Neurobiological Modeling of the Economic Agent

George Mengov, PhD,
Assistant Professor
Sofia University St. Kliment Òhridski

A computational neuroscientist, turned decision scientist

Road Map

- Levels of Decision Analysis
- Beyond Prospect Theory
- Need for a New Approach in Decision Research
- Neurobiological Modeling of the Agent

Four Levels of Decision Analysis

- Utility and Rationality

(*Expected Utility Theory, Game Theory*)

- Economic Psychology/ Behavioral Economics

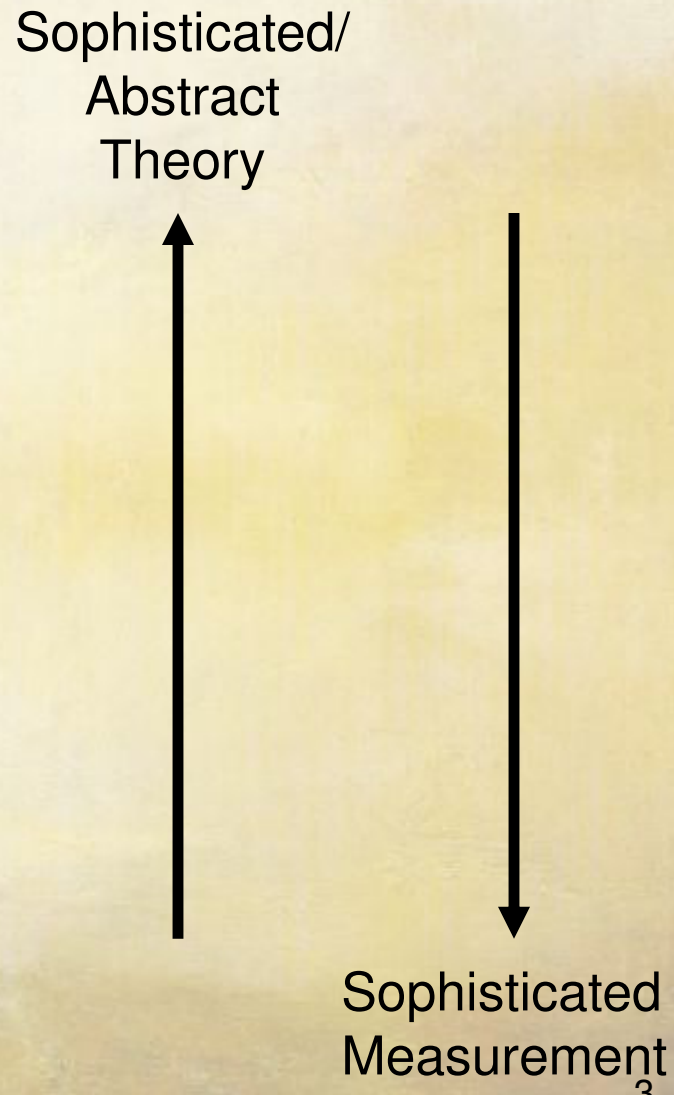
(*Prospect Theory, Heuristics & Biases Paradigm, Decision Field Theory etc.*)

- Computational Neuroscience/ Neurobiological Models of the Agent

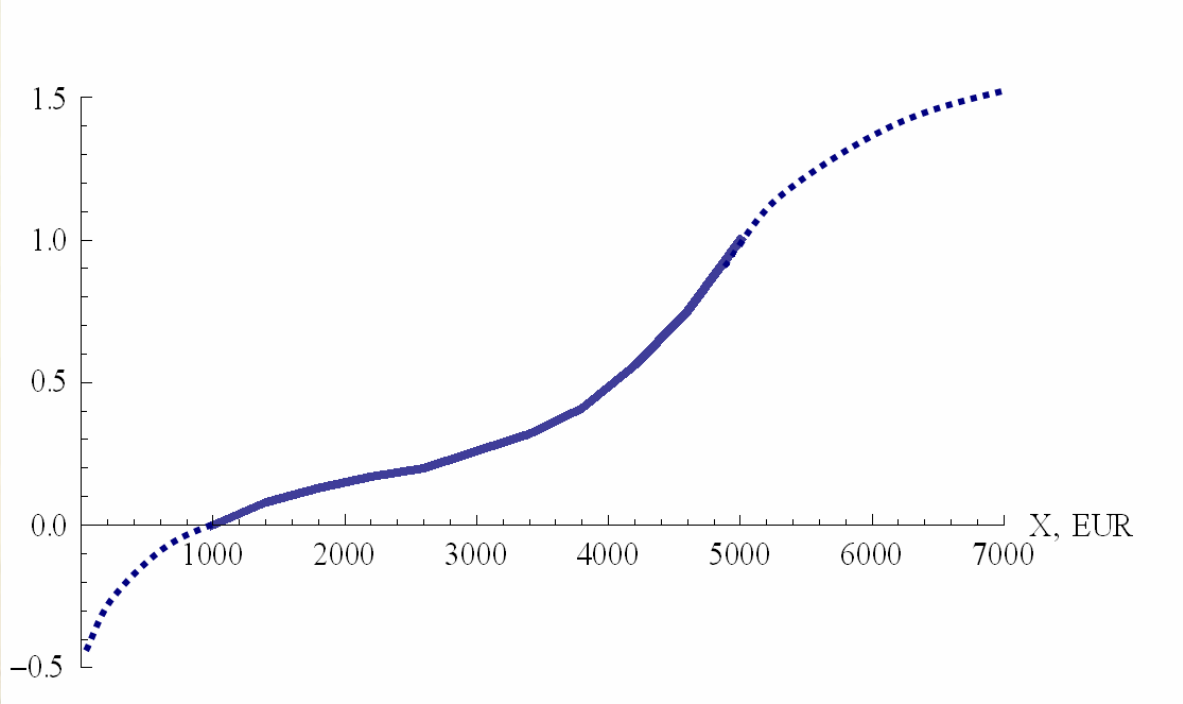
(*Affective Balance Theory, Mathematical Theory of Reflex Conditioning*)

- fMRI, "Neuroeconomics"?

(*No Theory Regarding Decisions Yet*)



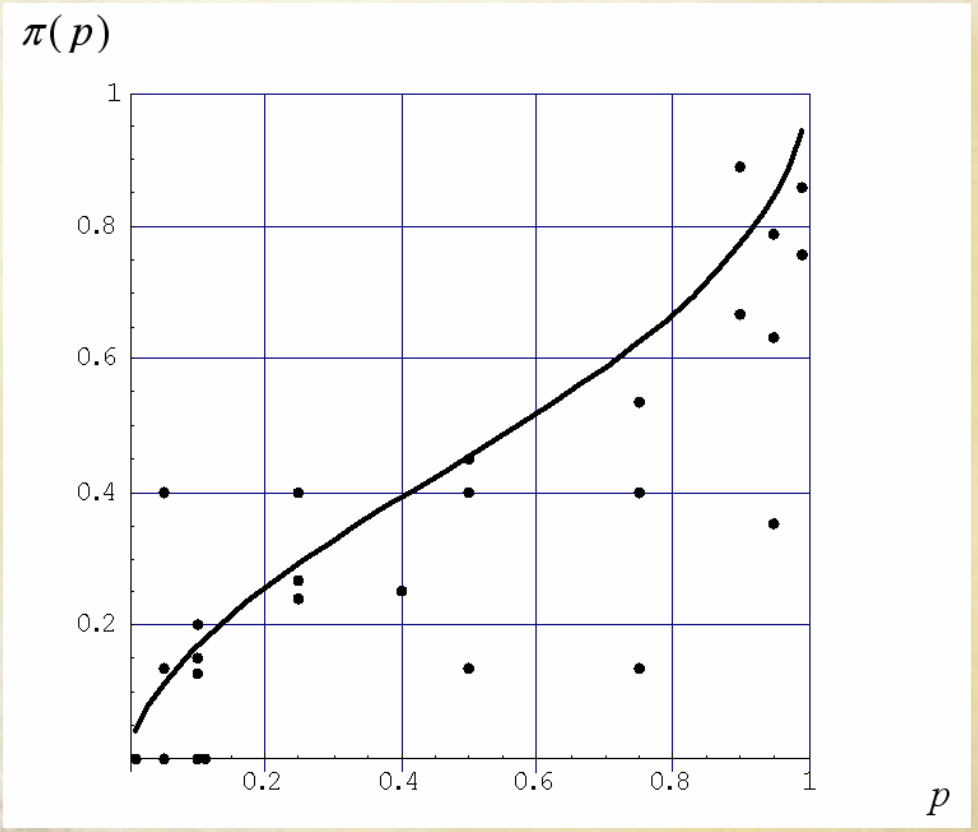
The utility curve of a German professor of economics



Anomalous convex shape …

Weighted probabilities in a Bulgarian student of economics

#	Gain	Probability	(Maximal) Price
1	150 EUR	5%	
2	50 EUR	50%	
3	200 EUR	10%	
4	150 EUR	50%	
5	100 EUR	95%	
6	200 EUR	25%	
7	400 EUR	99%	
8	100 EUR	90%	
9	50 EUR	10%	
10	200 EUR	5%	
11	150 EUR	75%	
12	150 EUR	95%	
13	100 EUR	10%	
14	50 EUR	90%	
15	150 EUR	25%	
16	100 EUR	40%	
17	200 EUR	95%	
18	100 EUR	75%	



Too much variability in the weighted probabilities …

$$\pi(p) = \frac{p^{\delta}}{\left(p^{\delta} + (1-p)^{\delta}\right)^{1/\delta}}$$

Birnbaum (2008)
On Prospect Theory

"During the last 25 years, Prospect Theory and its successor, Cumulative Prospect Theory, replaced Expected Utility as the dominant descriptive theories of risky decision making. Although these models account for the original Allais' paradoxes, **11 new paradoxes show where Prospect Theories lead to self-contradiction or systematic false predictions**."

Birnbaum (2008) Transfer of Attention Exchange (TAX) Theory

- People treat gambles as trees with branches rather than as prospects or probability distributions.
- TAX correctly predicted some of the violations of CPT in advance of experiments, gives a better description of both old and new data.
- Because a model [i.e. TAX] correctly predicted results in a series of new tests, it does not follow that it will succeed in every new test that might be devised.

Birnbaum (1999) On how various theories explain Allais' Paradoxes

One class of theories (including SWUT and original PT) retains ***branch independence*** but violates ***coalescing***, and thereby violates ***stochastic dominance***. Another class of theories (rank-dependent and rank- and sign-dependent UTs, including CPT) retains ***coalescing*** and ***stochastic dominance*** but violates ***branch independence***.

Birnbaum (1999) On how various theories explain Allais' Paradox – Reading of G.M.

One class of theories (including ***Theory1*** and ***Theory2***) retains ***Postulate1*** but violates ***Postulate2***, and thereby violates ***Postulate3***. Another class of theories (***Theory3*** and ***Theories4&5***, including ***Theory2A***) retains ***Postulate2*** and ***Postulate3*** but violates ***Postulate1*** .

Rieskamp, Busemeyer, & Mellers (2006) Meta Analysis

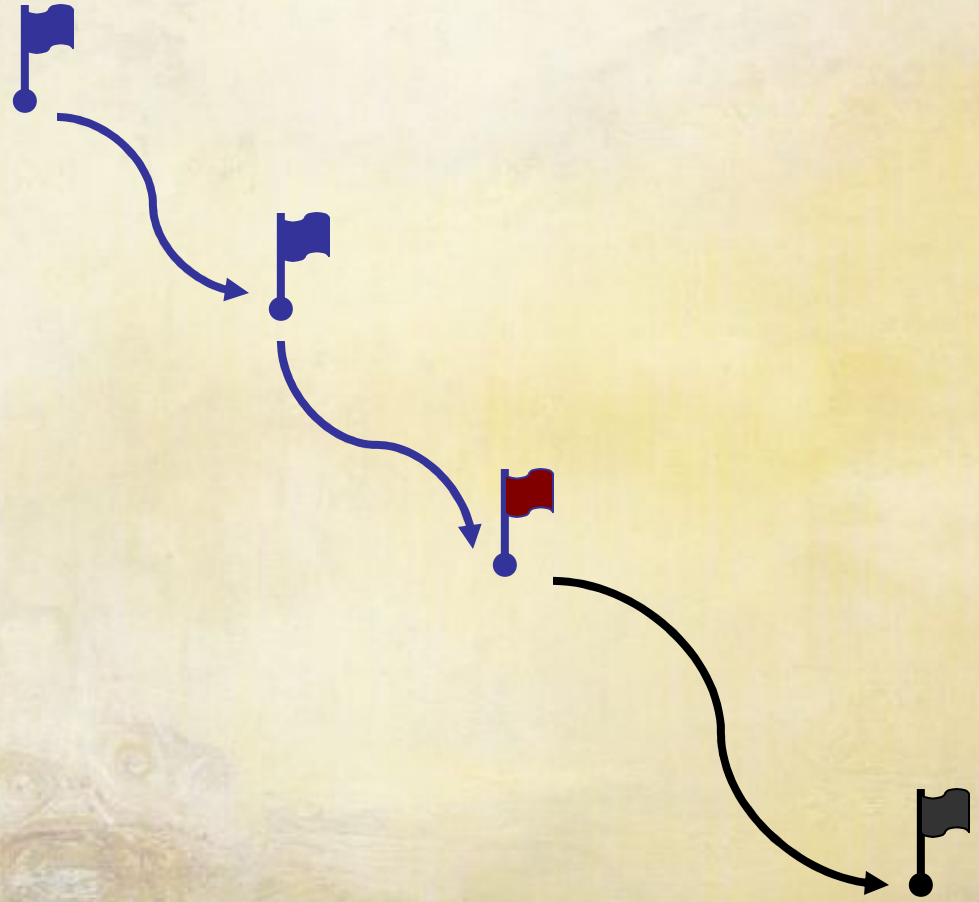
- "Consistency Principles":
  - ***Perfect consistency of choice (transitivity)***
  - ***Strong stochastic transitivity***
  - ***Independence from Irrelevant Alternatives***
  - ***Regularity***
  - ***Weak stochastic transitivity***
- The frequency and breadth of violations decline as one proceeds from stricter to weaker. E.g. in experiments WST is violated only 7-15%.

G.M.: Unsatisfactory state of affairs

- However complex the mental mechanisms employed by humans in their decision acts might be, it is unacceptable that the axiomatic base of decision science should be reformulated in response to each new psychological discovery with regard to choice behaviour.
- Can we imagine such treatment, for example, of Euclid's axioms arising every now and again due to daily engineering tasks?!

Road Map

- Levels of Decision Analysis
- Beyond Prospect Theory
- Need for a New Approach
- Neurobiological Modeling of the Agent



- What is needed, therefore, is an entirely new approach able to offer, in von Neumann & Morgenstern's (1944, 1.3.) words,

  "*…**methods… which could be extended further and further***."

I.e., opportunities to generalize, yet maintain consistency.

- Put differently, decision science needs a new paradigm, i.e. a novel system of attitudes, values, and techniques adopted by the research community.

[The new theory/ paradigm should], after an initial stage dealing with elementary problems, …[approach issues] beyond the obvious, [and eventually reach the level of] genuine prediction.

(Von Neumann & Morgenstern, 1944, 1.3. & 1.4.)

[The new paradigm should] "*…**in the future guide research on problems many of which neither competitor can yet claim to resolve completely. A decision between alternate ways of practicing science is called for. The decision is based on future promise rather than on past achievement**.*"

(Kuhn, 1962, Chapter XII.)

The Neurobiological Approach: capable to be generalized, does superior predictions, raises expectations

- **A bottom-up approach: From neurons and their interactions to observable human behaviour**
- Started with (McCulloch & Pitts, 1943; 1947). Used propositional logic and introduced a system of axioms describing most of what was known about the functioning of the nervous system at the time
- Failed (initially)

"*What the frog's eye tells the frog's brain*" (Lettvin, Maturana, McCulloch, & Pitts, 1959)

- The anatomy of connections between the retina and the inner neural layers suggested that,

  "*… the eye speaks to the brain in a language already highly organized and interpreted, instead of transmitting more or less accurate copy of the distribution of light on the receptors*."

"*… The operations found in the frog make unlikely later processes in his system of the sort described by two of us (McCulloch & Pitts) earlier*."

Stephen Grossberg, a psychologist with a doctorate in mathematics

- Started his analysis from observed psychological reactions and actions in humans and other species (experimental literature).
- Formulated new principles/ postulates about the organization and functioning of the nervous system.
- Developed mathematical models embedding the new postulates.

Grossberg's main achievement

- He successfully charted the road **from neural interactions at micro level**, to a more complex account of phenomena such as **short-term memory**, **long-term memory**, **recognition of visual images and auditory signals**, **emotion generation**, to end up with macro level behaviour such as **reflex conditioning** and **cognitive-emotional interactions**.

Example: Opponent Processing

- How humans and higher animals handle expected and unexpected events associated with potential benefit or danger
- E.g. Expecting a positive event that does not occur
  - Formally, there is no event and the stimulus–reaction models are not relevant
- In reality
  - First, a positive emotion of anticipation occurs
  - Disappointment due to the failed engagement. Anger
  - A new decision is taken – to do something different
  - The negative emotion extinguishes and opens the way for new (positive) experiences.
- This altering of opposite emotions is known as *opponent processing* – a vital mechanism for adaptive behavior, as it provides the drive to take adequate actions in response to the flow of environmental challenges.

Opponent processing in the market

- Warren Buffet: "*The market behaves as if it were a fellow named Mr. Market, a man with incurable emotional problems. At times he feels euphoric and can see only the favorable factors, while at other times he is depressed and can see nothing but trouble ahead for both the business and the world*."

- Wall Street traders are known for neurotic actions of a specific type:

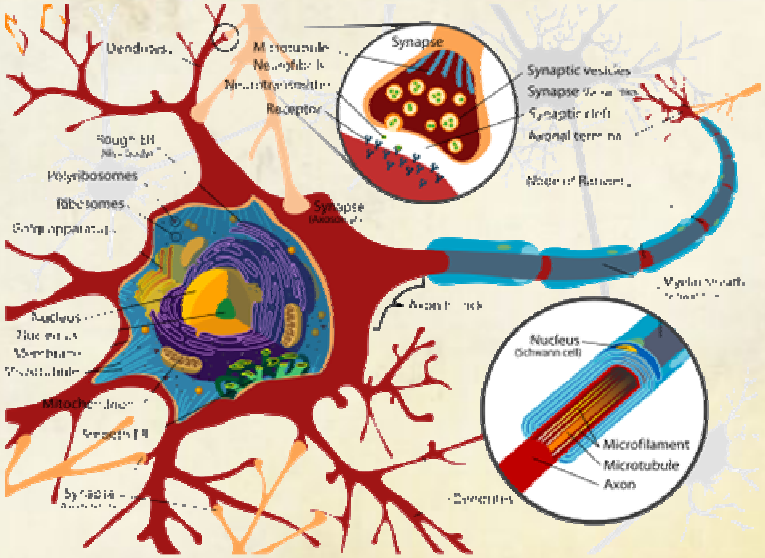
  Aggressive buying of stock after good news, followed by nervous selling of the same stock no matter what the following news would be.

A Neural Mechanism for Opponent Processing (or any Other Psychological Phenomenon)

- Three elementary mechanisms:

  (1) Exciting a single neuron, which makes it emit a signal to other neurons;

  (2) Transmission of a signal from one neuron to another via neurotransmitters;
  (3) Remembering a piece of information due to long-term biochemical change in a signal-receiving neuron.



- All brain processes take place in continuous time
- It is natural to describe them with differential equations

G.M.: Three ordinary nonlinear differential equations, describing the three elementary processes, instead of axioms!!!

Three elementary mechanisms

1. *Single neuron activation:*

$$\frac{dy_i}{dt} = -A_1 y_i + (A_2 - y_i) J_i^+ - (y_i + A_3) J_i^-$$

2. *Signal transmission from one neuron to another via a synaptic connection. Neurotransmitters are released.*

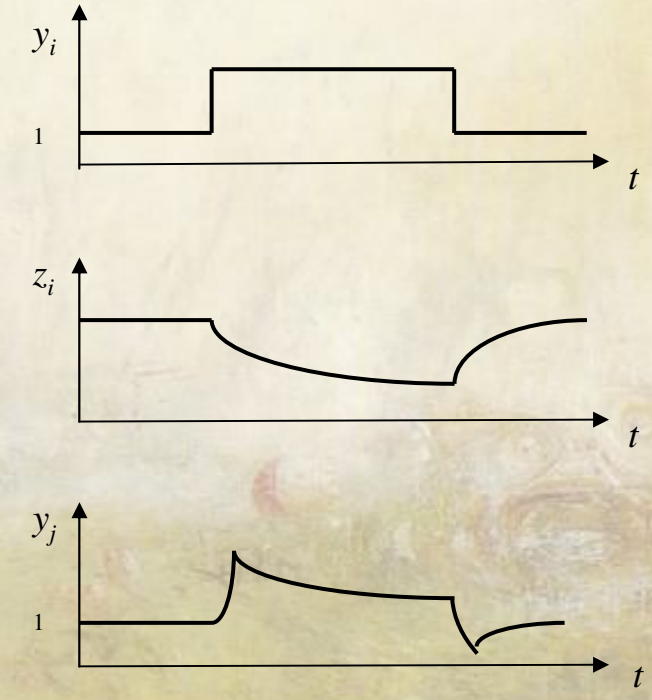
$$\frac{dz_i}{dt} = B(1 - z_i) - C y_i z_i$$

3. *Storing information in the memory by irreversible biochemical change in a receiving neuron:*

$$\frac{dz_{ij}}{dt} = y_i(-D_1 z_{ij} + D_2 y_j)$$

Neurons and Synapses

- A neuron sends signal by emitting neurotransmitters – mediating molecules causing biochemical change in the receiving neuron.
- Remembering – a long-term change in the synapse properties.



$$\frac{dy_i}{dt} = -A_1 y_i + (A_2 - y_i) J_i^+ - (y_i + A_3) J_i^-$$

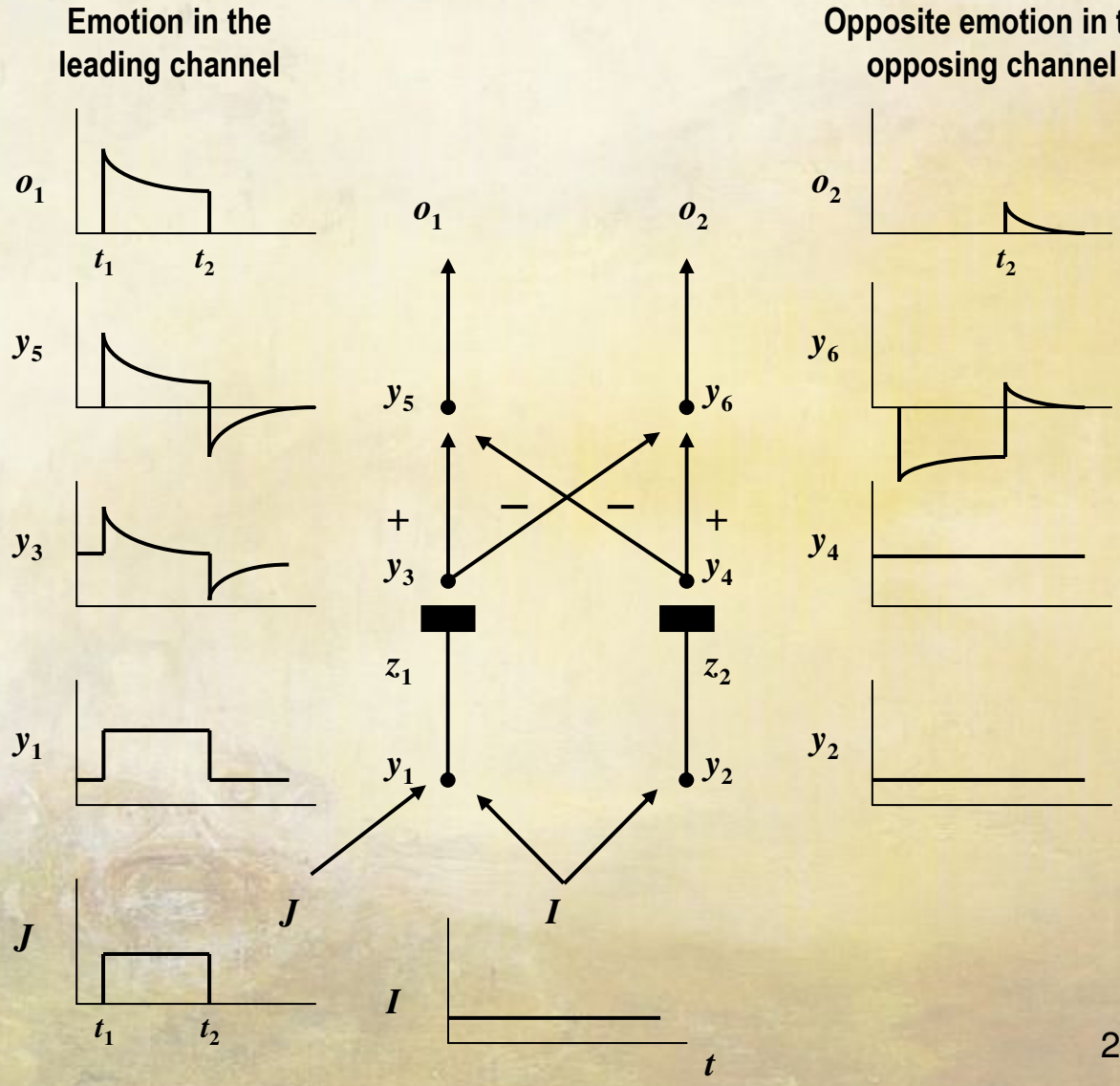
$$\frac{dz_i}{dt} = B(1 - z_i) - C.y_i z_i$$

y_i – neural signals; J_i^+, J_i^- sums of signals

z_i - neurotransmitters; A_j, B, C – real positive constants

Gated Dipole: The neural network performing opponent processing

- A microstructure in the brain where neurons release neurotransmitters to communicate emotion
- Accounts for opposing emotions like fear-relief, disappointment-satisfaction, etc.
- Described by a system of 8 differential equations
- *Grossberg et al.* 1972, 1987, 1990s, 2000s.



T*he Gambler's Fallacy in business or casino: An example of opponent processing*

- After a recently suffered loss, one becomes more willing to take risks above one's usual appetite
- Business people and casino gamblers take risky decisions on ongoing basis some of which end in failure
- A gated dipole explanation: Each event provokes neurotransmitter release in the channel for negative emotions (in response to a loss), or in the channel for positive emotions (due to a gain)
- Due to neurotransmitter exhaustion in the negative emotions channel, the unpleasant feeling after each new loss is attenuated. This effect "dulls the edge" of the emotion as a warning mechanism against further spending of resources – financial or any other.

Role of the dipole mechanism

- The two self-suppressing channels exist in order to quickly reinstate the emotional *equilibrium* – to rebalance the brain
- An important prerequisite for wise and adequate actions in general, the equilibrium is particularly relevant in decisions where all sorts of resources are spent.

Emotional balances in consumer choices: An experiment

"The consumer is to the manufacturer, the department stores and the advertising agencies, what the green frog is to the physiologist"

John Watson, 1922.

Experiment

- Objective: Predict consumer choices and satisfaction using an augmented opponent processing model – the mathematical theory of reflex conditioning.
- Brief Description: On a computer screen a participant receives offers of a hypothetical service resembling that of mobile phone suppliers. Other examples, some utilities etc. could have been just as appropriate. Each of two suppliers (A or B) provokes satisfaction or disappointment, and forms own reputation in the mind of the customer. No transaction costs are involved. No real money is paid. 17 rounds.

Experimental Screen

Supplier in this round is company **A**

Advertised price: **38**

Final price: **49**

Please indicate your satisfaction or disappointment due to this particular outcome according to the following scale:

Extremely disappointed	Very disappointed	Disappointed	More disappointed than satisfied	As much satisfied as disappointed	More satisfied than disappointed	Satisfied	Very satisfied	Extremely satisfied
-4	**-3**	**- 2**	**- 1**	**0**	**1**	**2**	**3**	**4**

Would you like to change your supplier?

No Yes

Experimental Screen

Supplier in this round is company **B**

Advertised price: **39**

Final price: **36**

Please indicate your satisfaction or disappointment due to this particular outcome according to the following scale:

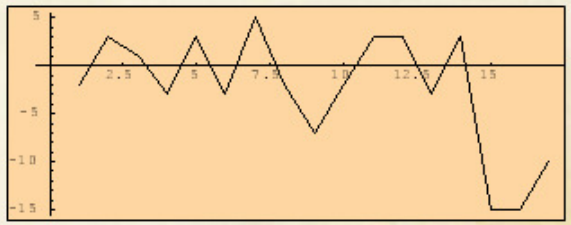
Extremely disappointed	Very disappointed	Disappointed	More disappointed than satisfied	As much satisfied as disappointed	More satisfied than disappointed	Satisfied	Very satisfied	Extremely satisfied
-4	**-3**	**- 2**	**- 1**	**0**	**1**	**2**	**3**	**4**

Would you like to change your supplier?

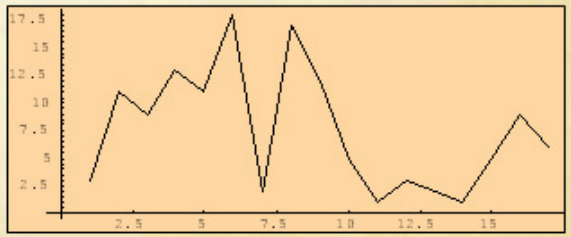
No Yes

Four Experimental Treatments

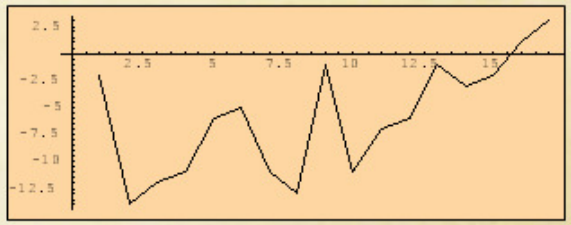
(A) A market with minor variability in price differences ($Pa - Pr$).



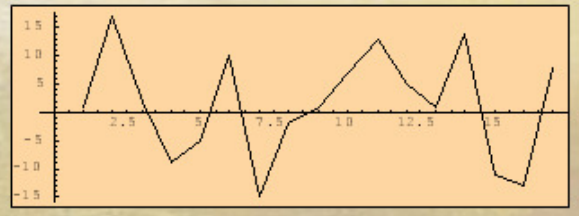
(B) A market with suppliers aggressively attracting consumers with favourable prices. ($Pa - Pr > 0$)



(C) Suppliers act to the disadvantage of their customers. ($Pa - Pr < 0$)



(D) A market with substantial price fluctuations.



Data Analysis

The decision to retain or abandon the current supplier could depend on these factors:

- Advertised price (Pa)
- Final price (Pr)
- Price difference (Pa – Pr)
- Immediately preceding choice/ change of supplier (ChS)
- All previous Pa, Pr, Pa – Pr, ChS
- Degree of Disappointment or Satisfaction (DS)
- All previous DS
- Reaction Times of the participant

Methods:

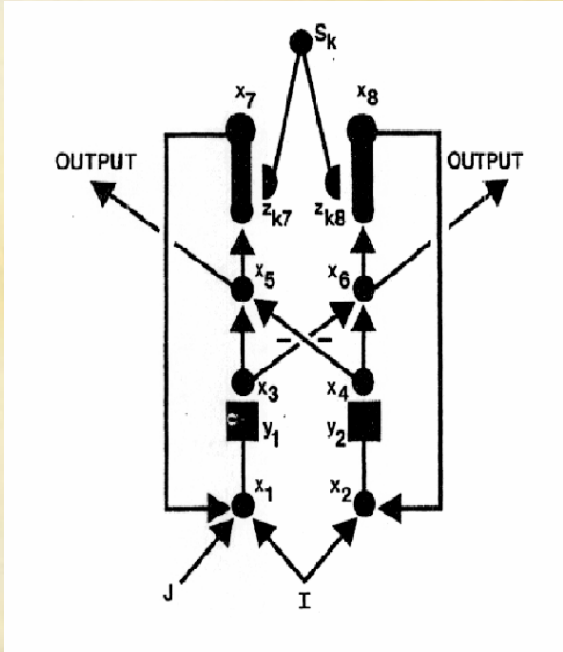
- Linear and Logistic Regression
- A computational neuroscience method

Recurrent Associative Gated Dipole (READ)

- Not only accounts for opposing emotions like fear-relief, joy-sorrow, disappointment-satisfaction etc, but also has **emotional memory**
- Is the material substrate of **Pavlovian and Skinnerian reflex conditioning**
- Described by a system of 12 differential equations

Recurrent Associative Gated Dipole (READ) Neural System of Equations

$$x1'[t] = -A\, x1[t] + Inp + J1 + f[x7[t]]$$
$$x2'[t] = -A\, x2[t] + Inp + J2 + f[x8[t]]$$
$$y1'[t] = B\,(1 - y1[t]) - Cc\, g[x1[t]]\, y1[t]$$
$$y2'[t] = B\,(1 - y2[t]) - Cc\, g[x2[t]]\, y2[t]$$
$$x3'[t] = -A\, x3[t] + Dd\, g[x1[t]]\, y1[t]$$
$$x4'[t] = -A\, x4[t] + Dd\, g[x2[t]]\, y2[t]$$
$$x5'[t] = -A\, x5[t] + (Ee - x5[t])\, x3[t] - (x5[t] + F)\, x4[t]$$
$$x6'[t] = -A\, x6[t] + (Ee - x6[t])\, x4[t] - (x6[t] + F)\, x3[t]$$
$$x7'[t] = -A\, x7[t] + G\,[x5[t]]^{+} + L\, SSk\, zk7[t]$$
$$x8'[t] = -A\, x8[t] + G\,[x6[t]]^{+} + H\, SSk\, zk8[t]$$
$$zk7'[t] = Sk\,(-K\, zk7[t] + L\,[x5[t]]^{+})$$
$$zk8'[t] = Sk\,(-K\, zk8[t] + L\,[x6[t]]^{+})$$

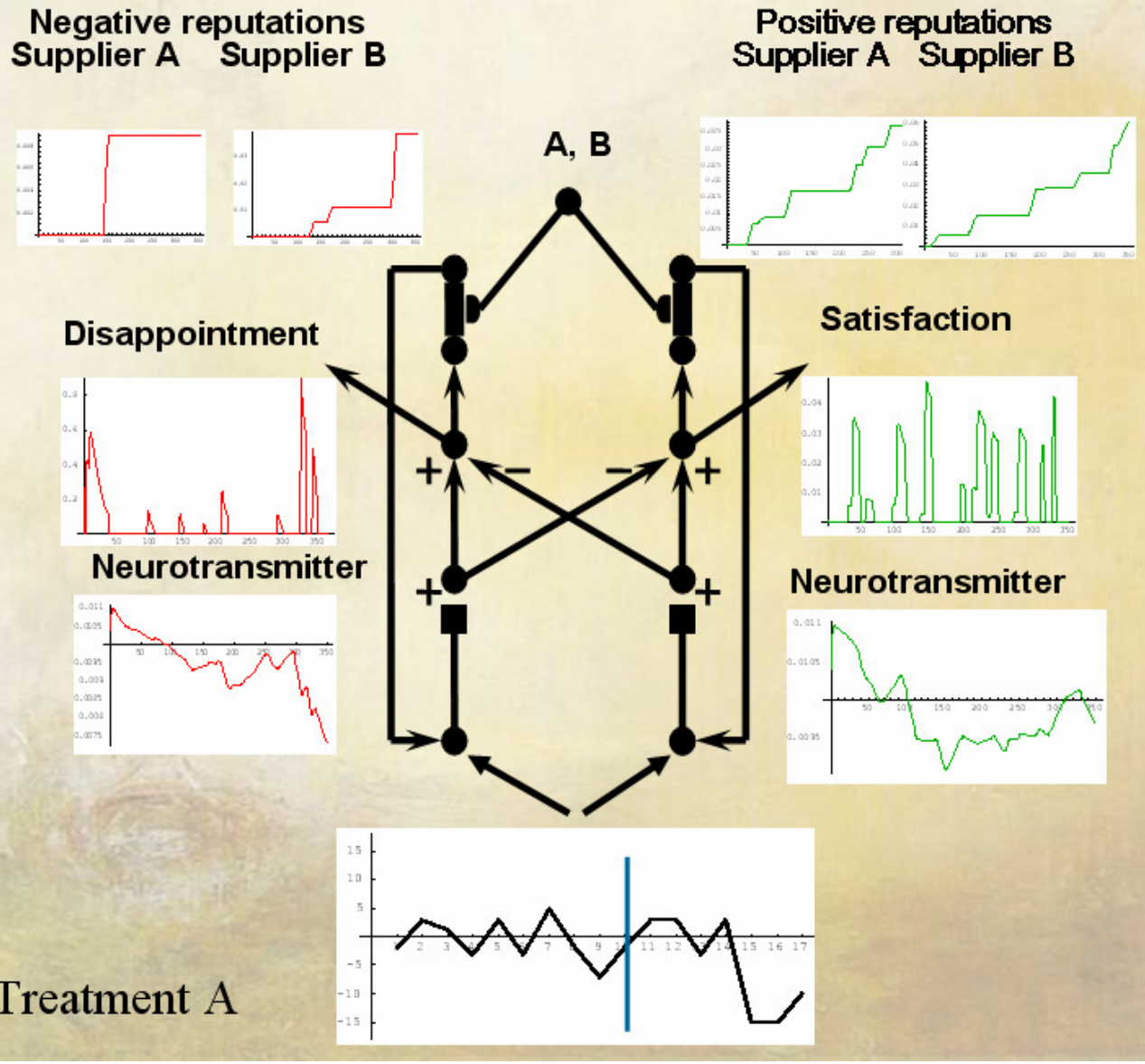


What we did

- We managed to relate neurobiological variables to economic variables. We gave neural interpretations to
  - Prices and price differences
  - Self-assessed emotions
  - Supplier reputation (emotional memory)
  - Decision (inequality between neural signals)

Modelling customer reactions

- Empirical data from 129 participants is transferred into the dipole equations.
- Green and red lines result from computer simulation
- Numerical solution of all differential equations



Treatment A

Experimental Results I: Choice Predictions

Correct predictions of supplier choices

	Logistic Regression 1: β_0, ΔP, ChS_{t-1}	**Logistic Regression 2:** β_0, DS	**READ Neural Model**
Derivation Sub-sample of first 10 rounds	**0.7580** (n = 1161)	**0.8031** (n = 1290)	**0.9574** (n = 1290)
Validation Sub-sample of last 7 rounds	**0.8284** (n = 903)	**0.8549** (n = 903)	**0.8682** (n = 903)
Statistically significant difference on validation sub-samples b/n Logistic Model 1 and READ (p = 0.018)			

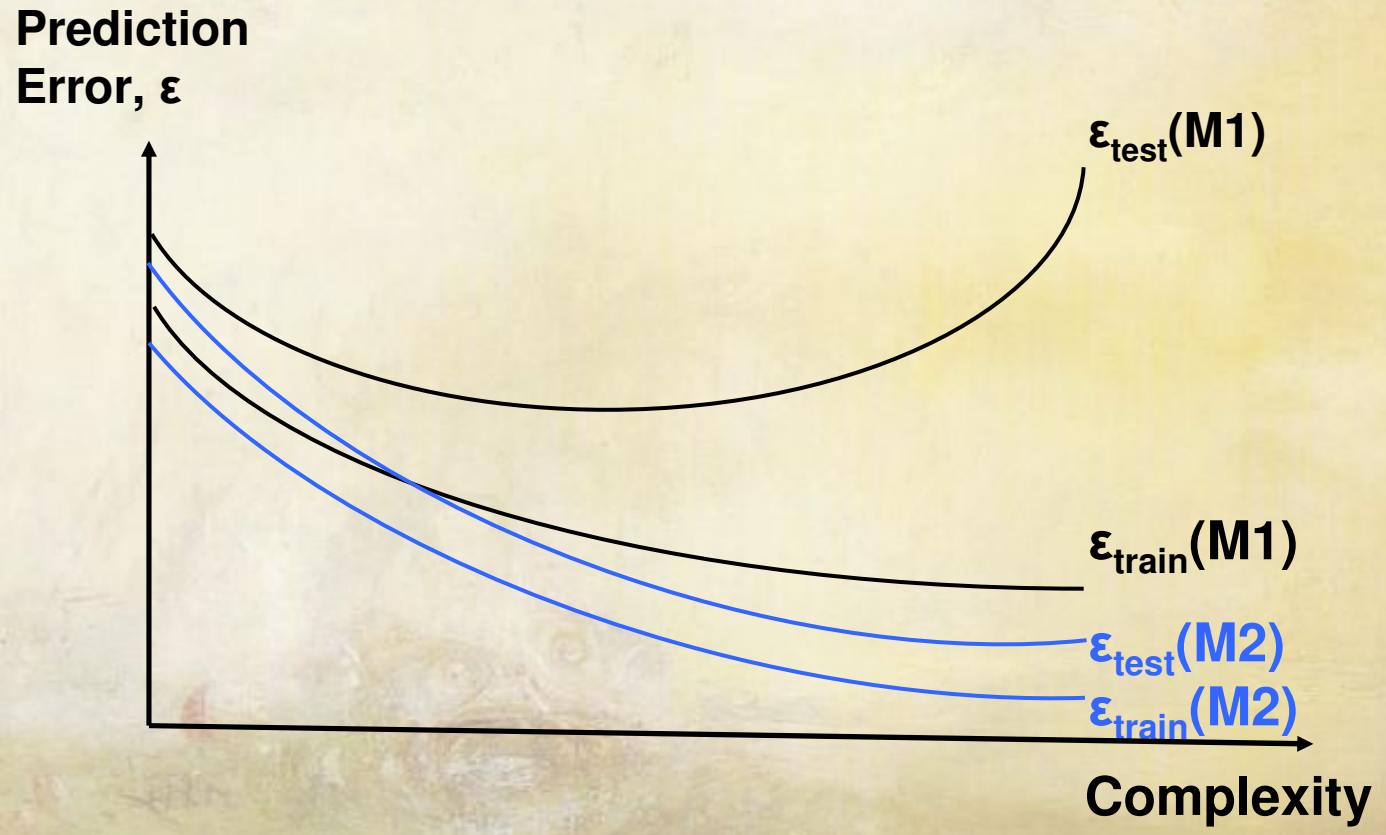
Experimental Results II: Predicting Consumer Disappointment and Satisfaction (Rank Correlations)

	Cnd.	Tr. A (s=31)	Tr. B (s=34)	Tr. C (s=36)	Tr. D (s=28)	All (s=129)
Linear Regression $b0 + b1\ \Delta P_t + b2\ \Delta P_{t-1} + b3\ \Delta P_{t-2} + b4\ DS_{t-1} + b5\ DS_{t-2}$	d 10	0.6867	0.6609	0.6552	0.8487	**0.7077**
	v 7	**0.8228**	**0.5196**	**0.6655**	**0.8584**	**0.7065**
READ Neural System	d 10	0.9068	0.8753	0.8759	0.9229	**0.8930**
	v 7	**0.8238**	**0.6529**	**0.8213**	**0.8575**	**0.7846**

'Favourable' Treatment B: People are sometimes disappointed by a discount considered to be too small.

'Hostile' Treatment C: People may be satisfied when they have to pay only a little more than initially told.

READ vs. Regressions



Conclusions I

- Drawing on models of neuron interactions, it looks promising to study important aspects of human behavior
  - Emotional (positive-negative) framing of choices
  - Moral hazard
  - Impulsive shopping
  - …

Conclusions II

- In the light of the neurobiological perspective we can say that **people's decisions are not governed entirely by the goal of utility maximization**, but by psychological mechanisms with a different purpose.
- **The goal of maintaining or quickly restoring our emotional balance is at the heart of our adequate and advantageous behavior.**
- Of course, satisfaction and its descendant – the emotional balance, often come after the agent has maximized some kind of material utility. **When**, however, that **utility gets too much in the way of our inner balance, the latter eventually prevails, and our "internal Homo Economicus" must retreat.**