Implications of a Dynamic Causal Modeling Analysis of fMRI Data

Andrea Stocco
University of Washington, Seattle
Production Rules and Basal Ganglia

- **Thalamus**
- **Striatum**
- **Pallidum**
- **Substantia Nigra**

Buffer
- Matching **Striatum**
- Selection **Pallidum**
- Execution **Thalamus**

Procedural Module
Production Rules Transfer Variables

Respond-if-asked

IF.....
Request
...
About...
....
Status...
...
Movie...
...
Status...
...
....
...THEN
Do........
....

Raise
Hand

Stranger
Things

Seen

Stranger
Things

Seen

Raise
Hand
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

• Question 1: Can we \textit{experimentally test} it?

• Question 2: Are we \textit{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

\[
d\mathbf{y}/dt = A\mathbf{y} + \sum_i x_i B(i) y + \sum_j y_j D(j) y + C x
\]

\[\mathbf{y} = \sum_i \beta_i^* \mathbf{x}_i\]
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

R PFC
R Caudate
Visual
ACC
LBG
Motor
LCaudate

L Caudate
L PFC
Motor
ACC
Visual
R Caudate
R Prefrontal
ACT-R’s Connectivity Matrix

... 120.545 PROCEDURAL CONFLICT RESOLUTION
120.595 PROCEDURAL PRODUCTION-FIRED PREPARE-FOR-ENCODING
120.595 PROCEDURAL CLEAR-BUFFER RETRIEVAL
120.645 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-0
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

Basal Ganglia Modulation of Incoming Signals to PFC

Modulatory Strength (Hz)

-0.2
-0.1
0.0
0.1
0.2
0.3

MFC
OCC
PFC

Source Region

ASD
Controls

Prat, Stocco et al., submitted
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

- Procedural Module
- Matching
- Selection
- Execution

- Striatum
- Pallidum
- Thalamus

Buffer

Substantia Nigra

Thalamus

Pallidum

Striatum
Basal Ganglia physiology and ACT-R

- **Thalamus**
- **Striatum**
- **Pallidum**
- **Substantia Nigra**

**Indirect Pathway (NO GO)**

**Direct Pathway (GO)**

To Frontal Cortex
Probabilistic Stimulus Selection (PSS)

---

Training Phase

Correct!

Feedback

Choice

ま-み

80% 20%

70% 30%

60% 40%

Test Phase

No Feedback

Choice

ま-み

Choose Accuracy

Avoid Accuracy

80% 20%

70% 30%

60% 40%

Frank, Seeberger, & O'Reilly, 2004, Science
Influence of Dopamine on Choose and Avoid Accuracies

Frank, Seeberger, O’Reilly, 2004

Decision Strategy

Choose

Avoid

Controls

Accuracy (%)
Dopamine in Parkinson Disease

Healthy control

Parkinson

Parkinson, on meds
Influence of Dopamine on Go & No-Go

Frank, Seeberger, O’Reilly, 2004

Accuracy (%)

Choose

Avoid

Decision Strategy

Controls

PD, Off
Influence of Dopamine on Go & No-Go

Frank, Seeberger, O’Reilly, 2004

The graph illustrates the accuracy (%) of different decision strategies: Choose and Avoid, for Controls, PD, On, and PD, Off conditions. The y-axis represents accuracy in percentage, ranging from 50 to 100. The x-axis represents the decision strategy, with two categories: Choose and Avoid. The graph shows a trend where PD, Off conditions have lower accuracy compared to PD, On and Controls, especially in the Avoid strategy.
Straightforward model

PSS Task

ACT-R

Visual Module

Object

Left: A
Right: B

Choose A
Choose B

Choose C
Choose D

Choose E
Choose F

Respond

Procedural Module

Motor Module

Index
Left
Press
Manual

Left
Location
Learning rate $\alpha$ ? Expected noise $s$ ?

Choose A

Avoid B

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<table>
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</table>
A Dual-Pathway Model

Standard ACT-R

Visual Module

Object

Choose A

Choose B

Choose C

Choose D

Choose E

Choose F

Motor Module

Index Left

Press

Manual

Respond

Procedural Module

PSS Task

ACT-R With Competitive Pathways

Visual Module

Object

Choose A

Avoid A

Choose B

Avoid B

Choose C

Avoid C

Choose D

Avoid D

Choose E

Avoid E

Choose F

Avoid F

Motor Module

Index Left

Press

Manual

Respond

Procedural Module

PSS Task
Results

Choose A  Avoid B

- 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
Results (Default parameters)

Choose A vs. Avoid B

- Control
- PD, On
- PD, Off
Implications for Executive Functions

“Press **left** if you see a **square**”

Congruent Trials

Incongruent Trials
Experimental Results

**Correlation Analysis**

- **Congruent Trials Response Times**
  - $R = 0.12$

- **Incongruent Trials Response Times**
  - $R = -0.2$
  - $R = 0.1$
  - $R = -0.38$

- **Saccade Effect (ms)**
  - (Incongruent - Congruent)
  - $R = 0.01$
  - $R = -0.43$

**Accuracy Comparison**

- **Choose Accuracy**
- **Avoid Accuracy**
Simon Task Model

Task

Model

Visual Buffer

“Circle”

“Left”

Process Shape

Don’t Process Shape

Process Position

Don’t Process Position

Working Memory Module

“Circle”

---

Motor Module

Respond

Spreading Activation

Long-Term Memory Module

Task Rule 1

Square Left

Task Rule 2

Circle Right
Model predictions

Model Incongruent Response Times by Levels of D1 and D2

Simulated Incongruent Response Time (ms)

Incongruent Trials

Congruent Trials

Value of D2 Parameter

D1 = 0.1
D1 = 0.2
D1 = 0.3
D1 = 0.4
D1 = 0.5
D1 = 0.6
D1 = 0.7
D1 = 0.8
D1 = 0.9
D1 = 1
D1 = 1.1
D1 = 1.2
D1 = 1.3
D1 = 1.4
D1 = 1.5

Stocco et al., submitted
Fluid Intelligence: Raven’s Advanced Progressive Matrices (RAPM)
Results: Experiment 1 ($N = 95$)

Correlation between Avoid and Intelligence

Correlation between Choose and Intelligence

$R = 0.34$

$R = 0.13$
Replication: Experiment 2 ($N = 83$)

Correlation between Avoid and Intelligence

Correlation between Choose and Intelligence

$R = 0.24$

$R = -0.14$
Model Strategy

Start

Retrieve solution

Found?

Select feature

Find pattern

Select rule

Done?

End

Uses **time** from last successful rule identification to decide when no progress can be made.
Crucial Steps

1. **Start**
   - Retrieve solution

2. **Select feature**
   - Found?
   - Pick Feature
     - Pick F1
     - Pick F2
     - Pick FN
     - Don’t Pick F1
     - Don’t Pick F2
     - Don’t Pick FN

3. **Select rule**
   - Pick Rule
     - Pick Rule 1
     - Pick Rule 2
     - Pick Rule N
     - Don’t Pick Rule 1
     - Don’t Pick Rule 2
     - Don’t Pick Rule N
Model Predictions

% RAPM Problems Solved

D2 = 1.00  D2 = 0.75  D2 = 0.50  D2 = 0.25  D2 = 0.10
Mean brain activity during problems

$p < 0.05$, FWE-corrected
Negative correlation with Accuracy

Bilateral Basal Ganglia
Negative correlations in the BG

Striatum

$R = -0.79$
Dynamic Causal Modeling

Imaginal

Visual

Caudate

Retrieval
Modulatory Effect of BG on *Negative* Connectivity Value (Visual to Prefrontal)

Parameter Value

Accuracy

$R = 0.35$, $p = 0.03$
• 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


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!)

Bilinguals > Monolinguals

\[ (p < 0.05, \text{FWE}) \]