Neural Control Of Sensory Signals to Outliers In The Human Brain

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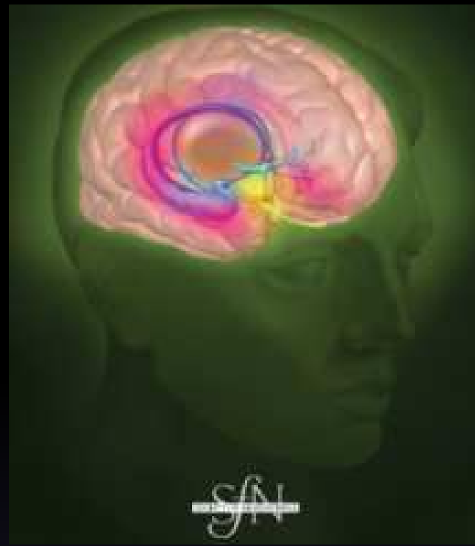
Principle



- **Real people are biological agents**
  - **They have a BRAIN**
  - **The brain, and hence, choices, are shaped by evolutionary fitness**
  - **The brain is an amazing computational device**

But maybe not well adapted to financial risks?

Today

An example of this work – on a type of risk

which is extremely important in finance

- Behavioral task was *informed by* neuroscience findings
- You cannot really understand the behavioral problems if you don't look at the *biology*

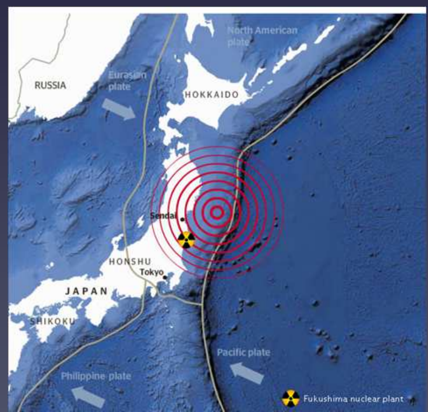
Overview

1. Motivation
2. Experimental Design
3. Behavioral Results
4. (fMRI) Imaging Results
5. Discussion

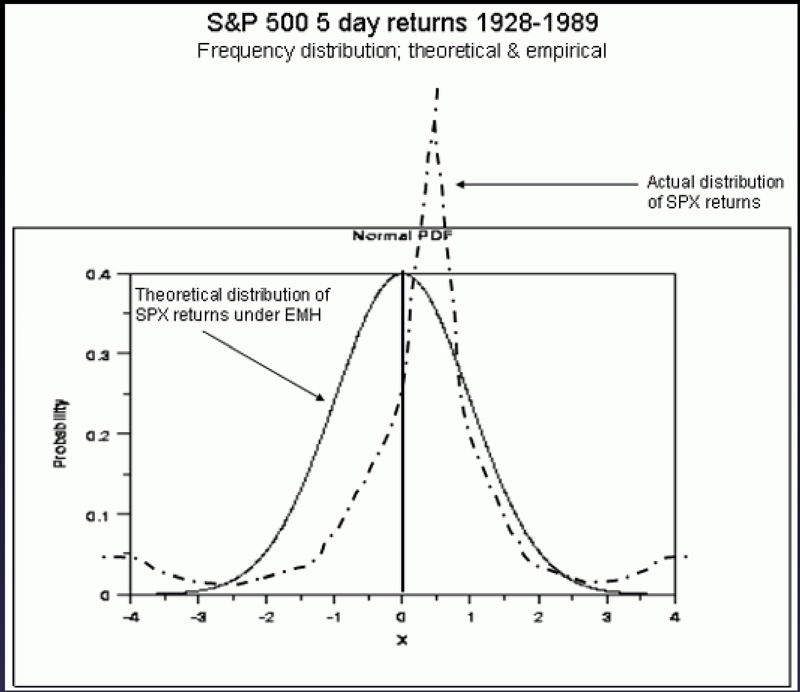
1. Motivation: What Are Outliers?

- *Outcomes in the tails of the Gaussian distribution*
- Extreme events, unexpected uncertainty (Yu-Dayan 2003-5; Nassar ea 2012), risk prediction errors (Preuschoff ea 2008, 2011), jumps (Payzan ea, 2013)

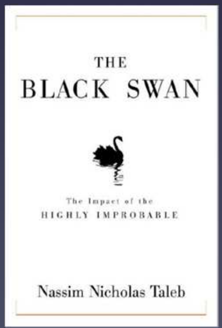
Do Humans (Animals) Over-React?



Outliers in Finance



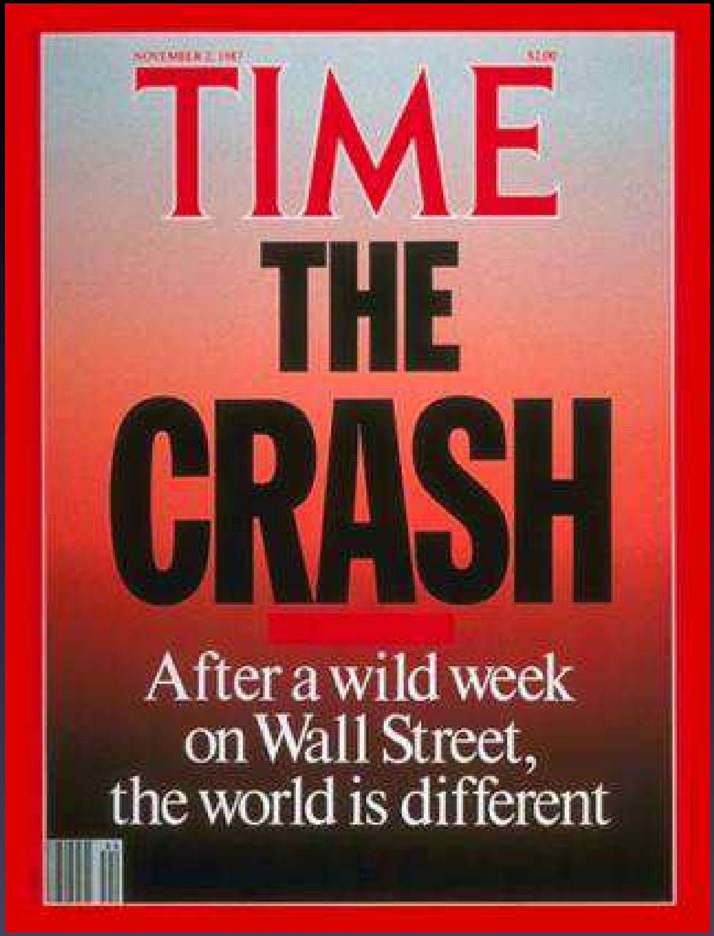
- Price changes in financial markets (NYSE, laboratory (!), 16th century,…) are *leptokurtic*
- "Black Swans" (Nassim Taleb)
  - But outliers are NOT rare in finance!
- Fair observation: We tend to pay a lot of attention to outliers, and perhaps over-rationalize



Over-Thinking Outliers?

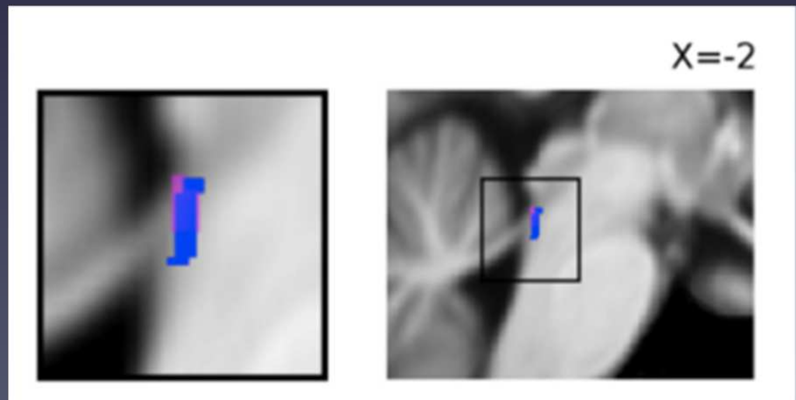
October 1987 Crash

- Reverted within one year
- Relevant only for those who studied a particular aspect of option pricing ("smiles and smirks" in violations of the Black-Scholes model)



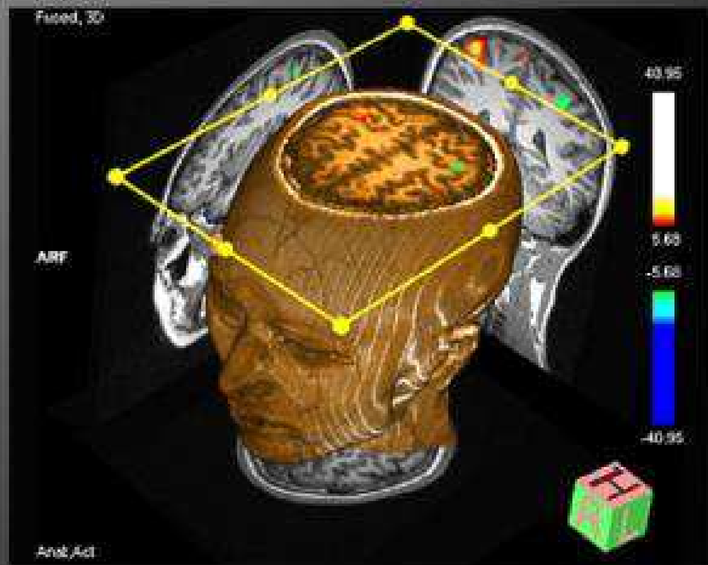
Neuroscience

- Outliers signal need to adapt to a new environment (Yu-Dayan 2003-5, Nassar ea 2012, Payzan ea 2013)
  - Often requiring renewed exploration (Cohen ea 2009)
- Proven involvement of neurotransmitter **norepinephrine**

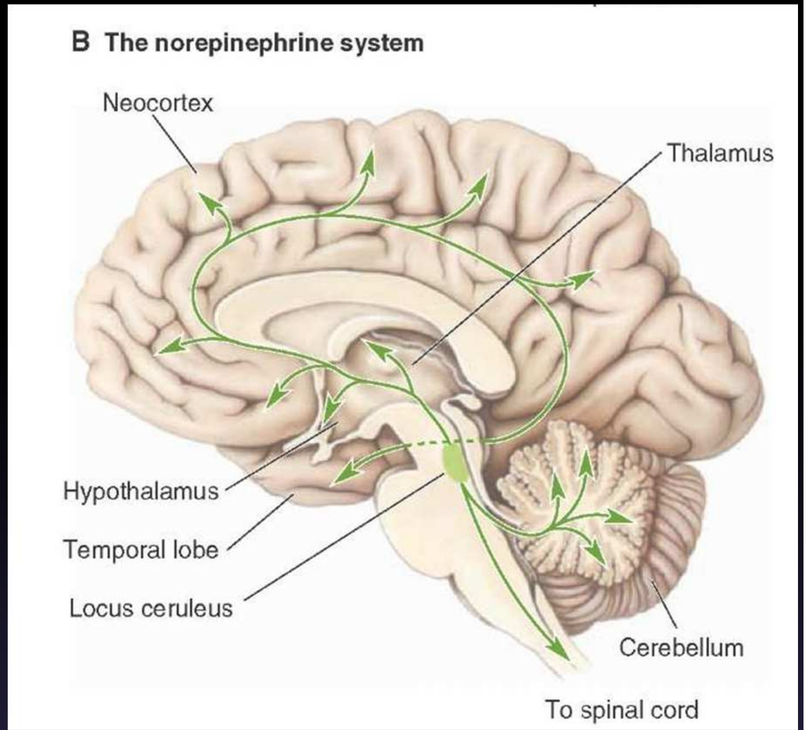


A Few Brain Facts

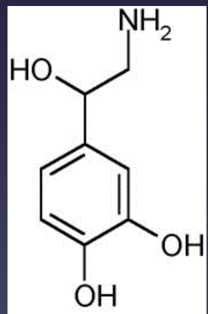
- Cells in the brain are called neurons
- Neurons “talk” to each other by means of neurotransmitters (like “money”): GABA, dopamine, serotonin, norepinephrine, acetylcholine, histamine,...
- fMRI: one way to indirectly (and with delay) detect neuronal activity



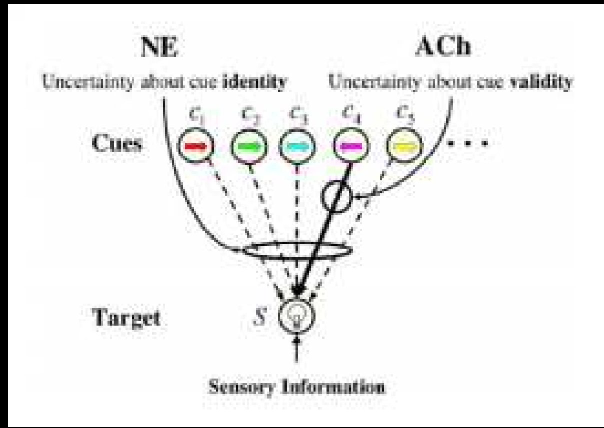
Norepinephrine



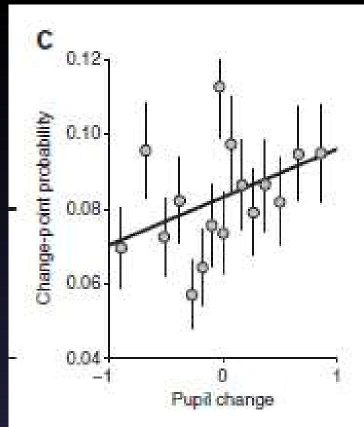
- Affects sympathetic autonomous nervous system
  - **"Stress hormone"** -> flight-fight choice, directly controlling:
    - Heart rate and blood flow to skeletal muscles
    - Pupil dilation
    - ...
- **Attention**

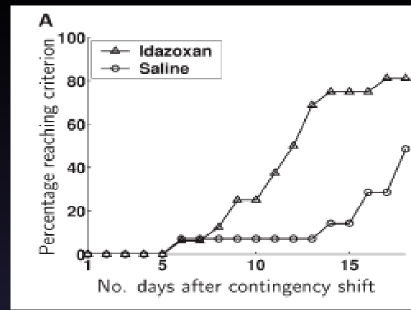


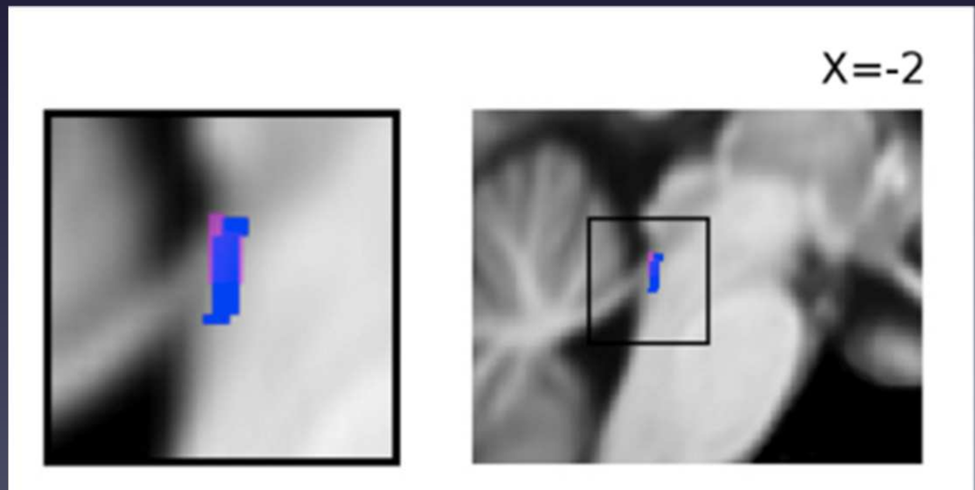
BACK TO OUTLIERS



$$\mathrm{NE} > \frac{\mathrm{ACh}}{(0.5 + \mathrm{ACh})}$$







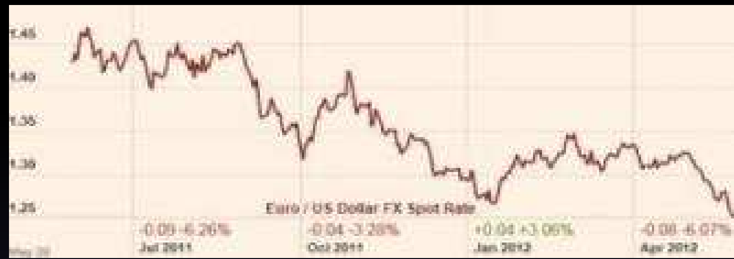
Norepinephrine system

(Locus Coeruleus)

- Signals outliers
- Modulates exploration

But Outliers Do Not Always Signal Change

Finance:

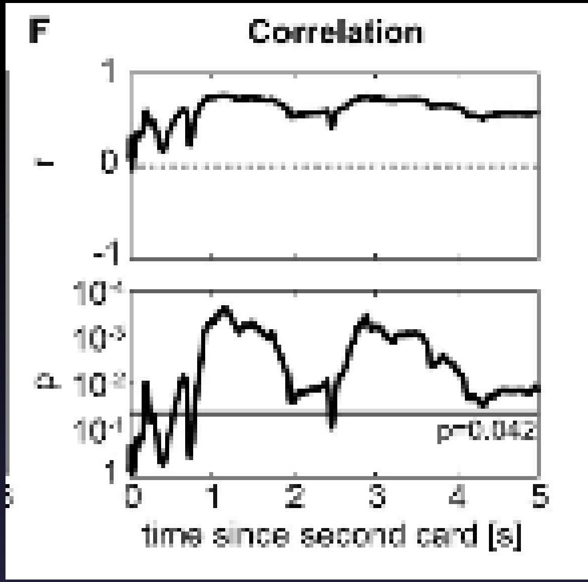


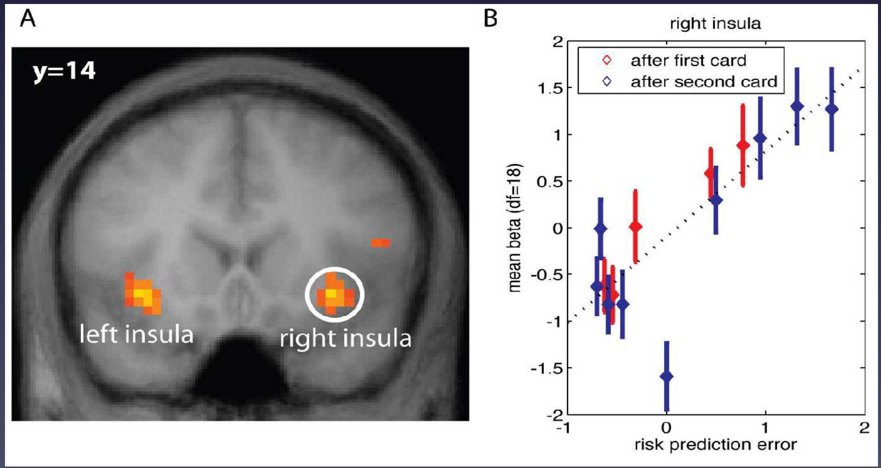
- Extreme events can be *fundamental* and have permanent effects

- Extreme events can be *transitory* and reverse at some point
  – "Here we analyze […] **18,520** ultrafast [transitory outliers] […] between 2006 and 2011" (*Johnson e.a., wp U Miami*)

Does Locus Coeruleus react indiscriminately to outliers?

- Pupil dilation (-> norepinephrine?) correlates with outliers even when nothing can be learned from them (Preuschoff ea, Frontiers DN 2011)
- Same for anterior insula activation (Preuschoff ea, Jneuro 2008)





Hypothesis

If the noradrenergic system automatically associates outliers with structural shifts, behavior could become maladaptive in the absence of neural control

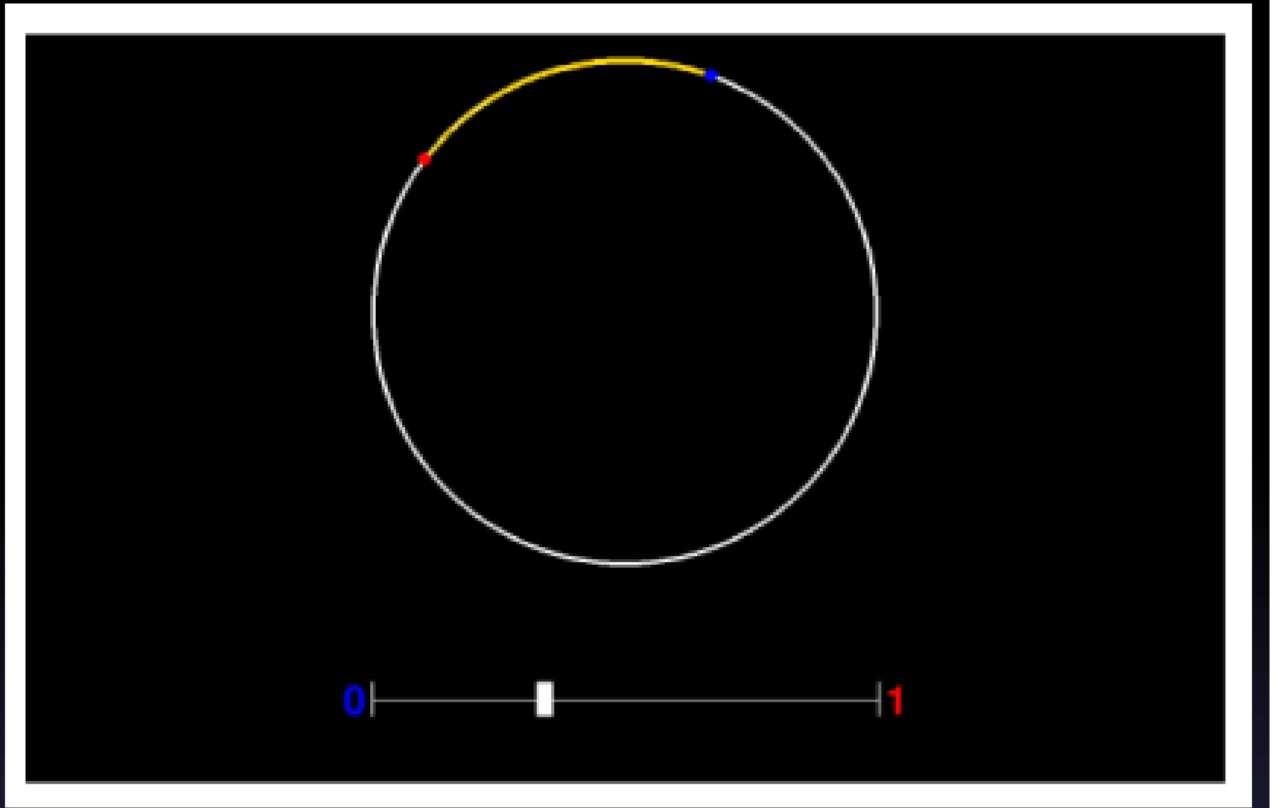
Neural Control – HOW?

1. Top-down biasing of sensory signals so maladaptive response is avoided

Neural Control – HOW?

2. *Wrong "Model of World" (Friston) needs to be confronted with data while behavior needs control*
   - *Sensory signals intact - thalamus, visual cortex*
   - *Integrative regions encode surprise – anterior insula, inferior frontal gyrus*
   - *Episodic memory recalls past effect of outliers (especially in reversal trials) – angular gyrus*
   - *Executive control of behavior – right superior frontal gyrus, frontal pole*

2. Experimental Design



- Subject controls Robot (blue)
- Robot should be as close as possible to Target (red) location
- Control = How much to catch up with Target (between 0 and 1; slider); **"learning rate"**
- (Yellow = AFTER move of Target, indicates distance between robot and target, i.e., "prediction error")

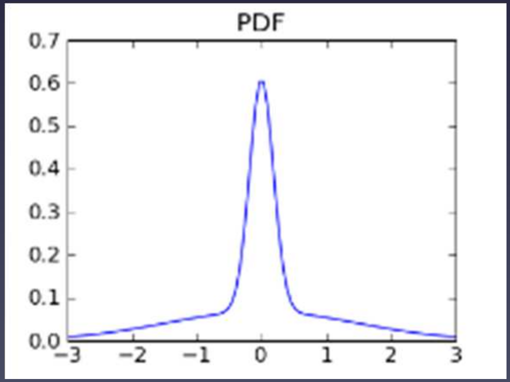
Two Treatments

(Two blocks of each)

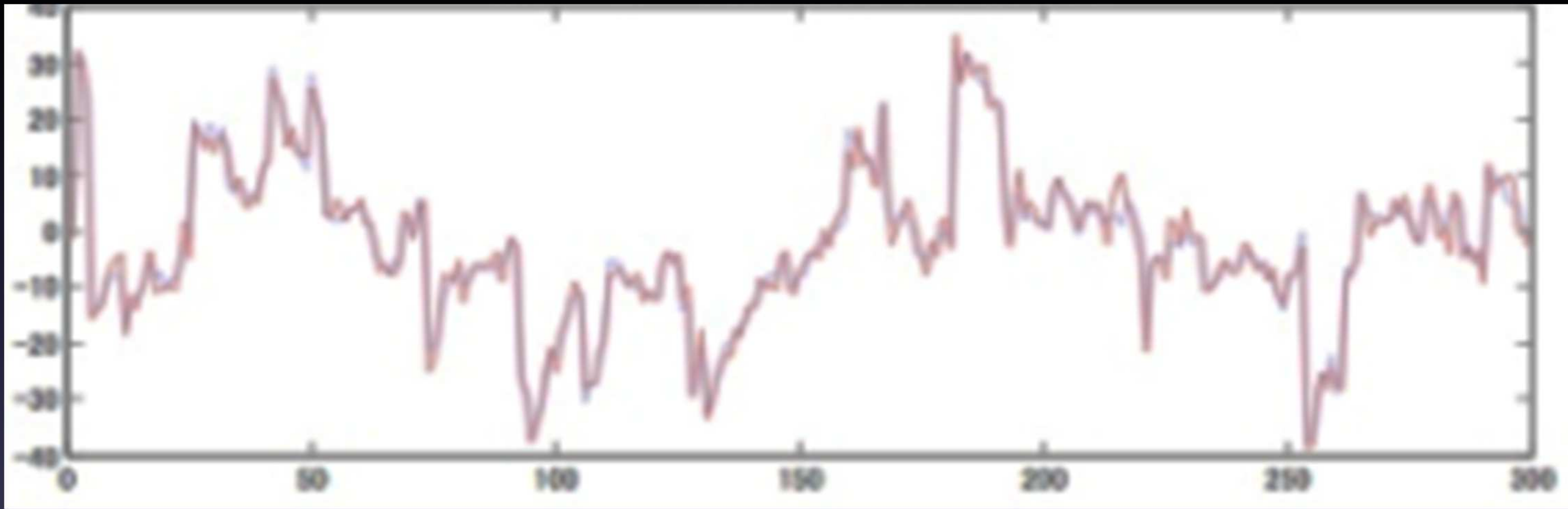
Yu-Dayan (2003) "simplified" and "extended":
y=observation, x=state,
epsilon=observation error,
eta=state innovation

- *Fundamental*: Extreme-value shock in state transition
- *Transitory*: Extreme-value shock in observation equation
- Same unconditional (stationary) distribution of changes

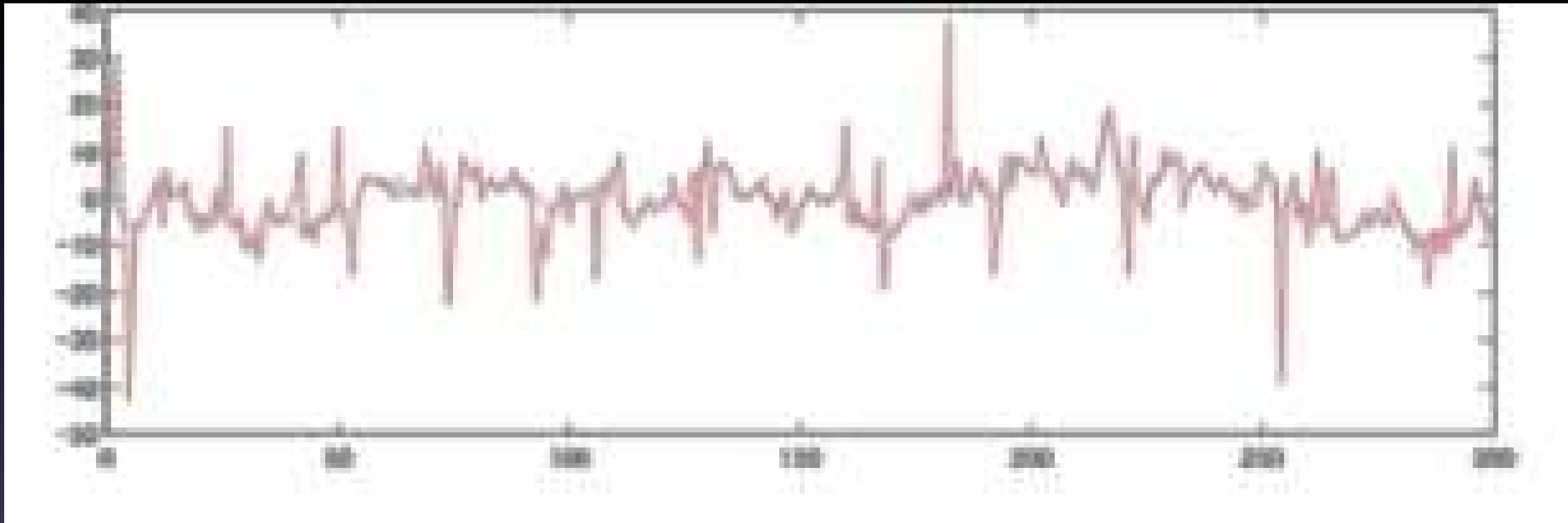
$$y_t = x_t + \epsilon_t$$
$$x_t = x_{t-1} + \eta_t$$



Fundamental

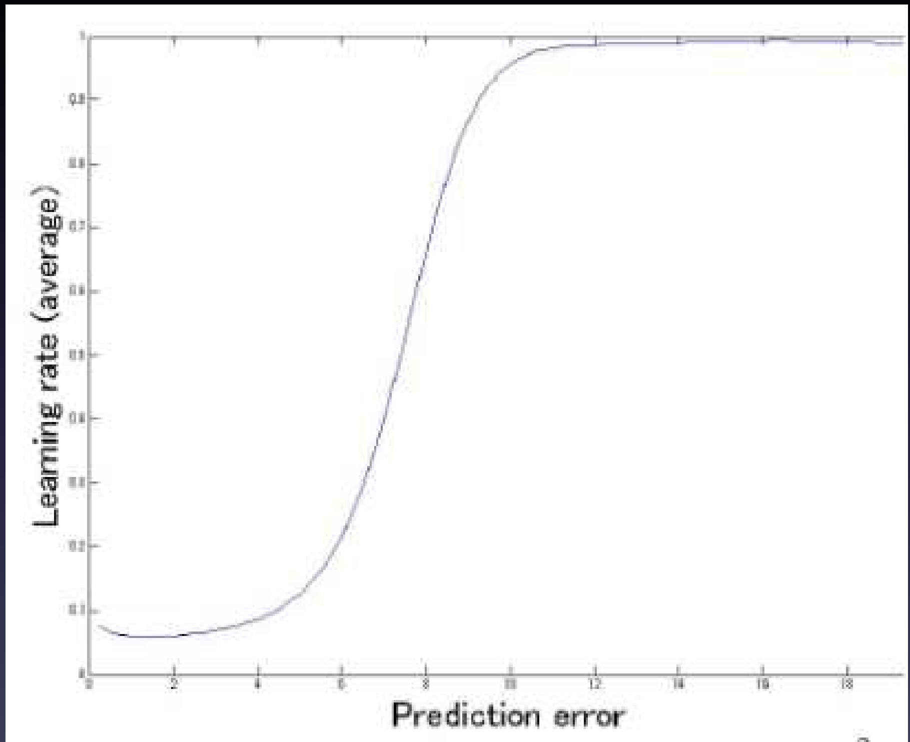


Transitory

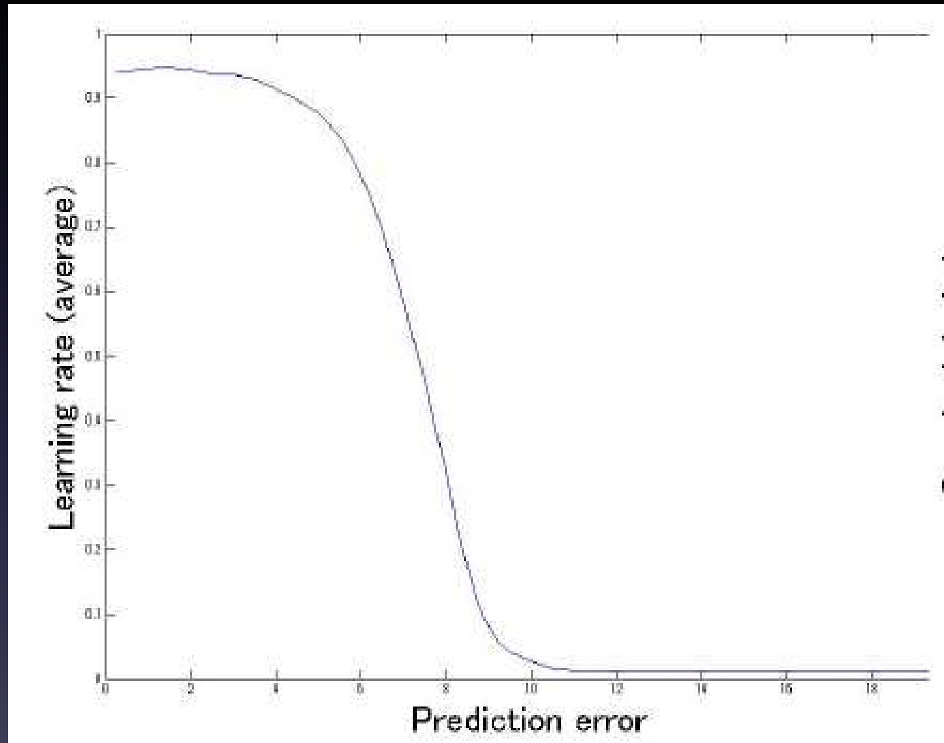


(Bayes) Optimal Learning Rate

(Based on Sequential Monte Carlo Analysis)



Fundamental



Transitory

Remark

- “Outlier” = Target move > 1.18rad [1 s.d. of empirical distribution, 1.6 s.d. of fitted normal distribution, so p=0.05]
- “Revert” = Target move > 1.18rad in opposite direction after outlier

Under “Wrong World Model” Hypothesis, REVERSAL TRIALS in transitory treatment are special:

- Surprise (despite predictable)
- Not sure how to react… reaction time lower

3. Behavioral Results

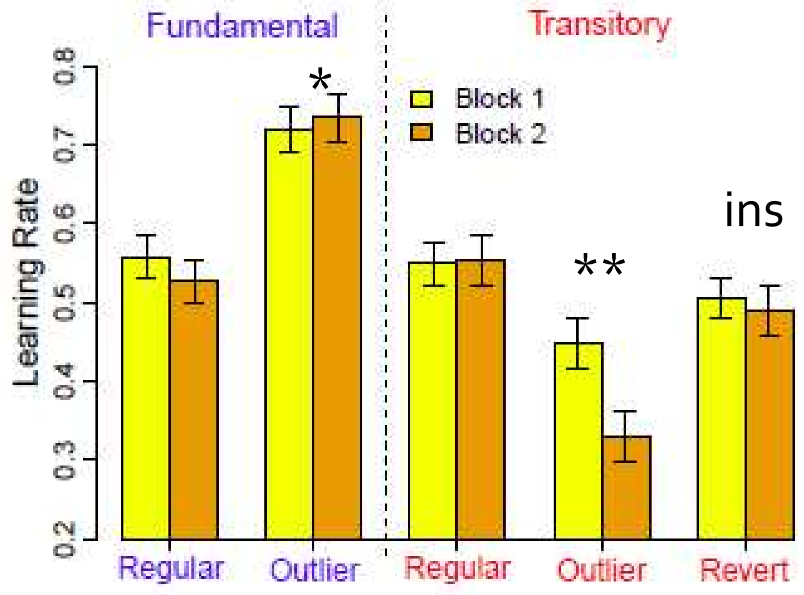


Figure 1: Learning rate in response to fundamental and transitory changes.

Learning Rate

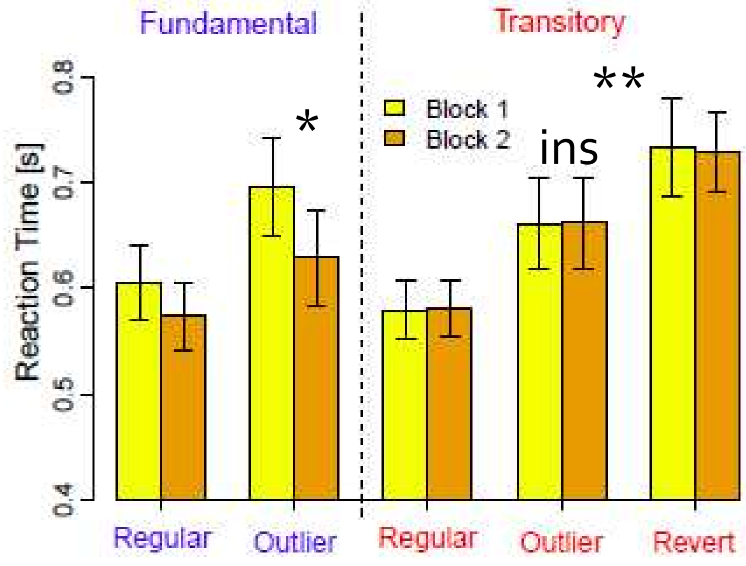


Figure 2: Deliberation time in response to fundamental and transitory changes.

Reaction Times

Performance

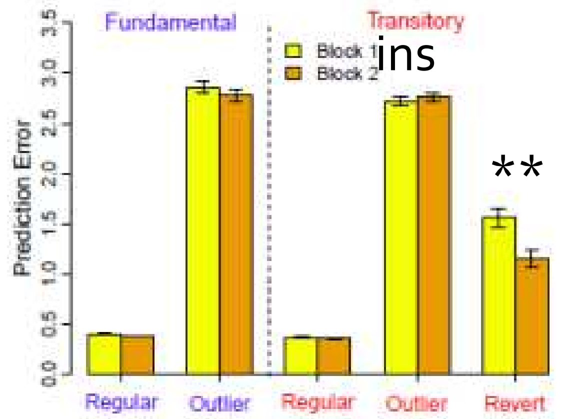


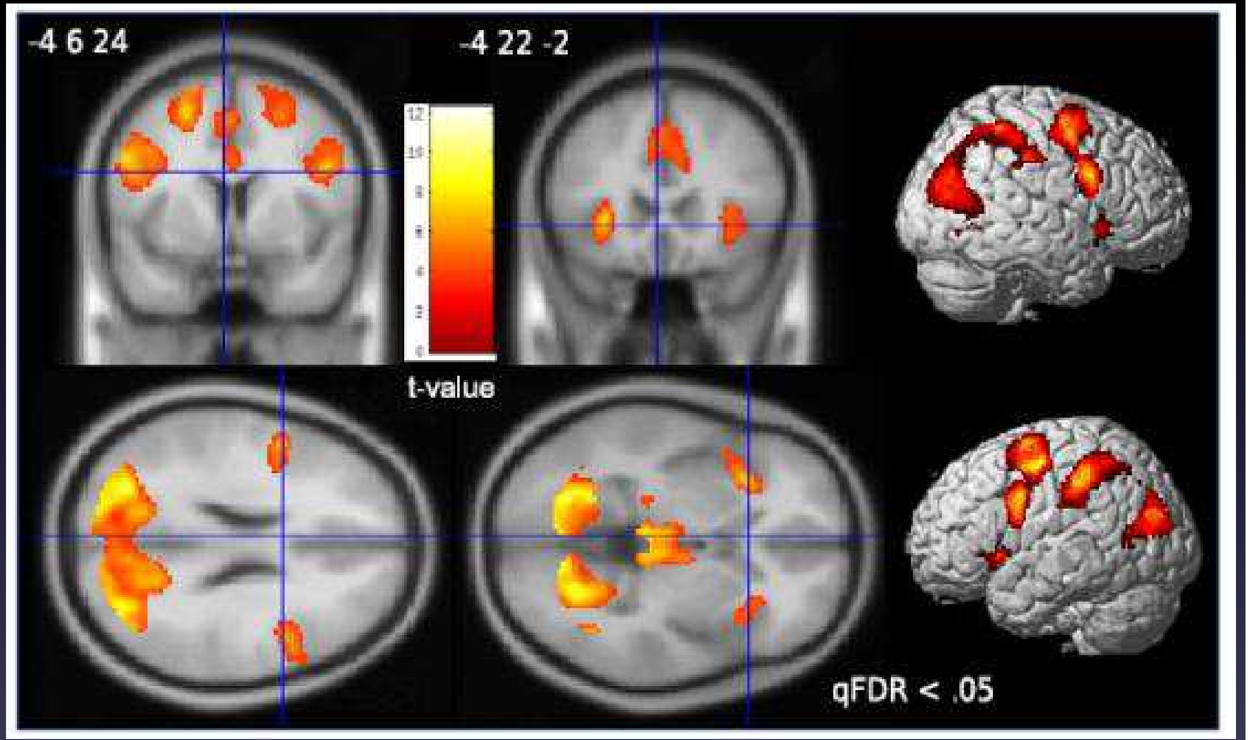
Figure 3: Error in predicting outliers in the fundamental and transitory conditions.

Behavioral - Conclusions

- Subjects learn to distinguish between two treatments
- Subjects "familiarize" themselves with fundamental treatment: deliberation times drop substantially
- Nevertheless, they continue to have difficulties in transitory treatment – deliberation times do not decrease and remain high especially in reversal trials

4. Imaging Results

(~ Target move *amplitude*, i.e. distance covered in trial)



(qFDR < 0.05; block 1 and 2 merged; ignoring behavioral heterogeneity)

NO significant interaction with Treatment

Sensory Signal Processing Regions

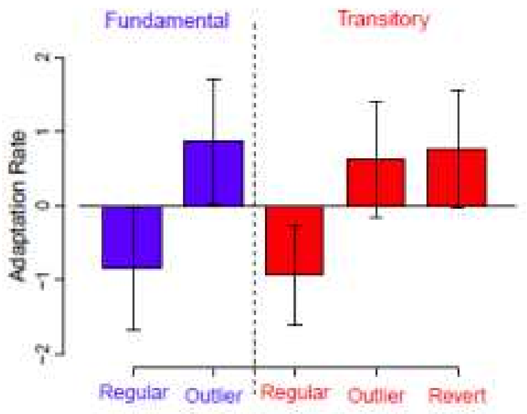


Figure 6: BOLD effect in the thalamus ROI for the fundamental and transitory conditions.

Thalamus

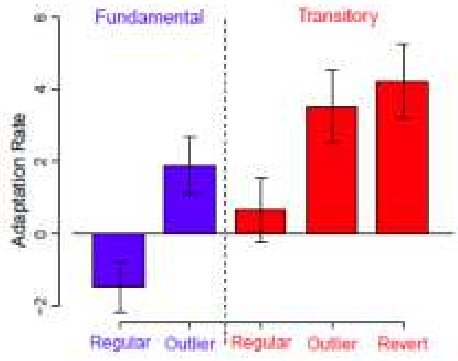


Figure 7: BOLD effect in the occipital/parietal ROI for the fundamental and transitory conditions.

Occipital/ Parietal

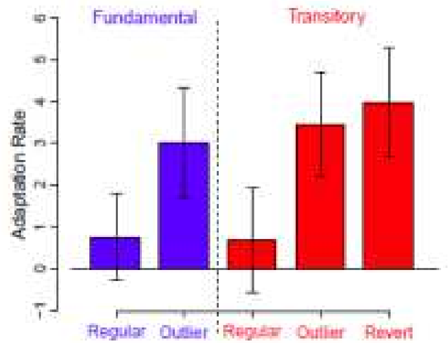


Figure 8: BOLD effect in the superior precentral ROI for the fundamental and transitory conditions.

Superior Precentral Gyrus (FEF?)

(Average activation using MarsBar; Leave-one-out protocol to avoid double dipping)

Transitory > Fundamental

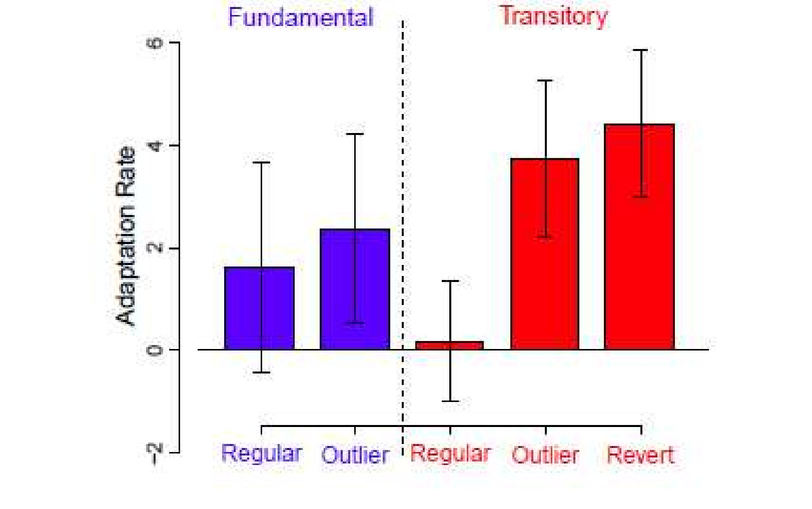


Figure 9: BOLD effect in the insula ROI for the fundamental and transitory conditions.

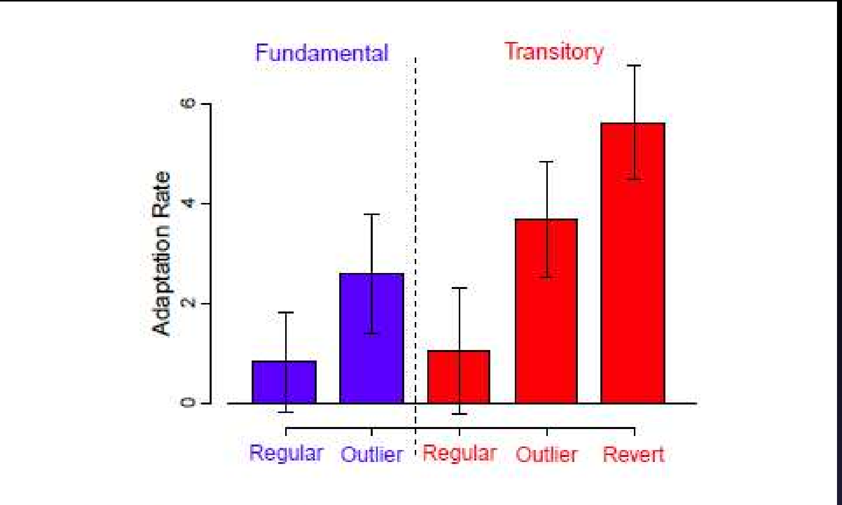


Figure 10: BOLD effect in the inferior frontal ROI for the fundamental and transitory conditions.

Anterior Insula

Inferior Frontal Gyrus

Integrative regions: confront sensory data with beliefs

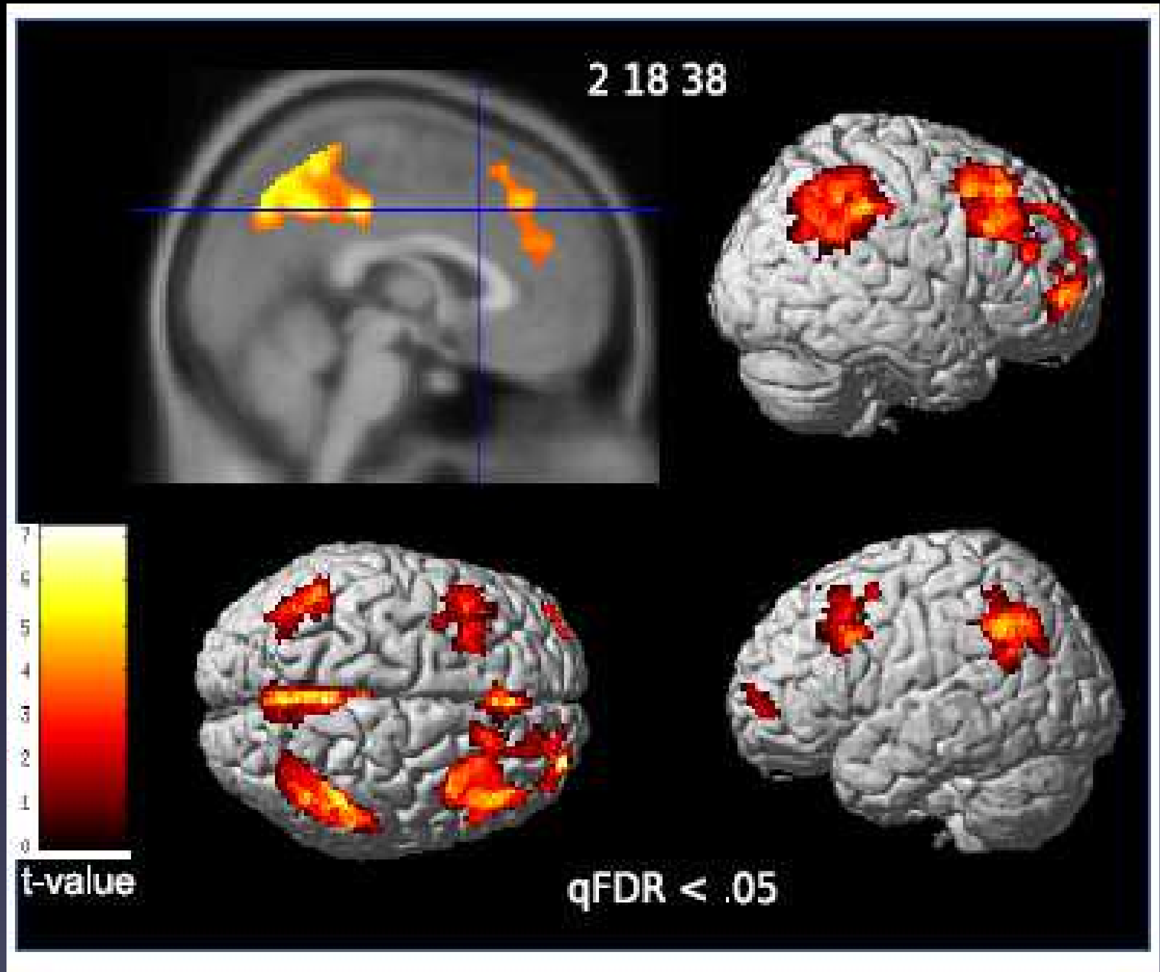
Effect Transitory > Fundamental Is Partly Focused On **Reversal Trials**

In Transitory:

(Reversal Target

Movement > Outlier

Target Movement)



Reversals

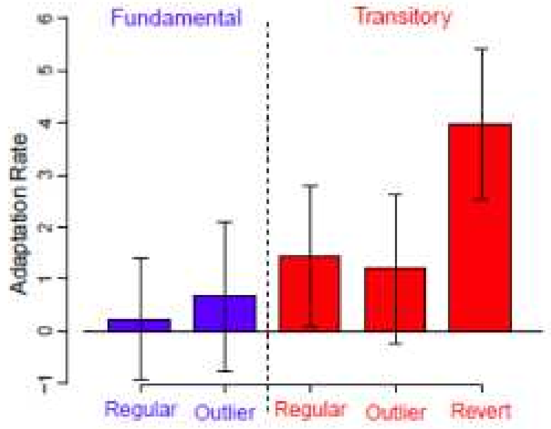


Figure 12: BOLD effect in the middle frontal gyrus ROI (DLPFC) for the fundamental and transitory conditions.

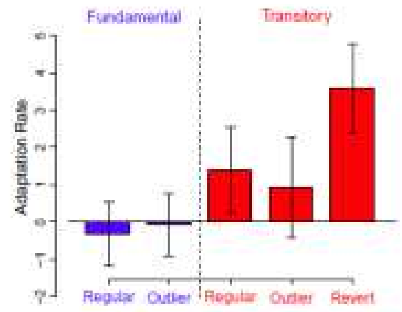


Figure 13: BOLD effect in inferior parietal cortex ROI for the fundamental and transitory conditions.

Inferior Parietal

Frontal Pole

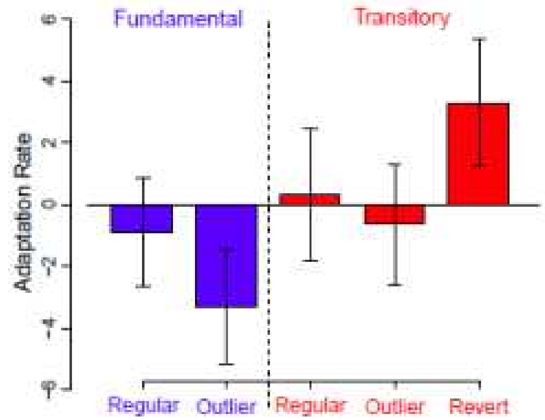


Figure 14: BOLD effect in anterior middle frontal gyrus ROI for the fundamental and transitory conditions.

"DLPFC"

(Analogous: Precuneus; Medial Superior Frontal Gyrus)

Executive control (dlpfc) and episodic memory (inferior parietal) regions

5. Discussion

1. Cognitive control becomes necessary when outliers are transitory – longer deliberation times needed, especially when reversals
2. Against direct top-down control: sensory neural signals (thalamus, occipital/parietal) react indiscriminately to outliers

(Discussion – c'd)

3. <u>Cognitive influence emerges in integrative regions</u>: anterior insula/IFG reaction to outliers stronger in transitory treatment
4. <u>Regions involved in executive control activated selectively in the "difficult" reversal trials:</u> Glaescher ea 2012 lesion study: *right* middle frontal gyrus, to frontal pole

(Discussion – c'd)

5. Episodic memory regions provide cognitive support in reversal trials: Angular gyri, precuneus (part of default mode network; engaged when updating frequencies, d'Acremont ea PLoS CB 2013)

(Discussion – c'd)

6. Relevance for finance:

   a. Identification of whether and when an outlier "reverts" seems to be important for *behavioral control of investment/trading*

      - *Galeano and Peña, 2013*

        » Fundamental > "Innovative" outlier

        » Transitory > "Additive" outlier

(Discussion – c'd)

b. Given the complications of human neurobiology when faced with outliers of the kind that are pervasive in financial markets, one wonders whether it is wise to *force* exposure to financial risks…

(Discussion – c'd)

c. Do transitory outliers in economic fundamentals transform into fundamental outliers through financial market participation -- contagion?

- *Controlled experiments with markets needed!*

(Discussion – c'd)

7. Relevance for Global Warming: Predicted increase in outliers that are *symptomatic* (of global warming) [Easterling ea, *Science* 2000; Wigley, 2009]
   - Outliers like cold spells do not signal further shifts (e.g., to ice age)

Bottom Line

Cognitive control in situations where outliers do not signal change (are transitory) works

NOT through top-down modulation

of sensory processing,

BUT through executive control

and supportive associative learning

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