

A Review of Multimodal Imaging and Causal Intervention in Delayed Deposition Neurons

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Abstract. This paper reviews the neural mechanism of delayed discounting, aiming to sort out the decision-making laws of individuals in instant reward and delayed reward selection and their brain base. In particular, it explores the involvement of the prefrontal cortex and the septum nucleus in delayed discounting, the relationship between neural connectivity and decision-making preferences, as well as the possible effects of neurostimulation on behavior. Existing studies have leveraged behavioral modeling, brain function imaging, and causal intervention methods to quantify individual preferences using the hyperbolic discounting model and discounting rate, while combining functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) to elucidate the functional connectivity and temporal dynamics of the prefrontal cortex (PFC) and the septum nucleus in decision-making. At the same time, transcranial magnetic stimulation (TMS) is employed to investigate the effects of neural modulation on discounting rates. The results demonstrate that the prefrontal cortex promotes rational decision-making, while the septum nucleus boosts the immediate reward attractiveness, so the interaction between the two significantly affects the selection behavior. Besides, individuals with strong functional connections are more inclined to choose delayed rewards, and the EEG study reveals the timing characteristics of impulse and rational switching in decision-making. In addition, TMS interventions can modulate discounting rates, indicating that delayed discounting is amenable to change. However, most studies use college student samples and short intervention periods, highlighting the need for further research and improved behavioral interventions.

Keywords: Delayed discounting, Neural mechanism, Brain function imaging, Causal intervention

1. Introduction

Delay discounting refers to the psychological phenomenon in which an individual's subjective valuation of a reward decreases as the delay to its receipt increases, leading to a preference for immediate rewards. This behavior is closely associated with unhealthy habits, such as smoking and alcohol use, as well as decision-making in learning and work contexts, and has become a key focus in the interdisciplinary study of neuroscience and psychology. Existing studies have demonstrated that the prefrontal cortex (PFC) is crucial for rational decision-making, whereas the septum nucleus

mediates the perception of immediate reward. They quantify discounting rates using the hyperbolic discounting model and, with the aid of technologies such as functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and transcranial magnetic stimulation (TMS), elucidate the brain region connectivity, the timing dynamics of decision-making, and the underlying mechanisms of causal modulation. However, research remains limited. Most studies examined college students, leaving effects across ages and cultures unexplored. And TMS interventions are often brief, making long-term effects unclear. Besides, the influence of factors such as emotion and decision-making pressure on brain region interactions has received limited attention, constraining a comprehensive understanding of the neural mechanisms underlying delay discounting. Based on this, by reviewing the key research results in the field of integration, this paper reviews brain function, neuroimaging, and causal regulation mechanisms to elucidate the neural basis of delay discounting. Meanwhile, by summarizing brain function and control mechanisms, this paper may help study impulse control and adverse behaviors, potentially guiding future educational and clinical studies.

2. Brain region function and the mechanisms of delay discounting

2.1. Brain region function and behavioral characteristics

The prefrontal cortex and septum nucleus underlie delay discounting, with the prefrontal cortex, at the front of the brain, managing rational choices, future planning, and inhibition of impulses. In the decision-making process of delayed discounting, its activities boost individuals' attention to future interests, so that individuals are more inclined to choose delayed rewards in the face of instant and delayed rewards [1]. Relatively speaking, the ventral septum nucleus is located in the brain reward system, which is mainly responsible for the pleasure perception of instant rewards. Activating the ventral septum nucleus enhances the attractiveness of short-term rewards, resulting in individuals ignoring long-term consequences and tending to choose instant rewards [2]. Previous studies have indicated that the interaction between the prefrontal cortex and septum nucleus is crucial for delay discounting, with individuals often favoring immediate rewards over long-term benefits when these processes conflict.

2.2. Behavioral modeling and quantitative metric

Behavioral modeling and quantitative indicators are used to accurately describe and quantify the phenomenon of delayed discounting, among which the hyperbolic discounting model is widely used [3]. The core idea of this model is that the subjective value of the reward will decline rapidly with the increase of time delay, and this decline is not uniform. For instance, when faced with a choice between 50 yuan immediately and 100 yuan in a month, individuals generally prefer the immediate reward. In contrast, when the choice involves 50 yuan in a year versus 100 yuan in thirteen months, a larger proportion choose the delayed reward, highlighting the significant impact of delay duration on decision-making. In addition, the key quantitative indicator "discount rate" in the model reflects the individual's preference for instant rewards. A higher discount rate indicates a stronger tendency to favor immediate rewards over future benefits. For example, smokers usually have a high discount rate, prioritizing the short-term relaxation from smoking while neglecting long-term health risks [4]. In contrast, individuals who maintain regular exercise tend to have lower discount rates, enduring short-term discomfort in exchange for long-term health gains. The discount rate can be measured experimentally through individuals' choices across varying delays and reward amounts, providing a

quantitative index of preferences and serving as a standard for predicting behavior and evaluating decision-making.

2.3. Brain region activity and model integration

The integration of brain region activity and behavior model reveals the synergy of different regions of the brain in delayed discount decision-making. Studies show that the interaction between the prefrontal cortex and the septum nucleus plays a key role in the decision-making process of delayed discounting. Through fMRI technology, McClure's team observed that when individuals prefer immediate rewards, septum nucleus activity is significantly increased, whereas choosing long-term rewards elicits strong activation in the prefrontal cortex [5]. This finding shows that the activity of the prefrontal cortex and the nucleus is competitive, which directly affects the decision-making of individuals, thus supporting the neurological basis of the hyperbolic discount model. In particular, when an individual hesitates in the decision-making process, the activation mode of the prefrontal cortex and the nucleus determines whether to choose instant reward or delayed reward in the end. In addition, the interaction between these brain regions is not fixed but dynamically modulated by factors such as emotion, decision-making pressure, and reward expectations. Thus, the integration of brain activity not only helps to deeply understand the phenomenon of delayed discounting, but also provides a theoretical basis for formulating more effective behavioral intervention strategies.

3. Brain functional imaging of delay discounting

3.1. fMRI activation and functional connectivity

fMRI technology reveals the activity patterns of the brain region by monitoring the changes in the blood flow of the brain. In the delay discounting, the functional interaction between the prefrontal cortex and nucleus accumbens is crucial. Studies have shown that the interaction between rational decision-making in the prefrontal cortex and immediate reward responses in the nucleus accumbens determines an individual's preference between delayed and immediate rewards.

Specifically, Bezzina G. investigated the functional connectivity between brain regions [6]. Their results showed that stronger connectivity between the prefrontal cortex and nucleus accumbens is associated with lower discount rates, indicating a greater tendency to choose delayed rewards. In the experiment, participants with strong functional connectivity could harness prefrontal cortex control to inhibit impulsive activity in the nucleus accumbens, thus preferring delayed rewards. In contrast, participants with weaker connectivity had more difficulty controlling nucleus accumbens impulses and tended to choose immediate rewards. For instance, when deciding whether to spend money immediately or save for a future purchase, individuals with strong connectivity tended to opt for saving, while those with weak connectivity were more likely to spend impulsively. This highlights the importance of communication between brain regions in decision-making. Unlike the activity of individual regions, the coordination and interaction between brain areas play a more critical role in determining delay discounting behavior. Through this mechanism, fMRI not only provides a more detailed neural explanation of decision-making but offers experimental support for the hyperbolic discounting model, demonstrating that the interplay between rational and impulsive processes is mediated by complex functional connectivity in the brain.

3.2. EEG frequency bands and temporal dynamics

EEG records electrical activity of the brain (brain waves) through electrodes placed on the scalp. In contrast to fMRI, EEG emphasizes the timing of neural activity and can monitor brain responses in real time. It is especially useful for studying delay discounting decisions, particularly when tracking theta-wave fluctuations.

Among them, theta wave (frequency 4-7 Hz) is closely related to the decision-making process. According to the psychologist Cohen, theta-wave amplitude varies depending on delay discounting decisions [7]. For example, when participants choose immediate rewards, increased theta activity in nucleus accumbens-related regions indicates an impulsive response to the reward. In contrast, if long-term reward is chosen, the theta wave can be enhanced in the prefrontal cortex, indicating that the brain is analyzing and controlling impulses rationally. Therefore, theta-wave changes can reveal how the brain switches between impulsive and rational processes during decision-making. Besides, theta activity changes very rapidly. Within 1-2 seconds from seeing the reward options to making a choice, theta waves already reflect the participant's decision tendency. This rapid responsiveness gives EEG an advantage over fMRI in capturing the temporal dynamics of decision-making, as it can track brain responses to different reward options in real time with millisecond precision. In comparison with the lower temporal resolution of fMRI, EEG can capture rapid, subtle changes in decision-making, offering more direct and precise measures of delay discounting behavior.

3.3. Multimodal signal integration and representation

The limitations of fMRI and EEG make it impossible to use them alone to provide comprehensive brain function characterization. fMRI accurately locates the brain region, but the response speed is relatively slow; although EEG can capture the timing changes of brain activity in real time, it lacks spatial resolution. Thus, multimodal signal integration has been developed, combining the strengths of both methods to provide a more comprehensive analysis of cognitive processes, demonstrating particular advantages in rapid-response tasks such as delay discounting decisions.

For example, Damasio's team used the combination of fMRI and EEG to study brain responses during delay discounting decisions [8]. In the experiment, fMRI and EEG data were collected at the same time as participants made delay discounting decisions. Their findings showed that immediate reward choices elicited fast theta-wave changes in the prefrontal cortex and nucleus accumbens, followed 3-5 seconds later by increased blood flow in the nucleus accumbens as measured by fMRI. For delayed reward choices, EEG revealed increased theta-wave activity in the prefrontal cortex, and fMRI indicated elevated blood flow in this region, thus highlighting the benefits of integrating temporal and spatial data. Specifically, EEG provides temporal data on brain responses, while fMRI precisely locates active regions. And the combination of the two techniques allows a more thorough analysis of the neural mechanisms underlying delay discounting. This integration reveals dynamic changes during decision-making and identifies key brain regions and their timing, offering practical guidance for interventions aimed at improving impulse control and promoting rational choices.

4. The causal modulation mechanisms of delay discounting

4.1. TMS procedures and intervention design

Transcranial magnetic stimulation regulates nerve activity in specific regions of the brain through magnetic fields, which has been widely adopted in delayed discounting research. By stimulating the

prefrontal cortex or septum nucleus, TMS can alter the trade-off between immediate and delayed rewards, thus affecting the discount rate. For instance, Halpern et al. applied TMS to the prefrontal cortex, lowering the discount rate in college students [9]. The experiment included an intervention group and a control group, and the intervention group received stimulation to the prefrontal cortex, whereas the control group received sham stimulation. The results showed that the discount rate of the intervention group decreased significantly, indicating that enhancing prefrontal lobe activity could reduce the preference for immediate rewards. However, there are some limitations in the existing research. Firstly, the experimental intervention time is relatively short, and it is difficult to evaluate its long-term effect. Secondly, most of the samples are college students, and other groups, including different ages and cultural backgrounds, have not been sufficiently studied. In addition, the differences in individual responses to TMS stimuli may affect the universality of experimental results. Future research should lengthen intervention duration, broaden the sample, and examine the long-term effects of TMS, as well as changes in brain networks using complementary technologies such as fMRI. These steps would help confirm the broader applicability of TMS in behavioral interventions.

4.2. Behavioral changes and causal validation

To determine how brain activity affects delay discounting behavior, causal intervention is a crucial method. By precisely regulating the activity of specific brain regions, changes in decision-making behavior can be directly observed, providing strong evidence for the underlying neural mechanisms. For example, prefrontal cortex stimulation with TMS produced a 30% reduction in the discount rate among students in the intervention group. Faced with the choice of “one hour of phone use now” versus “completing homework in a week for extra credits,” 70% of the intervention group chose the delayed reward. And the control group was only 35%. This change was maintained for two weeks after the intervention. This result shows that the enhancement of prefrontal lobe activity directly leads to a change in decision-making behavior, which verifies the causal relationship, not a simple correlation. In addition, other studies found that the desire of the subjects for immediate reward was notably reduced by inhibiting the activity of the nucleus by TMS. This highlights that the regulation of the activity of the septum nucleus can also change the delayed discounting behavior, which has potential application value in improving impulse control and bad hobbies.

4.3. Mechanism analysis and intervention implications

The key mechanism of TMS intervention in delay discounting lies in balancing brain region activity. By enhancing rational decision-making in the prefrontal cortex or suppressing impulsive responses to immediate rewards in the nucleus accumbens, the brain becomes more likely to favor long-term benefits during decision-making. This mechanism depends on the interaction and mutual regulation between the prefrontal cortex and nucleus accumbens, which play core roles in delay discounting behavior. For example, inhibiting the nucleus accumbens with TMS significantly lowered impulsive choices for immediate rewards, confirming its central role in impulsive decision-making. Through this intervention, the researchers succeeded in reducing the attractiveness of instant rewards and further enhancing the delayed discounting behavior. In addition, TMS also modulates the regulatory function of the dopamine system [10]. Dopamine, a neurotransmitter linked to reward, is released in the nucleus accumbens in proportion to the attractiveness of immediate rewards. Currently, boosted prefrontal cortex activity can effectively suppress dopamine release in the nucleus accumbens, thus reducing the appeal of immediate rewards. This illustrates the coordinated role of the prefrontal

cortex and nucleus accumbens in decision-making, with rational regulation by the prefrontal cortex suppressing impulsive activity in the nucleus accumbens.

5. Conclusion

This paper finds that the prefrontal cortex plays a key role in rational decision-making and impulse suppression, while the nucleus accumbens increases the appeal of immediate rewards, making their interaction a key factor in delay discounting behavior. At the same time, behavioral modeling, fMRI, EEG and multimodal signal integration reveal the relationship between discount rate and brain function and sequence dynamics. In addition, TMS intervention shows that brain region regulation can change discount preferences, which provides potential ideas for improving bad hobbies. There are still limitations in the existing research, due to most participants being college students, thereby leaving the applicability to other age groups and cultural backgrounds uncertain. Furthermore, the TMS intervention time is relatively short, so the long-term effect is still unclear. At the same time, brain interaction is regulated by many factors such as emotion and decision-making pressure, but the comprehensive consideration of these factors in existing research is still limited. Future research should include more diverse samples, lengthen the intervention period, and use multimodal imaging to study brain interactions, improving generalizability and guiding clinical practice.

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