Emotion and Reasoning in Human Decision-Making

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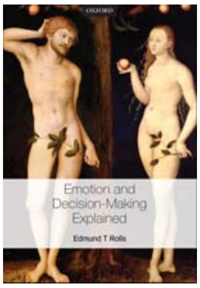


Oxford
University Press
2014

Neuroimaging:	*Computational Neuroscience*
F. Grabenhorst	S.M. Stringer
C. McCabe	G. Deco (Barcelona)
I. Araujo	A. Treves (SISSA, Trieste)
W. Cheng	P. Mills
J. Feng	T. Webb (Warwick)
Neuropsychology:	L. Robinson (Warwick)
J. Hornak	
H. Berlin	
Orbitofrontal Neurophysiology:	*Inferior Temporal Neurophysiology*
J.V. Verhagen	N. Aggelopoulos
M. Kadohisa	*Hippocampal Neurophysiology*
H. Critchley	J.-Z. Xiang

Principles of brain organization related to economic decision-making and macroeconomics

1. In macroeconomics, it is assumed that the economy behaves like one “representative” agent who can take rational and logical decisions, and who can maximize utility over a constraint.
2. Given the neuroscience of decision-making, the situation is more complex. The utility function may be multidimensional, the reward value along each dimension may fluctuate, the reasoning may be imperfect, and the decision-making process is subject to noise in the brain, making it somewhat random from occasion to occasion.
3. Moreover, each individual has a different set of value functions along each dimension, with different sensitivities to different rewards and punishers, which is expressed in the different personalities of different individuals.
4. Decisions may be made on emotional or rational bases, which have different mechanisms in the brain, and different interests; and noise may influence what bases are used for a particular decision.
5. These factors underlying the neuroscience of human decision-making need to be taken into account in building and utilizing macroeconomic theories.
6. These factors may need to be taken into account to understand decisions taken by major policy-makers.
7. Factors such as reputation may be important, not only economic utility.

Rolls (2014) Emotion and Decision-Making Explained (Oxford University Press).
Rolls (2016) Cerebral Cortex (Oxford University Press).
Rolls (2018) The Brain, Emotion, and Depression (Oxford University Press).
Rolls (2018) From brain mechanisms of emotion and decision-making to neuroeconomics. In The State of Mind in Economics. Eds. M.Teschl and A.Kirman. Cambridge University Press: Cambridge.

Neuroeconomics and classical economics

- **Classical economics assumes a few axioms, and rational, logical, application of those axioms.**
- **Neither may be correct.**
- **There may be multiple specific rewards that influence each decision.**
- **The decision-making may be produced by :**
  the emotional (short-term, with heuristics developed in evolution),
  or the rational (long-term, planning), system.
- **Which system is chosen, and the decision within each system, is subject to noise in the brain.**
- **Even in the rational system, logic may not be applied consistently well.**
- **Neuroeconomics may be able to identify many different value systems, and the probabilistic mechanisms used by the brain when making choices.**
- **Will neuroeconomics replace classical microeconomics?**

Rolls (2014) Emotion and Decision-Making Explained. Oxford.

Emotion: States elicited by Instrumental Reinforcers.
Role of Rewards & Punishers in Brain Design.

- Reward - an arbitrary instrumental action is performed to obtain a reward
- Punisher - an arbitrary instrumental action is performed to escape from or avoid a punisher
- Via natural selection, genes have built receptors for stimuli that by helping to encode primary (unlearned) rewards and punishers increase fitness.
- These gene-specified rewards and punishers (reinforcers) provide the goals for actions, which can be arbitrary, flexible and learned.
- Emotions are the states elicited by these gene-specified primary reinforcers and by secondary (learned) rewards and punishers. (Pleasures)
- Emotions are thus states elicited by rewards and punishers, which are the goals for action: emotions are not responses.
- Motivation (wants, desires) are the states in which we want to obtain these gene-specified reinforcers – a unifying, Darwinian, theory.
- A reasoning, rational, syntactic system allows these gene-specified emotion-related reinforcers to be deferred in terms of longer-term goals in the interests of the individual, the phenotype.
- Correction of these first order syntactic thoughts requires a Higher Order Syntactic Thought system – and this HOST system is associated with consciousness.
- Decisions between the genotype and the phenotype (genes vs phenes), and the effects of noise in the brain on decision-making and on free will.

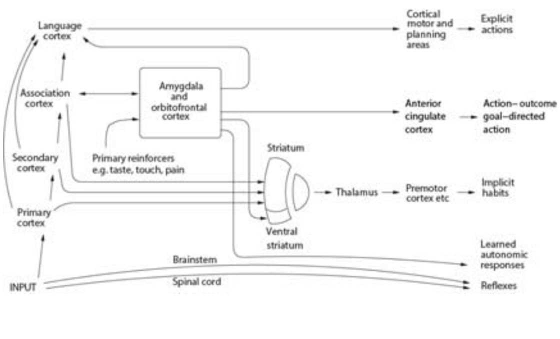
(E T Rolls. Emotion and Decision-Making Explained, 2014: Oxford)

Principles of brain organization for economic decision-making

1. Decisions are made by non-linear attractor neural networks in the brain, with noise produced by the random spiking times of neurons.
2. For this reason decision-making is probabilistic. Decisions should be taken several times.
3. There are two ways of making decisions:
   reward / emotion-based heuristics (habit; goal-directed; one trial reversal).
   the reasoning system.
4. The interests of these two systems are different:
   the reward / emotional system has genetic interests
   the rational / reasoning / language-based system can be influenced by the interests of the phenotype.
5. Who chooses between these systems?
   another noisy decision-making process in the brain
   and the rational system may confabulate
6. Even the rational system does not meet the criteria of microeconomics
   its logic and weighting of outcomes is imperfect
   it is noisy / probabilistic
7. There are many different rewards, many set as goals by genes.
   A common scale, but no common currency.
   There are many heuristics, not a few axioms.
   There are individual differences in the reward weightings in different individuals.
   Sensitivity to non-reward also differs between individuals, reflected in impulsiveness.
   In depression, there is an overactive non-reward system, and reduced impulsiveness.
   The opposite may be true in the manic phase of bipolar disorder.

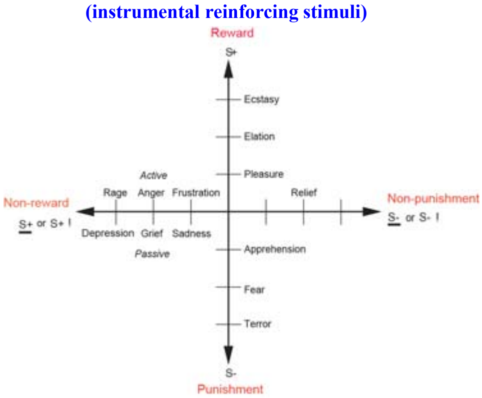
Rolls (2014) Emotion and Decision-Making Explained (Oxford University Press).
Rolls (2016) Cerebral Cortex (Oxford University Press).
Rolls (2018) The Brain, Emotion, and Depression (Oxford University Press).

Multiple routes for emotion-related responses

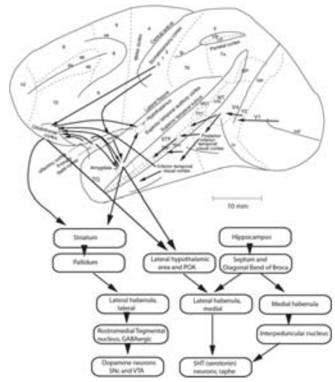


Rolls 2014 Emotion and Decision-Making Explained. Oxford

Emotions: States Elicited by Rewards and Punishers (instrumental reinforcing stimuli)

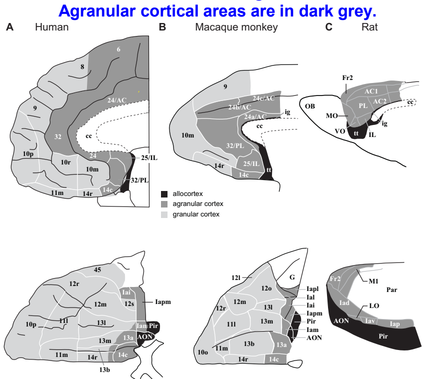


Orbitofrontal cortex inputs, and some outputs

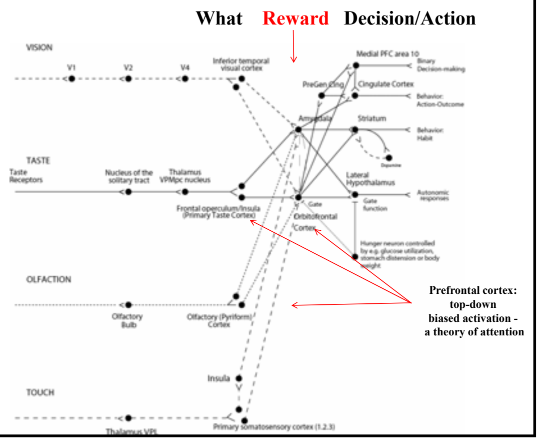


Rolls 2017 Neurosci Biobehav Rev

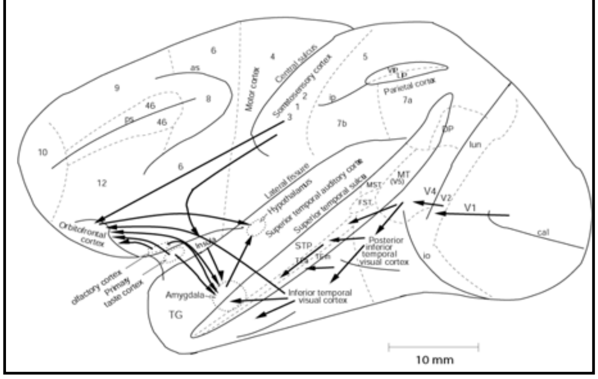
The orbitofrontal and cingulate cortices. Agranular cortical areas are in dark grey.

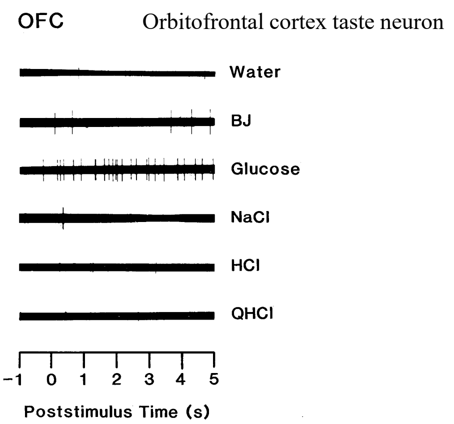


There may be no cortical area in rodents that is homologous to most of the primate including human orbitofrontal cortex: Wise (2008)

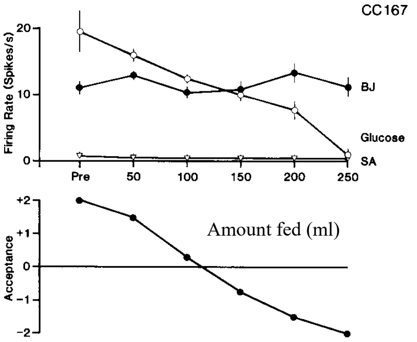


Taste, olfactory, somatosensory and visual inputs to the orbitofrontal cortex





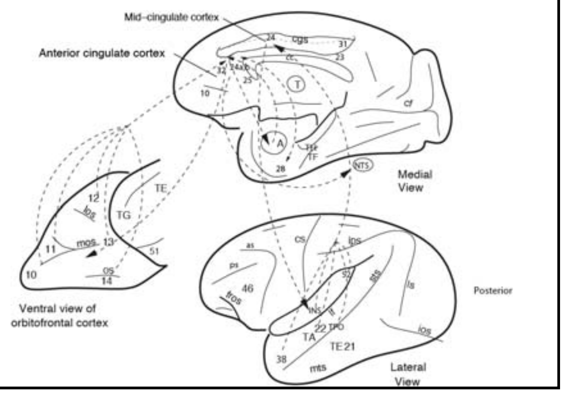
Orbitofrontal cortex reward value neurons



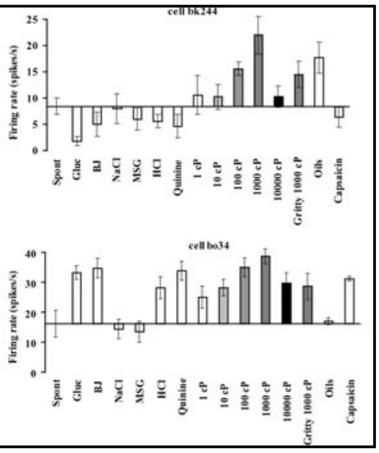
Sensory-specific satiety in the macaque orbitofrontal cortex

Rolls,E.T. et al (1989) European Journal of Neuroscience 1: 53-60.

Anterior cingulate cortex: action-outcome learning



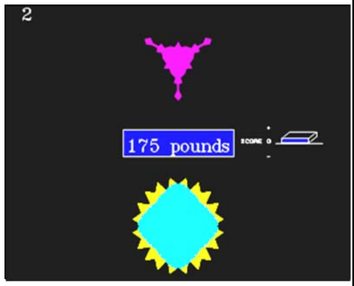
Orbitofrontal cortex representations of specific reward value:
Each orbitofrontal cortex neuron responds to a different combination of taste, odor, texture and temperature stimuli:
as a population they provide information about the specific reward value of many different stimuli.



Verhagen, Rolls and Kadohisa (2003) J Neurophysiology 90

Task Description

- Two Unfamiliar Fractals
- Random Position
- S+/S– = probabilistic gain/loss
- Choose S+ to maximise gain
- Reversal



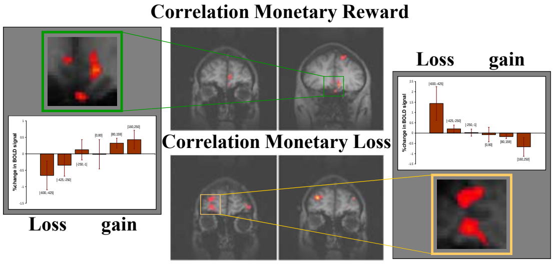
Orbitofrontal cortex neuronal responses

- **Taste reward. Only respond if hungry. Implement sensory-specific satiety.**
  - **All tastes are represented, including sweet, salt, bitter, sour and umami, and all are primary reinforcers.**
- **Olfactory reward.**
  - **Hunger dependent. Implement olfactory sensory-specific satiety.**
  - **40% reflect olfactory-taste association learning.**
- **Texture.**
  - **Reward - hunger dependent.**
  - **Fat texture. Fat is coded by texture, not by unsaturated fatty acids (eg linoleic)**
  - **Separate viscosity system. Separate astringency (tannic acid) system.**
- **Temperature.**
- **Visual**
  - **Reward. One-trial visual-to-taste association learning. Hunger dependent. Implement visual sensory-specific satiety.**
  - **Face-selective neurons**
- **Auditory, e.g vocalization**
- **Non-reward, error detection: "negative reward prediction error neurons"**
- **Activated from brain-stimulation reward sites**
- **High-dimensional representation of a very wide range of the sensory properties of both rewards and punishers, with secondary reinforcers linked to primary by stimulus-reinforcement association learning and reversal.**
- **A neuronal representation of stimulus value not of actions (cingulate) or habit responses (striatum). Used for one-trial reward value reversal.**

Rolls 2015 Progress in Neurobiology; Rolls 2017 Neuropsychologia

Neuroeconomics

Reciprocal relation between the medial OFC for reward and the lateral OFC for non-reward / loss / punishment



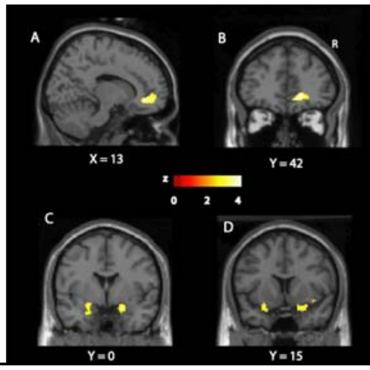
O'Doherty, Kringelbach, Rolls, Hornak and Andrews (2001)
Abstract reward and punishment representations in the human orbitofrontal cortex.
Nature Neuroscience 4: 95-102.

Conclusions: Economic Value in the human orbitofrontal cortex

- Activations in the medial orbitofrontal cortex are proportional to the monetary reward value gain.
- Activations in the lateral orbitofrontal cortex are proportional to the monetary value loss.
- Economic Value is represented in the human orbitofrontal cortex.

O'Doherty, Kringelbach, Rolls, Hornak and Andrews (2001)
Abstract reward and punishment representations in the human orbitofrontal cortex.
Nature Neuroscience 4: 95-102.

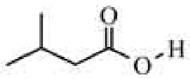
Cognitive modulation revealed by a correlation between the BOLD signal and the pleasantness ratings given to the Test odour.
A, B: anterior cingulate; C: amygdala; D: olfactory tubercle



Conclusions: A visually presented word label modulates representations of odors in reward value areas in the orbitofrontal cortex, amygdala, and ventral striatum. Cognition can influence subjective, conscious, affective representations in the orbitofrontal and pregenual cingulate cortices.

Isovaleric Acid

Cheddar Cheese



$(CH_3)_2CHCH_2COOH$

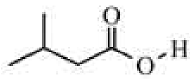
Body odour

De Araujo,I.E.T., Rolls,E.T., Velazco,M.I., Margot,C. and Cayeux,I. (2005)
Cognitive modulation of olfactory processing. Neuron 46: 671-679.

Conclusions: A visually presented word label modulates representations of odors in olfactory areas in the orbitofrontal cortex, amygdala, and olfactory tubercle. Cognition can influence subjective, conscious, affective representations in the orbitofrontal and pregenual cingulate cortices.

Isovaleric Acid

Cheddar Cheese



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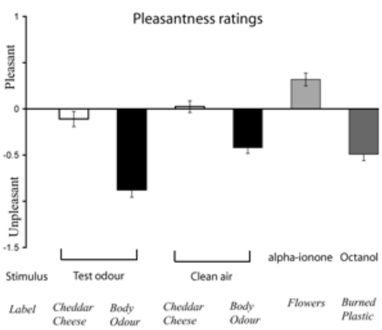
Effect of visually presented words ('cheddar cheese' vs 'body odor') on responses to a single Test odor, isovaleric acid



Do responses of the orbitofrontal cortex and pregenual cingulate cortex enable individual differences in affective behaviour and decision-making to be predicted?
Chocolate craving: a craving and a non-craving group

- Chocolate in the mouth – flavour differences?
- Sight of chocolate – conditioned cue differences?
- Sight of chocolate and chocolate in the mouth – greater supralinearity?
- Cognitive biasing: dark chocolate word label vs white chocolate word label
- Condensed milk – similar texture and sweetness to chocolate, but not craved.
- Tasteless control solution
- 8 cravers and 8 non-craver participants.
- SPM fMRI group random effects analysis with full correction or svc.

Rolls and McCabe (2007) European Journal of Neuroscience 26

fMRI of chocolate craving:

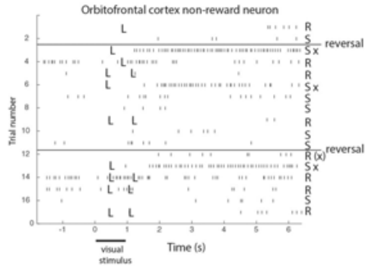
individual differences in brain activations predict craving and food intake

- There were no differences between chocolate cravers and non-cravers in responses to the flavour of chocolate in the primary taste cortex. Moreover the activations in the primary taste cortex were not correlated with the pleasantness or wanting ratings for chocolate. Thus it was not differences in the primary taste cortex, or physical sensitivity to taste and oral texture, that separated the cravers from the non-cravers.
- The flavour of chocolate produced more activation in cravers than non-cravers in the medial orbitofrontal cortex.
- The sight of chocolate produced more activation in chocolate cravers in the medial orbitofrontal cortex (OFC) and ventral striatum.
- A combination of the sight and flavour of chocolate produced more activation than the sum of the components in the medial orbitofrontal cortex, pregenual cingulate cortex, and striatum.
- This non-linearity was greater in the cravers than the non-cravers.
- The subjective pleasantness ratings of the chocolate and chocolate-related stimuli had higher positive correlations with the fMRI BOLD signals in the pregenual cingulate cortex and medial OFC in the cravers than in the non-cravers.
- The amount of chocolate eaten on a regular basis was higher in the cravers (370 g / week) than the non-cravers (22 g / week).
- Understanding individual differences in brain responses to very pleasant foods helps to understand the mechanisms that drive the liking for foods, and thus food intake and decision-making. Individual differences and personality.

Rolls and McCabe (2007) European Journal of Neuroscience 26: 1067-1076

A non-reward attractor theory of depression

- The orbitofrontal cortex contains error neurons that respond to non-reward for many seconds in an attractor state that maintains a memory of the non-reward.
- Measured on reversal trials in visual discrimination reversal in macaques by Thorpe, Rolls and Maddison (1983).



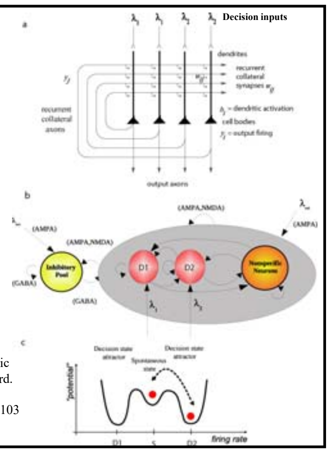
Rolls 2016 Neuroscience and Biobehavioral Reviews

Personality and reward systems in the brain

- Each specific type of reward (taste, flavour, water, touch …) is represented by different neurons.
- Each specific type of gene-specified reward is subject to variation between individuals as part of evolution by natural selection.
- Therefore different individuals may have different sensitivity to different specific types of reward, non-reward, etc.
- This variation may contribute to personality, and to high dimensionality of the space.
- This may be reflected in differential sensitivity in different individuals in how brain reward systems respond to different reinforcers.

An attractor network for probabilistic decision-making, with lambda 1 and 2 inputs, and noise from the neuronal spiking influencing which decision attractor, D1 or D2, wins.

This is also a model for short-term memory.



Rolls and Deco 2010 The Noisy Brain: Stochastic Dynamics as a Principle of Brain Function. Oxford.

Deco, Rolls et al 2013 Progress in Neurobiology 103

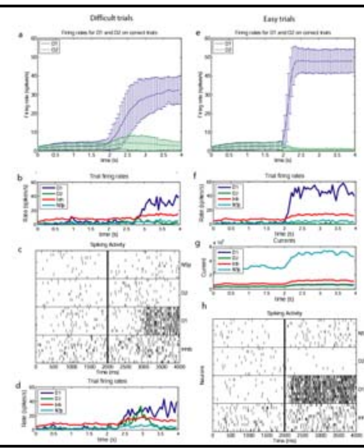
Orbitofrontal cortex neuroimaging

- Taste : Both pleasant and unpleasant tastes are represented
  - Amygdala: pleasant tastes are as much represented as unpleasant tastes
- Olfactory reward. Olfactory sensory-specific satiety.
- Olfaction: pleasant odours activate a particular region of the OFC
  - Anterior cingulate cortex is activated by pleasant and by unpleasant odors
  - Primary olfactory cortical areas represent the identity and intensity of odours
  - Cognitive inputs, word labels, modulate olfactory effects in the OFC and ant cingulate.
- Whole food: taste, odor and texture
  - Reward – reflects sensory-specific satiety.
  - Correlation of OFC activation with the subjective pleasantness of the food
- Oral viscosity and fat texture: insula and orbitofrontal cortex
- Flavour: olfactory-taste convergence
  - In the orbitofrontal cortex and adjoining agranular insula; MSG+savoury odor
  - The primary taste cortex in the insula is unimodal
- Individual differences: chocolate craving: orbitofrontal cortex and pregenual cingulate
- Somatosensory pleasure and pain more than neutral
  - Correlation of OFC activation with subjective pleasantness and pain
  - Anterior cingulate cortex: anterior - pleasant touch; mid - pain
- Abstract (monetary) reward and punishment (loss) in a reversal task
  - Separate representations of the magnitude of the gain (medial) and loss (lateral)
  - Expected value in a probabilistic task: Activation = probability x reward value
- Face reversal cued by changing face expression: reward prediction error
  - OFC activation related to an angry expression when it is used as a reversal cue
  - Activation in the fusiform face area does not reflect the reversal
- Amphetamine activates the medial orbitofrontal cortex
- Cognitive affective modulation of taste, flavour, odour and touch is implemented in the orbitofrontal and pregenual cingulate cortex.
  - www.oxcns.org

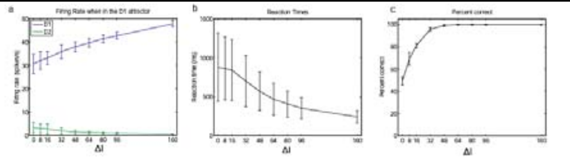
Integrate-and-fire simulations predict earlier and higher neuronal responses on easy vs difficult trials.

Confidence is reflected in the higher firing on easy trials.

The decision stimuli start at t=2 s



Rolls, Grabenhorst and Deco 2010 Neuroimage



- The theoretical framework based in statistical mechanics predicts higher and faster neuronal responses as Delta I, the difference between the two stimuli, increases.
- Delta I is a measure of the easiness of the decision, and subjective confidence ratings correlate with this.

Rolls, Grabenhorst and Deco 2010a Neuroimage

Principles of brain organization for economic decision-making (3)

1. Decisions are made by non-linear attractor neural networks in the brain, with noise produced by the random spiking times of neurons.
2. For this reason decision-making is probabilistic. Decision should be taken several times.
3. There are two ways of making decisions:
   reward / emotion-based heuristics (habit; goal-directed; one trial reversal).
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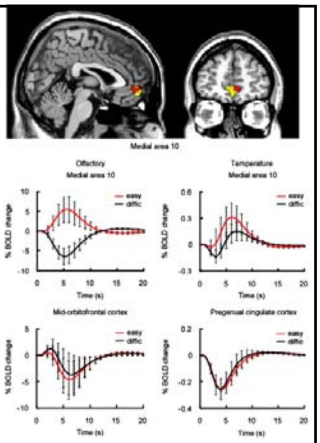
   The opposite may be true in the manic phase of bipolar disorder.

Rolls (2014) Emotion and Decision-Making Explained (Oxford University Press) . Rolls (2016) Cerebral Cortex (Oxford University Press)

- The Bold signal was, as predicted by the model, larger on easy vs difficult trials in medial prefrontal cortex area 10, implicated in decision-making; but not in mid-orbitofrontal cortex, implicated in a continuous representation of affective value
- Data from an olfactory and a thermal decision task



Rolls, Grabenhorst and Deco 2010 Neuroimage

Advantages of noise in the brain

1. Choices are made by competition to produce a single winner in an attractor network with separate attractors each biased by the separate continuous inputs.
   The decision-making is probabilistic because of the noise introduced by the (Poisson) randomness in the spike timing of neurons, which influences stochastically which attractor wins on a particular trial.
   This facilitates choosing less favourable options sometimes as in the matching law in which choice probability reflects reward value. This is adaptive, as the environment may change. Foraging...

2. Unpredictable behaviour: useful in predator avoidance, and in games. Can be evolutionarily adaptive.

3. Memory recall, the same process, is non-deterministic, and this allows creativity.
   Creativity in thought processes (as a noise influenced trajectory through a state space of associatively linked representations; also dreams)

4. Individual differences in noise may enable creativity with its dangers such as schizophrenia;
   vs greater stability of thought, focussing of attention on goals, with its dangers such as obsessive-compulsive disorder.

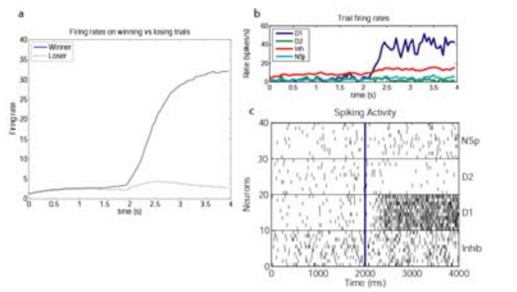
5. Decision-making between the emotional and rational (reasoning) systems.

6. Short-term memory is variable, with noise fluctuations freeing the short-term memory for further items.

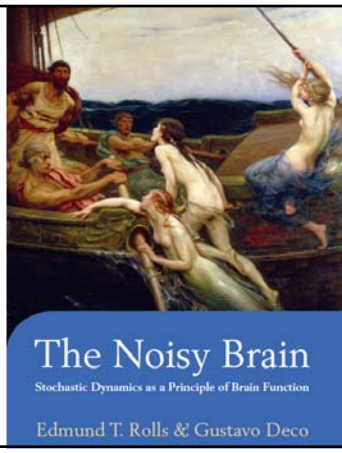
7. Signal detection close to threshold (as in stochastic resonance).

Rolls and Deco (2010) The Noisy Brain (Oxford University Press)
Rolls (2012) Neuroculture (Oxford University Press)
Rolls (2016) Cerebral Cortex (Oxford University Press)

Prediction of a decision at 70% correct, before the evidence is provided at t=2 s



Rolls and Deco (2010) The Noisy Brain. Oxford University Press
Rolls and Deco (2011) Frontiers in Neuroscience 5



Oxford University Press 2010

www.oxcns.org

Neuroeconomics and reward systems in the brain

1. **Value representations of many different reinforcers in the orbitofrontal cortex.**
2. **The value of each reinforcer must be scaled by natural selection on a common scale that promotes choosing of each reinforcer sometimes, in the interests of fitness (reproductive success by individual genes, which must cooperate as well as compete).**
3. **However, natural selection involves genetic variation, and therefore the profile of reinforcers will be different in different individuals.**
4. **Thus a few axioms applied logically to the rational decision-maker (classical microeconomics) will not do.**
5. **Instead, we must develop an understanding of value systems that are specific for different types of value, different in different individuals, and often influence behaviour by heuristics not by rational calculation.**
6. **Humans in any case are often poor at calculation of expected value (rewards and costs in probabilistic decision-making).**
7. **Animals (including humans) will be very sensitive to expected losses (e.g. injury, wealth and resources, reputation), as a single loss could impair reproductive success.**
8. **Noise in the brain can influence decision-making.**
9. **Humans have two ways of making decisions:**
   1. **The emotional system optimising gene-specified reinforcers in the interests of the 'selfish' genes.**
   2. **The rational system optimising reinforcers in the interests of the 'selfish' individual.**
   3. **Noise in the brain may influence even the decisions between these two systems.**
10. **Will neuroeconomics replace classical microeconomics?**

Rolls 2014 Emotion and Decision-Making Explained. Oxford University Press

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1. In macroeconomics, it is assumed that the economy behaves like one "representative" agent who can take rational and logical decisions, and who can maximize utility over a constraint.
2. Given the neuroscience of decision-making, the situation is more complex. The utility function may be multidimensional, the reward value along each dimension may fluctuate, the reasoning may be imperfect, and the decision-making process is subject to noise in the brain, making it somewhat random from occasion to occasion.
3. Moreover, each individual has a different set of value functions along each dimension, with different sensitivities to different rewards and punishers, which is expressed in the different personalities of different individuals.
4. Decisions may be made on emotional or rational bases, which have different mechanisms in the brain, and different interests; and noise may influence what bases are used for a particular decision.
5. These factors underlying the neuroscience of human decision-making need to be taken into account in building and utilizing macroeconomic theories.
6. These factors may need to be taken into account to understand decisions taken by major policy-makers.
7. Factors such as reputation may be important, not only economic utility.

Rolls (2014) Emotion and Decision-Making Explained (Oxford University Press).
Rolls (2016) Cerebral Cortex (Oxford University Press).
Rolls (2018) The Brain, Emotion, and Depression (Oxford University Press).
Rolls (2018) From brain mechanisms of emotion and decision-making to neuroeconomics. In The State of Mind in Economics. Eds. M.Teschl and A.Kirman. Cambridge University Press: Cambridge.