

# Neural Oscillations and Fronto-Parietal Network Dysregulation in Decision-Making under Uncertainty in Adolescent Depression

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## Abstract

Adolescence is a critical developmental period characterized by ongoing prefrontal-limbic maturation, heightened emotional reactivity, and increased sensitivity to social and environmental feedback, making this stage particularly vulnerable to depressive disorders. Adolescent Major Depressive Disorder (MDD) is associated with pervasive negative cognitive biases, diminished reward responsiveness, and heightened loss aversion, which collectively drive conservative or avoidance-oriented decision-making under conditions of uncertainty. Behavioral evidence indicates that these biases impair adaptive cost-benefit evaluation, limit exploration, and reinforce withdrawal and low motivation. Neurophysiological studies using electroencephalography (EEG) reveal that these behavioral alterations are underpinned by disruptions in neural oscillations and large-scale network dynamics: beta-band activity supports reward integration and goal-directed behavior, frontal midline theta reflects heightened monitoring of negative outcomes and cognitive control, and alpha oscillations mediate inhibitory regulation and attentional gating. In adolescent depression, aberrant modulation of these frequency bands, together with imbalanced fronto-parietal connectivity and reduced engagement of motivational circuits, promotes rigid, risk-averse strategies. Understanding these neural mechanisms provides insight into maladaptive decision-making and suggests that longitudinal studies integrating EEG with structural and functional neuroimaging, as well as interventions such as cognitive training or neurofeedback targeting beta, theta, and alpha dynamics, may enhance reward processing, reduce excessive loss monitoring, and support adaptive neurocognitive development in depressed adolescents.

## Keywords

Adolescent Depression, Decision-making under Uncertainty, Neural Oscillations, Fronto-parietal networks, Reward and Loss Processing.

## 1. Introduction

Adolescence represents a critical developmental stage characterized by profound neurobiological, cognitive, and socio-emotional changes. During this period, large-scale brain reorganization occurs, including synaptic pruning, myelination, and the progressive maturation of prefrontal-limbic circuits that support cognitive control and affect regulation. At the same time, adolescents experience heightened emotional reactivity and increased sensitivity to social and environmental feedback [1]. Epidemiological evidence indicates that the incidence of depressive disorders rises sharply during this stage, making adolescent depression a major global public health concern. Major Depressive Disorder (MDD) in adolescence is associated

not only with persistent low mood and anhedonia but also with impairments in executive functioning, reward processing, motivation, and decision-making under conditions of ambiguity and risk. These cognitive-affective disturbances can negatively influence academic performance, interpersonal relationships, and long-term psychosocial adjustment.

Decision-making under uncertainty is central to daily functioning. Adolescents are frequently required to evaluate ambiguous outcomes, weigh potential gains against possible losses, anticipate future consequences, and regulate emotional responses to feedback. Compared with adults, adolescents tend to show greater variability in risk preferences, partly due to the asynchronous development of reward-related subcortical regions and prefrontal control systems. Emerging evidence suggests that depression fundamentally alters how adolescents process risk and uncertainty. In particular, depressive symptoms are associated with heightened sensitivity to negative outcomes, diminished responsiveness to reward, maladaptive expectations about future events, and increased behavioral avoidance. These alterations may bias cost–benefit evaluations and contribute to rigid or overly cautious decision patterns in uncertain contexts.

With the advancement of neuroimaging and electrophysiological techniques, electroencephalography (EEG) has become a valuable tool for examining the neural dynamics underlying decision-making processes. Owing to its high temporal resolution, EEG enables the capture of millisecond-level changes in neural oscillatory activity and large-scale network coordination during different stages of decision-making, including anticipation, choice selection, and feedback processing. Time–frequency analyses provide insight into the functional roles of specific frequency bands, while functional connectivity measures reveal patterns of communication between distributed cortical regions [2]. This review integrates current findings on neural oscillations and functional connectivity associated with uncertainty-related decision-making in adolescent depression, with a particular focus on beta ( $\beta$ ), theta ( $\theta$ ), and alpha ( $\alpha$ ) frequency bands and fronto–parietal network interactions. By synthesizing evidence across behavioral, electrophysiological, and network-level perspectives, the review aims to clarify the neurocognitive mechanisms through which depression shapes decision-making under uncertainty during adolescence.

## **2. Depression-Related Alterations in Risk Evaluation and Framing Sensitivity**

### **2.1. Cognitive Biases and Reward Dysfunction**

A core feature of depression is pervasive negative cognitive biases and disruptions in reinforcement learning. The cognitive theory proposed by Aaron T. Beck emphasizes that individuals with depression often develop maladaptive schemas that distort the interpretation of ambiguous or uncertain events. In decision-making contexts, these cognitive distortions may amplify perceived threats while diminishing the subjective value of potential rewards, biasing individuals toward risk avoidance rather than proactive exploration. Such maladaptive processing contributes to selective attention to negative outcomes and pessimistic expectations, shaping decision patterns in uncertain environments [3].

In addition, anhedonia—extensively discussed by Diego A. Pizzagalli—refers to a diminished capacity to experience pleasure and reduced motivational drive. This deficit can impair the evaluation of potential gains and decrease approach behavior toward rewarding stimuli. Concurrently, heightened sensitivity to punishment or negative feedback may further increase avoidance tendencies. From a learning perspective, depression has been associated with altered prediction error signaling and biased belief updating, whereby negative outcomes are overestimated and positive outcomes are underweighted. Together, these asymmetries

contribute to cautious, risk-averse strategies, particularly in contexts involving uncertainty, and reinforce patterns of withdrawal and reduced engagement with rewarding experiences.

## **2.2. Framing Effects and Loss Sensitivity**

Framing effects illustrate how identical outcomes can evoke markedly different decisions depending on whether they are presented as potential gains or losses. This phenomenon highlights the strong interplay between cognitive evaluation and emotional processing in decision-making. Emotional states can significantly modulate sensitivity to framing: individuals experiencing negative moods or depressive symptoms often allocate greater attention to loss-related information, perceive potential losses as more salient, and demonstrate heightened loss aversion. In adolescents, whose socio-emotional and cognitive control systems are still maturing, these effects can be particularly pronounced. Loss-framed contexts may more readily activate negative cognitive schemas, leading to pessimistic expectations, heightened emotional reactivity, and selective attention toward potential threats, thereby shaping decision biases in ways that reinforce avoidance and risk aversion [4].

According to the dual-systems model proposed by Laurence Steinberg, adolescent risk-taking emerges from the dynamic interaction between socio-emotional reward systems, which drive approach behavior, and prefrontal cognitive control systems, which support planning and inhibitory regulation. Depression may disrupt this balance by attenuating responsiveness to rewards while simultaneously amplifying inhibitory control and conflict monitoring processes. As a result, adolescents with depressive symptoms may adopt overly conservative decision patterns, particularly in loss-framed situations, prioritizing safety and risk minimization over flexible engagement with uncertain opportunities. Such rigidity can manifest as avoidance-oriented strategies, reduced exploration, and limited adaptive adjustment to changing contingencies, ultimately reinforcing maladaptive decision patterns and contributing to the persistence of depressive behaviors.

## **3. Neural Oscillatory Mechanisms of Reward and Loss Processing**

Decision-making unfolds over milliseconds, requiring rapid coordination of emotional salience detection, cognitive evaluation, and behavioral preparation. EEG research highlights the importance of oscillatory activity in distinct frequency bands in shaping these processes.

### **3.1. Beta Oscillations and Reward Integration**

Beta-band activity has been closely linked to the maintenance of cognitive set, preparation for motor responses, and the processing of reward-related information. In reinforcement learning contexts, beta synchronization is thought to reflect the integration of motivationally salient cues with ongoing behavioral strategies, supporting the stabilization of goal-directed actions. Specifically, increases in beta power during reward anticipation or feedback may facilitate the alignment of cognitive control and motor planning with expected positive outcomes, thereby promoting adaptive decision-making [5]. In adolescents, whose prefrontal and striatal systems are still maturing, beta oscillations may play a critical role in translating reward signals into consistent behavioral strategies, helping them learn from experience and regulate approach-avoidance tendencies.

Alterations in beta activity observed in depressive states may signal a reduced sensitivity to positive outcomes and a diminished capacity to engage with rewarding stimuli. Blunted beta responses during gain evaluation or reward anticipation can reflect decreased motivational salience, reduced reinforcement learning efficiency, and impaired updating of value representations. Functionally, this may manifest as limited behavioral adjustment in response to positive feedback, contributing to apathy, low goal-directed behavior, and social withdrawal. In adolescent depression, these neural patterns may exacerbate vulnerability to maladaptive

decision-making, reinforcing cycles of avoidance and reduced engagement with potentially rewarding experiences, and highlighting the critical role of beta-band oscillations in supporting adaptive reward processing and motivated behavior.

### **3.2. Theta Oscillations and Control of Negative Outcomes**

Theta-band oscillations, particularly in frontal midline regions, are widely associated with cognitive control, conflict detection, and feedback-based learning. Within contemporary neurocognitive models, frontal theta is considered a neural signature of adaptive control recruitment in situations requiring behavioral adjustment. The theoretical framework advanced by John F. Cavanagh and Michael J. Frank proposes that frontal theta activity reflects the engagement of medial prefrontal systems responsible for monitoring performance, detecting prediction errors, and signaling the need for strategic modification [6]. In contexts involving uncertainty or unexpected outcomes, increased theta synchronization supports flexible updating of action policies. During loss-related decision-making, elevated theta activity may therefore index the mobilization of control mechanisms aimed at evaluating negative feedback and minimizing future risk.

In depressive states, however, this control-related theta response may become exaggerated or dysregulated. Heightened theta reactivity to adverse information can reflect hyper-monitoring of potential threats and an amplified sensitivity to negative outcomes. While increased monitoring may initially appear adaptive, persistent over-engagement of control systems can foster indecision, cognitive rigidity, and rumination. This pattern is particularly relevant during adolescence, a developmental period marked by ongoing maturation of prefrontal executive networks. Because regulatory circuits are still refining their efficiency and integration, excessive theta-mediated control processes may interact with immature executive systems in a maladaptive manner. The result may be overly cautious and inflexible behavioral strategies, especially in uncertain environments where balanced evaluation of gains and losses is required. Thus, altered frontal theta dynamics in adolescent depression may signify not only intensified loss processing but also a developmental imbalance between monitoring systems and flexible decision implementation.

### **3.3. Neural Oscillatory Mechanisms**

Alpha-band activity has long been conceptualized as a neural mechanism underlying functional inhibition and attentional gating. According to the inhibition-timing hypothesis proposed by Wolfgang Klimesch, alpha oscillations regulate access to stored information by selectively suppressing task-irrelevant neural activity. Rather than reflecting cortical idling, alpha synchronization is now widely understood as an active top-down control process that shapes perceptual selection and cognitive prioritization. In emotionally salient contexts, particularly those involving potential loss or negative feedback, alpha dynamics may serve to manage interference arising from affective stimuli. By modulating the balance between excitation and inhibition, alpha oscillations help stabilize ongoing processing and protect goal-directed behavior from distraction [7].

In adolescent depression, however, this inhibitory mechanism may operate in an exaggerated or maladaptive manner. Depressed adolescents often show persistent attentional bias toward negative information and difficulty disengaging from adverse cues. Enhanced alpha synchronization during emotional decision-making may therefore represent compensatory attempts to regulate overwhelming negative affect. While such engagement may initially serve a protective function, sustained or excessive inhibitory control can reduce cognitive flexibility. Under conditions of uncertainty, over-suppression of alternative options may limit exploratory behavior, constrain adaptive updating, and reinforce avoidance-oriented strategies. Consequently, altered alpha dynamics may contribute to rigid decision patterns and heightened

risk aversion, reflecting a neural imbalance between emotional salience processing and flexible cognitive control.

#### 4. Network-Level Dysregulation and Clinical Implications

Effective decision-making under uncertainty depends not only on localized neural activity but also on coordinated communication across distributed brain networks. Contemporary cognitive neuroscience emphasizes that adaptive behavior emerges from dynamic interactions between prefrontal control systems and parietal regions involved in attention and value integration. In adolescent depression, accumulating evidence suggests that these large-scale networks function in an imbalanced manner. The medial and dorsolateral prefrontal cortices play central roles in uncertainty evaluation, strategic planning, and cognitive regulation. These regions interact closely with parietal areas responsible for attentional allocation and evidence accumulation during risk assessment [8]. When functioning optimally, this fronto-parietal network enables flexible updating of strategies in response to changing environmental feedback. However, depressive symptomatology appears to disrupt this balance.

One prominent pattern observed in depressive states is heightened synchronization within control-related circuits during loss-related processing. Increased coupling between prefrontal and parietal regions may reflect intensified monitoring of potential negative outcomes. While such engagement might serve a compensatory purpose, excessive coherence within regulatory networks can reduce behavioral flexibility. Adolescents experiencing depression may therefore devote disproportionate cognitive resources to anticipating adverse consequences, resulting in cautious or avoidance-oriented strategies. In addition to alterations in control networks, reduced functional integration of reward-related systems may further contribute to maladaptive decision patterns. Diminished engagement of motivational circuits can weaken approach behavior and limit sensitivity to positive reinforcement. The combination of hyperactive monitoring of losses and blunted responsiveness to gains creates a neural environment biased toward risk avoidance.

Importantly, network-level abnormalities offer valuable insight into the clinical characteristics of adolescent depression. Cognitive rigidity, indecision, and excessive rumination may reflect dysregulated communication among prefrontal, parietal, and limbic regions. Understanding these patterns provides a bridge between observable behavior and underlying neurophysiological mechanisms. From a clinical perspective, electrophysiological markers of network synchronization hold potential for early identification and intervention. EEG-based measures are non-invasive, relatively cost-effective, and well suited for adolescent populations. Patterns of oscillatory connectivity may serve as candidate indicators of maladaptive decision tendencies before full clinical manifestation. Moreover, interventions targeting neural dynamics—such as neurofeedback training or cognitive remediation—may help restore functional balance within control and reward systems [9].

Future research should adopt longitudinal approaches to clarify whether network abnormalities represent vulnerability markers or consequences of prolonged depressive states. Integrating EEG findings with structural and functional neuroimaging may further illuminate how distributed networks interact to shape decision-making behavior. By situating adolescent depression within a network neuroscience framework, researchers can move beyond localized deficits toward a more comprehensive understanding of affective dysfunction.

#### 5. Summary

Adolescent depression is consistently associated with significant alterations in decision-making under uncertainty. Behavioral and cognitive evidence indicates that depressed adolescents exhibit pervasive negative biases, reduced reward sensitivity, and heightened loss

aversion, which collectively drive overly conservative or avoidance-oriented strategies when evaluating ambiguous outcomes. These maladaptive decision patterns can interfere with academic, social, and emotional functioning, reinforcing cycles of low motivation, withdrawal, and negative affect.

Neurophysiological studies provide converging evidence that these behavioral changes are underpinned by disruptions in neural oscillatory activity. Alterations in beta-band oscillations may reflect impaired reward integration and reduced engagement with motivationally salient cues, while elevated frontal midline theta activity signals heightened monitoring of negative outcomes and excessive recruitment of cognitive control. Alpha-band dynamics, in turn, appear to index inhibitory regulation and attentional gating, which may become over-engaged in depressive states, limiting cognitive flexibility and exploratory behavior. At the network level, imbalanced fronto-parietal connectivity and weakened engagement of reward-related circuits further exacerbate risk-averse and rigid decision patterns, suggesting that adolescent depression involves both localized oscillatory dysfunction and large-scale network dysregulation.

Understanding these neural mechanisms provides critical insight into the cognitive and affective disturbances observed in adolescent depression and offers a framework for mechanistically guided interventions. Future research should prioritize longitudinal designs to determine whether specific oscillatory and network patterns represent vulnerability markers or emerge as consequences of prolonged depressive states. In particular, beta oscillations may serve as an early indicator of reduced reward sensitivity, frontal midline theta as a marker of heightened loss monitoring, and alpha dynamics as an index of maladaptive inhibitory control. Integrating EEG with functional and structural MRI could further elucidate how localized oscillatory activity interacts with distributed networks to shape decision-making behavior.

From a clinical perspective, these mechanistic insights offer promising avenues for targeted intervention. Cognitive training protocols or neurofeedback interventions aimed at normalizing beta, theta, and alpha activity could enhance reward responsiveness, reduce hyper-monitoring of losses, and restore flexible fronto-parietal communication. Additionally, tracking oscillatory and network markers over time may allow early identification of at-risk adolescents, enabling preemptive strategies to mitigate maladaptive decision patterns before the full clinical onset of depressive symptoms. By combining cognitive theory, electrophysiology, and network neuroscience, future studies can move toward a comprehensive understanding of how adolescent depression reshapes decision-making, and ultimately inform personalized prevention and intervention strategies that support healthy neurocognitive development.

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