The neurobiology of simple choice

Antonio Rangel

Caltech
Goals of neuroeconomics

• Characterize the computational processes used by the brain to make different types of choices

• Understand how does the neurobiology implements and constraints those computations

• Characterize the computational and neurobiological differences underlying decision maker heterogeneity

Ex:
> addicts vs non-addicts
> healthy eaters vs. Big Mac lovers
Simple economic choice
Why study simple choice?

- Simplest setting to study the neurobiology of human DM
- Foundation for more complex choice situations
- Insights about limitations and unexpected features of DM circuitry already be present here
A simple but useful framework
Useful conceptual framework

Recognize & define decision problem

value options

choice

response

Compare

Motor selection
II

Valuation
### Experiment 1

**JNeuro 2007, Plassmann O’Doherty Rangel**

<table>
<thead>
<tr>
<th>Fast for 4 hrs</th>
<th>Experiment: Bid in 100 trials &amp; 50 items</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- 50 free trials</td>
</tr>
<tr>
<td></td>
<td>- 50 forced trials</td>
</tr>
<tr>
<td></td>
<td>Select random trial implement BDM auction</td>
</tr>
<tr>
<td></td>
<td>Stay in lab for 30 min eat prize (if applicable)</td>
</tr>
</tbody>
</table>

#### Free Bid Trials
- 4s food item onset
- 4-10s blank
- 4s bidding
- 1s feedback
- 1-15s fixation

#### Forced Bid Trials
- 4s food item onset
- 4-10s blank
- 4s bidding
- 1s feedback
- 1-15s fixation

**Bid $?**
- **Bid $3**
- **Bid $2**

**Fast for 4 hrs**

**Stay in lab for 30 min eat prize (if applicable)**
MAIN RESULT: mOFC and DLPFC encode for WTP in free trials, but not in forced trials

$p < 0.001$ (unc)
Experiment 2

JNeuro 2010, Plassmann O’Doherty Rangel

Subjects ate 2 hours prior to the experiment.

Bidding task in fMRI scanner

Select random trial & implement auction

Stay in lab for 30 min and eat item (if applicable)

Bidding task:

- trial onset
- 4s food item onset
- mean 5s blank
- 4s bidding
- 1s feedback
- mean 8s fixation

Free bid trials:
- bid $?

Forced bid trials:
- bid $2
- $3
- $2

50 free bid trials + 50 forced bid trials = 100 trials
Areas with increased activity with bid (i.e., with aversive value)

$p < 0.01$ (uncor), 5 voxel
Conjunction of appetitive vs aversive goal value signals

- Increased activity changes: modulation by appetitive DVs in free bid trials
- Decreased activity changes: modulation by aversive DVs in free bid trials
Experiment 3

Cerebral Cortex 2010, Lit et al

Pre-scanning liking rating task

Eating decision task in scanner

Select random trial for eating/not-eating

Receive selected food item (if applicable)

trial onset

food item onset & rating decision: \( \min\{RT, 2s\} \)

(2s - response RT) blank

mean 4s blank

time

Attention-motor-arousal

value
Experiment 3
Chib, O’Doherty, Rangel, JNeuro, 2009

Pre-scanning
free response time
BDM auction

During fMRI Scanning
2 sec
binary choice
$2.35
1-10 sec fixation

+
Behavior

B

\[
\begin{align*}
\text{% of Bids for Item } x & \quad \text{WTP ($)} \\
[0] & \quad (0 - 1) & \quad (1 - 2) & \quad (2 - 3) & \quad (3 - 4) \\
\text{Money} & \quad \text{Trinkets} & \quad \text{Snacks}
\end{align*}
\]

C

\[
\begin{align*}
\text{% Item Selected} & \quad \text{WTP ($)} \\
0 & \quad 0.25 & \quad 0.5 & \quad 0.75 & \quad 1
\end{align*}
\]

- **Money**
- **Trinkets**
- **Snacks**
choices against a fixed monetary bid

choices against a fixed snack item
Value only activity

- mOFC: Beta = 1, n.s.
- L-dPCC: Beta = 0.5, n.s.
- L-rACC: Beta = 1.5, n.s.

Color codes:
- Yellow: p < 0.005
- Orange: p < 0.001
Saliency only activity

- **L-dACC**: p < 0.005
- **L-Insula**: n.s.
- **R-Precentral gyrus**: p < 0.001
Value & saliency related activity
III

Comparison
Common reduced from view

SOFT-MAX:

\[ P_i = \frac{\exp (k V_i)}{\sum \exp (k V_k)} \]
Ratcliff’s Drift-Diffusion Model

Relative action value

\[ RV(t) = RV(t-1) + a(V_{\text{left}} - V_{\text{right}}) + \text{Gaussian noise} \]
Experimental 4
Nature Neuro 2010, Krajbich Armel Rangel

3hr fast
- Stay in lab for 30 mins
- Allowed to eat food chosen in random trial food (but nothing else)

Liking-rating: 70 food items
Binary Choice: 100 trials

2000 ms (enforced)
Free RT
1000 ms

Collect eye-fixations @ 50 Hz
Computational model

\[ V(t) = V(t-1) + a(v_{\text{target}} - \theta v_{\text{non-target}}) + u_t \]
\[ u_t \sim N(0, s^2) \]
Examples of simulations

Key features:

- Fixation lengths drawn from common distribution
- Integrator follows a random walk with slope $r_{\text{target}} - 0.3r_{\text{non-target}}$
Estimation-prediction exercise

• Free model parameters:
  -- $a =$ slope of integration
  -- $s^2 =$ noise variance
  -- $\theta =$ attentional bias

• Estimate parameters in even trials using ML
  Match: choices and reaction times

• Simulate model in odd trials
Basic psychometrics
Basic fixation patterns

![Graph showing fixation patterns and their durations related to item ratings.](image-url)
Key tests of the model
Predicted choice biases

- Graph showing the relationship between left rating - right rating and the probability of choosing left, with error bars and a trend line.
  - Legend: ○ last fix left, Δ last fix right.

- Graph showing the probability of choosing left vs. final time advantage left [ms], with a trend line and p-value.
  - p = 0.0002

- Graph showing the probability of choosing left vs. first fixation duration [ms], with a trend line and p-value:
  - p = 1e-06

- Scatter plot showing the correlation between p(choose left) and p(look left first), with a linear trend:
  - r = 0.38 (p = 0.017)
Experiment 5
under review, Seung O’Doherty Rangel

A

B

C

D

E

F

G

H

I

J

K

L

M

N

O

P

Q

R

S

T

U

V

W

X

Y

Z

\[ P(L \text{ item}) \]

\[ V^L - V^R \]

\[ T^L > T^R \]

\[ T^L < T^R \]

\[ P < .05 \]

\[ ns \]
mOFC encodes attention modulated relative value signals

\[ y = 16 \]

\[ x = -6 \]

\[ \text{fix}^L \cdot (V^L - V^R) \]

\[ \text{fix}^R \cdot (V^L - V^R) \]

\[ y = 16 \]

\[ \text{fix}^L \]

\[ \text{fix}^R \]

\[ P < .005 \]

\[ P < .05 \]

\[ P < .001 \]

\[ P < .05 \]

\[ \text{vmPFC} \]

\[ \text{vStr} \]
Attentional effect modulated by the STS
Relationship with computational model

\[ r(t) = r(t-1) + f(V_{attend} - \theta \cdot V_{unattend}) + u_t \]

\[ x = -6 \]

\[ \text{fix}^L (V_L - V_R) \]

\[ \text{fix}^R (V_L - V_R) \]

\[ \text{barrier L} \]

\[ \text{barrier R} \]

\[ \text{choose right} \]

\[ \text{time} \]
IV
From choices to motor output
Experiment 6
under review, Hare O’Doherty Schulz Rangel
mOFC correlates with stimulus values
Markers of a region involved in comparison

1. Should exhibit aggregate activation pattern consistent with predictions of plausible neural implementations of the DDM

2. Should exhibit connectivity w/ vmPFC valuation areas at time of choice

3. Should exhibit choice dependent connectivity with motor cortex output areas
dmPFC activity correlates with predictions of simple neural implementation of best fitting DDM
dmPFC modulates transformation of values into motor responses
V
Self-control
Neural mechanisms of dietary self-control

Hare, Camerer, Rangel (Science 2009)
Behavioral differences across groups

- Disliked Healthy
- Disliked Unhealthy
- Liked Unhealthy
- Liked Healthy

Percent Yes

Legend:
- SC
- NSC
Hypotheses

H1) vmPFC encodes a common decision value signal that has different properties in good and poor self-controllers

H2) Attentional self-control involves DLFPC modulation of the vmPFC valuation system
Activity in vmPFC is correlated with a behavioral measure of decision value (regardless of SC)
vmPFC BOLD signal reflects both taste and health ratings
The effect of HR in the vmPFC is correlated with its effect on behavior.

Robust reg

Coef = .847
SC group has greater DLPFC than NSC when implementing self-control

\[ p < .001 \]

\[ p < .005 \]
More activity in DLPFC in successful SC trials than in failed SC trials

SC group

NSC group

*
DLPFC activity does not correlate with HR

*Error bars = 95% confidence intervals
Attentional self-control network

Sagittal

Coronal
Group difference in PPI

$p < 0.007$

PPI Beta

SC group

NSC group
Remarks

- Evidence attentional self-control involves modulation of vmPFC value signals by dIPFC so that they incorporate all dimensions of stimuli.

- Healthy eaters in sample can do this. Unhealthy eaters cannot do this.

- Have replicated results in a monetary discounting task.
V
Final Remarks
Key points

- mOFC/vmPFC plays critical role in valuation during decision-making, probably by computing relative values
- A modified DDM provides very high accuracy description of psychometric data
- Both the valuation and comparison process are modulated by visual attention
- Evidence that dmPFC might be part of the comparator process that transforms values into motor responses
Next steps: Examples of critical open questions

Valuation:
> How EXACTLY are the value signals in mOFC computed at time of choice?
> What is the network of inputs that help at work in different decision problems and situations?
> What EXACTLY is the code used in OFC to represent value of a stimulus?
> How are the various components of the valuation learnt?
> How does the brain know when to start and stop valuing a stimuli & which stimuli to evaluate?
Next steps: Examples of critical open questions

Comparison:
> More detailed models of comparator process and neurobiological basis
Ex:
-- how are multiple value neurons integrated in comparison
-- how is the DDM mapped to underlying neurobiology
Next steps: Examples of critical open questions

Motor:
> How are stimuli and action representations mapped to each other?
> Role of Supplementary Motor Areas
> Role of basal ganglia- thalamic- cortical loops
> Computational role for IPS
Interested in post-doc or PhD studies in neuroeconomics?

rangel@hss.caltech.edu