Neurobiology of Decision-Making

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Outline

- Basic Definition of Decision-making
- Neural Substrates underlying Decision-making
- Examples of Neural Substrate Processing:
  - Risk & Ambiguity
  - Framing / Gains & Losses
  - Outcomes
- 3-Stage Model of Decision-making
Decision-making - Overview

- Decision-making:
  - the process of making choices or reaching conclusions.

- Comprises temporally and functionally distinct processes:
  - (1) the **assessment** and formation of preferences among possible options
  - (2) the **selection** and execution of an action
  - (3) the experience or evaluation of an **outcome**.
Approaches To Understand Decision-Making

○ Decision-making components
  ● Type of decision-making

○ Mathematical Models
  ● Quantifying the contributions of probability, value, and time on likelihood of selecting an option.

○ Conceptual Models
  ● Dissecting decision-making into component processes.
Decision-making Processes

- Use time as the main independent variable:

- Processes that are serialized in time:
  - Input
    - Assessment of Options
  - Process / Computation
    - Option – Value Association
  - Output
    - Selection of Action
  - Feedback
    - Learning, Option – Value Adjustment
Preference Structure of Options

- Preferences are based on
  - Reward Magnitude
  - Probability of wanted/unwanted outcomes
  - Time to outcome
  - Preference characteristics of competing options.
Neural Substrates Underlying Decision-Making
Orbitofrontal Cortex

- Value
  - as it relates to **learning** and
  - state-dependency (Kringelbach 2005)
- During choice OFC neurons encode the **value** of offered and chosen options. (Padoa-Schioppa & Assad, 2006)
Anterior Cingulate

- Action–outcome associations:
  - Guiding decisions about whether the expected value of a reward means that it is worth acting (Rushworth, 2004)
- Monitoring and evaluating the outcomes of actions
  - Conflict
  - Errors (Botvinick, 2004)
Insular Cortex

- **Interoception:**
  - the sense of the physiological condition of the entire body (Craig 2002)
- “How do you feel”
- “How might you feel if...”
- “What does your body tell you?”
Striatum

- Striatum
  - Caudate
  - Putamen
- Topographic
  - Ventral-Dorsal
- Modulation by
  - Dopamine
  - AC
  - GABA
Hedonic Hotspots in the Striatum

- The ventral pallidum and the nucleus accumbens:
  - hedonic hot spots for taste rewards, (μ-opioid receptors)
- Modulation of hedonic valuation
Network of Reward/Reinforcement

- Cortical-subcortical Networks
- Cognitive – Affective Loops
- Connection:
  - Actions with Values
  - Options with Incentives
Neural Systems and Reward

- **Reward Network**
  - Brain structures that, when manipulated, alter the way people respond to rewards:
    - Learning
    - Valence
    - Choice behavior

Fig. 2: Brain structures for core “liking” and affective neural circuits discussed here.
Prospect Theory

- Prospect theory (Kahneman and Tversky, 1979)
  - explains non-normative decision-making phenomena.
- Prospect: the probability and value associated with an option.
- Individuals subjectively transform
  - probabilities into decision weights
  - outcomes into values,
- relative to a reference point
  - individuals expectation, aspiration and situation.
Mapping Probabilities and Outcomes

Figure 3.—A hypothetical value function.
Prospect Theory

- Probabilities, $p$, in decision-making situations are transformed nonlinearly into weights $w(p)$:

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

- Outcomes, $x$, are transformed into values, $v(x)$ according to:

$$v(x) = x^{\sigma^+}$$
Risk and Ambiguity

Choosing with / without probabilistic information

Fig. 1. Sample screens from the experiment. The conditions in the top panel are called ambiguous because the subject is missing relevant information that is available in the risk conditions (bottom panel). Subjects always choose between betting on one of the two options on the left side or taking the certain payoff on the right. (A) Card-Deck treatment: Ambiguity is not knowing the exact proportion; risk is knowing the number of cards (indicated by numbers above each deck). (B) Knowledge treatment: Ambiguity is knowing less about the uncertain events (e.g., Tajikistan) relative to risk (e.g., New York City). (C) Informed Opponent treatment: Ambiguity is betting against an opponent who has more information (who drew a three-card sample from the deck) than in risk (where the opponent drew no cards from the deck). Bets win if subject chooses the realized color and opponent chooses the opposite color; otherwise, both take the certain payoff [see (17)].
Amygdala & Lateral OFC: Ambiguity > Risk
Striatum: Risk > Ambiguity

- Probabilistic information during assessment of option engages reinforcement/reward prediction areas.
Framing
Gains & Losses
Framing and Decisions

- Valuation is relative to a reference point:
  - Gain domain
  - Loss domain
Framing Effect

- **Amygdala:**
  - Risk-taking in loss frame
  - Conservative behavior in gain frame

- **Anterior Cingulate:**
  - Risk-taking in gain frame
  - Conservative in loss frame
Losses loom larger than gains:
- To gamble or not to gamble
Striatum / VMPFC – Tracking Loss Aversion

- **Ventral Striatum:**
  - Stronger activation – more loss aversion

- **VMPFC:**
  - More activation with more gain.
Weighing Time
Temporal Discounting

- Temporal discounting:
  - a reward (or punishment), which occurs now, is valued more than a reward (or punishment) that occurs some time in the future.

- Humans (Rachlin et al 1991) and animals (Mazur 1989).
- Losses versus Gains (Shelley 1994).
- Risk (Stevenson 1992).
- Context (Chapman 1996).
- Punishment or reward magnitude (Green et al 1997)
Hyperbolic Discounting

- The delayed reward value is a power law function of the delay.
- Hyperbolicity:
  - Integrating possible longer delayed and larger future rewards can overcome smaller but more immediate rewards.
  - “Planning helps to reap greater rewards!”
Temporal Discounting: Behavior

- Two regions of hyperbolic discounting:
  - Shallow slope for $d < 1$ year
  - Steeper slope for $d > 1$ year
Differential activation: delayed versus immediate

- Bilateral insula:
Processing and Integrating Outcomes
Differential Win vs. Loss

- Simple Paradigm to gauge effects of wins and losses:

A.

- $T = T - 1$
- $C = 1$
- $T = T + c$
- Bank or Bet?

B.

- 2 sec
- Bank or Bet?
- Chips won: 8
- Total chips: 24
- 2, 4, or 8 sec
Levels of Risk: Behavior

- Losses induce risk
- Risk decreases over time
Win versus Loss: Brain Activation

- Two brain networks:
  - Medial orbitofrontal - Win
  - Lateral orbitofrontal - Loss
Conjunction – Behavior / Outcome

- Striatum – gains and risk
- Medial OFC – loss and risk
- Lateral OFC – gains and risk
- Insula – loss and risk
Stage I: 
Formation of Preference

Assessment Processes:
1. Editing:
   - Nonlinear transformation of probabilities
   - Discontinuous transformation (neglect, combination)
   - Certainty versus probability
   - Reward versus punishment
   - Framing
   - Added irrelevance

2. Comparing:
   - Relative versus absolute values
   - Weighing dimension (concreteness)
   - Compatibility

3. Affective Tagging
   - Associative evaluation
   - Automated processing
   - Component appraisal (affect)
   - Familiarity, control, threat, fairness, obstruction
   - Component integration
   - Simplification

4. Updating:
   - Adjusting according to option history

Selection and actualization of the option
Stage II: Execution of Action(s)

To select a goal and/or execute an action.

**Strategic Processing:**
- planning
- timing
- inhibition
- rule setting

**Affective Processing:**
- motivation
- anticipation
- discounting

ACC:

“action–outcome associations - guiding decisions about whether the expected value of a reward means that it is worth acting” – Rushworth, 2004

“if the ACC is involved in monitoring and evaluating the outcomes of actions, it may be that conflict is among the outcomes to which the ACC is sensitive.” – Botvinick, 2004
Stage 3: Experiencing The Outcome

**Striatum**: “ventral and dorsal striatum contribute to stimulus-reward and stimulus-response learning.” – O’Doherty, 2004

**OFC**: “In some regions of OFC and medial prefrontal cortex, activity was related to valence of outcome, whereas in adjacent areas activity was associated with behavioral choice, signaling maintenance of the current response strategy on a subsequent trial.” O’Doherty, 2004

**Insula**: Caudolateral OFC–anterior insula was activated by punishing feedback.
Putting it all together

### Areas

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<th>Outcome Processing</th>
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### Stages

**Stage 1: Assessment**
- Option A
- Option B
- Option C

**Stage 2: Execution (decision-making proper)**
- Action B
  - To execute and complete an action.
  - "cognitive" factors:
    - planning
    - motor sequencing
  - "affective" factors:
    - motivation
    - affective monitoring
  - anticipation
  - discounting

**Stage 3: Outcome processing**
- Option B - Outcome B
  - The hedonic experience and processing of action-outcome pairs:
    - cognitive:
      - probabilistic, logical heuristic
    - affective:
      - appraisal

**Integration (Learning)**

- Action/Outcome B - Option B
- Action/Outcome B - Option A
- Action/Outcome B - Option C

To update the weight and value due to change in association between options and outcomes:
- conditional probabilities
- weight updating
- affective "tags" updating
- valuation / devaluation of options
Application of this Model

- Conceptualizing dysfunction of decision-making as altered:
  - Assessment
  - Action selection
  - Outcome processing
  - Integration of Action-Outcome associations

- Relating Processes to Brain Regions or Circuits