# Dopamine and Reward Prediction Error

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# The Proposed Axiomatic Method

- Work joint with Mark Dean, Paul Glimcher, and Robb Rutledge
- The potential for neuroeconomic researchers lies in **complementarities**
  - Neuroscientific measurement and biological understanding
  - Economic modelling and organizational principles
- Crucial that there is a methodolgical framework which allows communication across disciplines
  - "Utility" should not mean different things to neuroscientist than to economist

# The Proposed Axiomatic Method

- The **axiomatic** approach developed by decision theorists can provide a unifying role in mature theories
  - Not "abstract" axioms connecting non-observables to one another
  - But "testable axioms connecting latent variables to (ideal) experimental data
  - Novelty of neuroeconomics lies in hybrid nature of data and theories
- Economists introduced methods out of frustration with other treatments of latent variables
  - The same reasons apply with even more force in neuroscience
- Ideally leads to a progressive experimental agenda:
  - When data fail to satisfy, amend theory
  - When data do satisfy, refine e.g. to expected utility theory

# The Proposed Axiomatic Method

- Intuitions concerning utility also important in neuroeconomics
- Dopamine is a neurotransmitter: transmits information from one part of the brain to another
- Neurobiological studies have associated dopamine with:
    - **Choice:** Dopamine manipulations affect choice behavior in animals
    - **Preference:** Dopamine encodes information on 'revealed preferences'
    - **Beliefs:** Changes in expectations modify dopamine activity
    - **Learning:** Dopamine manipulations affect the way people learn
    - **Addiction:** Many drugs of addiction act directly on dopamine
- Understanding dopamine may give valuable insight into economic behavior

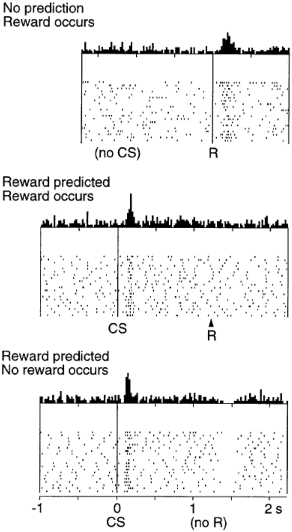
# Our Approach

- There remain barriers to incorporating understanding from dopamine into economics
  - Competing theories of what dopamine does
  - No common language between economics and neuroscience
  - Treatment of unobservables
- We take an axiomatic approach to testing a model of dopamine
  - Provide a complete list of testable predictions
  - Provide a common language between disciplines by *defining* unobservables
  - Failure of particular axioms will aid model development
- Our aim is to systemize current neurobiological understanding
- Initially this may prove to be as much an 'export from,' as an 'import to' economics

# Dopamine and Reward Prediction Error

Schultz et al. [1997]

- Dopamine fires only on receipt of *unpredicted* rewards
- Otherwise will fire at *first predictor* of reward
- If an expected reward is not received, dopamine firing will pause



# Reward Prediction Error

- Reward Prediction Error hypothesis: Dopamine responds to the difference between *experienced* and *anticipated* reward
  - Information on preferences?
  - Information on beliefs?
  - Involved in reinforcement learning?
- We provide an axiomatic basis for this model of dopamine activity
- Use these axioms to develop parsimonious, non-parametric tests of the hypothesis
- Use experimental data from humans to perform these tests

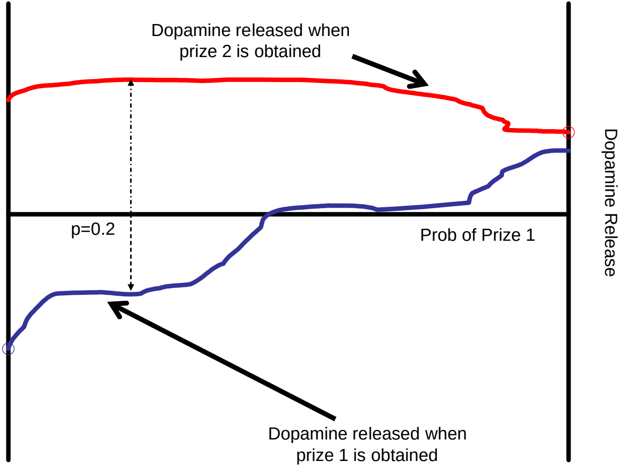
- We consider the simplest possible environment in which we can think about reward prediction error
- Consists of prizes and lotteries:
  - $Z$: A metric space of prizes with typical elements $z$, $w$
  - $\Lambda$ : Set of all simple probability distributions (lotteries) on $Z$ with typical element $p$, $q$
  - $\Lambda(z)$: Set of all probability distributions whose support includes $z$
- Let $e_z$ be the lottery that gives prize $z$ with certainty

- In our idealized data set, we assume we observe a function:

$$\begin{aligned} \delta &: M \rightarrow \mathbb{R} \\ M &= \{(z,p) | z \in Z,\ p \in \Delta(z)\} \end{aligned}$$

where $\delta(z,p)$ is the amount of dopamine released when a prize $z$ is obtained from a lottery $p \in \Lambda(z)$

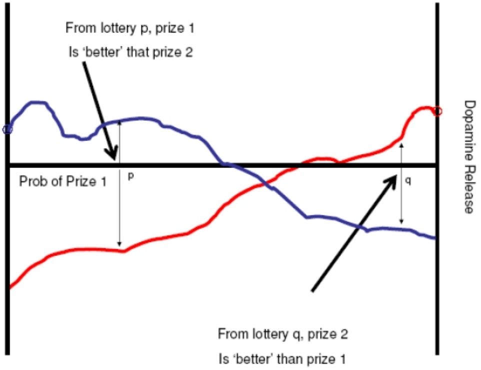
# A Graphical Representation



# A Formalization of the RPE hypothesis

- Need to find some way of defining predicted reward from lotteries and experienced reward for prizes such that:
  - Contains all the information which determines dopamine response
  - Dopamine response is increasing in experienced and decreasing in predicted reward
  - Dopamine always responds to 'no surprise' in the same way
- Demand predicted reward of $e_z$ equal to the experienced reward of $z$
- We say that a dopamine release function has an RPE representation if we can find functions $r : \Lambda \rightarrow \mathbb{R}$ and $E : r(Z) \times r(\Lambda)$ such that:
  - $\delta(z, p) = E[r(e_z), r(p)]$
  - $E$ is strictly increasing in its first argument and decreasing in its second argument
  - $E(x, x) = E(y, y)$ for all $x, y \in r(Z)$

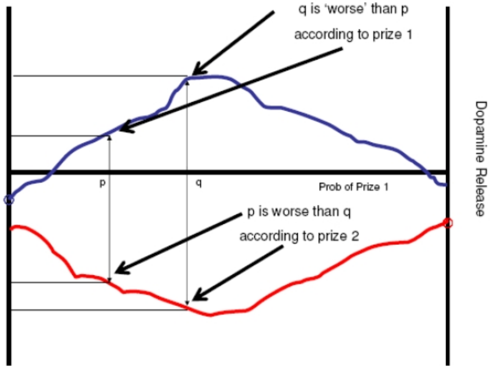
# Necessary Condition 1: Coherent Prize Dominance




- **Axiom A1: Coherent Prize Dominance**

$$\text{for all } (z,p),(w,p),(z,q),(w,q) \in M$$
$$\delta(z,p) > \delta(w,p) \Rightarrow \delta(z,q) > \delta(w,q)$$

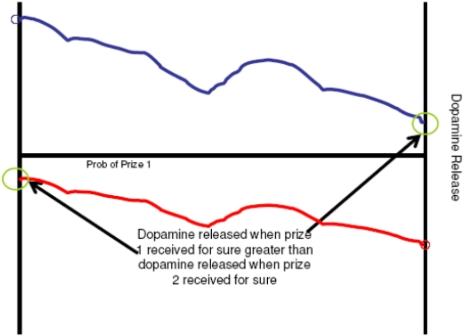
# Necessary Condition 2: Coherent Lottery Dominance




**Axiom A2: Coherent Lottery Dominance**

$$\text{for all } (z,p),(w,p),(z,q),(w,q) \in M$$
$$\delta(z,p) > \delta(z,q) \Rightarrow \delta(w,p) > \delta(w,q)$$

# Necessary Condition 3: Equivalence of Certainty




- **Axiom A3: No Surprise Equivalence**

$$\delta(z, e_z) = \delta(w, e_w) \;\forall\; z, w \in Z$$

# A Representation Theorem

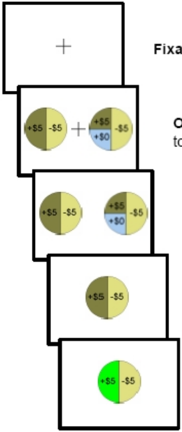
- In general, these conditions are necessary, but not sufficient for an RPE representation
- However, in the special case where we look only at lotteries with two prizes they are
- **Theorem 1:**
  If $|Z| = 2$, a dopamine release function $\delta$ satisfies axioms A1-A3 **if and only if** it admits an RPE representation
- Thus, in order to test RPE in case of two prizes, we need only to test A1-A3

# Aim

- Generate observations of $\delta$ in order to test axioms
- Use a data set containing:
  - Two prizes: win \$5, lose \$5
  - Five lotteries: $p \in \{0, 0.25, 0.5, 0.75.1\}$
- Do not observe dopamine directly
  - Use fMRI to observe activity in the Nucleus Accumbens
  - Brain area rich in dopaminergic neurons

# Experimental Design

Task design




**Fixation:** 12 seconds

**Options:** 3.6 seconds
to view options

Lottery 1 EV: $0
Lottery 2 EV: -$1.25

**Choice selection:** 1.2 seconds
to make a choice by button press
(fixation cross extinguished)

**Choice:** 8.4 seconds to
view the choice just made

**Outcome:** 3.6 seconds to
view outcome of choice
(outcome illuminated)

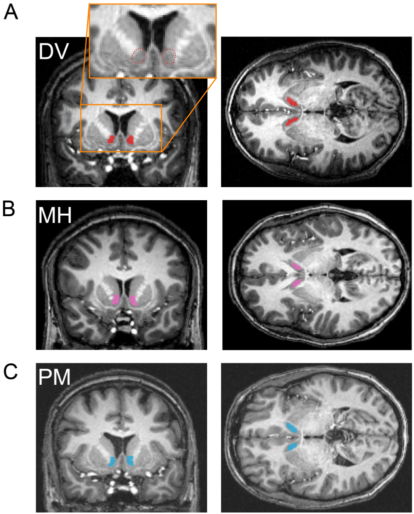
Trial length:

~29 seconds

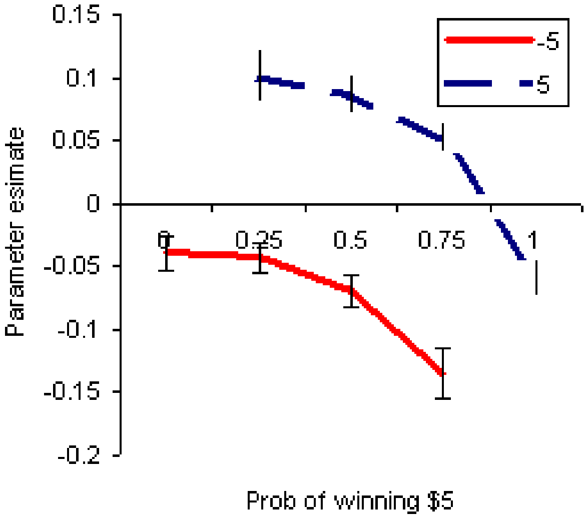
# Experimental Details

- 14 subjects (2 dropped for excess movement)
- ‘Practice Session’ (outside scanner) of 4 blocks of 16 trials
- 2 'Scanner Sessions' of 8 blocks of 16 trials
- For Scanner Sessions, subjects paid \$35 show up fee, + \$100 endowment + outcome of each trial
- In each trial, subject offered one option from ‘Observation Set’ and one from a ‘Decoy Set’

- Need to determine which area of the brain is the Nucleus Accumbens
- Two ways of doing so:
  - Anatomical ROIs: Defined by location
  - Functional ROIs: Defined by response to a particular stimulus
- We concentrate on anatomical ROI, but use functional ROIs to test results

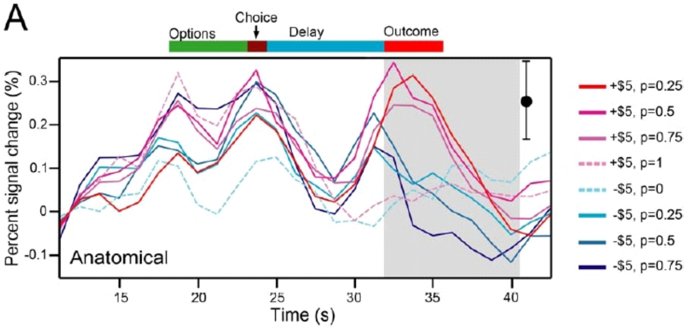

A
DV
B
MH
C
PM

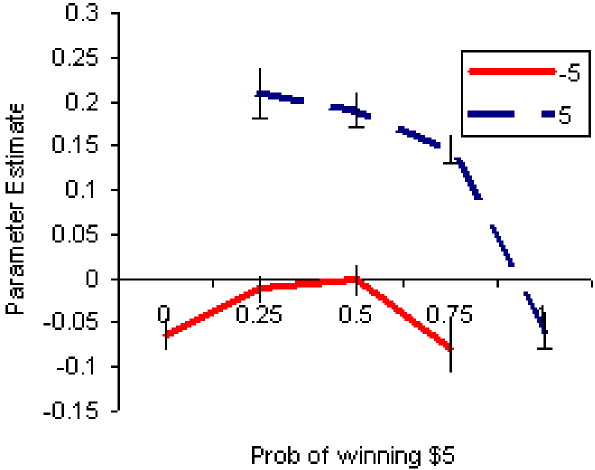
- We now need to estimate the function $\bar{\delta}$ using the data
- Use a between-subject design
  - Treat all data as coming from a single subject
- Create a single time series for an ROI
  - Average across voxels
  - Convert to percentage change from session baseline
- Regress time series on dummies for the revelation of each prize/lottery pair
  - $\bar{\delta}(x, p)$ is the estimated coefficient on the dummy which takes the value 1 when prize $x$ is obtained from lottery $p$


0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
0.25
0.5
0.75
1
Parameter esimate
Prob of winning $5
-5
5

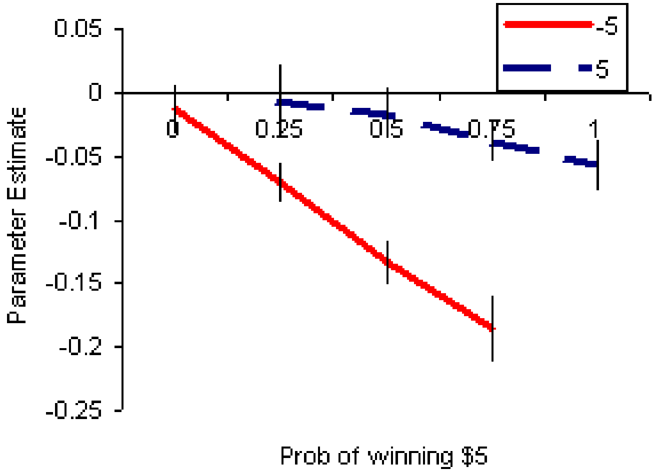
# Results

- Axioms hold
- Nucleus Accumbens activity in line with RPE model
- Experienced and predicted reward ‘sensible’


A
Options
Choice
Delay
Outcome
Percent signal change (%)
0.3
0.2
0.1
0
-0.1
Anatomical
15
20
25
30
35
40
Time (s)
+$5, p=0.25
+$5, p=0.5
+$5, p=0.75
+$5, p=1
-$5, p=0
-$5, p=0.25
-$5, p=0.5
-$5, p=0.75

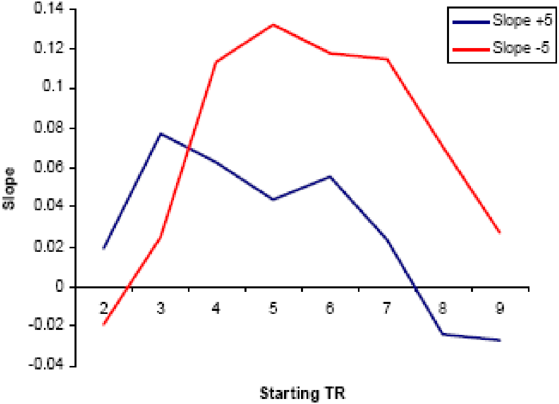

0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Parameter Estimate
0
0.25
0.5
0.75
1
Prob of winning $5
-5
5

# Late Period



0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
Parameter Estimate
0
0.25
0.5
0.75
1
Prob of winning $5
-5
5

# Two Different Signals?



# Key Results

- fMRI activity in Nucleus Accumbens does satisfy the necessary conditions for an RPE encoder
- However, this aggregate result may be the amalgamation of two separate signals
  - Vary in temporal lag
  - Vary in magnitude

- Axioms + experimental results tell us we can assign numbers to events such that NAcc activity encodes RPE according to those numbers
- Can we use these numbers to make inferences about beliefs and rewards?
    - Are they 'beliefs' and 'rewards' in the sense that people usually use the words?
    - Can we find any 'external validity' with respect to other observables?
        - Behavior?
        - Obviously rewarding events?
    - Can we then generalize to other situations?

# Economic Applications

- New way of observing beliefs
- Makes 'surprise' directly observable
- Insights into mechanisms underlying learning
- Building blocks of 'utility'

- We provide evidence that NAcc activity encodes RPE
- Can recover consistent dopaminergic ‘beliefs’ and ‘rewards’
- Potential for important new insights into human behavior and ‘state of mind’