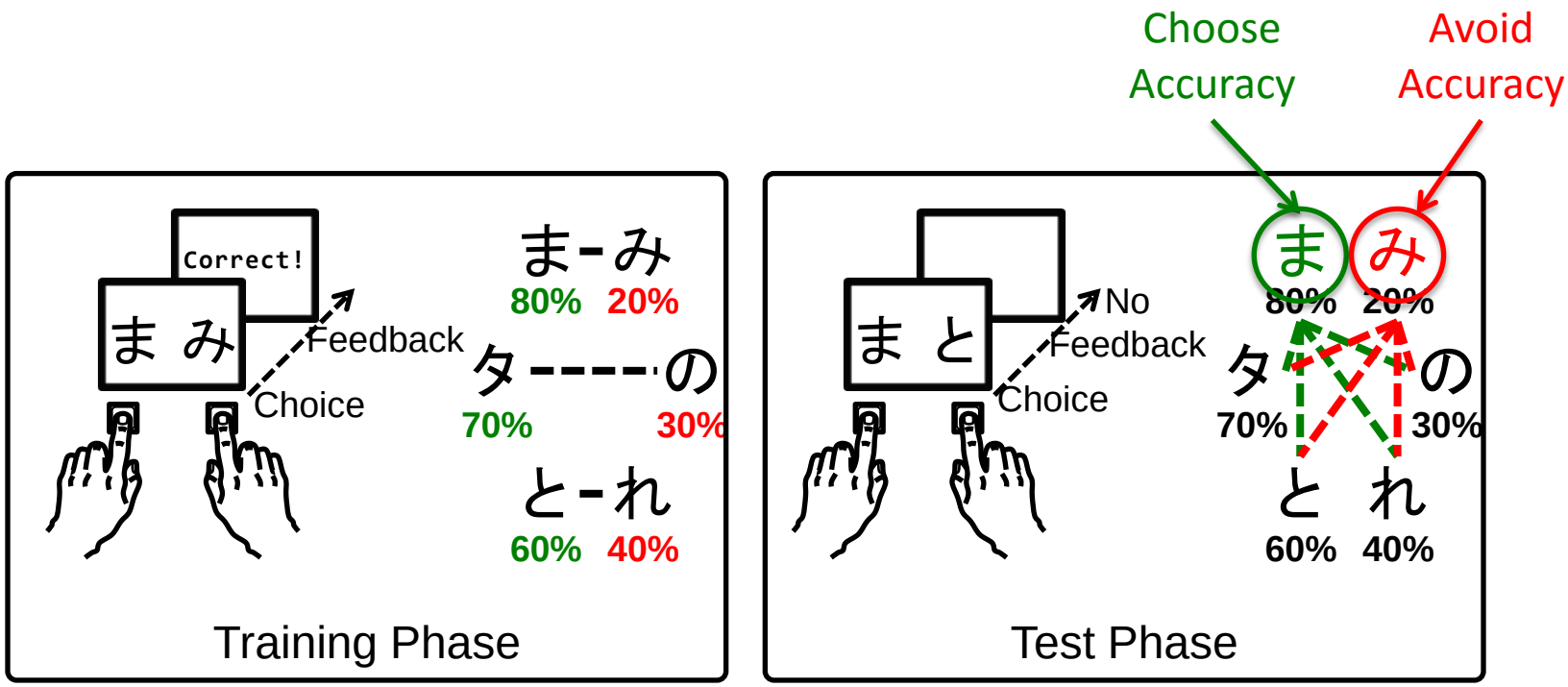


Indirect Pathway **(NO GO)**

Direct Pathway **(GO)**

To Frontal Cortex

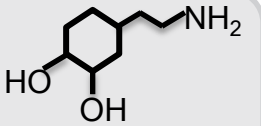
Probabilistic Stimulus Selection (PSS)



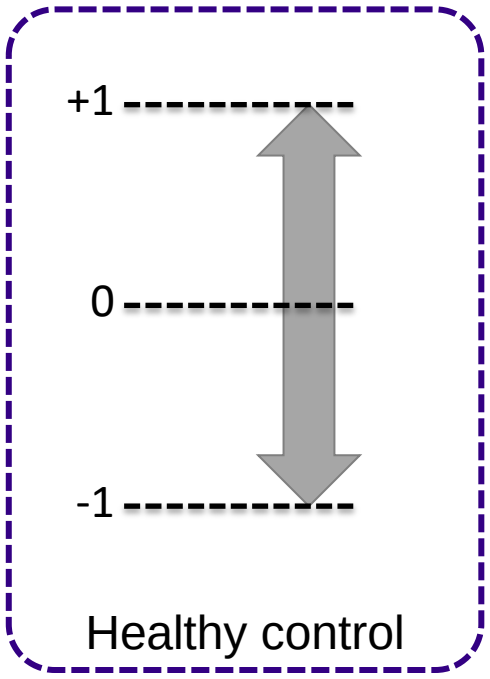
Frank, Seeberger, & O'Reilly, 2004, *Science*

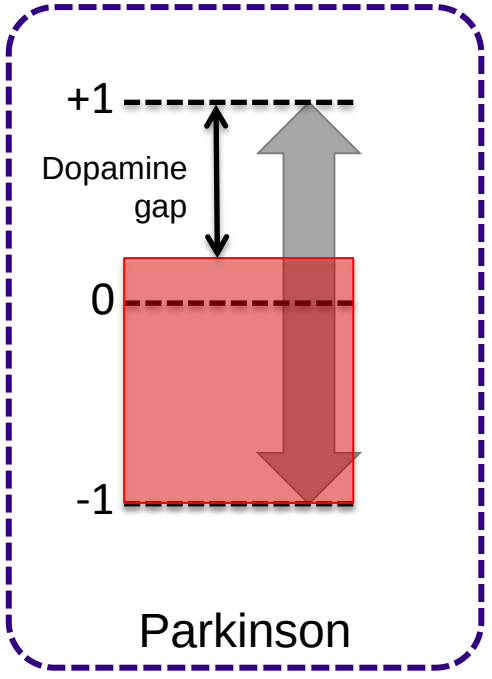
Influence of Dopamine on Choose and Avoid Accuracies

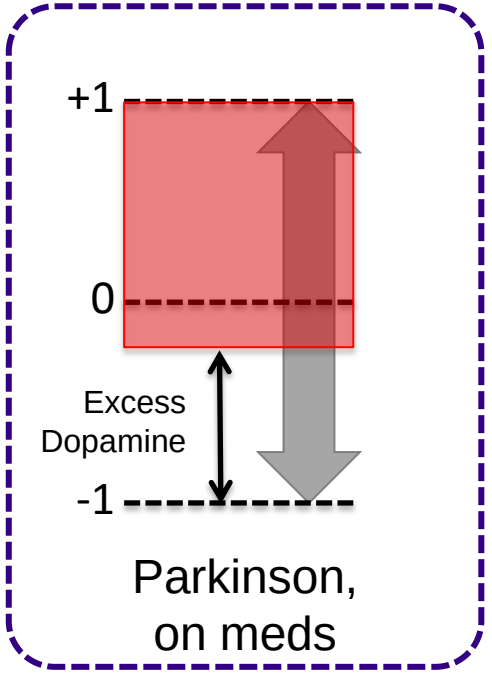
Dopamine in Parkinson Disease



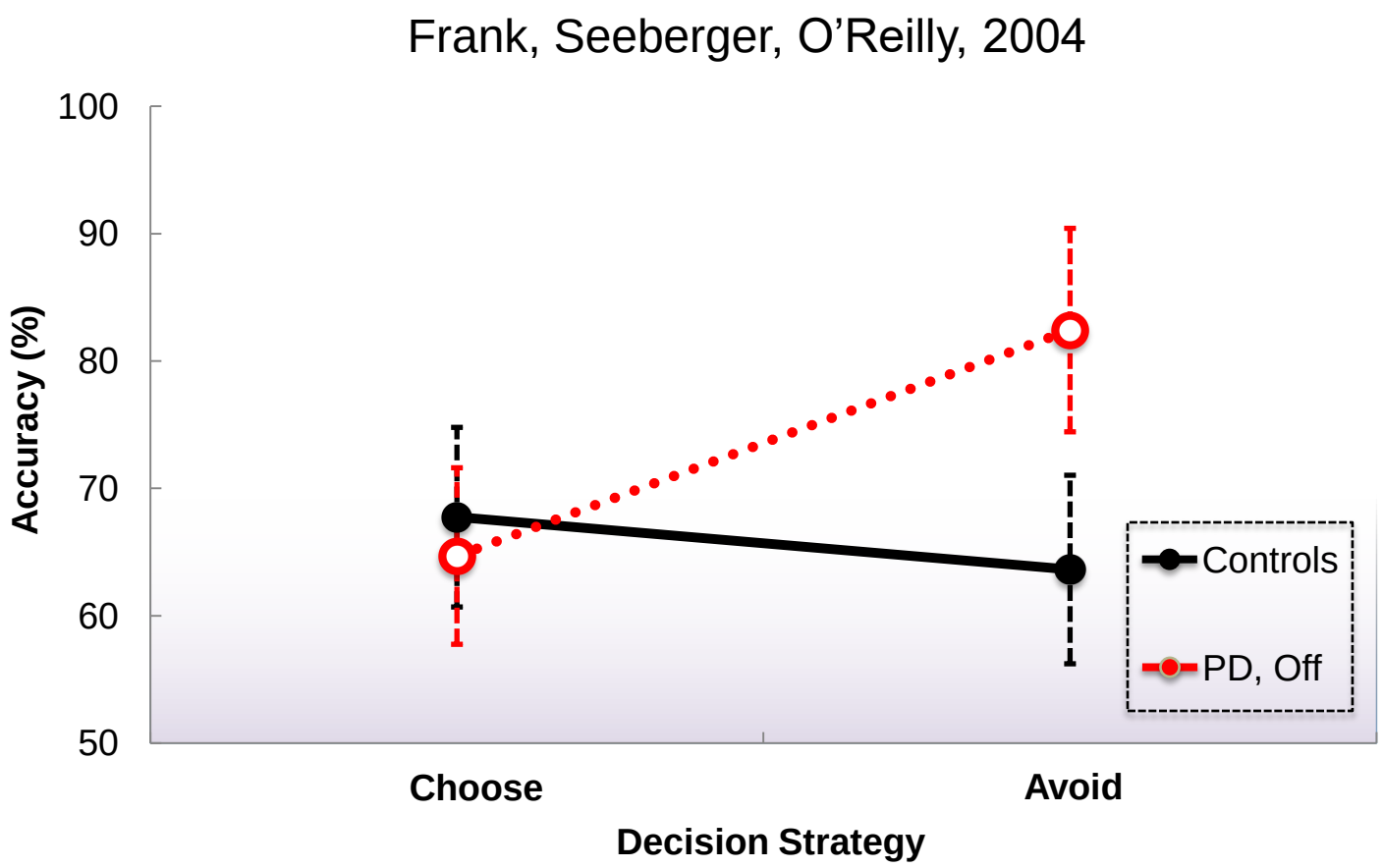
Dopamine



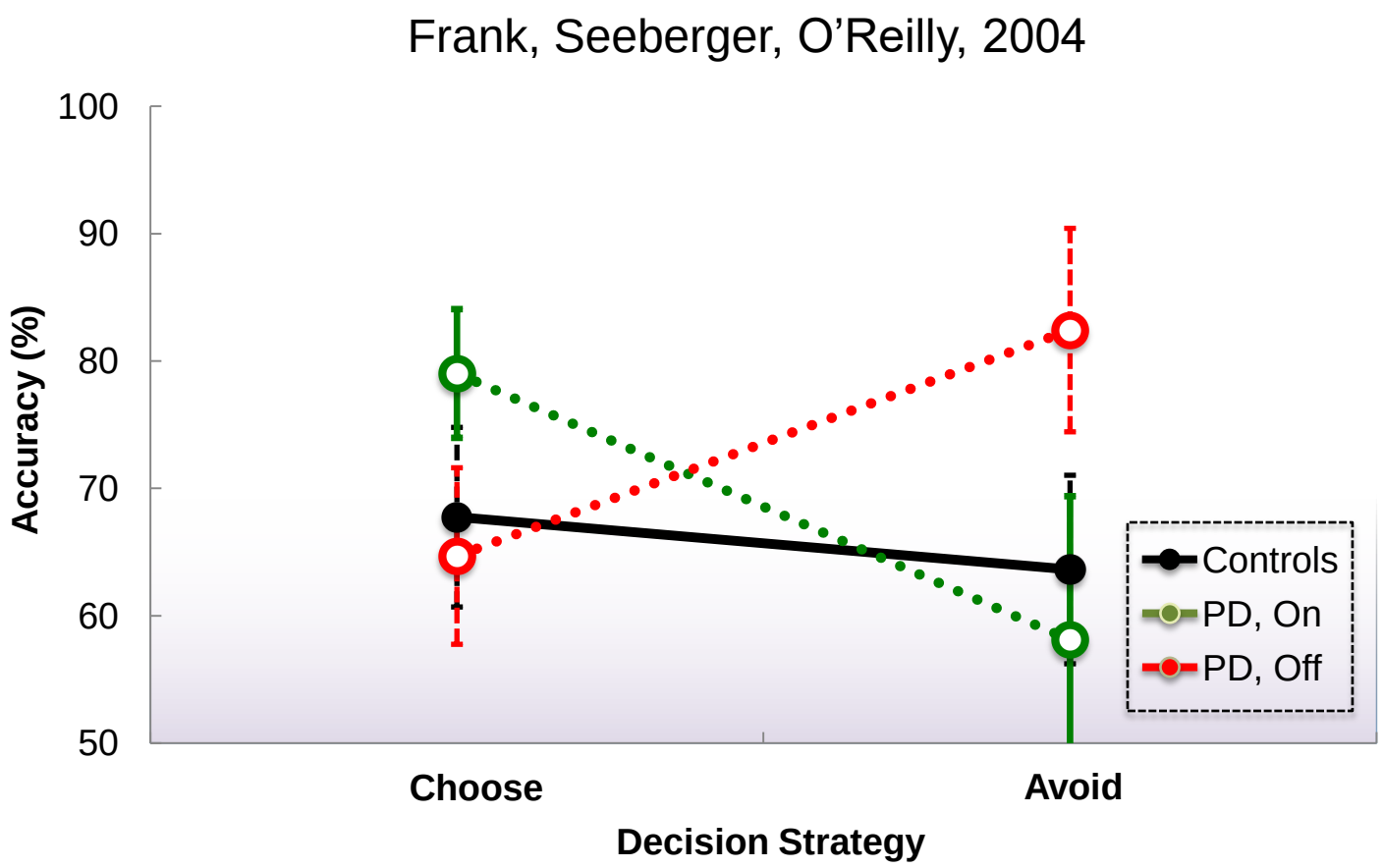




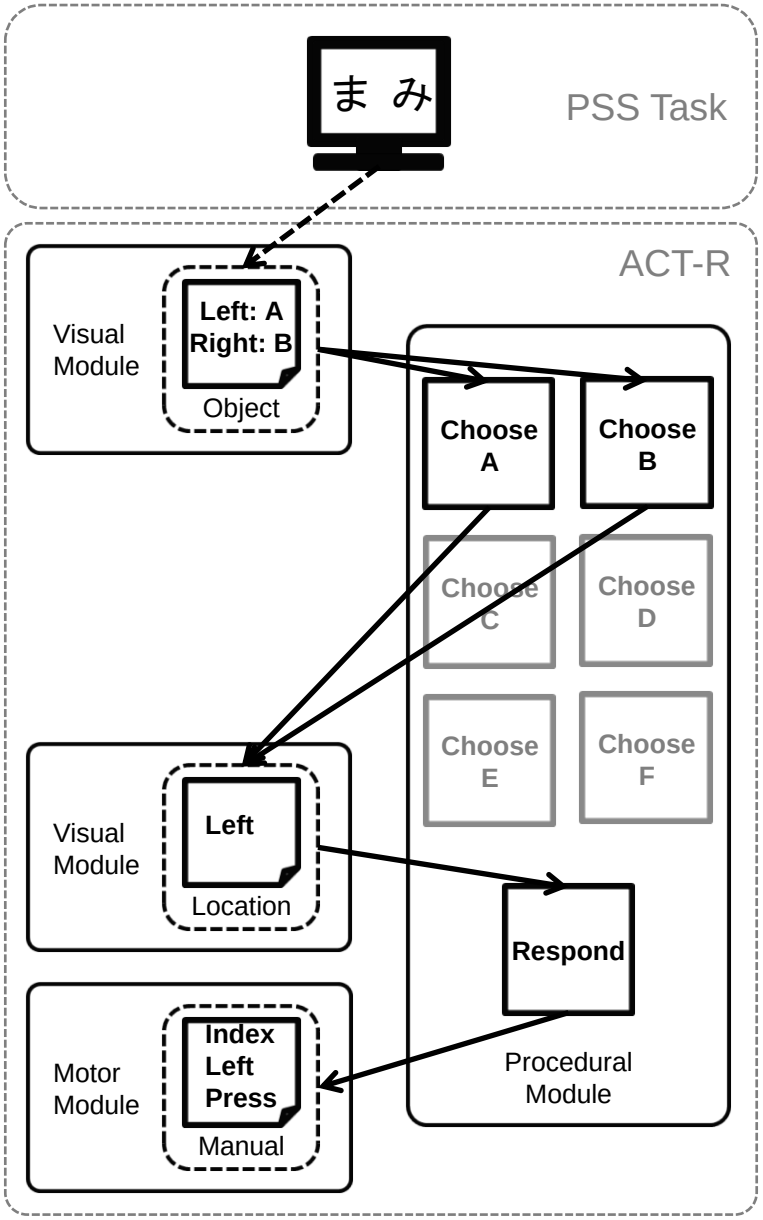
Influence of Dopamine on Go & No-Go



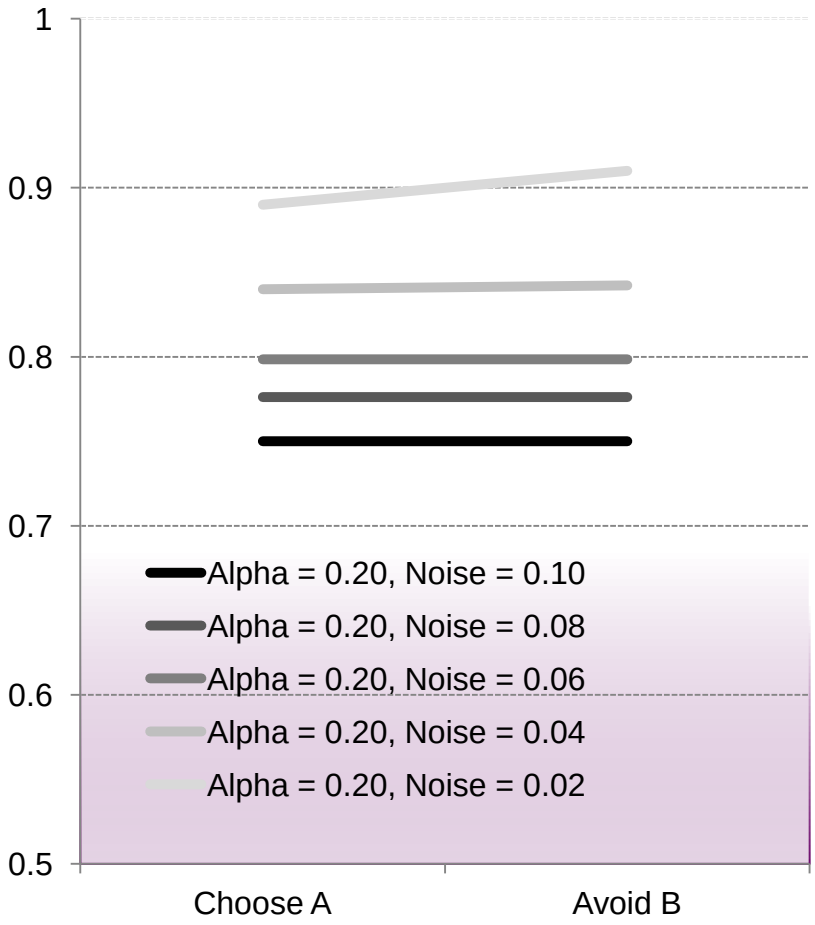
Influence of Dopamine on Go & No-Go

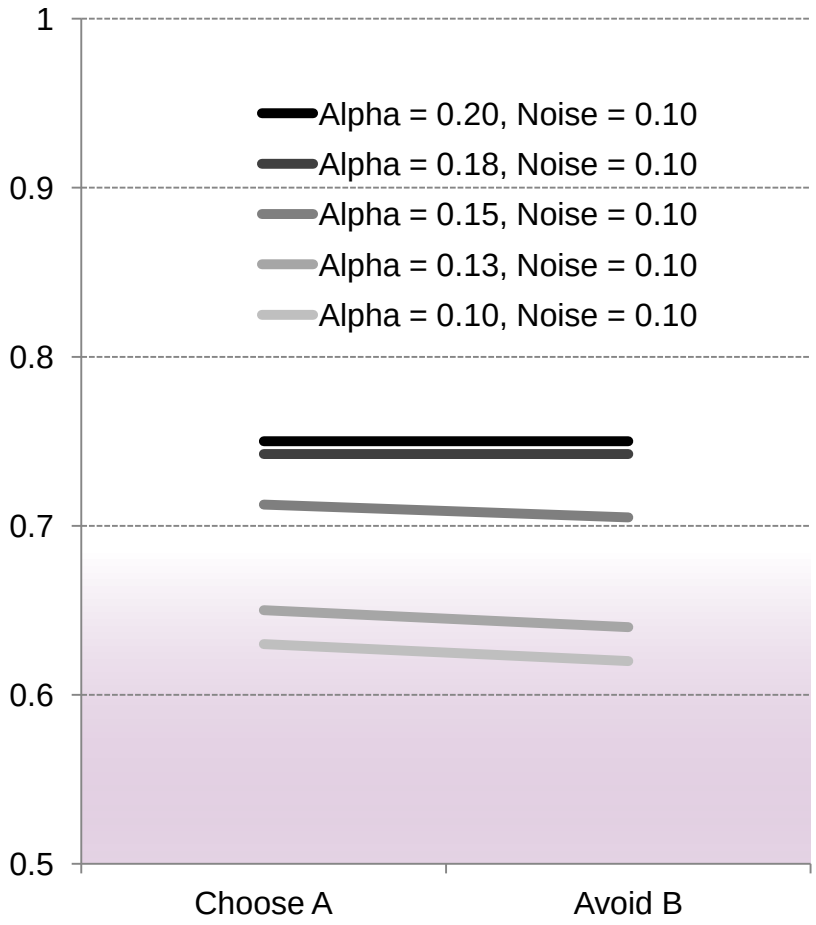


Straightforward model

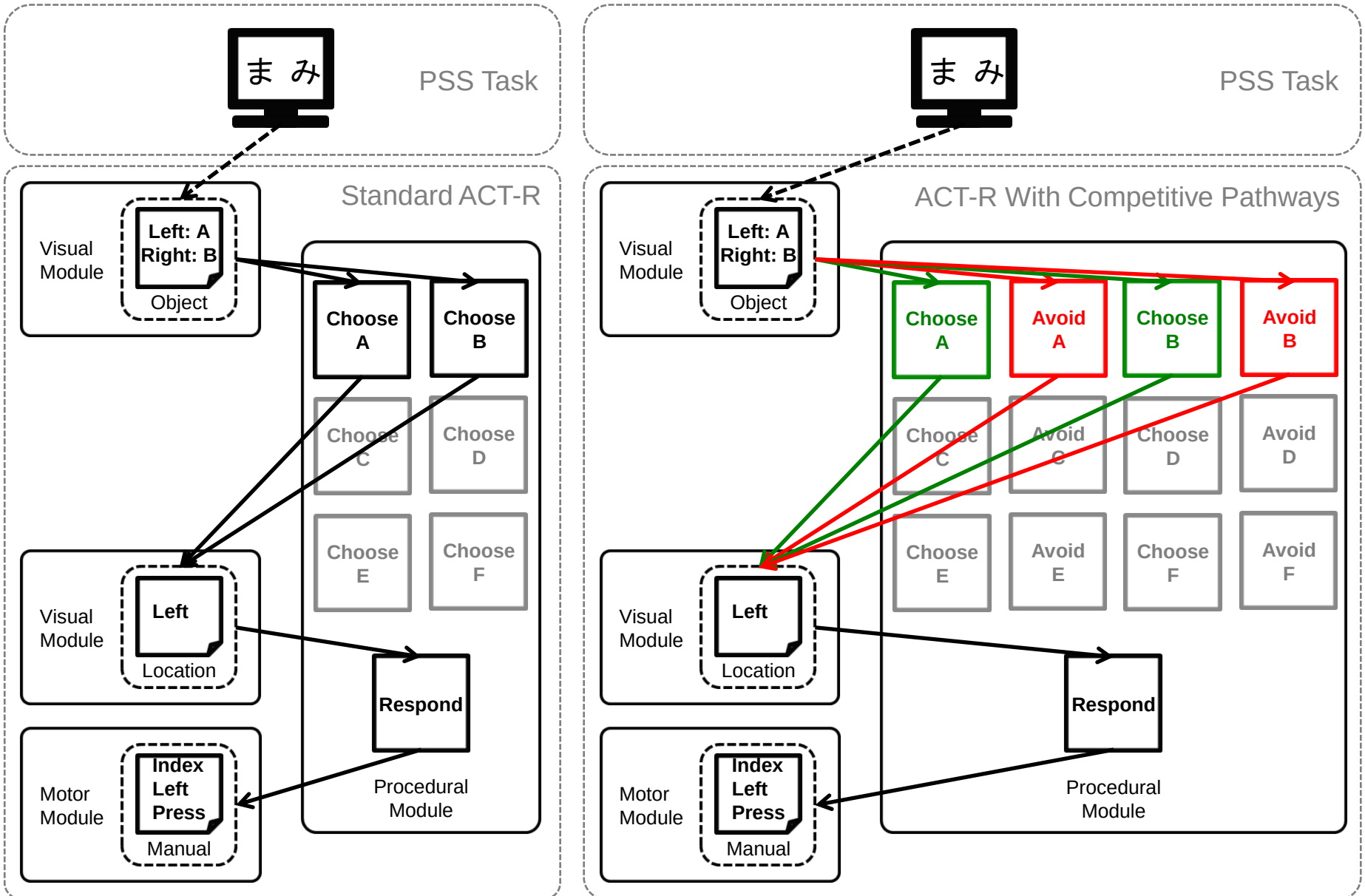


Learning rate α ? Expected noise s ?

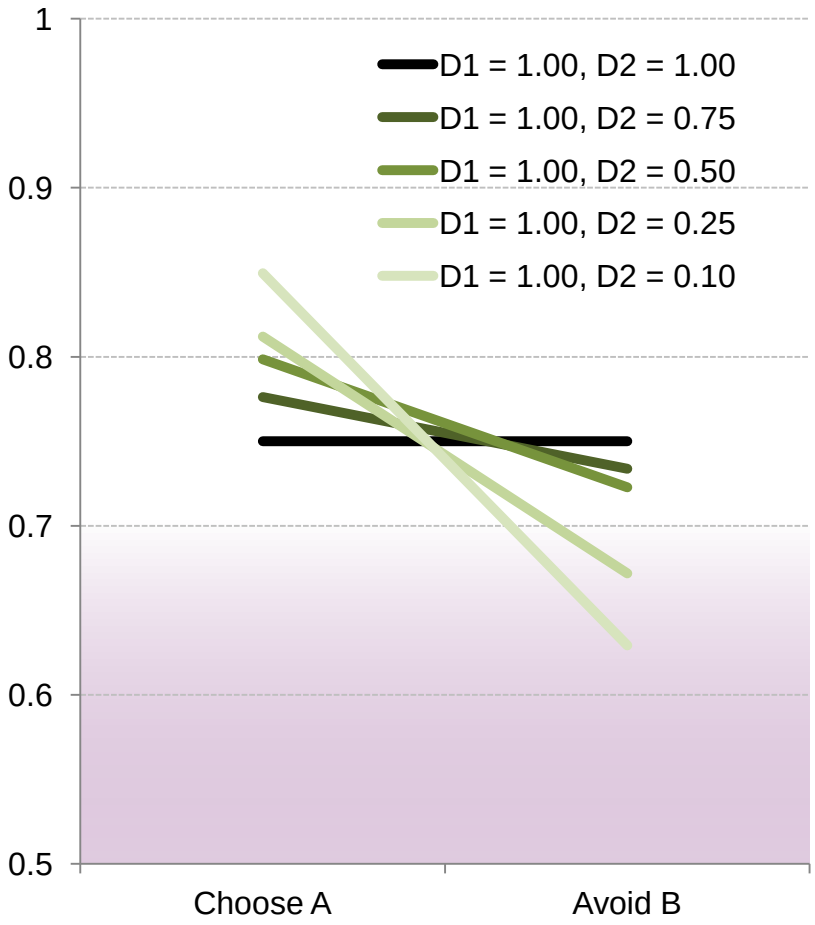


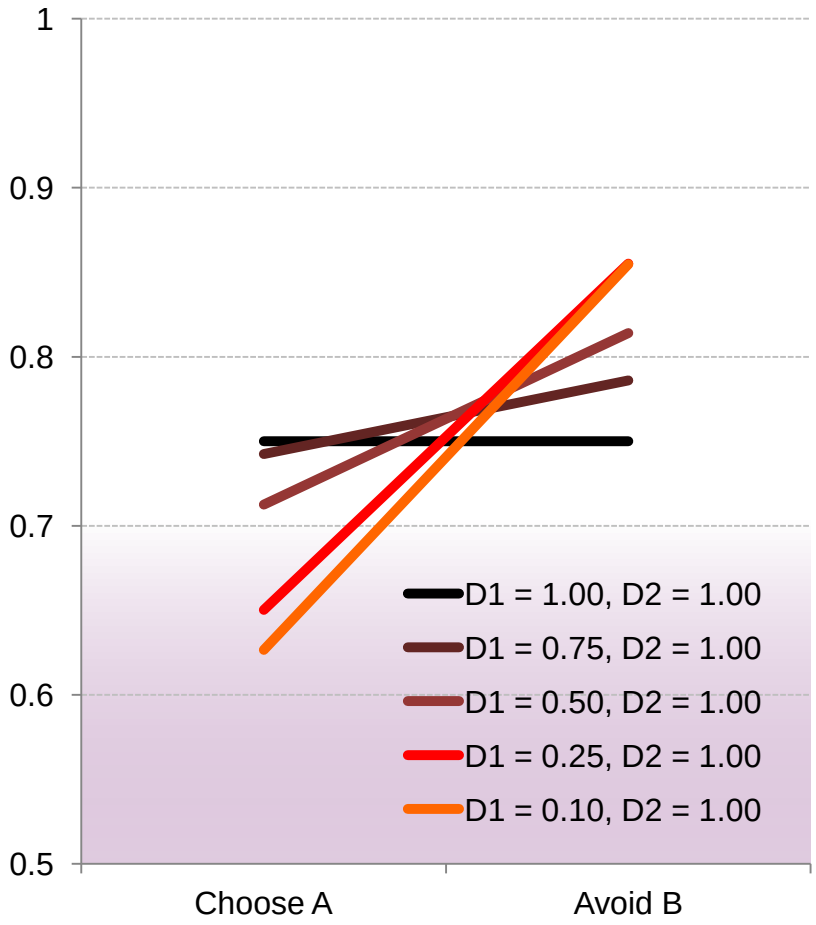


A Dual-Pathway Model

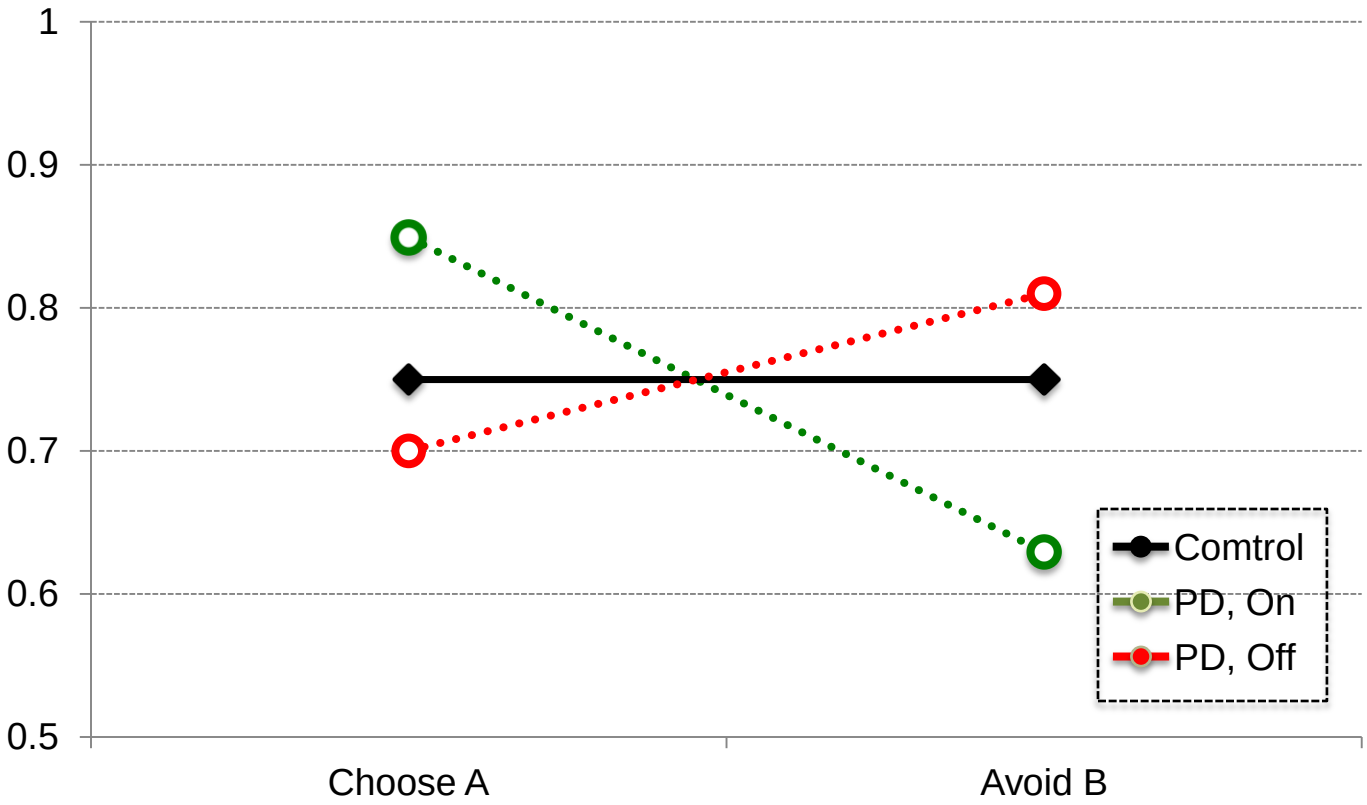


Results


1
0.9
0.8
0.7
0.6
0.5
D1 = 1.00, D2 = 1.00
D1 = 1.00, D2 = 0.75
D1 = 1.00, D2 = 0.50
D1 = 1.00, D2 = 0.25
D1 = 1.00, D2 = 0.10
Choose A
Avoid B


1
0.9
0.8
0.7
0.6
0.5
D1 = 1.00, D2 = 1.00
D1 = 0.75, D2 = 1.00
D1 = 0.50, D2 = 1.00
D1 = 0.25, D2 = 1.00
D1 = 0.10, D2 = 1.00
Choose A
Avoid B

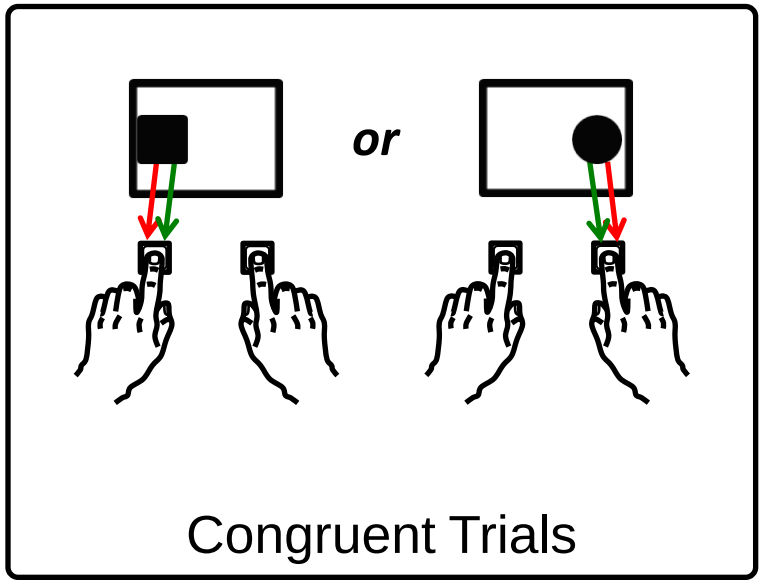
Results (Default parameters)



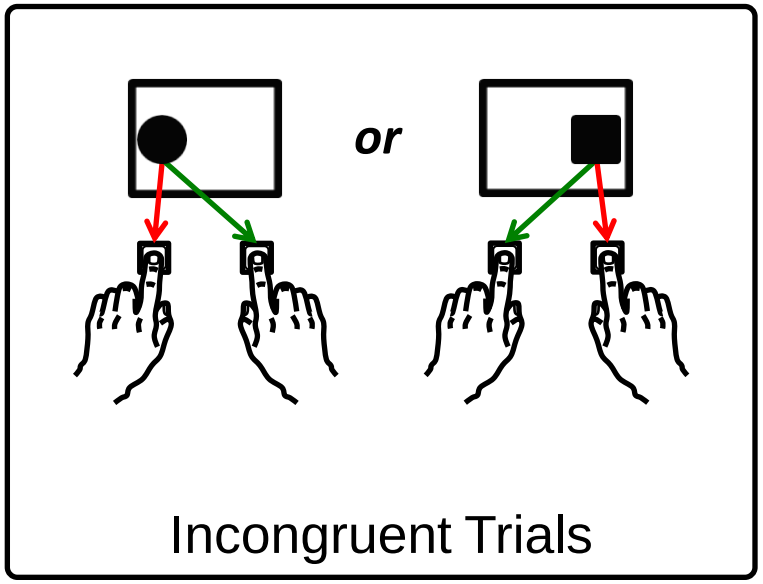
Stocco, *submitted*

Implications for Executive Functions

"Press **left** if you see a **square**"

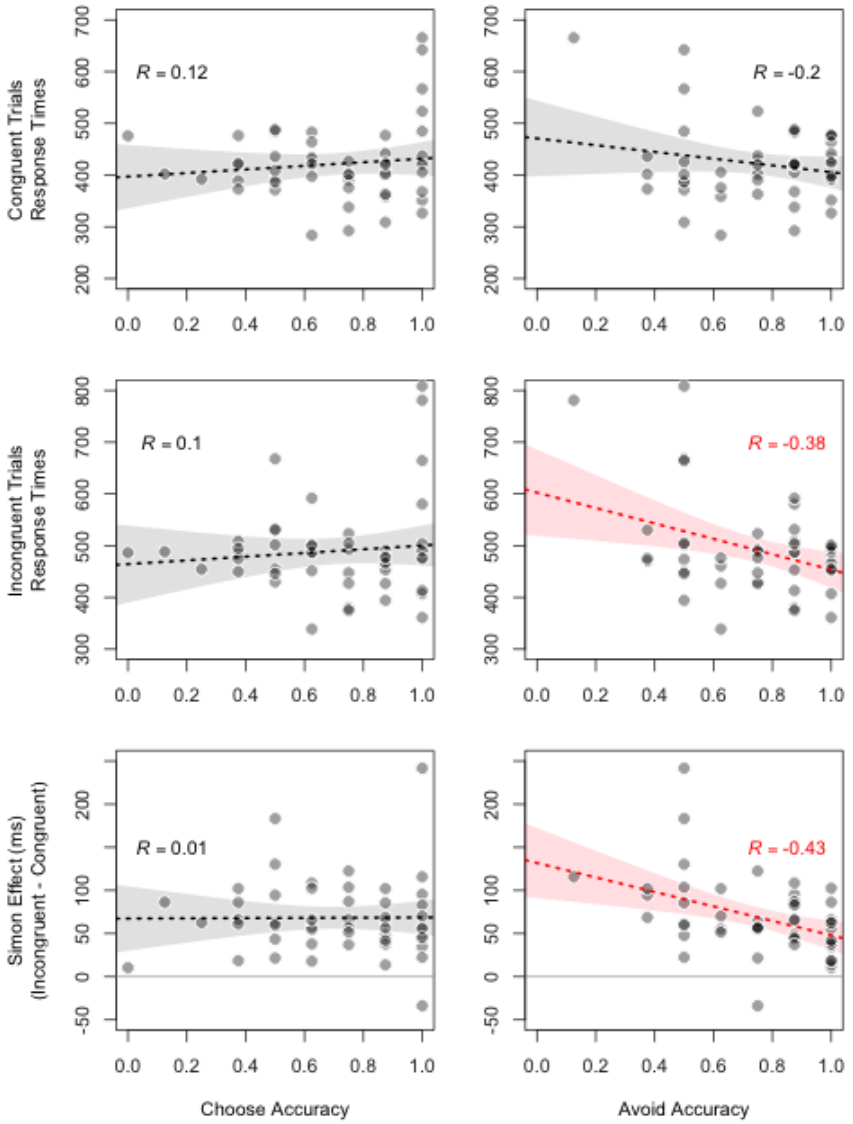


Congruent Trials

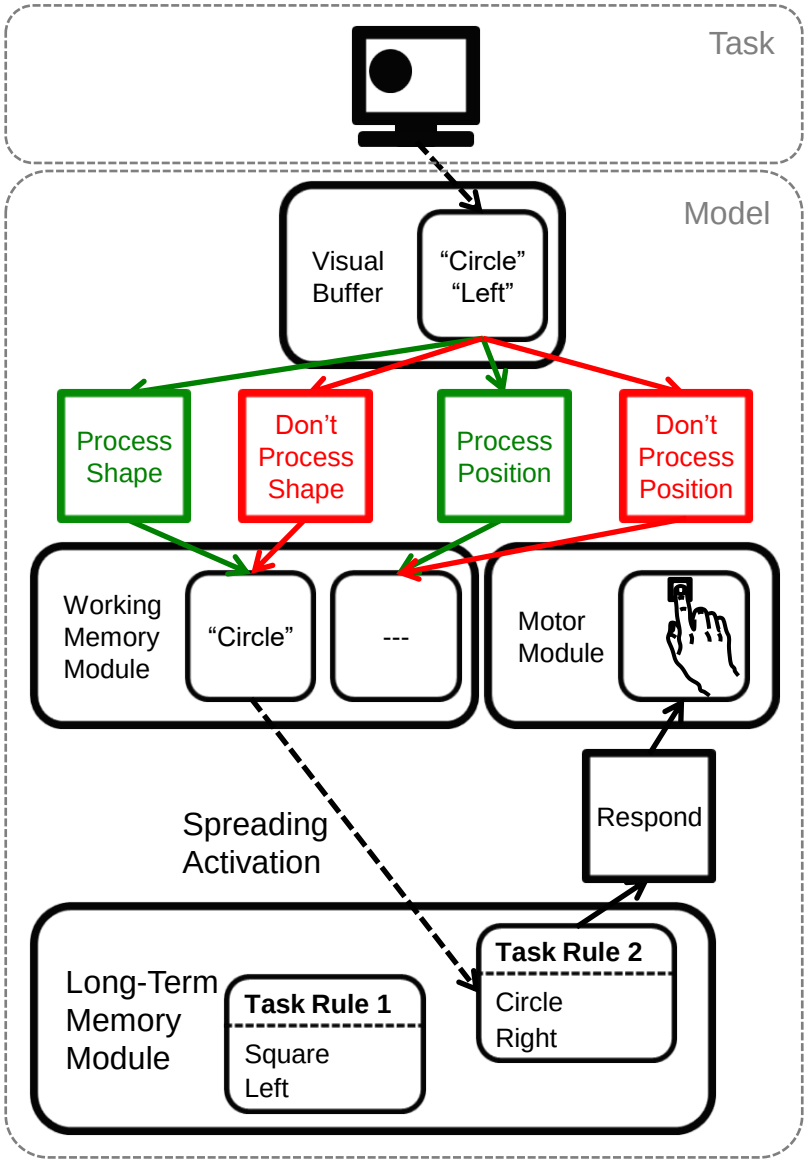


Incongruent Trials

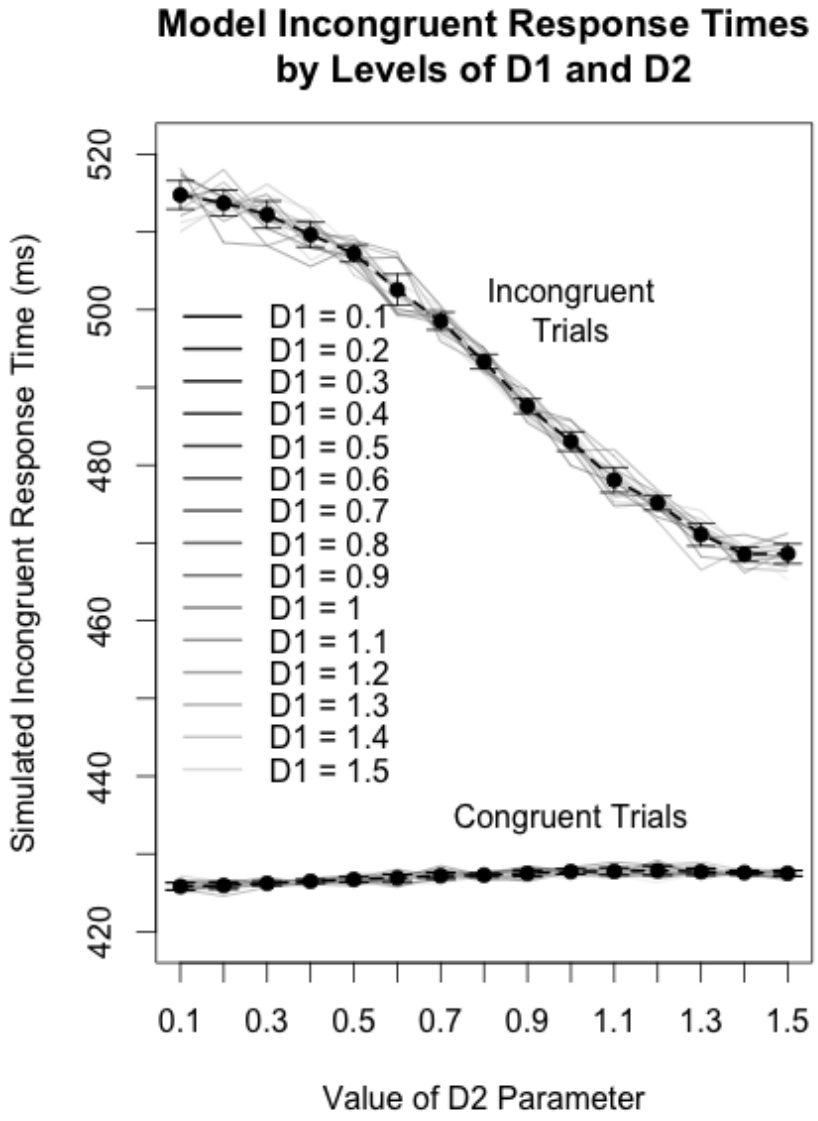
Experimental Results



Simon Task Model

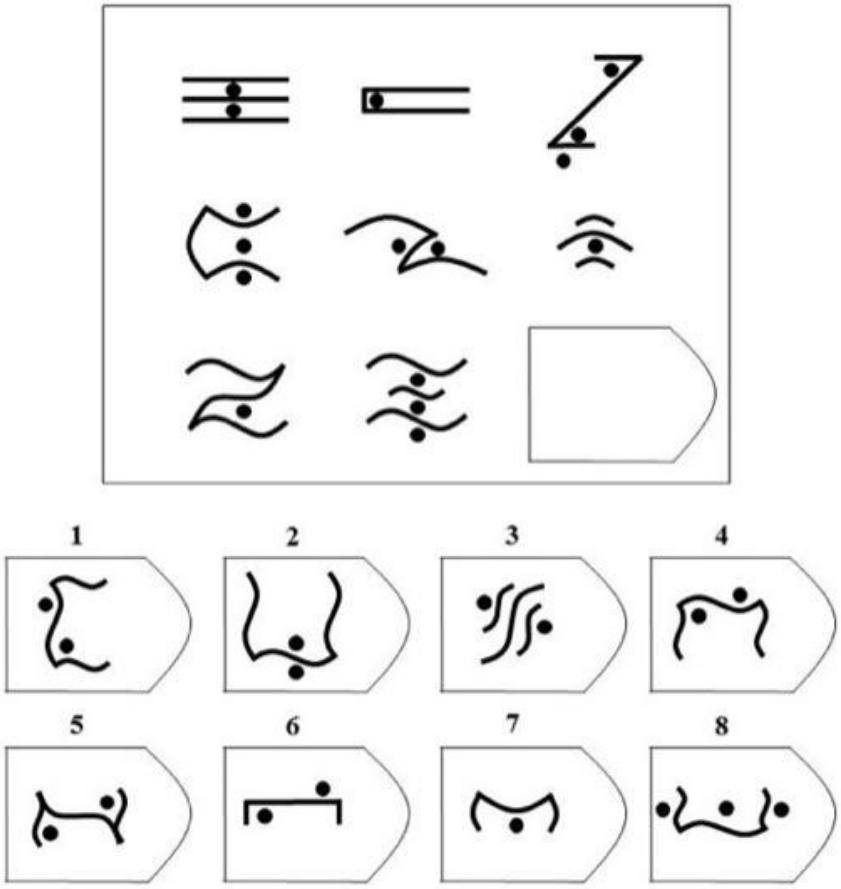


Model predictions

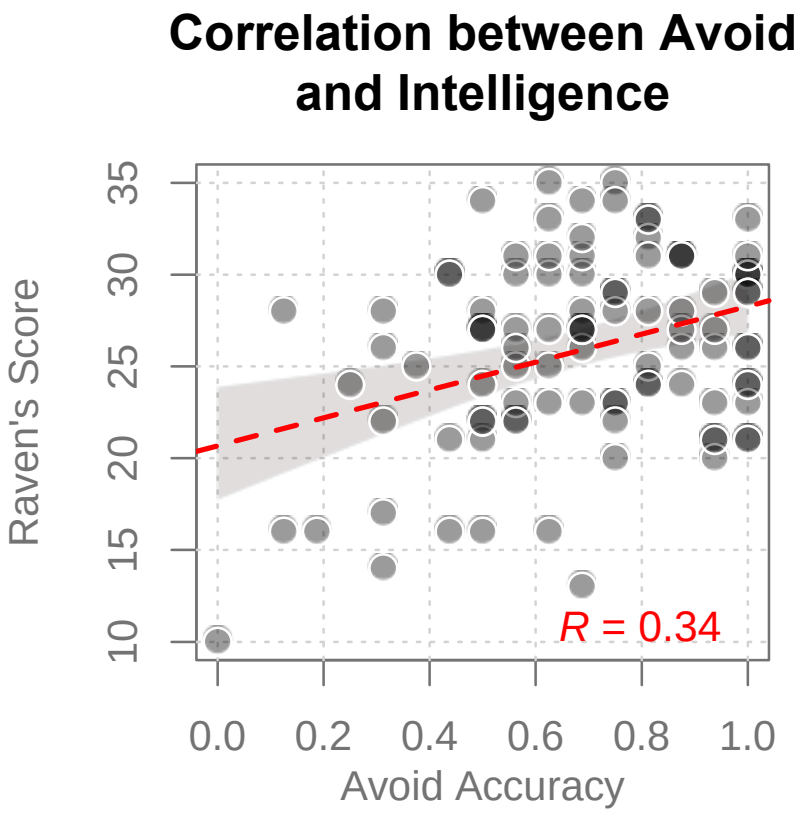


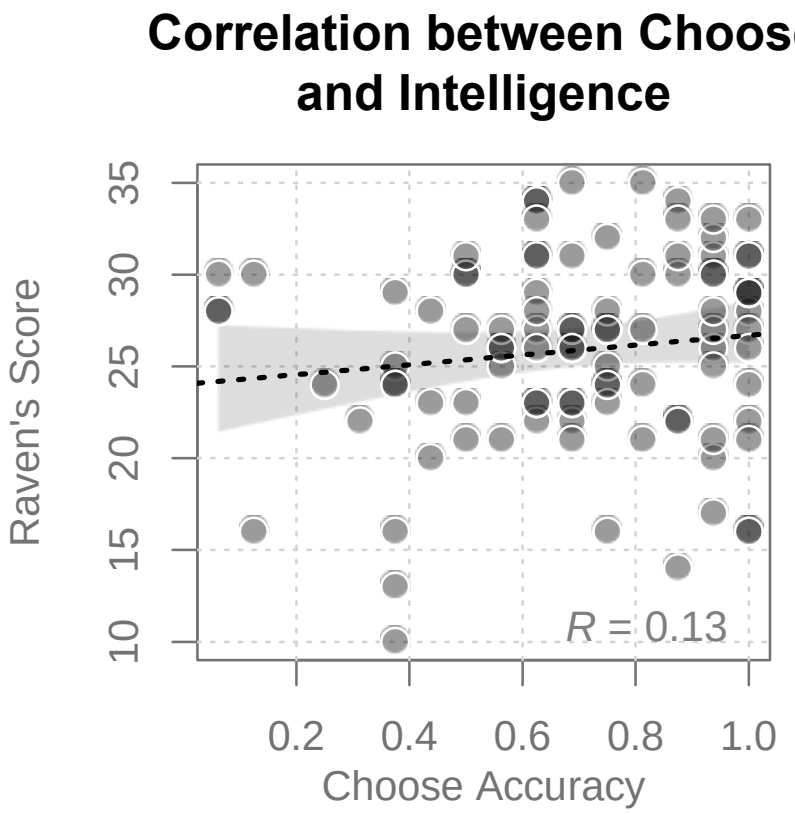
Stocco et al., *submitted*

Fluid Intelligence: Raven's Advanced Progressive Matrices (RAPM)

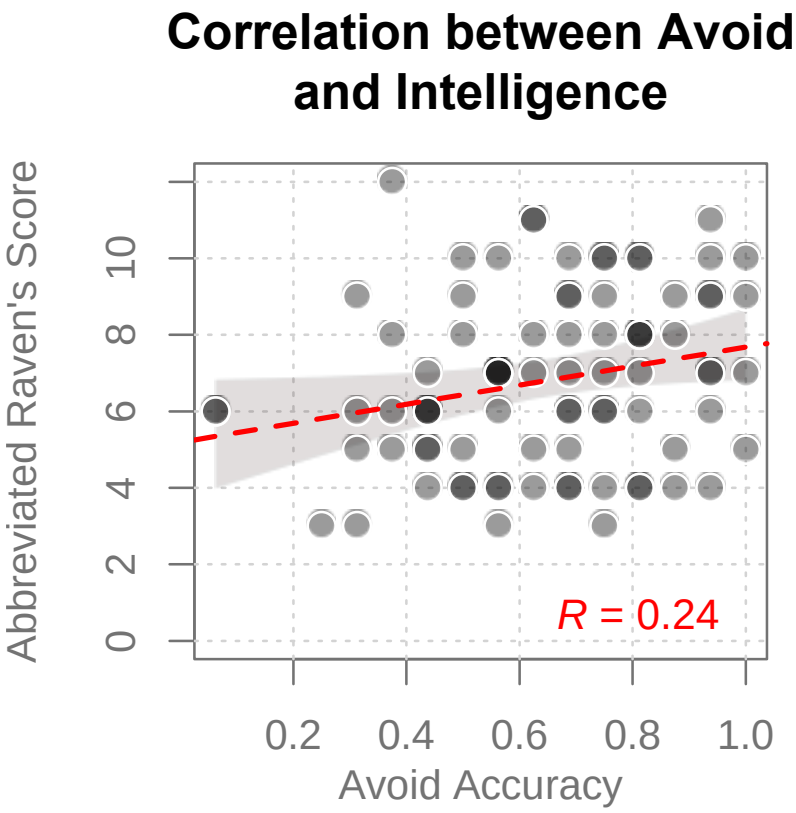


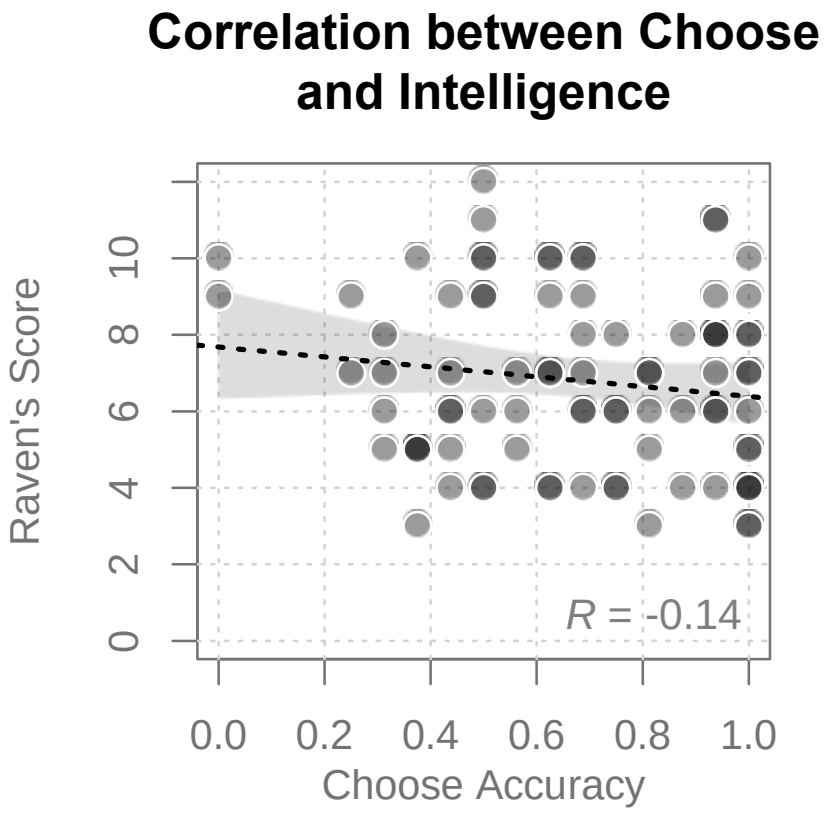
Results: Experiment 1 (N = 95)



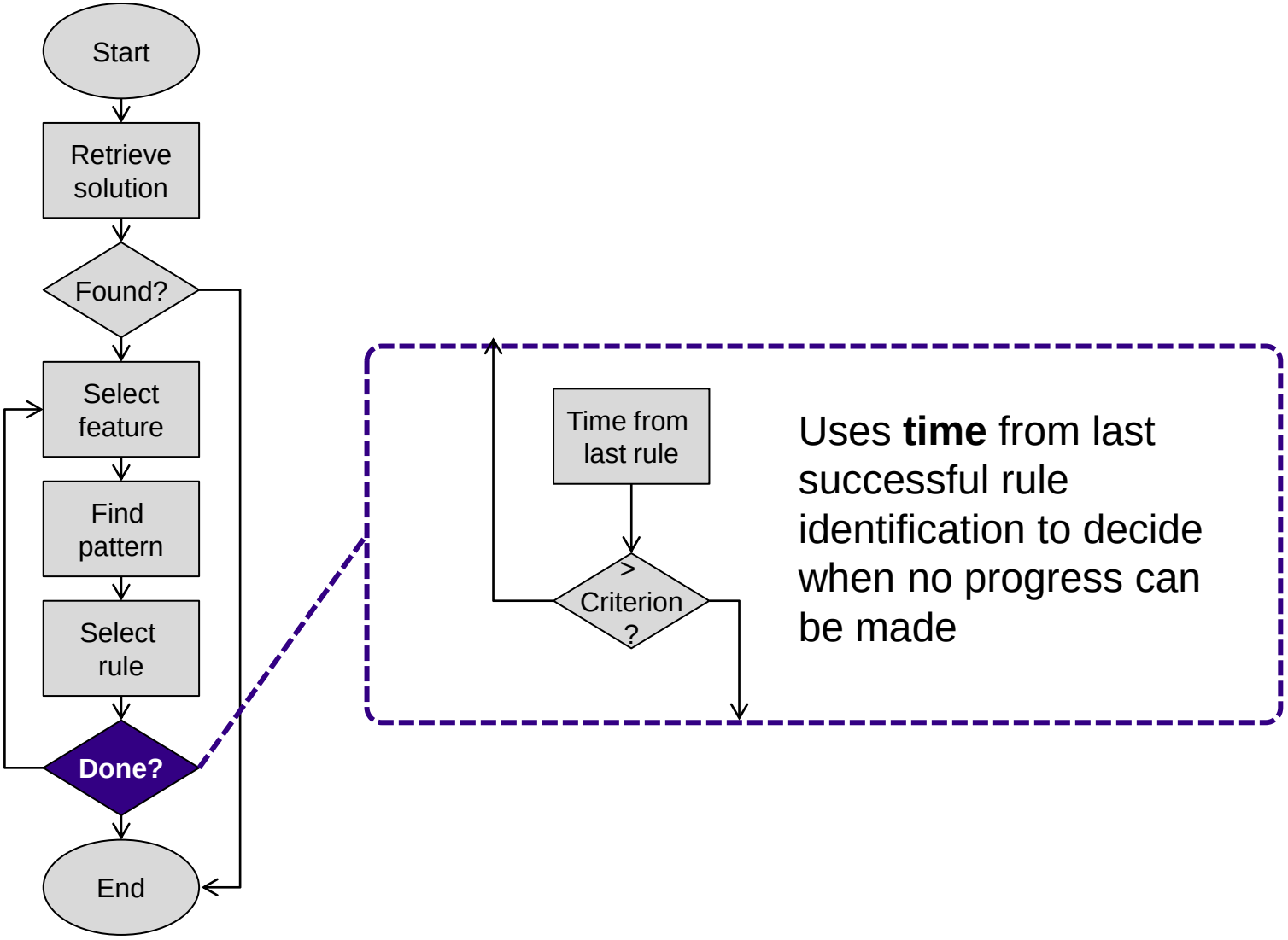


Replication: Experiment 2 (*N* = 83)

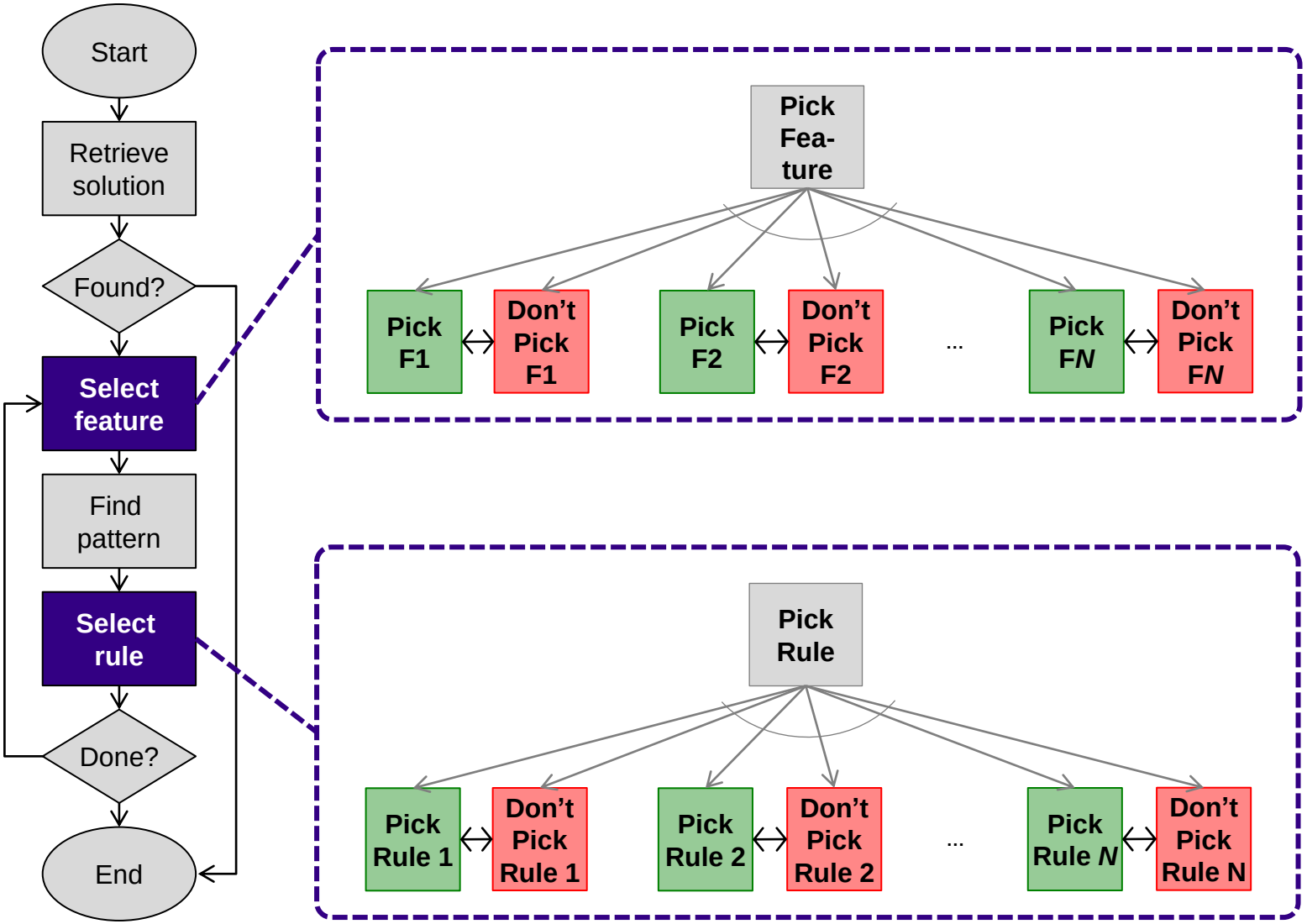




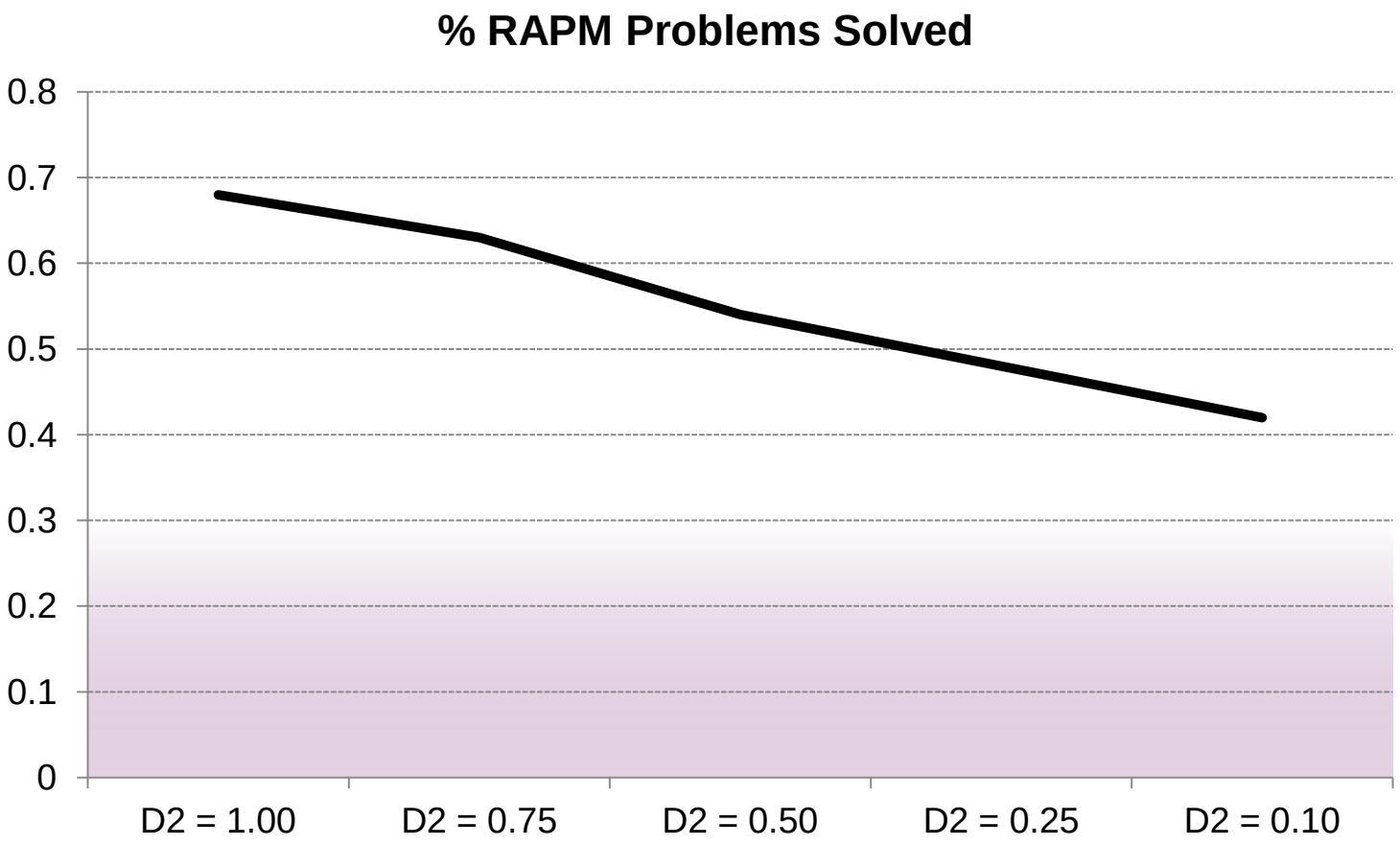
Model Strategy



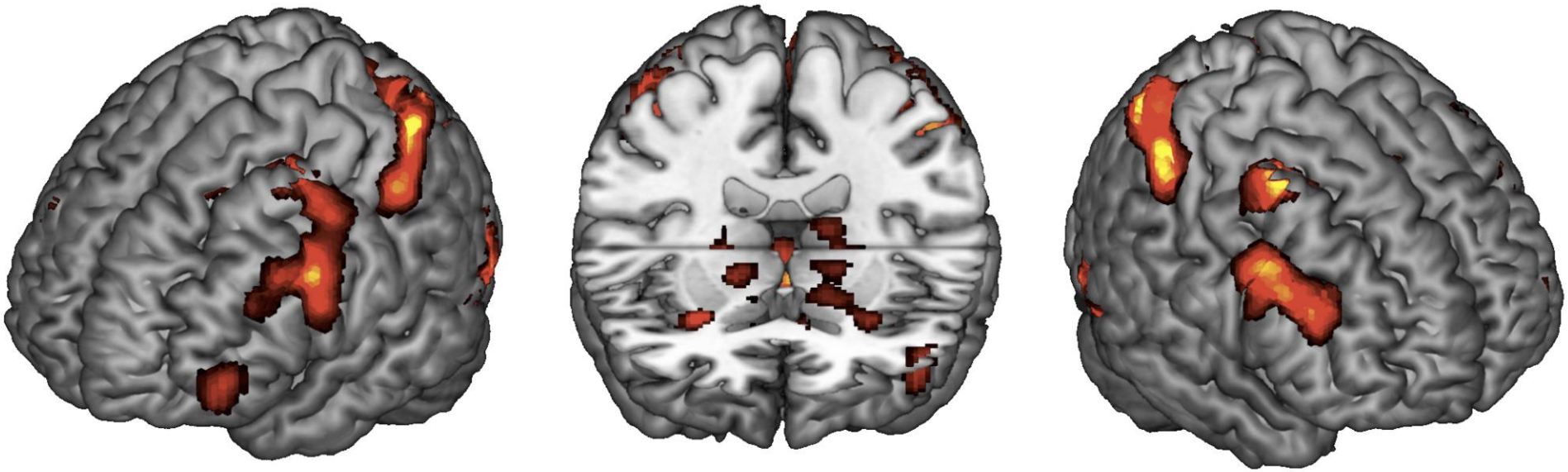
Crucial Steps



Model Predictions

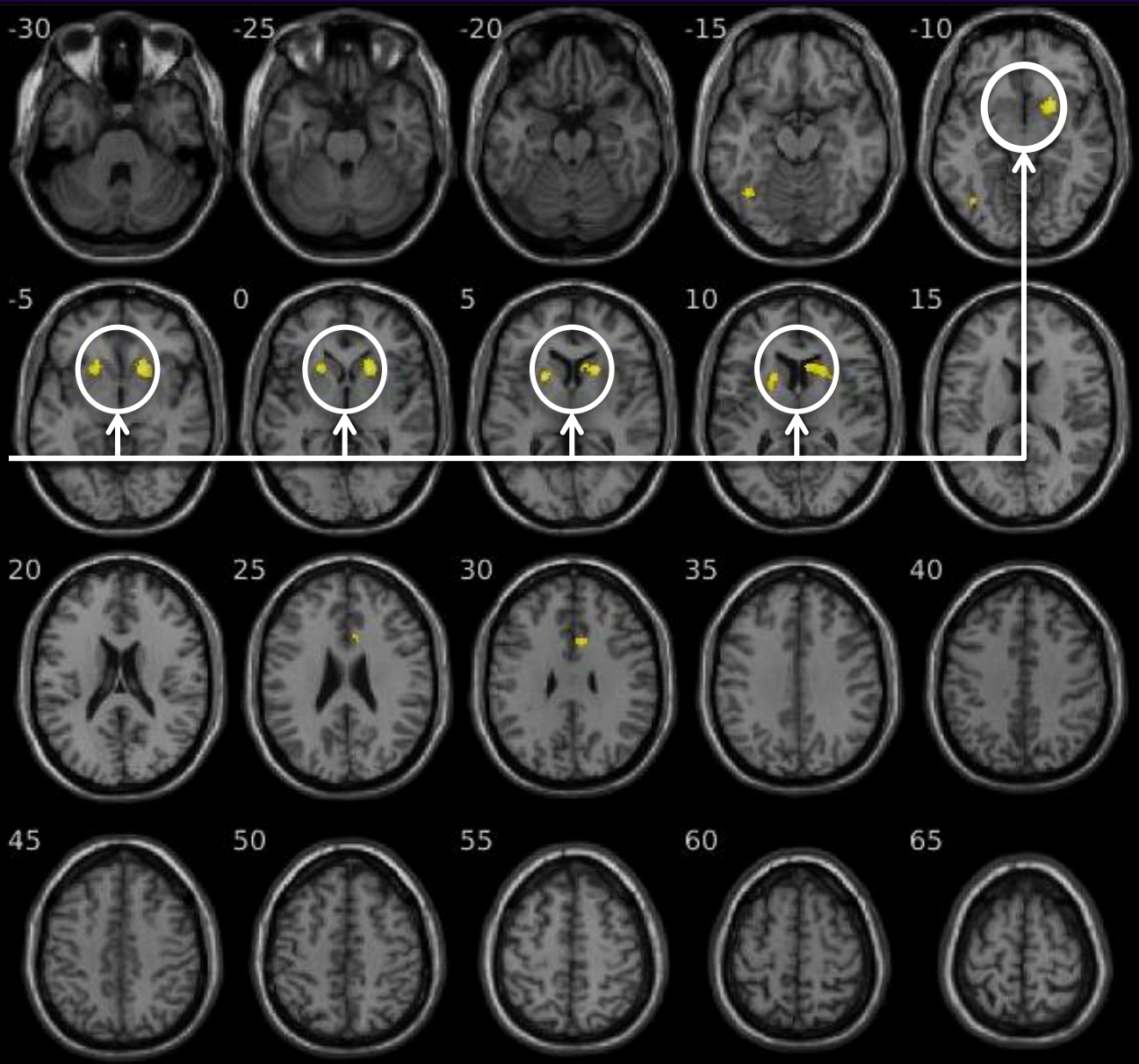


Mean brain activity during problems



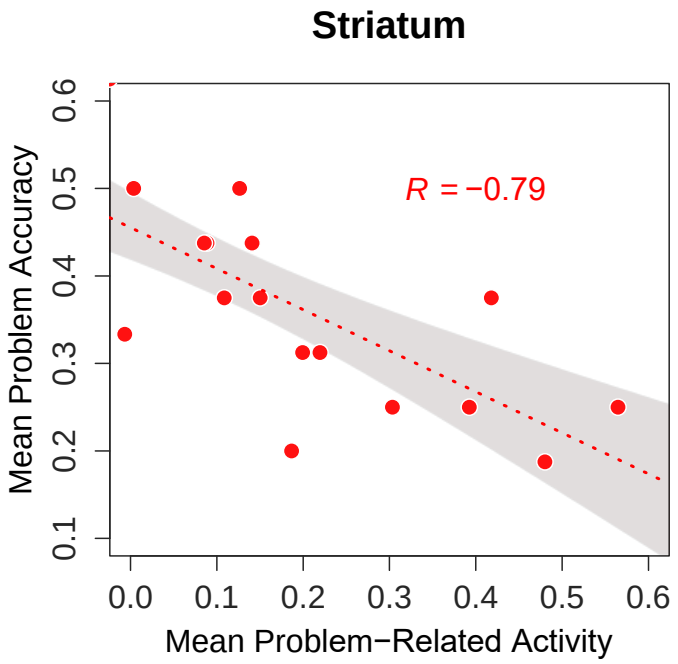
$p < 0.05$, FWE-corrected

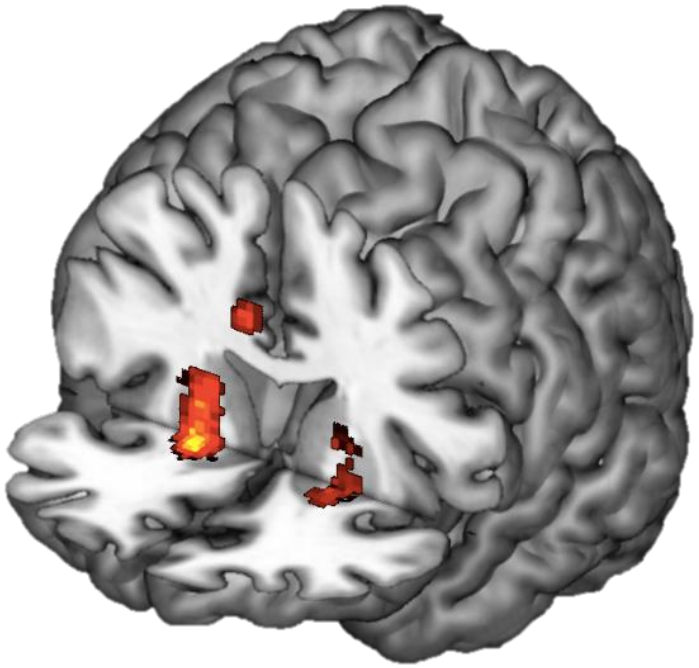
Negative correlation with Accuracy



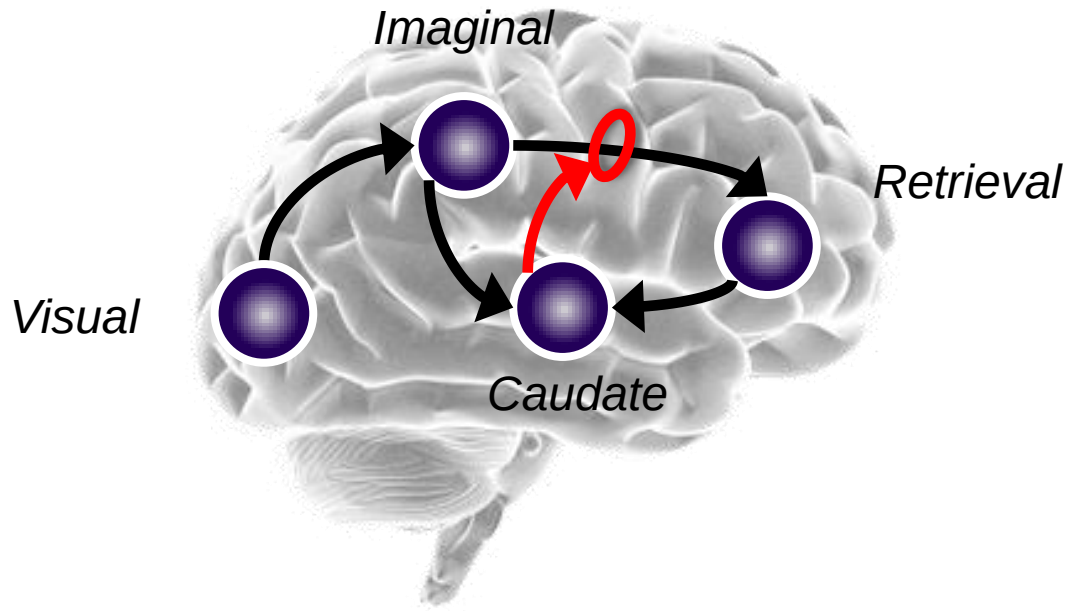
Bilateral
Basal Ganglia

Negative correlations in the BG

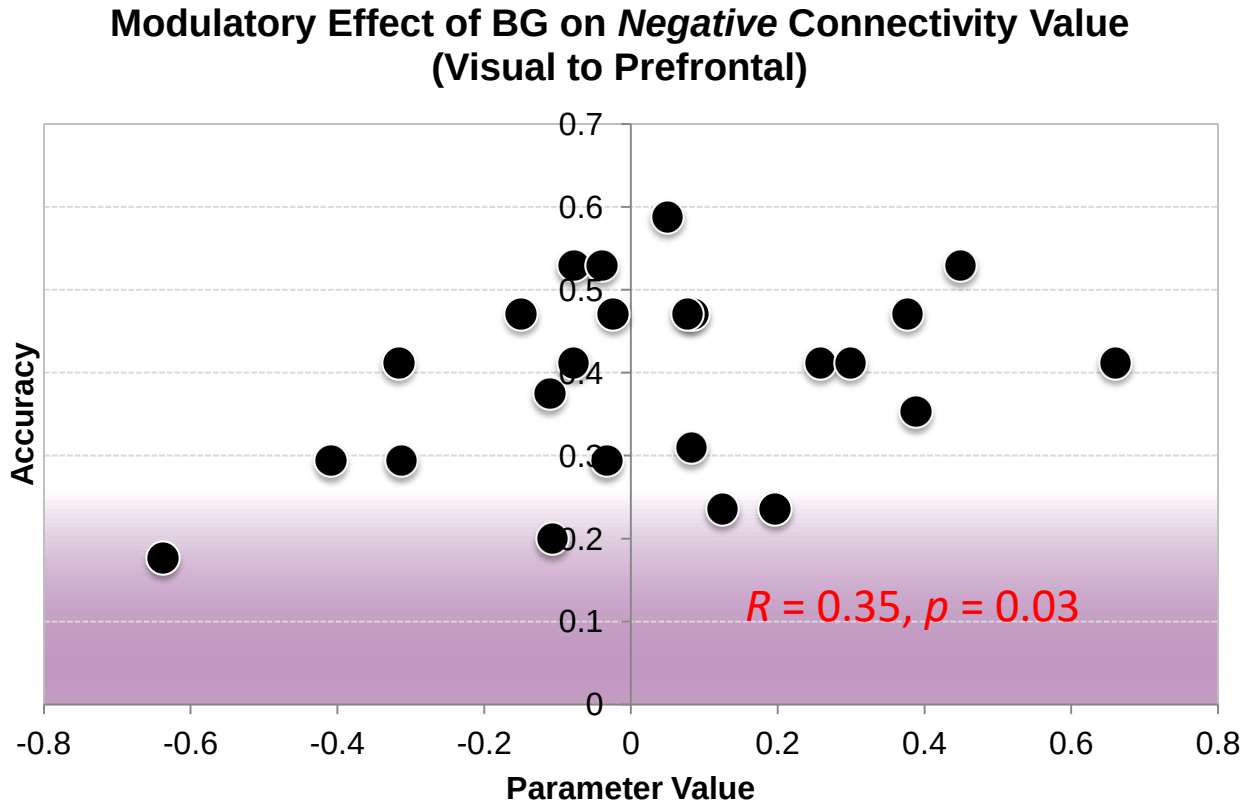




Dynamic Causal Modeling



Dynamic Causal Modeling



Summary, part 2

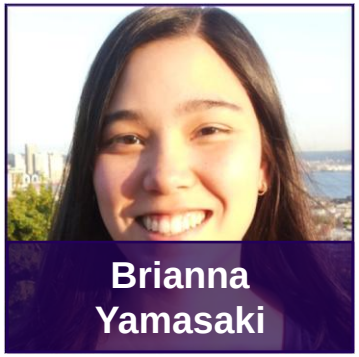
- The effect of production rules can be measured through **effective connectivity**
- Effective connectivity patterns can be used to **test ACT-R models**
- Anatomically, we are missing the functional distinction between **two pathways**
- It seems to play an important functional role across **multiple domains**.

Thank You!

The Basal Gang @ UW

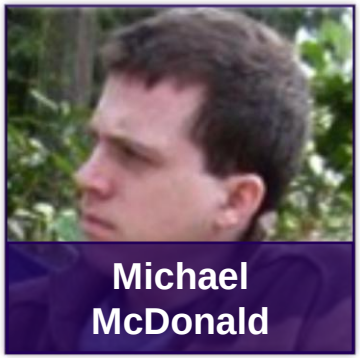

Chantel Prat


Lauren Graham


Brianna Yamasaki


Jose Ceballos


Patrick Rice

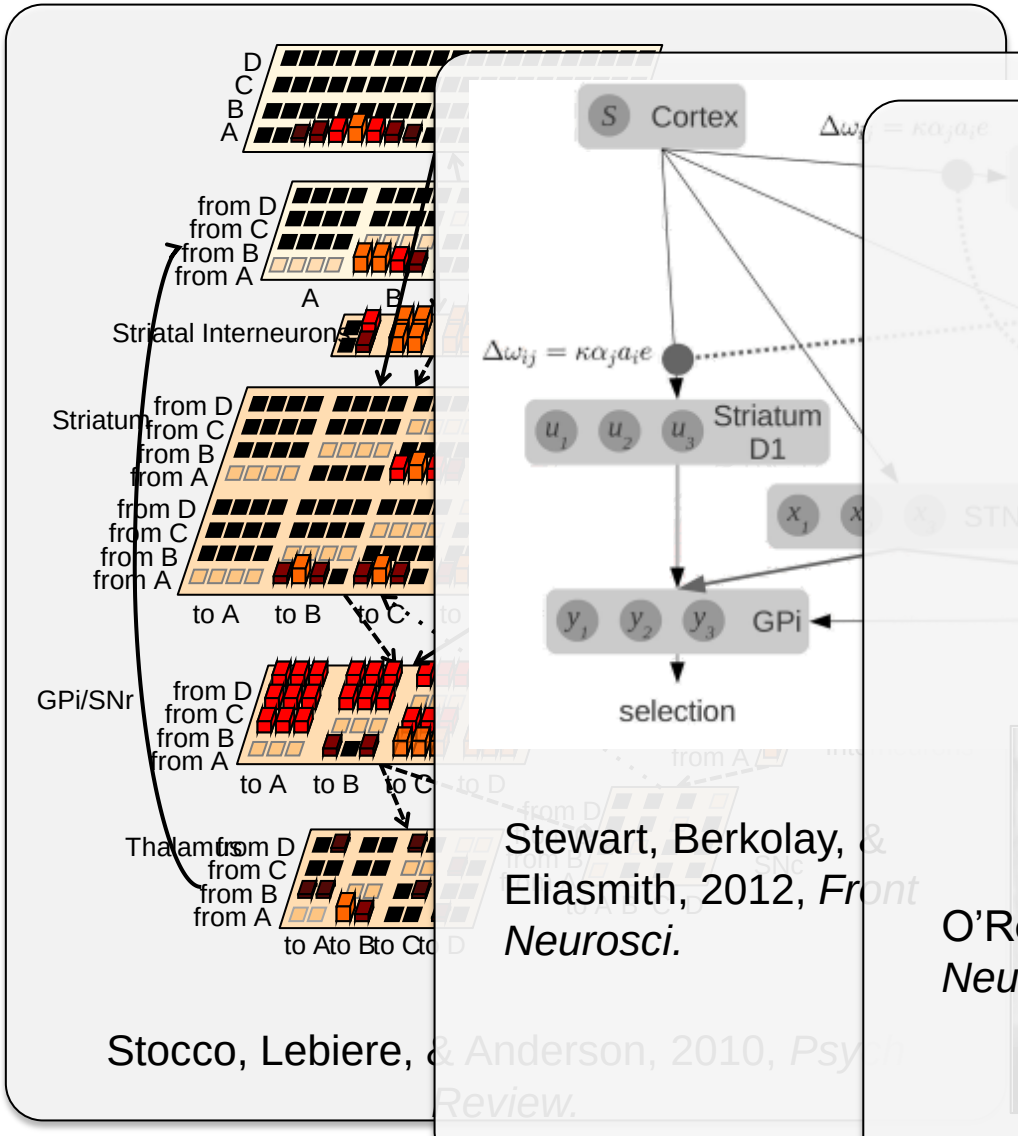

Michael McDonald


Nicole Murray

After the talk…

EXTRA SLIDES

Plausibility of BG as Production Rules

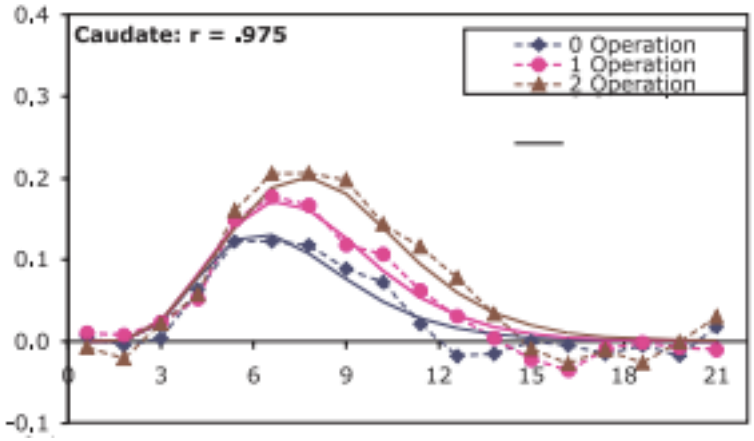


Stocco, Lebiere, & Anderson, 2010, *Psych. Review.*

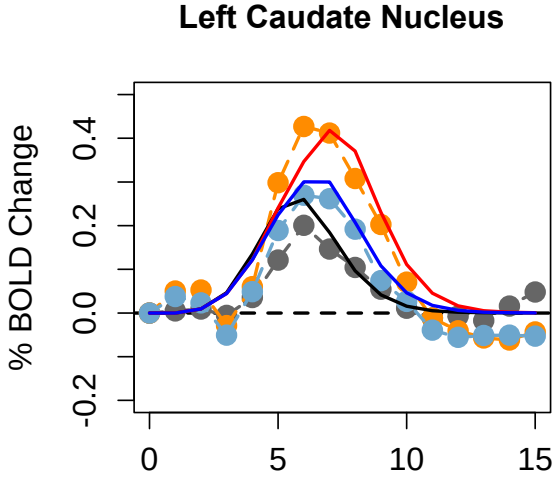
Stewart, Berkolay, & Eliasmith, 2012, *Front. Neurosci.*

O'Reilly & Frank, 2006, *Neural Netw.*

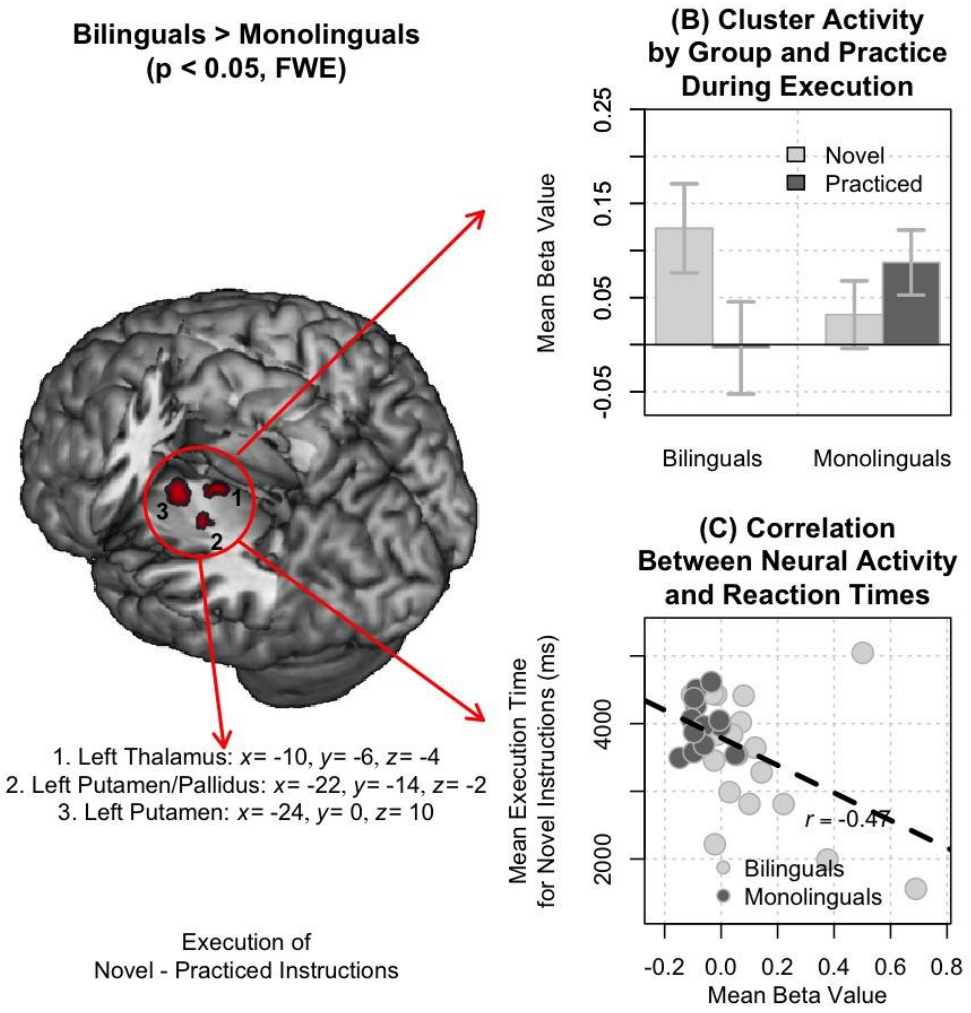
A Few Empirical Verifications



Anderson, 2005: Basal ganglia activity varies with number of rules



Stocco & Anderson, 2008: Basal ganglia activity varies with number of variables in a rule



Stocco & Prat, 2014: Basal ganglia activity varies with bilingualism (larger set of rules!)