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Neurobiological bases of intertemporal choices: A comprehensive review☆,☆☆

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ABSTRACT

Intertemporal choices (ICs) are choices that involve trade-off between costs and benefits that take place at different moments in time. The aim of this article is to present a comprehensive literature review on neurobiological bases of IC. We present the functional models of IC and data from neuroimaging studies, namely ALE analysis. With this paper we intended to show the presence of immediate value preference beyond that predicted by a single-parameter exponential discounting model and its mapping to the dual-systems model for brain function. Studies indicate that individuals tend to show inconsistent preferences depending on the time until the rewards are available and support a perspective that intertemporal evaluation reflects neural mechanisms that differ from other forms of choice, although associated value signals are later represented in the context of a common reward system. The IC induces activations in a “nuclear network” and auxiliary areas including inferior prefrontal cortex, medial prefrontal cortex, temporo-parietal cortex, and peri-splenial posterior cingulate. The network of areas sensitive to value is comprised of several regions that include ventral striatum, medial prefrontal cortex, orbitofrontal cortex, and anterior insula. Evidence from neuroimaging and EEG studies corroborates that choices are determined by a dual evaluation system.

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1. Introduction

Adaptive decision-making facilitates the consumption and distribution of resources in the quest for survival. Some decisions involve choices between two options available immediately that differ in aspects of value (e.g., relative preferences between attributes) or their probability of occurrence (e.g., risk and uncertainty). However, an important class of decisions involves the comparison of options that differ in the time they will be available, such as in choosing between smaller rewards available immediately and larger rewards that can only be obtained after some time. Choices that involve exchanges between costs and benefits that occur at different points in time are defined as intertemporal choices (ICs) (Johnson, 2012; Pimentel, Gonçalves, Scholten, Carvalho, & Correia, 2012).

In this type of IC situations, decision makers must adjust the subjective value of the delayed reward to take into account the waiting time until arrival. Delay discounting (DD) is the process of devaluing results that happen in the future (e.g., Ainslie, 1974; Green & Myerson, 2004; Logue, 1988; Rachlin & Green, 1972), as a means to study IC.

2. Models of intertemporal choices and the Allais Paradox

There is extensive literature on how to model IC behavior. The finding that most individuals willingly sacrifice the value to obtain the reward in a shorter time interval was initially described by Samuelson (1937) and is now replicated and expanded in many studies (Frederick, Loewenstein, & O'Donoghue, 2002; Kalenscher & Pennartz, 2008; Loewenstein & Prelec, 1992; Pimentel et al., 2012). These discounting effects are ubiquitous for both primary rewards (e.g., food, juice; Ainslie, 1974; Kobayashi & Schultz, 2008; McClure, Ericson, Laibson, Loewenstein, & Cohen, 2007; Richards, Mitchell, Wit, & Seiden, 1997) and secondary rewards (e.g., money; Loewenstein & Prelec, 1992; Strotz, 1956; Tesch & Sanfey, 2008; Thaler, 1981). An opposite phenomenon is often observed for repulsive stimuli, which may become more negative if they are located further in time (i.e., increasingly feared; Berns et al., 2006).

2.1. Exponential model

In Samuelson's formula, DD was modeled as an exponential decay function where subjective value (U) after a delay (D) is given by $U = Ae^{-\beta D}$, where A is the amount of reward and β is the discounting rate.

2.2. Hyperbolic model

Newer formulas have adopted alternative mathematical structures to explain irregularities in IC behaviors. Individuals tend to show inconsistent preferences depending on the time until the rewards are available (Prelec & Loewenstein, 1991; Thaler, 1981). For example, when choosing between $100 now and $110 in two weeks, most individuals prefer the smaller and more immediate reward. However, when choosing between $100 in 36 weeks and $110 in 38 weeks, almost everyone chooses the larger reward — although the delay in this latter scenario is identical to the previous one. This inconsistency, often called the immediacy effect, implies that the mechanism used to compute the intertemporal value shows a strong preference for immediate rewards, but in larger temporal distances the discounting curve becomes smoother (Pimentel et al., 2012). Alternative models that account for these characteristics propose a hyperbolic (Kirby & Marakovic, 1995; Laibson, 1997, 1998; Strotz, 1956) or a quasi-hyperbolic function using two exponential decay functions (Loewenstein, 1996; Phelps & Pollak, 1968; Shefrin & Thaler, 1988).

2.3. Allais Paradox

Although the models described above have proven to be useful, when decisions are made in the face of uncertainty, human attitude toward risk is not consistent (Iqbal, 2013). The classic model of decision under risk is based on the theory of expected utility (Cohen, 2015; von Neumann & Morgenstern, 1944), but the observed behavior of decision-makers is often at odds with the expected utility model. This can be exemplified with the effect that was coined as the Allais Paradox (Allais, 1953).

The Allais Paradox is a well-known bias where the preferences of individuals result in conflicting choices between two identical pairs of options, but with different expected utility and value. Studies have demonstrated that these reversals of preference depend on how the information is presented and described (Harman & Gonzalez, 2015).

In the Allais Paradox, firstly, individuals are typically asked to choose between options A and B and, afterwards, between options C and D (Allais, 1953). For example, individuals have to start by choosing between: (A) $1 million for sure or (B) a 10% chance of receiving $5 million, 89% chance of receiving $1 million, and 1% chance of receiving nothing. Then, individuals have to choose between: (C) 11% chance of receiving $1 million or (D) 10% chance of receiving $5 million.

The expected value of option A is $1 million and the expected value of option B is $ 1.39 million. According to the expected utility model, individuals are expected to choose the option with the highest expected value, meaning the preference of B over A, and this entails the preference of D over C (Da Silva, Baldo, & Matsushita, 2013). In turn, a preference for A rather than B implies a preference for C instead of D. Nevertheless, individual choices contrast with the predictions of the theory (Koçaslan, 2014). Although showing a preference for D over C, most people choose A in the first set of choices (thus the paradox), and this tendency was labeled as "certainty effect" (Kahneman & Tversky, 1979). Individuals prefer certain options when they are asked to choose between a risky alternative and a certain one. In this scenario, certainty contributes to risk aversion and their decisions become inconsistent between trials.

3. Neurobiological basis of intertemporal choices

It is known that dysfunctions in the mechanisms of IC contribute to a wide variety of anomalies related to decision-making, from inequities in the distribution of resources (Angeletos, Laibson, Repetto, Tobacman, & Weinberg, 2001; Laibson, 1997), to pathologies in which decision-making is altered, such as in addictions (Bickel & Marsch, 2001; Perry & Carroll, 2008), in attention deficit disorders (Critchfield & Kollins, 2001; Plichta et al., 2009), and in antisocial personality disorders (Petry, 2002), among other conditions.

Through a systematic review, Monterosso and Luo (2010) postulate that DD in humans is determined by the competition between two evolutionary brain systems, a more primitive one that discounts delay prematurely, and a more recent one that shows very little discounting. The more recent system comprises sophisticated cognitive functions, such as memory and self-signaling, leading to greater appreciation of subsequent alternatives that are implicit in neocortical structures. These capabilities do not affect choices through competition, but through a process of mediation of primitive and central structures for motivation and reward.

In adults, there are a number of functional neuroimaging studies that shed light on the neural bases of IC. The neurobiological mechanism of IC may be analyzed in two phases: evaluation and choice. As demonstrated in a study by Liu, Feng, Wang, and Li (2012), distinct brain regions seem to be involved in each phase. Specifically, the evaluation phase was associated with the activation of the ventral striatum (VS) and the ventromedial prefrontal cortex (vmPFC). In turn, the processes of choice were associated with the activation of the dorsolateral