# Reward Learning Mechanisms in Anhedonia and Dynamic Modulation of Sense of Control

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## Abstract

Anhedonia, defined as a marked reduction or loss of the capacity to experience pleasure, is both a warning signal and a risk factor for multiple psychiatric disorders. However, current pharmacological and psychological interventions have limited efficacy in alleviating anhedonia, highlighting the urgent need to develop novel intervention paradigms. Existing studies have not yet clarified the mechanisms by which reward learning contributes to anhedonia, and there is a particular lack of research on how individuals' perception of reward–action contingencies influences reward learning and anhedonia. Therefore, the present study plans to adopt a multidimensional approach to: (1) use behavioral experiments and reinforcement learning modeling to test whether sense of control dynamically regulates reward learning in individuals with anhedonia; (2) employ functional magnetic resonance imaging to examine the underlying neural mechanisms; and (3) conduct a randomized controlled trial to manipulate sense of control and assess its intervention effects on reward learning and anhedonia. On this basis, the study proposes a dual-layer "internal–external loop" hypothesis of reward learning, which may help elucidate the mechanisms of reward learning in anhedonia, reveal the role of sense of control therein, and open up a new paradigm for intervention in anhedonia.

## Full Text

## Reward Learning Mechanisms in Anhedonia and Dynamic Modulation of Perceived Control

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**Abstract:** Anhedonia, characterized by marked diminishment or loss of pleasure, serves as both a warning signal and risk factor for multiple psychiatric disorders. However, current pharmacological and psychological interventions show limited efficacy in treating anhedonia, necessitating the development of novel intervention paradigms. Existing research has not yet clarified the mechanistic role of reward learning in anhedonia, particularly lacking studies on how individuals' perception of reward-behavior contingencies influences reward learning and anhedonia. Therefore, this study proposes a multi-dimensional approach: 1) to verify whether perceived control dynamically modulates reward learning in individuals with anhedonia through behavioral experiments and reinforcement learning modeling; 2) to explore the underlying neural mechanisms using functional magnetic resonance imaging; and 3) to test the intervention efficacy on reward learning and anhedonia through randomized controlled trials targeting perceived control. Building upon this, we propose the Dual-Loop Reward Learning Hypothesis, which illuminates the reward learning mechanisms in anhedonia, reveals the role of perceived control, and opens new avenues for anhedonia intervention.

**Keywords:** anhedonia, subclinical high-risk population, psychological intervention, reinforcement learning model, perceived control

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## 1. Research Significance

Mental health encompasses not merely the absence of psychiatric illness, but also the capacity to think, learn, and comprehend one' s own emotions and responses to others. Since the "Healthy China 2030" Planning Outline issued by the CPC Central Committee and State Council in October 2016 elevated mental health promotion to a national development strategy, the importance of mental health has become increasingly prominent. The Third Plenary Session of the 20th CPC Central Committee further emphasized "promoting the comprehensive development of individuals," making mental health concerns an unavoidable and critical contemporary issue. Anhedonia—marked reduction or loss of pleasure—functions both as a warning signal and risk factor for depression, anxiety, post-traumatic stress disorder, and other mental disorders, while also representing an important dimension within broader frameworks of happiness and well-being. Research on anhedonia embodies the implementation of a "comprehensive health" perspective and contributes to the scientific pursuit of comprehensive human development.

From a scientific standpoint, investigating the mechanisms and interventions for anhedonia represents not only an innovation in traditional psychiatric diagnosis but also a paradigm shift in psychotherapy. First, anhedonia research constitutes a powerful exploration to overcome limitations of traditional categorical psychiatric diagnoses, which suffer from high comorbidity rates and lack reliable biological markers. Developing new diagnostic systems is an imperative solution to current problems. Emerging diagnostic frameworks based on mental health continuums posit that anhedonia originates at the pre-clinical stage of traditionally defined mental disorders. Therefore, exploring brain circuits and biological markers associated with anhedonia may reveal fundamental pathological causes. Second, the treatment resistance of anhedonia has long challenged traditional pharmacological and psychological therapies, making the discovery of effective interventions and development of new therapeutic paradigms a primary research direction. A recent *Nature* study exploring anhedonia reversal mechanisms in rodents underscores the scientific importance of this topic and establishes a solid foundation for human anhedonia research.

In terms of theoretical contribution, this study integrates meta-reinforcement learning theory, computational modeling, and cognitive neuroscience to propose an innovative theoretical framework for anhedonia mechanisms and interventions. Through reinforcement learning computational models, we examine contradictions in the "motivation-pleasure dissociation" hypothesis, adopting a unified computational framework from a reward learning perspective, and consequently propose the Dual-Loop Reward Learning Model.

Regarding practical significance, our findings will inform prevention of mental disorders and intervention for anhedonia, facilitating "prevention before illness" and "early treatment for minor symptoms." As anhedonia represents a crucial warning sign and risk factor across multiple mental disorders, investigating its mechanisms from a reward learning perspective promotes mental health and prevents psychiatric illness. Moreover, while psychiatric medications show inconsistent effects on anhedonia and traditional psychological interventions primarily target negative emotion alleviation, exploring a "perceived control-reward learning" pathway offers a novel intervention paradigm to overcome these limitations.

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## 2.1 The Connotation of Reward Learning in Anhedonia

Anhedonia refers to marked reduction or loss of pleasure. Based on previous research, we have synthesized a "Mental Health-Pleasure" dual-dimension model [Figure 1: see original paper]. From a mental health continuum perspective, anhedonia emerges in subclinical states and represents a common feature across multiple mental disorders. From a disease course perspective, anhedonia serves as both a critical risk indicator for onset of many mental disorders and a specific predictor of poor treatment response and prognosis, permeating the entire course of multiple mental disorders while closely correlating with social functioning and quality of life.

Anhedonia can be understood through various theoretical lenses, including stage-specific pleasure deficit theory, reward processing impairment theory, and emotion-to-behavior conversion deficit theory. The representative reward processing impairment theory posits that anhedonia results from impairments in one or more components of reward processing, including reward anticipation, reward response, and reward learning. Among these, reward learning constitutes the critical link connecting reward anticipation and reward response. This stage requires learning from previous reward outcomes to update future reward expectations [Figure 2: see original paper].

Previous research on anhedonia and reward learning has primarily focused on "already ill" psychiatric frameworks, with insufficient investigation of reward learning in anhedonia at the "pre-illness" stage. Studies have found that depressed individuals show impaired reward learning compared to healthy controls, specifically manifesting as less accumulation of reward-maximizing behaviors from feedback. However, another study found no significant differences in reward learning between depressed, social anxiety, and healthy groups. Such inconsistencies likely arise because reward learning impairments in mental disorders actually reflect anhedonia-specific reward learning deficits. Compared to these impairments, what characterizes reward learning in "pre-illness" stage anhedonia? Do differences lie in severity or pattern? These questions remain unanswered.

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## 2.2 Research on Reward Learning in Anhedonia

Common paradigms for studying reward learning in anhedonia include probabilistic reinforcement learning tasks, reward delay tasks, Iowa Gambling Task, and N-arm bandit tasks. These paradigms fundamentally feature different probabilities of winning rewards, requiring participants to adjust behavior based on reward feedback. We review this research from behavioral and neural mechanism perspectives.

### 2.2.1 Behavioral Research on Reward Learning in Anhedonia

Behavioral research on reward learning in anhedonia has evolved through two phases: traditional behavioral studies and computational modeling-based research. The first phase employed traditional behavioral measures including total rewards obtained, proportion of high-reward stimulus choices, probability of repeating rewarded actions, and accuracy under reward conditions. These studies essentially examined the degree to which participants exhibited reward-approaching behavior. While results were not entirely consistent, they generally indicated that mental disorder groups with anhedonia as a primary feature showed less reward-approaching behavior. Although straightforward, these group-level averages could not identify underlying mechanisms. For instance, while depressed individuals earned fewer average rewards in probabilistic tasks, traditional approaches could not determine whether this stemmed from difficulties integrating reward information, reduced exploration of high-reward options, or excessive influence from prior beliefs.

The second phase utilizes computational modeling to investigate underlying mechanisms and capture individual-level explanations. Models such as drift-diffusion, reinforcement learning, and Bayesian models have been applied, with reinforcement learning models being most suitable and interpretable for anhedonia research. Meta-analytic findings indicate that individuals with mood and anxiety disorders exhibit lower reward learning rates and lower inverse temperature parameters (representing reward sensitivity or exploration-exploitation trade-offs) during reward learning tasks. Similar patterns appear in severe anhedonia populations.

### 2.2.2 Neural Mechanisms of Reward Learning in Anhedonia

Research on neural mechanisms of reward learning in anhedonia has yielded substantial findings from EEG/ERP and fMRI studies. EEG/ERP offers millisecond temporal resolution crucial for capturing reward processing dynamics. Reward learning, connecting reward response and anticipation, involves reacting to single reward outcomes and updating future expectations based on reward prediction errors (RPE). Consequently, EEG research focuses on key components 200-500 ms post-feedback, including reward-related positivity (RewP) and feedback-P3 (fb-P3). RewP, a classic reward sensitivity index reflecting outcome prediction errors, shows significantly reduced amplitude with higher anhedonia levels across multiple studies, indicating diminished reward sensitivity even at early feedback processing stages. The subsequent fb-P3 represents attention allocation and further processing of feedback, with anhedonic patients showing reduced fb-P3 amplitude and insensitivity to reward magnitude during anticipation, suggesting impaired reward processing persists into later integration stages.

Given that ERP components inevitably mix overlapping neural processes and cannot reveal trial-by-trial variations in learning rates and motivation, time-frequency analyses have been employed to parse functional roles of different frequency bands (delta, theta, beta) across learning stages. Delta (<3 Hz) correlates with positive RPE and constitutes an important oscillatory component of RewP, while theta (4-7 Hz) is sensitive to losses, value judgments, and control demands, with anhedonic populations showing differential responses to reward types (monetary vs. social).

Perceived control refers to subjective judgments that one' s actions can influence outcomes, serving as a crucial modulator of reward value and learning rates. ERP studies show that in high-control contexts, typical individuals exhibit enhanced RewP, fb-P3, and delta power, whereas low-control contexts produce stronger theta power, reflecting positive feedback experience and regulated learning under negative feedback. Depressed individuals show blunted RewP to positive feedback in "choice" contexts but not in "no-choice" contexts, suggesting perceived control may be a prerequisite for normal reward response enhancement and that anhedonia may impair sensitivity to self-caused rewards, affecting reward learning. This aligns with computational modeling findings that perceived control influences learning rates across contexts.

Neuroimaging research on anhedonia operates at three levels: brain region localization (including ventral tegmental area, prefrontal cortex, hippocampus, amygdala, dorsal anterior cingulate, and anterior insula), functional connectivity (particularly between nucleus accumbens and other regions), and connectome-level analyses. For instance, stronger resting-state functional connectivity between paraventricular thalamus and nucleus accumbens correlates with more severe anhedonia, while altered connectivity between nucleus accumbens and default mode network (DMN) or frontoparietal network also relates to anhedonia.

However, neuroimaging studies of reward learning in anhedonia have primarily focused on brain localization. Researchers typically use computational modeling to estimate expected rewards for each choice, then calculate RPE as actual minus expected reward to represent reward learning, subsequently examining correlations between brain regions and RPE. Meta-analyses reveal altered activity in bilateral cerebellum, left fusiform and cuneus cortices (enhanced), and left putamen, middle frontal gyrus, bilateral caudate, superior frontal gyrus, right thalamus, parahippocampal/lingual gyrus, calcarine and rectal gyri (reduced) during reward learning in depression, with more severe anhedonia showing greater functional changes. Few studies have examined functional connectivity mechanisms, with one study finding reduced ventral tegmental area-striatal connectivity during reward learning in depression without further testing anhedonia correlations. This highlights the need for more comprehensive functional connectivity investigations.

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## 2.3 The Role of Perceived Control in Reward Learning

Perceived control refers to the degree to which individuals believe their actions can produce expected outcomes. Before discussing its role in reward learning, we must distinguish it from related concepts. First, perceived control represents subjective judgment, distinct from objective environmental controllability and situational controllability. Objective controllability emphasizes whether real conditions permit outcome modification (e.g., early adversity, psychological abuse as typical uncontrollable situations). Situational controllability focuses on power resources conferred by social roles or structures (e.g., higher social class confers greater situational control). In contrast, perceived control emphasizes subjective inference about action-outcome relationships, which may remain high even under objectively low controllability and vice versa. Research indicates perceived control often predicts emotional and adaptive variables better than objective controllability.

Structurally, perceived control comprises multiple interrelated beliefs: (1) control beliefs (whether one can achieve goals), (2) means-ends beliefs (whether specific actions effectively produce outcomes), and (3) agency beliefs (whether one possesses capabilities or resources to execute behaviors). This structural distinction, widely used in education, health, and personality research, helps reveal perceived control' s role in task execution and motivation regulation. At the experiential level, our focus on perceived control differs from general sense of control across life domains, which represents a stable trait correlating with well-being and self-efficacy.

Additionally, illusion of control relates to but differs from perceived control. The illusion represents systematic cognitive bias where individuals overestimate their influence over random or uncontrollable outcomes, extensively studied in gambling and risk decision-making. While perceived control may deviate from objective reality, it is not inherently directional bias; in reward learning frameworks, we focus on its regulatory role in action-outcome learning rather than biased judgments about randomness.

Synthesizing these conceptual distinctions, we uniformly employ "perceived control" in the reward learning framework as it is most commonly used across theoretical backgrounds and best fits our focus on subjective judgments of task-specific controllability. Given that our manipulations of reward probability depend on immediate contexts, we term this specific component low-level perceived control to distinguish it from cross-situationally stable high-level perceived control.

Building on this, we examine how perceived control modulates behavioral strategies and neural mechanisms in reward learning. Individuals should update action-value beliefs only when perceiving that actions influence outcomes. Laboratory studies demonstrate that participants estimate environmental controllability and adjust belief updating accordingly. For example, participants rely more on "default" strategies under uncontrollable conditions but utilize instrumental learning of stimulus-action values when actions have causal efficacy. Perceived control estimation depends on the striatum, while using these estimates to modulate subsequent learning involves the prefrontal cortex, suggesting the need to examine prefrontal-striatal functional connectivity and broader executive control-reward network coupling in anhedonic reward learning.

Furthermore, individual differences exist in the degree to which people update beliefs under controllable conditions versus rely on default responses under uncontrollable conditions. Research has examined these differences across age groups, finding that adults show higher reward learning rates when reward outcomes are more controllable than negative outcomes, a pattern not observed in children. Whether such differences exist across varying degrees of anhedonia remains unanswered.

Perceived control interventions can be categorized into laboratory manipulations and psychological interventions. Laboratory studies typically estimate outcome controllability by comparing the probability of consequences following specific actions versus no actions. When all actions produce outcomes with equal probability, the outcome is considered uncontrollable. As differences between these probabilities increase, participants typically develop stronger perceived control and correspondingly increase learning from experienced outcomes. This manipulation assumes that greater objective controllability necessarily increases perceived control. However, as noted, objective controllability does not equal subjective perceived control, which shows individual variation. Consequently, researchers have improved manipulation methods by providing performance feedback indicating whether rewards depended on participants' performance.

Psychological intervention studies reveal that positive autobiographical recall, particularly recalling successful overcoming of difficulties, can enhance perceived control. A randomized controlled trial found that one week of positive autobiographical recall training significantly improved participants' internal judgments and confidence in accomplishing tasks while reducing anxiety. Another trial with combat veterans with PTSD found that recalling successful overcoming experiences increased confidence in future task completion and improved social problem-solving abilities compared to controls. Mechanistically, positive autobiographical recall operates not primarily through transient emotional arousal but by reconstructing memory representations of action-outcome associations, strengthening beliefs that one' s behaviors can produce expected outcomes. Autobiographical memory research indicates that individuals preferentially retrieve positive events perceived as highly controllable and influential for subsequent development, which hold central importance in self-construction and control belief formation. Life review interventions similarly demonstrate that recalling and integrating meaningful life experiences enhances perceived control, self-efficacy, and meaning in life while effectively reducing depression and anxiety symptoms.

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## 3. Problem Statement

Reviewing anhedonia reward learning theories and research reveals several gaps: (1) Most research focuses on psychiatric disorder frameworks, often examining "reward learning in depression/anxiety/PTSD" before noting anhedonia as a primary feature. While foundational, heterogeneity within disorders (e.g., melancholic depression with anhedonia as core feature versus other subtypes) may limit these approaches. As anhedonia constitutes a major risk factor across disorders, investigating pre-illness anhedonia is essential. How does reward learning in "pre-illness" stage anhedonia compare to that in mental disorders and healthy adults? Do differences lie in severity or pattern? (2) Perceived control plays a vital role in reward learning, with estimation depending on striatum and regulation involving prefrontal cortex. Neuroimaging advances have identified brain localization and functional connectivity for reward prediction error mapping. Yet questions remain: How does reward learning vary with perceived control, and do these patterns differ between healthy and anhedonic groups? Does perceived control influence reward learning or vice versa? (3) Traditional pharmacological and psychological treatments show limited efficacy for anhedonia. Can intervening on perceived control improve anhedonic reward learning and consequently alleviate anhedonia?

In summary, this study proposes a hypothetical model of anhedonic reward learning based on previous theory and empirical research, specifically focusing on perceived control' s dynamic regulatory role and differences between pre-illness anhedonia, mental disorders, and healthy adults. We will then examine and validate the hypothesized dynamic modulation of anhedonic reward learning by perceived control through behavioral measures and fMRI, and finally test intervention efficacy using laboratory manipulations and positive autobiographical recall in randomized controlled trials.

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## 4. Research Design

The overarching goal is to describe dynamic characteristics of anhedonic reward learning as perceived control varies, explain underlying mechanisms, and design perceived control interventions to test their efficacy, using meta-reinforcement learning and locus of control theories with a focus on the "pre-illness" stage of mental disorder prevention. Specific objectives include: (1) Describing dynamic features of anhedonic reward learning across perceived control variations through sensorimotor synchrony manipulation of high-level perceived control and reinforcement learning modeling to quantify impairments and compare groups; (2) Explaining mechanisms through probabilistic reward learning tasks and fMRI; (3) Intervening on perceived control via laboratory manipulation and psychological intervention to test effects on reward learning and anhedonia.

The overall research framework is illustrated in [Figure 3: see original paper].

### 4.1 Study 1: Existence Testing of Dynamic Changes in Anhedonic Reward Learning with Perceived Control

Individuals in high-controllability contexts learn more from reward feedback (instrumental learning), whereas those in low-controllability contexts rely more on "default" response patterns. We propose that objective controllability does not equal perceived control, which varies across individuals, and present the theoretical framework of the Dual-Loop Reward Learning Model: low-level perceived control reflects immediate perception of single action-outcome associations within specific tasks (internal loop), while high-level perceived control reflects more stable, general beliefs about behavioral effectiveness formed across longer timescales and contexts (external loop). These internal beliefs partly originate from repeated action-reward associations and regulate reward learning strategies when low-level perceived control changes, with accumulated experiences subsequently promoting belief updating.

Study 1 aims to describe dynamic characteristics of anhedonic reward learning across perceived control variations, comprising two sub-studies: Experiment 1 examines reward learning dynamics with perceived control in healthy populations; Experiment 2 compares differences across groups, focusing on reward learning impairment features in subclinical anhedonic populations.

**Experiment Purpose:** To test characteristics of reward learning dynamically changing with perceived control in general populations by priming prior high-level perceived control through sensorimotor synchrony and simulating low-level perceived control through agent interference.

**Experimental Method:** A 2 (between-subjects) × 2 (within-subjects) mixed design. The between-subjects variable is prior high-level perceived control manipulated through sensorimotor synchrony tasks (high vs. low synchrony). Research indicates that perceived control formation requires integration of sensorimotor cues and subjective evaluation, making manipulation of temporal synchrony effective for altering control perceptions. In continuous action tasks, stable action-feedback synchrony facilitates subjective experience of behavioral control, whereas delayed or perturbed feedback significantly reduces this perception. The within-subjects variable is low-level perceived control simulated through agent interference (high vs. low). Dependent variables include reward learning performance (e.g., reinforcement model learning rate parameters, best-fitting models).

Healthy adult participants without psychiatric history are randomly assigned to high or low synchrony groups.

**Procedure:** Participants first complete a 5-minute active control task (keyboard-controlled cursor movement without rewards or specific goals), randomly assigned to either high synchrony (immediate, precise behavior-visual feedback matching) or low synchrony (random delays or trajectory perturbations) conditions. State high-level perceived control is measured before and after this task using two items ( "Right now I feel I can influence upcoming task outcomes through my actions" ; "Right now I feel my behavior is effective in the environment" ) on 7-point scales to verify successful manipulation of perceived action effectiveness.

Participants then complete a modified probabilistic reward learning task where agent interference simulates high and low low-level perceived control conditions. To test whether primed high-level perceived control maintains or updates during the task, a subset of participants will be re-assessed on high-level perceived control after the reward learning task.

**Modified Probabilistic Reward Learning Task:** Adapted from Dorfman et al. (2019), participants imagine mining gold by choosing between two differently colored mines, receiving small monetary rewards (0.2 yuan) for finding gold and none for finding stones, attempting to discover and select the more rewarding mine. After task comprehension, participants complete two blocks of 50 trials each, occurring in random order across two territories featuring different agent types (wealthy individuals or robbers). In robber territories, robbers only randomly remove rewards, making reward occurrence necessarily behavior-triggered (high low-level perceived control). In wealthy territories, rewards may come from either the wealthy agent or participant actions (low low-level perceived control). Individual trial procedures are shown in [Figure 4: see original paper].

**Data Analysis and Expected Results:** Linear mixed models will test whether sensorimotor synchrony manipulation successfully altered prior high-level perceived control and compare reward learning performance across conditions. Reinforcement learning modeling will estimate parameters like learning rates to test high-level perceived control' s moderating effects. According to our hypothesis, when low-level perceived control is high (strong action-reward association), participants will primarily rely on immediate reward feedback, showing better reward learning performance. Here, reward learning is mainly driven by the internal loop, with high-level perceived control having relatively smaller influence. When low-level perceived control is low, participants will rely more on prior experiences from the external loop. Specifically, high synchrony participants may show better reward learning rates in low low-level perceived control contexts than low synchrony participants, reflecting external loop influence on internal loop reward learning.

**Experiment Purpose:** To compare reward learning dynamics with perceived control across healthy, subclinical anhedonia, and clinical anhedonia groups, quantifying impairment characteristics through reinforcement learning modeling.

**Experimental Method:** A 3 (between-subjects) × 2 (within-subjects) mixed design. The between-subjects variable is group (healthy/subclinical anhedonia/clinical anhedonia), and the within-subjects variable is low-level perceived control (high/low). Dependent variables include reward learning performance (reinforcement model learning rates, best-fitting models). High-level perceived control measured by scales will be included as a continuous variable to test its moderating effect on internal loop reward learning.

**Procedure:** Participants are divided into groups based on Chinese version Snaith-Hamilton Pleasure Scale (SHAPS) scores and psychiatric diagnosis. Before tasks, high-level perceived control is measured using the Chinese version of Lachman and Weaver' s (1998) Sense of Control Scale (SCS) revised by Li (2012), reflecting general beliefs about action-outcome effectiveness formed through long-term experience. Participants then complete the same modified probabilistic reward task as Experiment 1.

**Data Analysis and Expected Results:** Linear mixed models will analyze three-way interactions among group, low-level perceived control, and high-level perceived control. Following Cohen et al. (2020), multiple reinforcement learning models will be tested, comparing model fit across groups using protected exceedance probabilities (PXP). Models include: single learning rate, dual learning rates, empirical Bayesian, territory-based empirical Bayesian, adaptive Bayesian, hierarchical Bayesian, and dynamic hierarchical reinforcement learning models.

Expected results: Under high low-level perceived control (robber territory), all three groups should show high learning rates with no significant group differences. Under low low-level perceived control (wealthy territory), all groups should show lower learning rates than in robber territory. We hypothesize that anhedonic groups generally have lower high-level perceived control than healthy individuals, thus showing poorer reward learning performance than healthy controls in low low-level perceived control contexts. The clinical anhedonia group may show similar patterns to the subclinical group but with greater heterogeneity. Regarding best-fitting models, we expect healthy participants' behavior to better match empirical Bayesian models, while anhedonic groups may better fit hierarchical Bayesian or dynamic hierarchical reinforcement learning models. High-level perceived control' s relationship with model parameters should be more stable in healthy groups but weakened or significantly heterogeneous in anhedonic groups.

### 4.2 Study 2: Neural Mechanisms of Perceived Control' s Influence on Anhedonic Reward Learning

While Study 1 tested existence, Study 2 examines underlying neural mechanisms. Previous research has separately investigated neural mechanisms of reward learning and perceived control, but limited work has explored their interactions, particularly regarding connectivity differences between anhedonic and healthy groups during reward learning tasks. Study 2 aims to capture neural modulation of internal loops by external loops, testing how high-level perceived control influences prefrontal-striatal learning patterns and whether anhedonia damages this regulatory mechanism.

**Experimental Method:** A 2 (between-subjects) × 2 (within-subjects) mixed design. The between-subjects variable is group (healthy/subclinical anhedonia), and the within-subjects variable is low-level perceived control (high/low). Dependent variables include reward learning performance and functional connectivity in regions of interest. Procedures mirror Study 1 Experiment 2, with participants completing a practice version before fMRI scanning. Psychophysiological Interaction (PPI) analysis will identify brain region pairs significantly modulated by control conditions and high-level perceived control (SCS scores). Effective connectivity analysis will examine directional connections and task modulation parameters, testing high-level perceived control' s influence on this mechanism across groups.

**Expected Results:** PPI analysis should reveal significant group × control interactions in dorsolateral prefrontal-striatal connectivity, with high-level perceived control as a moderator. Specifically, in healthy participants, higher SCS scores should predict stronger maintenance of this connectivity under low low-level perceived control, while this moderating effect should be significantly attenuated in subclinical anhedonia. Effective connectivity analysis should show anhedonic deficits in feedforward control, with significantly lower experimental modulation (B values) of dorsolateral prefrontal → striatal connections than in healthy participants. Feedforward models should show highest model evidence for healthy participants, while other models may be superior for anhedonic participants.

### 4.3 Study 3: Intervention Effects of Perceived Control on Anhedonic Reward Learning

Study 1 tested existence, Study 2 explained mechanisms, and Study 3 manipulates and intervenes on perceived control to test effects on anhedonia and reward learning. Study 3 includes two experiments: Experiment 1 manipulates low-level perceived control in the laboratory to analyze its impact on internal loops; Experiment 2 enhances high-level perceived control through psychological intervention, changing cross-situational experiences that external loops depend on, and tests whether external loop changes can improve internal loop reward learning and reduce anhedonia.

**Experiment Purpose:** To test intervention effects of laboratory manipulation of low-level perceived control on immediate positive affect and reward learning performance changes.

**Experimental Method:** A randomized controlled trial with subclinical anhedonic adults (SHAPS scores > 1 SD above norm). Both intervention and control groups complete the modified probabilistic reward task. The intervention group receives explicit information after each reward about whether it was agent-triggered or self-caused, reinforcing perception of "behavior-outcome" causality, while the control group receives no such information. Differences in reward learning performance are compared, and immediate positive affect is measured pre- and post-intervention. To verify successful manipulation, immediate low-level perceived control is measured during (every 10-20 trials) and after the task using two items ("In the just-completed task, I felt whether I found gold was determined by my own choices"; "I felt mining outcomes were more controlled by my behavior than by chance") on 7-point scales.

**Outcome Measures:** Immediate positive affect measured by Chinese version Positive and Negative Affect Scale-Positive (PANAS-P), low-level perceived control manipulation assessed through in-task questions, and reward learning performance evaluated by task accuracy, reaction time, reinforcement learning model learning rates, and reward sensitivity.

**Data Analysis and Expected Results:** Linear mixed models will analyze changes across time points between groups, testing whether low-level perceived control mediates the relationship between manipulation condition and internal loop reward learning performance. Compared to controls, the intervention group should show higher low-level perceived control, greater positive affect improvement, higher task accuracy, faster reaction times, and higher reinforcement learning model learning rates and reward sensitivity.

**Experiment Purpose:** To test short- and long-term intervention effects of psychological intervention (positive autobiographical recall) on high-level perceived control, reward learning, and anhedonia.

**Experimental Method:** A randomized controlled trial with the same participants as Experiment 1. The intervention group receives an 8-week online positive autobiographical recall intervention targeting perceived control, while the control group waits 8 weeks. Positive affect is measured before each session, post-intervention, and at 1-month follow-up; perceived control, anhedonia levels, and probabilistic reward task performance are measured pre-intervention, post-intervention, and at 1-month follow-up.

**Outcome Measures:** PANAS-P for positive affect, SCS for perceived control, SHAPS for anhedonia, and probabilistic reward task behavioral indices and reinforcement learning model parameters for reward learning performance.

**Data Analysis and Expected Results:** Intent-to-treat analysis using multilevel modeling (MLM). For repeatedly measured positive affect and high-level perceived control, growth curve models (linear, quadratic, or logarithmic) will be fitted. We hypothesize that compared to the waitlist group, the intervention group will show significantly increased high-level perceived control, reduced anhedonia, and improved reward learning performance at post-test and 1-month follow-up, with positive affect increasing across sessions. We further hypothesize that intervention effects on anhedonia are mediated by increased high-level perceived control.

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## 5. Theoretical Construction and Innovation

This study addresses the core question of reward learning mechanisms in preillness stage anhedonia and perceived control' s dynamic regulatory role. Based on theoretical and empirical review, we propose the Dual-Loop Reward Learning Model.

The anhedonia field has long debated "motivational anhedonia" (intact consummatory pleasure but motivational deficits) versus "consummatory anhedonia" (reduced pleasure capacity). Motivational deficits may stem from metacognitive biases about task structure (e.g., underestimating action-reward associations or one' s learning capacity), while pleasure reduction may relate to low-level value computation—both closely linked to reward learning. This study tests contradictions in the motivation-pleasure dissociation hypothesis through reinforcement learning computational modeling, integrating perspectives within a unified computational framework to propose the Dual-Loop Reward Learning Model [Figure 5: see original paper].

The process of learning from reward outcomes spans multiple timescales, making the "action-reward feedback-learning" process not a closed loop but a spiral progression. At shorter timescales, the "internal loop" adjusts actions based on reward-outcome associations (low-level perceived control). When perceiving clear action-reward associations (high low-level perceived control), individuals engage in reward learning and act in new states. When perceiving ambiguous associations (low low-level perceived control), they rely more on beliefs about reward-behavior associations formed from past experiences (high-level perceived control). Compared to healthy adults, subclinical anhedonic groups show lower low- and high-level perceived control in ambiguous contexts, while clinical groups may show greater heterogeneity.

At longer timescales and across environmental changes, the "external loop" involves learning how to learn. This loop represents relatively stable internal beliefs about rewards formed from past experiences, influencing behavioral tendencies and actual actions to obtain rewards. For instance, individuals holding "effort pays off" beliefs remain willing to wait and persist for long-term rewards despite repeated failures, while "seize the day" believers prioritize short-term rewards, and "destined fortune" believers may not alter effort for rewards. Generally, individuals act based on daily experiences, but after observing state-action-reward associations, they update their learning approach through the external loop, gradually adjusting to environmental demands more effectively. This differs from single-trial behavioral changes, representing cross-situation, cross-timescale experience accumulation that modulates initial states, strategy preferences, or neural patterns in subsequent reward learning. Notably, internal and external loops interact: repeated action-reward associations form the basis of internal reward beliefs, while current associations may strengthen, update, or adjust these beliefs in future phases. These learning processes occur across multiple environments over time, adjusting learning biases through long-term experience.

Addressing this model, Study 1 tests existence, Study 2 explains neural mechanisms, and Study 3 manipulates and intervenes on perceived control to test effects on anhedonia and reward learning. Specific innovations include: (1) **Research perspective innovation**: Shifting from disorder-focused to mental health dimension perspectives on anhedonia, embodying comprehensive health perspectives, and focusing on subjective perception differences underlying anhedonia variation rather than just objective conditions. (2) **Methodological innovation**: Integrating experimental, questionnaire, and randomized controlled trial methods with reinforcement learning modeling and fMRI, combining PPI and dynamic analyses to achieve deep coupling of computational modeling and neuroimaging for multi-dimensional validation. (3) **Intervention paradigm innovation**: Developing a positive autobiographical recall intervention that shifts from traditional negative emotion-focused approaches to "gain-oriented" strategies, emphasizing perceived control' s role in positive affect enhancement.

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**References**

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