

# Neural Oscillatory and Network Mechanisms of Uncertainty Processing in Adolescent Anxiety: A Narrative Review

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## Abstract

Adolescence represents a sensitive developmental period characterized by profound neurobiological maturation and increased vulnerability to anxiety disorders. Among the cognitive domains influenced by anxiety during this stage, uncertainty processing occupies a central position. Uncertainty arises when environmental outcomes are ambiguous, unpredictable, or probabilistic, requiring integration of cognitive control, emotional regulation, reward evaluation, and attentional allocation. Converging evidence suggests that adolescents with elevated anxiety exhibit heightened sensitivity to potential threat, reduced tolerance of ambiguity, and altered neural responses during uncertain situations. Electroencephalography (EEG) has emerged as a powerful method for investigating the temporal dynamics of neural oscillations underlying uncertainty processing. Frequency-specific oscillatory activity in the theta, alpha, and beta bands has been linked to cognitive control, vigilance, and top-down regulatory processes. In addition, functional connectivity analyses reveal large-scale network coordination patterns that shape adaptive responses to uncertainty. Alterations in oscillatory power and phase synchronization may reflect dysregulated interaction between prefrontal control systems and emotion-related circuits in anxious youth. This narrative review synthesizes current developmental and electrophysiological research on neural oscillations and network mechanisms associated with uncertainty processing in adolescent anxiety. By integrating findings across cognitive neuroscience and developmental psychopathology, this review aims to clarify potential neural pathways underlying anxiety-related biases and to outline directions for future investigation.

## Keywords

Youth Anxiety; Uncertainty Processing; Cortical Oscillations; Electroencephalography; Brain Network Connectivity; Adolescent Brain Development.

## 1. Introduction

Adolescence is marked by rapid neurodevelopmental change involving structural refinement, synaptic pruning, and functional reorganization of cortical and subcortical systems. Prefrontal regions associated with executive control continue to mature into early adulthood, whereas limbic structures involved in emotional reactivity develop earlier. This developmental imbalance may heighten sensitivity to emotionally salient or uncertain stimuli.

Anxiety disorders are among the most prevalent psychiatric conditions during adolescence. The World Health Organization has identified anxiety disorders as a leading contributor to

disability among youth globally. Early anxiety symptoms are associated with academic difficulties, impaired social functioning, and increased risk of later mood disorders.

A core cognitive feature of anxiety involves altered processing of uncertainty [1]. Uncertainty refers to situations in which outcomes are unpredictable or probabilities are ambiguous. Successfully navigating uncertain environments requires dynamic coordination between cognitive control mechanisms, attentional systems, affective evaluation processes, and motivational regulation. In anxious individuals, these processes may become biased toward threat detection and avoidance.

Neurocognitive models propose that anxiety is characterized by hyper-responsivity within threat-monitoring systems and insufficient regulatory modulation by prefrontal control regions. Such imbalance may be particularly pronounced during adolescence, when regulatory circuits are still undergoing maturation. Understanding how these neural dynamics unfold during uncertainty processing is therefore critical for clarifying mechanisms of vulnerability.

Electroencephalography (EEG) provides a noninvasive method for examining neural oscillations with high temporal resolution. Oscillatory rhythms reflect coordinated neuronal activity across distributed networks and are thought to support information integration and communication between brain regions. Time–frequency analyses allow quantification of power within specific frequency bands, while connectivity measures assess synchronization across cortical areas. These approaches offer valuable insight into the dynamic neural architecture of uncertainty processing.

The present review synthesizes research on oscillatory activity and functional connectivity patterns associated with uncertainty processing in adolescents with elevated anxiety. Rather than focusing on any single experimental paradigm, this review adopts a systems-level perspective grounded in developmental neuroscience [2].

## 2. Key Concepts and Theoretical Frameworks

Uncertainty processing refers to the cognitive and affective mechanisms by which individuals evaluate, interpret, and respond to situations in which outcomes are unpredictable or ambiguous. In adolescence, a developmental stage characterized by heightened sensitivity to social and environmental feedback, uncertainty processing plays a critical role in shaping decision-making and emotional responses. Intolerance of uncertainty (IU) is a dispositional tendency to perceive uncertain situations as threatening, leading to increased anxiety, avoidance behaviors, and excessive information seeking. Elevated IU in adolescents has been linked to exaggerated emotional reactivity and maladaptive coping strategies, which can interfere with adaptive learning and flexible decision-making.

Another central concept is threat bias, which reflects the preferential allocation of attention toward potentially threatening or ambiguous cues. Adolescents with heightened anxiety often demonstrate sustained vigilance toward uncertain stimuli, amplifying anticipatory worry and limiting the ability to accurately assess environmental risks [3]. This cognitive-emotional style is closely intertwined with neural systems involved in salience detection and cognitive control. Several theoretical models provide a framework for understanding these phenomena. Cognitive control theories emphasize the role of prefrontal regions in regulating attention, suppressing irrelevant information, and resolving conflict during uncertainty. Emotion regulation models highlight how the dynamic interplay between affective responses and regulatory processes shapes behavioral outcomes under ambiguous conditions. At the neural circuit level, the prefrontal–limbic interaction model posits that adaptive uncertainty processing relies on flexible communication between executive control regions (e.g., dorsolateral and medial prefrontal cortex) and limbic structures such as the amygdala.

Dysregulated interactions in this network may manifest as heightened anticipatory anxiety, biased attention, and maladaptive decision-making in uncertain contexts.

These conceptual and theoretical frameworks not only clarify the mechanisms underlying adolescent anxiety but also guide experimental design and interpretation of data. By manipulating levels of uncertainty or ambiguity and measuring corresponding cognitive, emotional, and neural responses, researchers can probe the multidimensional nature of uncertainty processing and its dysregulation in anxious adolescents.

### **3. Cognitive, Affective, and Neural Mechanisms of Uncertainty Processing**

Adaptive processing of uncertainty involves a dynamic interplay between cognitive, affective, and neural mechanisms. In adolescence, a developmental period characterized by heightened sensitivity to social and environmental challenges, these mechanisms are particularly salient, as immature regulatory systems may amplify emotional reactivity and bias decision-making under ambiguous conditions[4]. In the following sections, we first examine the cognitive and affective characteristics associated with intolerance of uncertainty and attentional threat bias, highlighting how these psychological features shape behavior and emotional responses. We then turn to neural mechanisms, reviewing frequency-specific oscillatory dynamics in theta, beta, and alpha bands, which reflect the engagement of executive control, vigilance, and attentional gating processes. Finally, we discuss functional connectivity and large-scale network coordination, focusing on prefrontal–limbic interactions and the integration of fronto-parietal, salience, and reward-related networks, which together support adaptive evaluation and response to uncertain environments. This framework provides a comprehensive view of how psychological and neural processes interact to influence uncertainty processing in anxious adolescents.

#### **3.1. Cognitive and Affective Characteristics of Uncertainty Processing**

##### **3.1.1. Intolerance of Uncertainty**

Intolerance of uncertainty (IU) is considered a transdiagnostic feature of anxiety disorders, reflecting a stable dispositional tendency to perceive ambiguous or unpredictable situations as threatening or distressing. Adolescents with elevated anxiety frequently report discomfort when faced with uncertain circumstances, often responding with excessive reassurance-seeking, rigid planning, or avoidance of ambiguous contexts. Such behaviors can be conceptualized as maladaptive strategies aimed at reducing perceived threat, yet they may paradoxically maintain or exacerbate anxiety over time.

From a cognitive perspective, high IU is associated with increased attention to potential negative outcomes and difficulties in flexible decision-making. Adolescents with elevated IU tend to overestimate the likelihood and severity of adverse events, which can amplify anticipatory anxiety and heighten emotional reactivity [5]. This hypervigilant cognitive style may interfere with adaptive learning, as repeated avoidance of uncertain situations limits opportunities to experience corrective feedback and update threat-related beliefs. Over time, these patterns can reinforce maladaptive schemas about safety and control, creating a self-perpetuating cycle of anxiety and avoidance.

Developmentally, adolescence is a period marked by heightened social, academic, and environmental demands. The increased exposure to complex and unpredictable situations may magnify the impact of IU, rendering adolescents particularly susceptible to maladaptive coping patterns. Neurobiologically, IU has been linked to altered engagement of prefrontal regulatory regions, such as the dorsolateral and ventromedial prefrontal cortex, which are involved in risk evaluation, inhibitory control, and cognitive appraisal of uncertainty. Dysregulation in these

circuits may contribute to exaggerated anticipatory responses and difficulty modulating emotional reactions under ambiguous conditions..

### 3.1.2. Threat Bias and Vigilance

Anxiety is consistently associated with attentional bias toward threat-related information. Under conditions of uncertainty, ambiguous cues are more likely to be interpreted as potentially harmful, prompting sustained vigilance and heightened monitoring of the environment. Such hypervigilance can consume significant cognitive resources, reducing flexibility and limiting the capacity to engage in goal-directed behavior.

This attentional bias is thought to emerge from dynamic interactions between prefrontal control regions and limbic structures, particularly the amygdala, which is central to threat detection and emotional salience processing[6]. In anxious adolescents, prefrontal regulatory mechanisms may be insufficiently developed or disrupted, resulting in exaggerated amygdala responses to uncertain or ambiguous stimuli. Consequently, environmental cues that would typically be evaluated as neutral may instead elicit anticipatory anxiety and enhanced arousal, further biasing attention toward potential threats.

Behaviorally, threat bias can manifest as increased scanning for danger, prolonged focus on negative cues, or avoidance of situations perceived as ambiguous. Over time, these patterns may reinforce maladaptive beliefs about environmental danger and personal vulnerability. Developmentally, the ongoing maturation of prefrontal-limbic circuits during adolescence suggests a window of both vulnerability and opportunity: while immature regulatory systems may exacerbate anxiety and biased attention, targeted interventions could strengthen cognitive control and improve adaptive responses to uncertainty.

## 3.2. Neural Oscillatory Mechanisms

Neural oscillations represent rhythmic fluctuations in electrical activity that coordinate communication within and between brain regions. Frequency-specific oscillatory patterns have been linked to distinct cognitive and affective processes, serving as functional signatures of information processing, attentional control, and emotional regulation. In adolescence, when cortical networks are still maturing, oscillatory dynamics may provide insight into the neurodevelopmental mechanisms underlying anxiety and uncertainty processing.

### 3.2.1. Theta Oscillations

Theta-band activity (4–7 Hz), particularly over frontal midline regions, has been consistently associated with conflict monitoring, cognitive control, and adaptive performance adjustment. Theta oscillations are thought to support the integration of information across distributed brain regions, facilitating top-down regulation of behavior in the face of ambiguity or cognitive challenge.

In anxious adolescents, elevated theta power often emerges during situations involving uncertainty, reflecting intensified monitoring of potential threat signals. Enhanced frontal theta synchronization may indicate increased recruitment of executive control systems attempting to regulate emotional reactivity and resolve conflict. Developmentally, the prefrontal cortex and its connections to subcortical structures are still undergoing maturation, suggesting that heightened theta responses may serve as compensatory mechanisms to support adaptive functioning in the context of immature regulatory networks. Dysregulated theta activity may therefore contribute to excessive vigilance, impaired decision-making, and difficulty updating threat-related beliefs.

### 3.2.2. Beta Oscillations

Beta-band activity (13–30 Hz) has been linked to maintenance of cognitive sets, top-down control, and anticipatory processing. Sustained beta power is thought to reflect preparatory engagement, vigilance, and the stabilization of ongoing cognitive and behavioral strategies.

In anxiety, beta dynamics are often altered during uncertain or anticipatory contexts. Elevated beta activity may index persistent monitoring of environmental cues, heightened sensitivity to potential threat, and a bias toward cautious behavioral strategies. In adolescence, when networks supporting executive control and reward evaluation are still developing, heightened beta synchronization may reflect the neurophysiological basis for prolonged arousal states and sustained attentional focus on uncertain or potentially threatening stimuli [7]. These oscillatory patterns may also interact with theta dynamics to reinforce adaptive or maladaptive coping strategies under uncertainty.

### 3.2.3. Alpha Oscillations

Alpha-band oscillations (8–12 Hz) are commonly interpreted as markers of attentional gating and cortical inhibition. Decreases in alpha power typically indicate enhanced engagement with task-relevant or emotionally salient information, whereas increases in alpha may reflect active suppression of irrelevant input.

Anxious adolescents often show atypical alpha modulation during emotional or uncertain situations. Inefficient alpha suppression may indicate difficulty filtering irrelevant or threatening information, leading to biased allocation of attentional resources. This altered alpha activity can interact with heightened theta and beta oscillations, shaping a neural profile characterized by over-monitoring of uncertainty and difficulty flexibly adapting behavior. Developmentally, these patterns may be particularly pronounced in adolescence, when neural circuits mediating attention and inhibition are still maturing, potentially amplifying the impact of uncertainty and threat on cognitive and emotional processing.

Overall, theta, beta, and alpha oscillations collectively provide a multi-dimensional view of the neural mechanisms underlying uncertainty processing. Examining these frequency-specific dynamics offers insight into how cognitive control, attentional allocation, and emotional regulation are coordinated in anxious adolescents, and may help identify neural markers for risk assessment and intervention.

## 3.3. Functional Connectivity and Network Coordination

Beyond localized oscillatory power, adaptive uncertainty processing relies on the coordinated interaction of distributed neural networks. Functional connectivity provides a window into how distinct brain regions communicate to support the integration of cognitive control, attention, and emotional regulation. Phase-based connectivity metrics, such as the phase-locking value (PLV), quantify synchronization between oscillatory signals across cortical regions. Moderate synchronization may reflect efficient communication, whereas excessive or overly rigid coupling may indicate reduced flexibility, limiting the system's ability to adapt to changing environmental demands.

### 3.3.1. Prefrontal-Limbic Interactions

Theoretical frameworks of anxiety emphasize dysregulated interactions between prefrontal regulatory systems and limbic threat-processing circuits. The prefrontal cortex, particularly dorsolateral and medial regions, supports cognitive control, inhibition, and evaluation of ambiguous stimuli, while limbic regions such as the amygdala detect salience and potential threat. Efficient uncertainty processing requires flexible modulation of limbic responses by prefrontal control regions, allowing individuals to appropriately calibrate vigilance and emotional reactions.

During adolescence, these prefrontal-limbic pathways are still maturing. Altered connectivity between these regions may amplify anticipatory anxiety, enhance threat bias, and reduce adaptive flexibility in uncertain situations. Hyperconnectivity within limbic circuits, or weakened top-down regulation from the prefrontal cortex, may underlie heightened emotional reactivity and over-monitoring of ambiguous cues. Conversely, adolescents exhibiting more

balanced prefrontal–limbic communication may demonstrate greater tolerance for uncertainty and more adaptive decision-making under ambiguous conditions.

### 3.3.2. Large-Scale Network Integration

Uncertainty processing also engages large-scale networks, including fronto-parietal control networks, salience networks, and reward-related systems. Effective integration across these networks supports balanced evaluation of environmental cues, flexible allocation of attention, and goal-directed behavioral planning [8].

Anxiety may disrupt this network-level coordination by strengthening connectivity within threat-related circuits while weakening cross-network communication, resulting in a system biased toward vigilance and risk avoidance. Such network imbalance may contribute to the persistence of maladaptive cognitive and emotional patterns, including overestimation of potential threats and reduced engagement with potentially rewarding or ambiguous opportunities. Developmentally, adolescence represents a sensitive period for network maturation, suggesting both vulnerability to dysregulation and potential plasticity that could be targeted in interventions. Understanding these network-level dynamics provides a framework for linking oscillatory activity, connectivity patterns, and behavioral manifestations of anxiety under uncertainty.

## 4. Summary

In conclusion, uncertainty processing in adolescents involves a complex interplay of cognitive, affective, and neural mechanisms that together shape how individuals perceive, evaluate, and respond to ambiguous or unpredictable situations. At the cognitive and emotional level, heightened intolerance of uncertainty and attentional threat bias predispose anxious adolescents to exaggerated vigilance, anticipatory worry, and maladaptive coping strategies, including avoidance, excessive reassurance-seeking, or rigid planning. These behaviors can, in turn, reinforce maladaptive beliefs about threat and safety, creating a self-perpetuating cycle that exacerbates anxiety and reduces adaptive decision-making under uncertainty.

Neurophysiologically, uncertainty processing is supported by coordinated activity across multiple frequency bands. Theta oscillations reflect engagement of executive control systems and conflict monitoring, beta oscillations index anticipatory processing and maintenance of cognitive sets, and alpha oscillations govern attentional gating and inhibition of irrelevant or distracting information. Dysregulated oscillatory patterns in these bands may contribute to heightened vigilance, difficulty flexibly allocating attention, and impaired emotional regulation in anxious adolescents. Beyond localized oscillations, functional connectivity among distributed neural networks plays a critical role in integrating cognitive control, affective evaluation, and motivational processes. Prefrontal–limbic interactions are particularly important for modulating emotional responses, while integration across fronto-parietal, salience, and reward-related networks supports flexible and adaptive evaluation of uncertain environments. Disruptions in these networks can amplify threat sensitivity and bias behavioral responses toward avoidance or over-caution.

From a developmental perspective, adolescence represents a period of heightened vulnerability but also considerable neural plasticity. The ongoing maturation of prefrontal regulatory circuits and large-scale networks renders adolescents particularly sensitive to uncertainty and emotional challenge, while simultaneously offering opportunities for interventions aimed at strengthening cognitive control and adaptive coping. Understanding the multidimensional mechanisms of uncertainty processing provides critical insights for designing targeted interventions, such as cognitive-behavioral strategies, attentional training, or neuromodulatory approaches, to reduce maladaptive anxiety responses and enhance flexible decision-making. Furthermore, identifying neural markers of dysregulated uncertainty

processing could inform early risk detection, personalized treatment planning, and longitudinal monitoring of developmental trajectories.

Overall, the integration of cognitive, affective, and neural perspectives emphasizes that anxiety-related vulnerabilities in adolescence cannot be fully understood at a single level of analysis. Instead, a systems-level approach that considers interactions among behavior, brain dynamics, and network-level coordination is essential. Such a framework not only advances theoretical understanding of anxiety and uncertainty processing but also provides practical guidance for interventions designed to promote resilience and adaptive functioning in youth facing uncertain or ambiguous environments.

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## References

- [1] DeSerisy M, Musial A, Comer JS, et al. Functional connectivity of the anterior insula associated with intolerance of uncertainty in youth. *Cogn Affect Behav Neurosci*. 2020, Vol. 20 (No. 3), p.493-502.
- [2] Eguinoa R, San Martín R, Luna P, et al. An EEG correlation framework to study state anxiety and learning under uncertainty. *Journal of Neural Engineering*. 2026, Vol. 23 (No. 1), p.1-15.
- [3] Yang S, Zhang M, Xu J, et al. The electrophysiology correlation of the cognitive bias in anxiety under uncertainty. *Sci Rep*. 2020, Vol. 10 (No. 1), p.1-10.
- [4] Schade E, White PJ, Maramaldi P, et al. Self-consciousness in adolescent and adult social anxiety: A systematic review of fMRI and EEG findings. *Biol Psychol*. 2025, Vol. 202, p.109137
- [5] Krain AL, Gotimer K, Hefton S, et al. A functional magnetic resonance imaging investigation of uncertainty in adolescents with anxiety disorders. *Biol Psychiatry*. 2008, Vol. 63 (No. 6), p.563-568
- [6] Intrinsic functional brain connectivity in adolescent anxiety. *PubMed*. 2024, Vol. 8 (No. 2), p.135-148.
- [7] Eidelman-Rothman M, Levy J, Feldman D, et al. EEG power and functional connectivity characteristics of generalized anxiety disorder. *Sci Rep*. 2025, Vol. 15 (No. 1), p.1-12.
- [8] Neural and psychophysiological markers of intolerance of uncertainty in youth. *Neurosci Biobehav Rev*. 2023, Vol. 152, p.295-307.