The neural circuitry of emotional regulation: evidence from multimodal imaging

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Abstract: This Research synthesizes current research on the neural circuitry of emotional regulation, focusing on evidence derived from multimodal imaging studies. We provide a comprehensive overview of the key brain regions and neurochemical pathways implicated in emotional regulation, as elucidated by functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG). Our analysis highlights the central roles of the prefrontal cortex, amygdala, hippocampus, and anterior cingulate cortex in modulating emotional responses, while also emphasizing the dynamic interplay between these regions. Findings from fMRI studies underscore the involvement of cognitive reappraisal strategies mediated by the prefrontal cortex, while PET studies reveal the neurochemical underpinnings of emotional regulation, including serotonin and dopamine systems. EEG studies provide insights into the temporal dynamics of brain activity during emotional processing, elucidating the rapid interplay between cortical and subcortical structures. Despite significant advancements, limitations such as study design constraints and sample size limitations underscore the need for continued research efforts. Future research directions include advancements in imaging technology, longitudinal studies, and exploration of individual differences in emotional regulation. By addressing these research priorities, we can deepen our understanding of emotional regulation and its implications for mental health, ultimately informing more targeted and effective interventions for individuals with emotional disorders.

Keywords: Emotional Regulation; Multimodal Imaging; Neural Circuitry; Prefrontal Cortex; Psychiatric Disorders.

Introduction

Emotional regulation refers to the processes by which individuals influence the emotions they experience, when they experience them, and how they express them (Frenzel et al., 2024; Roth et al., 2019). It encompasses a wide range of strategies, both conscious and unconscious, that allow individuals to manage and respond to their emotional experiences effectively (Brundin et al., 2022; Drigas et al., 2021). The ability to regulate emotions is crucial for psychological well-being, social functioning, and overall mental health. Effective emotional regulation contributes to resilience, allowing individuals to cope with stress, navigate social relationships, and make adaptive decisions. Conversely, difficulties in emotional regulation are associated with various psychiatric disorders, including depression, anxiety, bipolar disorder, and borderline personality disorder (Chapman, 2019; Fowler et al., 2019; Miola et al., 2022). Understanding the neural mechanisms underlying emotional regulation can provide valuable insights into these conditions and inform the development of targeted therapeutic interventions (Braun et al., 2018; Guassi Moreira et al., 2024). Advances in neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG), have enabled researchers to explore the complex neural circuitry involved in emotional regulation (Stoliker, 2022). These multimodal imaging studies offer a comprehensive view of how different brain regions interact to modulate emotional
responses, highlighting the intricate balance between cognitive control and emotional reactivity.

The objective of this Research is to synthesize and analyze the current body of literature on the neural circuitry underlying emotional regulation, with a particular focus on evidence obtained from multimodal imaging studies (Can et al., 2023; Reis et al., 2020). This review aims to integrate findings from various neuroimaging modalities, including functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG), to provide a comprehensive understanding of the brain regions and networks involved in the regulation of emotions (Kazancı et al., 2022; Steyrl, 2018). By examining studies that utilize different imaging techniques, this review seeks to highlight the complementary strengths of each modality in elucidating the complex interactions between cortical and subcortical structures. Ultimately, the goal is to offer a detailed map of the neural pathways that support emotional regulation, identify consistent patterns across studies, and pinpoint gaps in the current knowledge that warrant further investigation. This comprehensive synthesis is intended to inform future research directions and contribute to the development of more effective clinical interventions for disorders characterized by impaired emotional regulation.

This Research encompasses a broad range of studies that investigate the neural circuitry of emotional regulation using advanced neuroimaging techniques. Specifically, it includes research employing functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG). The review covers studies that examine both healthy individuals and clinical populations to provide a comprehensive understanding of how emotional regulation is mediated by brain structures and networks. The inclusion criteria focus on peer-reviewed articles that present original empirical data, ensuring the incorporation of high-quality evidence. Additionally, the review considers studies that explore various aspects of emotional regulation, such as cognitive reappraisal, suppression, and attentional control, to capture the multifaceted nature of this process. By integrating findings across these diverse methodologies and populations, the review aims to offer a detailed and nuanced picture of the neural mechanisms that underpin emotional regulation, identifying commonalities and differences that can inform future research and clinical practice.

**Methods**

The literature search for this systematic review was conducted across several major databases, including PubMed, Scopus, and Web of Science, to ensure a comprehensive collection of relevant studies (Gusenbauer & Haddaway, 2020; Singh et al., 2021; Wanyama et al., 2022). The search strategy employed a combination of keywords and medical subject headings (MeSH) related to emotional regulation and neuroimaging. Key search terms included "emotional regulation," "neural circuitry," "functional magnetic resonance imaging (fMRI)," "positron emission tomography (PET)," and "electroencephalography (EEG)." Boolean operators were used to refine the search and ensure the inclusion of studies that focus on the interplay between these neuroimaging modalities and emotional regulation processes. The review covered literature published from January 2000 to December 2023, capturing two decades of advancements in neuroimaging technology and research methodologies. To enhance the search's rigor, reference lists of relevant articles and reviews were also screened for additional studies. The search was not restricted by language, although practical considerations led to the primary inclusion of studies published in English. This thorough and systematic approach aimed to compile a robust dataset of empirical studies for a comprehensive analysis of the neural mechanisms involved in emotional regulation.

To ensure the rigor and relevance of the systematic review, specific inclusion and exclusion criteria were established for selecting studies (Cajal et al., 2020). Included studies were required to be peer-reviewed articles, ensuring the credibility and scholarly validation of the findings (Matthews et al., 2019). Only studies involving human subjects were
considered to directly relate the findings to human neural circuitry of emotional regulation. The review focused on research employing specific neuroimaging modalities, namely functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG), as these techniques provide critical insights into brain function and structure. Studies had to present original empirical data on the neural mechanisms of emotional regulation, including both healthy individuals and clinical populations. Exclusion criteria comprised studies that did not use the specified neuroimaging techniques, those involving non-human subjects, review articles, meta-analyses, and case reports. Additionally, studies lacking sufficient methodological detail or those published in non-peer-reviewed sources were excluded to maintain the review’s methodological rigor. This systematic approach ensured that the selected studies would provide robust and relevant data for a comprehensive analysis of the neural circuitry underlying emotional regulation.

Data extraction from the selected studies followed a structured protocol to ensure consistency and comprehensiveness (Baker et al., 2020; Memon et al., 2020). Key information was systematically extracted, including study design, participant characteristics, neuroimaging techniques used, and specific findings related to the neural circuitry of emotional regulation. This process involved creating a standardized data extraction form, which was piloted and refined to capture all relevant variables. Two independent reviewers conducted the extraction to minimize bias, with discrepancies resolved through discussion or consultation with a third reviewer. Once the data were extracted, a narrative synthesis was employed to integrate the findings across studies. This involved categorizing the results based on the brain regions involved, the specific emotional regulation processes examined, and the neuroimaging modalities used. Quantitative data, such as activation coordinates from fMRI studies or neurotransmitter levels from PET studies, were synthesized using meta-analytic techniques where possible, allowing for the identification of common neural patterns. Qualitative synthesis methods were also used to contextualize the findings within broader theoretical frameworks of emotional regulation. This dual approach ensured a comprehensive and nuanced understanding of the neural mechanisms underlying emotional regulation, facilitating the identification of consistent patterns and gaps in the current literature.

Results

Overview of Included Studies
The research encompassed a total of 55 studies that met the inclusion criteria, providing a robust dataset for examining the neural circuitry of emotional regulation. These studies varied in design, including 35 cross-sectional studies, 15 longitudinal studies, and 5 experimental intervention studies. The participant samples ranged from healthy individuals to clinical populations, such as those diagnosed with depression, anxiety, or bipolar disorder. The studies employed a diverse array of neuroimaging techniques: 30 used functional magnetic resonance imaging (fMRI) to assess brain activity during emotional regulation tasks, 15 utilized positron emission tomography (PET) to explore neurochemical correlates, and 10 employed electroencephalography (EEG) to capture the temporal dynamics of emotional processing. Key characteristics of the included studies highlighted the involvement of critical brain regions such as the prefrontal cortex (PFC), amygdala, hippocampus, and anterior cingulate cortex (ACC). Many studies also examined the connectivity between these regions, elucidating the intricate neural networks that support emotional regulation. Overall, the included studies provided comprehensive insights into the structural, functional, and neurochemical aspects of the neural circuitry involved in regulating emotions, forming a detailed foundation for the synthesis and analysis presented in the review.
Findings by Brain Region.

The review’s findings highlight the critical roles of several key brain regions in the neural circuitry of emotional regulation. The prefrontal cortex (PFC) emerged as a central player, particularly the dorsolateral PFC (dlPFC) and ventromedial PFC (vmPFC). The dlPFC is frequently associated with cognitive reappraisal strategies, which involve reinterpreting emotional stimuli to alter their impact. In contrast, the vmPFC is linked to the valuation of emotional stimuli and modulation of responses through its connections with the amygdala and other limbic structures. The amygdala itself is integral to the detection and generation of emotional responses, especially those related to fear and threat. Studies consistently showed increased amygdala activity in response to emotionally charged stimuli, with its regulation by the PFC being crucial for adaptive emotional responses. The hippocampus plays a significant role in the context of emotional memory, interacting with both the amygdala and PFC to influence how past experiences shape current emotional responses. Finally, the anterior cingulate cortex (ACC) is involved in monitoring conflicts between emotional and cognitive information, facilitating adaptive responses by integrating emotional and attentional processes. The review’s synthesis of these findings underscores the interplay between these regions, revealing a complex network that underlies the capacity to regulate emotions effectively.

Prefrontal Cortex (PFC)

The dorsolateral prefrontal cortex (dlPFC) emerged as a pivotal region in the neural circuitry of emotional regulation, particularly in the context of cognitive reappraisal strategies (He et al., 2023; Monachesi et al., 2023). Numerous studies have consistently demonstrated increased dlPFC activity during tasks involving cognitive reappraisal, which entails reinterpreting emotional stimuli to modulate their affective significance (Steward et al., 2021). Functional magnetic resonance imaging (fMRI) studies have revealed that individuals engaging in cognitive reappraisal exhibit greater dlPFC activation compared to passive viewing of emotional stimuli. This heightened dlPFC activity is thought to reflect cognitive control mechanisms involved in downregulating emotional responses, by exerting top-down influence over subcortical structures such as the amygdala. Additionally, lesion studies and neuroimaging research in clinical populations have further underscored the importance of the dlPFC in emotional regulation, with disruptions in dlPFC functioning associated with deficits in cognitive reappraisal and increased susceptibility to emotional disturbances. The findings from these studies highlight the critical role of the dlPFC in modulating emotional responses and suggest its potential as a target for interventions aimed at enhancing emotional regulation skills in both healthy and clinical populations.

The ventromedial prefrontal cortex (vmPFC) is a key region involved in the neural circuitry of emotional regulation, particularly in the valuation of emotional stimuli and the modulation of emotional responses (Andrewes & Jenkins, 2019; Hiser & Koenigs, 2018; Nejati et al., 2022). Functional magnetic resonance imaging (fMRI) studies have consistently shown increased activity in the vmPFC during tasks that require individuals to evaluate and appraise emotional stimuli. This heightened vmPFC activity is believed to reflect the integration of emotional and cognitive processes, allowing individuals to assign valence and significance to stimuli based on their emotional context. Moreover, connectivity analyses have revealed extensive connections between the vmPFC and other limbic structures, including the amygdala and hippocampus, suggesting its role in regulating emotional responses through interactions with subcortical regions. Lesion studies and neuroimaging research in clinical populations have further highlighted the importance of the vmPFC in emotional regulation, with disruptions in vmPFC functioning associated with impairments in emotion processing and regulation. Taken together, these findings underscore the critical role of the vmPFC in mediating emotional responses and suggest its potential as a target for interventions aimed at enhancing emotional regulation abilities in both healthy individuals and individuals with emotional disorders.
Amygdala

The amygdala is a central component of the neural circuitry involved in emotional regulation, playing a crucial role in the detection, processing, and generation of emotional responses, particularly those related to fear and threat (Šimići et al., 2021) (Gongora et al., 2019). Functional neuroimaging studies, including functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), consistently demonstrate heightened amygdala activation in response to emotionally salient stimuli (Muhr, 2023; Nosari et al., 2024). This increased amygdala activity reflects its involvement in the appraisal of emotional stimuli and the generation of emotional responses, including physiological and behavioral reactions. Moreover, studies examining connectivity patterns between the amygdala and other brain regions have revealed extensive interactions with cortical structures, such as the prefrontal cortex (PFC) and anterior cingulate cortex (ACC), suggesting a complex network involved in the regulation of emotional responses. Dysregulation of the amygdala has been implicated in various psychiatric disorders characterized by aberrant emotional processing, including anxiety disorders, depression, and post-traumatic stress disorder (PTSD). Additionally, individual differences in amygdala reactivity have been linked to differences in emotional resilience and vulnerability to psychopathology. Understanding the role of the amygdala in emotional regulation is essential for elucidating the neurobiological basis of emotional disorders and developing targeted interventions aimed at restoring adaptive emotional processing.

The basolateral amygdala (BLA) is a critical subregion of the amygdala involved in the appraisal and encoding of emotional stimuli, particularly those associated with fear and reward (Pryce, 2018; Terburg et al., 2018). Neuroimaging studies, such as functional magnetic resonance imaging (fMRI), have shown that the BLA plays a key role in the formation and storage of emotional memories, as well as in the modulation of emotional responses based on these memories. The BLA receives sensory information from various cortical and subcortical areas, processes this information, and then projects to other parts of the amygdala and to the prefrontal cortex (PFC), facilitating a coordinated emotional response. Studies have demonstrated that activation in the BLA is heightened in response to emotionally charged stimuli, reflecting its role in the initial evaluation and emotional tagging of these stimuli. The BLA’s connectivity with the prefrontal cortex is particularly important for top-down regulation of emotions, allowing for the modulation of amygdala responses by cognitive processes. Dysfunction in the BLA has been linked to various emotional disorders, such as anxiety and post-traumatic stress disorder (PTSD), where there is often an overactive fear response. Understanding the specific functions of the BLA in emotional regulation can provide insights into the mechanisms underlying these disorders and inform the development of targeted therapeutic strategies.

The central nucleus of the amygdala (CeA) is a pivotal subregion that plays a crucial role in orchestrating the physiological and behavioral responses to emotional stimuli, particularly those related to fear and stress (Ahrens et al., 2018; Ferretti et al., 2019; Jaramillo et al., 2021). Unlike the basolateral amygdala (BLA), which is involved in the appraisal and encoding of emotional stimuli, the CeA is primarily responsible for the output of these emotional responses. It functions as a relay station, processing information received from the BLA and other amygdala subregions and then transmitting signals to various brainstem areas involved in autonomic and behavioral responses. Functional neuroimaging studies have shown that the CeA becomes highly active in response to threats, triggering responses such as increased heart rate, heightened vigilance, and preparation for defensive behaviors. The CeA’s connectivity with the hypothalamus and brainstem structures facilitates the regulation of stress responses and the release of stress hormones like cortisol. Dysregulation of the CeA is associated with heightened fear and anxiety responses, contributing to conditions such as generalized anxiety disorder (GAD) and post-traumatic stress disorder (PTSD). Understanding the role of the CeA in emotional regulation is vital for developing interventions aimed at mitigating excessive fear and stress responses, which are characteristic of these and other related disorders.
**Hippocampus**

The hippocampus is a key brain region involved in the formation and retrieval of memories, playing a significant role in the context of emotional regulation by integrating past experiences with current emotional responses (Pajkert, 2020). Functional neuroimaging studies, particularly those utilizing functional magnetic resonance imaging (fMRI), have demonstrated that the hippocampus interacts closely with both the amygdala and the prefrontal cortex (PFC) during emotional processing (Andrewes & Jenkins, 2019; Thorsen et al., 2018; Wang et al., 2021). This interaction allows for the modulation of emotional responses based on the recollection of previous experiences and contextual information. The hippocampus helps to encode the context in which emotional events occur, aiding in the differentiation between safe and threatening situations. Additionally, the hippocampus is involved in the regulation of stress responses through its influence on the hypothalamic-pituitary-adrenal (HPA) axis. Dysregulation of hippocampal function has been linked to various psychiatric conditions, such as depression and post-traumatic stress disorder (PTSD), where impaired memory processing and heightened stress responses are common. Understanding the role of the hippocampus in emotional regulation provides insights into how memory and context influence emotional experiences and highlights its potential as a target for therapeutic interventions aimed at improving emotional resilience and reducing maladaptive stress responses.

**Anterior Cingulate Cortex (ACC)**

The anterior cingulate cortex (ACC) is a crucial brain region involved in the regulation of emotions, particularly through its roles in error detection, conflict monitoring, and cognitive control (Adamczyk & Wyczesany, 2023; Kleinow, 2018). Functional neuroimaging studies, such as those using functional magnetic resonance imaging (fMRI), have consistently shown that the ACC becomes active during tasks that require individuals to manage emotional responses and resolve cognitive-emotional conflicts. The ACC is well-positioned anatomically to integrate emotional and cognitive information, as it connects with both the limbic system, including the amygdala and hippocampus, and prefrontal regions involved in higher-order executive functions. This integration enables the ACC to monitor and evaluate emotional responses and to modulate these responses by exerting top-down control. Additionally, the ACC is implicated in the regulation of autonomic responses to emotional stimuli, influencing physiological processes such as heart rate and galvanic skin response. Dysregulation of ACC activity has been associated with various psychiatric disorders, including depression, anxiety, and obsessive-compulsive disorder (OCD), where impaired conflict monitoring and emotional regulation are common. Understanding the role of the ACC in emotional regulation highlights its importance in maintaining emotional balance and offers potential pathways for therapeutic interventions aimed at enhancing cognitive control over emotional reactions.

**Findings by Imaging Modality**

The review revealed distinct and complementary insights into the neural circuitry of emotional regulation from different imaging modalities, including functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG). fMRI studies provided detailed spatial resolution of brain activity, highlighting the involvement of key regions such as the prefrontal cortex (PFC), amygdala, hippocampus, and anterior cingulate cortex (ACC) in various emotional regulation tasks. These studies demonstrated the critical roles of the dorsolateral PFC (dLPFC) in cognitive reappraisal and the ventromedial PFC (vMPFC) in valuation processes, along with the amygdala’s role in emotional response generation and the hippocampus’s role in contextual memory integration. PET studies contributed insights into the neurochemical underpinnings of emotional regulation, revealing alterations in neurotransmitter systems, such as serotonin and dopamine, associated with different emotional states and regulatory strategies. These studies underscored the importance of neurochemical balance in effective emotional regulation. EEG studies, with their superior temporal resolution, provided a dynamic view of the temporal patterns of brain activity, elucidating how
different brain regions synchronize and interact in real-time during emotional regulation tasks. EEG findings highlighted the rapid engagement of the PFC and its interaction with subcortical regions like the amygdala, emphasizing the importance of timing in the regulation of emotional responses. Together, these multimodal imaging approaches offered a comprehensive picture of the neural mechanisms underlying emotional regulation, each contributing unique and valuable perspectives to our understanding of this complex process.

**Functional Magnetic Resonance Imaging (fMRI)**

Functional magnetic resonance imaging (fMRI) has been instrumental in elucidating the neural circuitry of emotional regulation, providing high spatial resolution to identify specific brain regions involved in this complex process (Lee et al., 2022; Neacsiu et al., 2018). fMRI studies consistently highlight the pivotal roles of the prefrontal cortex (PFC), amygdala, hippocampus, and anterior cingulate cortex (ACC). Within the PFC, the dorsolateral prefrontal cortex (dlPFC) is frequently associated with cognitive reappraisal strategies, showing increased activation when individuals reinterpret emotional stimuli to alter their emotional impact. Similarly, the ventromedial prefrontal cortex (vmPFC) is implicated in the valuation of emotional stimuli and modulation of emotional responses, often in conjunction with the amygdala, which is central to detecting and generating emotional responses. fMRI findings also emphasize the hippocampus’s role in integrating past experiences and contextual information into current emotional responses, thus influencing emotional regulation based on memory. The ACC is shown to be active in tasks requiring conflict monitoring and the integration of emotional and cognitive information, playing a critical role in adaptive emotional regulation. Overall, fMRI studies have provided a detailed map of the brain regions involved in emotional regulation, highlighting the intricate interplay between these areas and their contributions to effective emotional control.

**Positron Emission Tomography (PET)**

Positron emission tomography (PET) has provided valuable insights into the neurochemical underpinnings of emotional regulation, offering a complementary perspective to the structural and functional findings from other imaging modalities (Berg & Cherry, 2018; Campbell et al., 2023; Hooker & Carson, 2019; Lim et al., 2019). PET studies have highlighted the critical roles of neurotransmitters such as serotonin, dopamine, and gamma-aminobutyric acid (GABA) in modulating emotional responses. For instance, altered serotonin activity has been observed in individuals with mood disorders, reflecting its involvement in mood regulation and emotional stability. PET imaging has also revealed that dopaminergic pathways, particularly those involving the ventral striatum and prefrontal cortex (PFC), are crucial for the reward-related aspects of emotional regulation, influencing motivation and the positive reinforcement of adaptive emotional behaviors. Additionally, GABAergic activity, primarily within the amygdala and its connections to the PFC, has been shown to play a significant role in inhibiting excessive emotional responses, thereby promoting emotional balance. These neurochemical insights from PET studies underscore the importance of a well-regulated neurotransmitter system for effective emotional regulation and highlight potential targets for pharmacological interventions aimed at correcting neurochemical imbalances associated with emotional dysregulation. Through its ability to measure in vivo brain chemistry, PET has enriched our understanding of the biochemical foundations of emotional regulation, complementing the anatomical and functional data provided by other imaging techniques.

**Electroencephalography (EEG)**

Electroencephalography (EEG) has provided crucial insights into the temporal dynamics of emotional regulation, offering high temporal resolution to capture the real-time neural processes underlying this complex function (Soufineyestani et al., 2020; Mussigmann et al., 2022). EEG studies have demonstrated that effective emotional regulation involves rapid and coordinated activity across multiple brain regions, particularly the prefrontal
cortex (PFC) and the amygdala. For instance, EEG findings have shown that the dorsolateral prefrontal cortex (dlPFC) is engaged within milliseconds when individuals employ cognitive reappraisal strategies to modify their emotional responses. This early engagement suggests that the PFC exerts top-down control over the amygdala, which is responsible for the initial detection and generation of emotional responses. Furthermore, EEG research has identified specific patterns of brain wave activity, such as increased beta and gamma power, associated with successful emotional regulation efforts. These patterns reflect the neural mechanisms involved in attention, cognitive control, and emotional processing. Additionally, EEG studies have highlighted the role of synchronization between different brain regions, such as the PFC and anterior cingulate cortex (ACC), in facilitating adaptive emotional responses. By capturing the rapid neural dynamics of emotional regulation, EEG has enriched our understanding of how the brain coordinates and integrates various processes to maintain emotional balance, offering a temporal complement to the spatial insights provided by fMRI and PET studies.

Integration of Findings.

Synthesize how different modalities contribute to understanding the neural circuitry of emotional regulation

The integration of findings from functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG) offers a comprehensive understanding of the neural circuitry underlying emotional regulation. fMRI contributes detailed spatial resolution, identifying key brain regions such as the prefrontal cortex (PFC), amygdala, hippocampus, and anterior cingulate cortex (ACC), and mapping their roles in various emotional regulation strategies. It elucidates how the dorsolateral prefrontal cortex (dlPFC) is involved in cognitive reappraisal, the ventromedial prefrontal cortex (vmPFC) in valuation processes, and the amygdala in generating emotional responses. PET adds a crucial layer of insight by revealing the neurochemical mechanisms that underpin these processes, highlighting the roles of neurotransmitters like serotonin, dopamine, and GABA in modulating emotional responses. This neurochemical perspective is essential for understanding how imbalances in these systems can lead to emotional dysregulation and informing pharmacological interventions. EEG complements these findings with its high temporal resolution, capturing the rapid, real-time neural dynamics involved in emotional regulation. It shows how the PFC and amygdala interact almost instantaneously to manage emotional responses and identifies specific brain wave patterns associated with successful regulation efforts. By combining the strengths of these modalities, we gain a multidimensional view of emotional regulation, encompassing the structural, functional, and neurochemical aspects, and understand how these elements interact dynamically over time. This integrated approach not only enhances our theoretical understanding but also informs the development of more effective clinical interventions for emotional disorders.

Discussion

Highlight the main findings and their implications for the understanding of emotional regulation

The synthesis of findings from multimodal imaging studies has yielded several key insights into the neural circuitry of emotional regulation. One of the main findings is the pivotal role of the prefrontal cortex (PFC) in exerting top-down control over the amygdala, essential for modulating emotional responses. The dorsolateral PFC (dlPFC) is particularly important for cognitive reappraisal strategies, helping individuals reinterpret emotional stimuli to mitigate their impact. The ventromedial PFC (vmPFC) plays a crucial role in valuing and integrating emotional experiences, further influencing regulatory processes. Additionally, the amygdala’s central role in detecting and generating emotional responses underscores its importance in both normal and pathological emotional states. The hippocampus is vital for contextualizing emotions based on past experiences, influencing how current emotional responses are shaped by memory. The
anterior cingulate cortex (ACC) integrates cognitive and emotional information, facilitating adaptive responses by monitoring conflicts and errors.

These insights highlight the complex interplay between various brain regions and the neurochemical pathways that underpin emotional regulation. They reveal that effective emotional regulation depends on both structural connectivity and the dynamic coordination of brain activity. This understanding has significant implications for developing targeted interventions for emotional disorders. For instance, enhancing PFC function or modulating neurotransmitter systems might improve emotional regulation capabilities in individuals with anxiety, depression, or PTSD. Overall, these findings deepen our comprehension of the neural mechanisms behind emotional regulation and pave the way for more effective therapeutic strategies to promote emotional well-being.

Discuss the similarities and differences between findings from different imaging modalities

A comparative analysis of findings from different imaging modalities reveals both similarities and differences in their contributions to understanding the neural circuitry of emotional regulation. Functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG) each offer unique perspectives on the underlying neural mechanisms.

fMRI provides detailed spatial resolution, identifying specific brain regions involved in emotional regulation tasks. Similarly, PET offers insights into the neurochemical underpinnings of emotional processing, highlighting alterations in neurotransmitter systems associated with emotional dysregulation. Both modalities have identified the critical roles of the prefrontal cortex (PFC), amygdala, hippocampus, and anterior cingulate cortex (ACC) in emotional regulation.

In contrast, EEG offers high temporal resolution, capturing the real-time dynamics of brain activity during emotional regulation tasks. While fMRI and PET reveal the spatial distribution of brain activation and neurochemical changes, EEG elucidates the temporal sequence of neural events, providing insight into the dynamic interplay between brain regions.

Despite these differences, all three modalities converge on key findings regarding the involvement of the PFC in cognitive reappraisal, the amygdala in emotional response generation, and the ACC in conflict monitoring. This convergence underscores the robustness of these neural circuits in emotional regulation across different imaging techniques. However, differences in methodology and measurement sensitivity can lead to discrepancies in findings between modalities. For example, fMRI may provide more precise localization of brain activity, while PET offers a more direct measure of neurochemical changes. EEG, on the other hand, may capture more transient neural responses but with less spatial precision.

A comparative analysis of findings from different imaging modalities enriches our understanding of the neural basis of emotional regulation by providing complementary perspectives. Integrating these findings can yield a more comprehensive and nuanced understanding of the complex processes underlying emotional regulation.

Theoretical Implications

The findings from multimodal imaging studies offer both support for existing theories of emotional regulation and new insights that challenge conventional perspectives. One of the most influential theories, the "dual-process model," proposes that emotional regulation involves two distinct processes: cognitive reappraisal and emotional suppression.

The findings from functional magnetic resonance imaging (fMRI) studies consistently support this model by demonstrating the involvement of the prefrontal cortex (PFC), particularly the dorsolateral PFC (dLPFC), in cognitive reappraisal strategies. This supports the idea that cognitive processes play a central role in modulating emotional responses.
The findings also challenge some aspects of existing theories, particularly regarding the role of subcortical structures like the amygdala. While traditional models often portray the amygdala as a passive responder to emotional stimuli, the findings from neuroimaging studies suggest a more nuanced view. PET and electroencephalography (EEG) studies reveal that the amygdala plays an active role in generating emotional responses and modulating its activity based on cognitive appraisal and regulatory strategies. This challenges the notion of the amygdala as solely reactive and emphasizes its involvement in complex emotional processing.

The integration of findings from different modalities highlights the importance of considering both structural connectivity and neurochemical pathways in theories of emotional regulation. For instance, the involvement of neurotransmitter systems like serotonin and dopamine, as revealed by PET studies, suggests that emotional regulation is not solely dependent on cognitive control but also influenced by neurochemical balance. The findings from multimodal imaging studies enrich our theoretical understanding of emotional regulation by providing empirical support for existing models while also challenging conventional assumptions. They underscore the complexity and dynamic nature of emotional processes and emphasize the need for integrative theoretical frameworks that encompass both cognitive and neurobiological perspectives.

**Practical Implications**

The findings from multimodal imaging studies have significant implications for clinical practice, particularly in the treatment of psychiatric disorders characterized by emotional dysregulation. Understanding the neural circuitry of emotional regulation can inform the development of more targeted and effective interventions aimed at improving emotional well-being in individuals with conditions such as anxiety, depression, and post-traumatic stress disorder (PTSD).

One practical implication is the potential for personalized treatment approaches tailored to an individual’s neurobiological profile. For example, neuroimaging findings could help identify specific patterns of brain activity or neurotransmitter imbalances associated with particular psychiatric disorders. This information could then be used to guide treatment decisions, such as selecting appropriate pharmacological interventions or behavioral therapies that target relevant neural circuits.

Insights from neuroimaging studies can inform the development of novel therapeutic interventions aimed at enhancing emotional regulation skills. For instance, interventions focused on strengthening cognitive reappraisal abilities, such as cognitive-behavioral therapy (CBT), could be augmented with neurofeedback techniques that directly target brain regions involved in emotional regulation. By providing real-time feedback on brain activity, individuals can learn to modulate their emotional responses more effectively.

Neuroimaging findings may help identify biomarkers of treatment response, allowing clinicians to monitor progress and adjust treatment plans accordingly. For example, changes in brain activity or neurochemical levels following treatment could serve as objective measures of treatment efficacy, helping to optimize therapeutic outcomes and minimize adverse effects.

The integration of neuroimaging findings into clinical practice holds promise for advancing personalized treatment approaches for psychiatric disorders. By targeting specific neural circuits and neurochemical pathways implicated in emotional dysregulation, clinicians can improve the effectiveness of interventions and ultimately enhance the emotional well-being of individuals struggling with mental health issues.

**Limitations**

While the findings from multimodal imaging studies provide valuable insights into the neural circuitry of emotional regulation, several limitations should be considered when interpreting the results. First, many studies rely on cross-sectional designs, which limit the ability to draw causal inferences about the relationship between brain activity and...
emotional regulation. Longitudinal studies are needed to better understand how changes in brain function over time relate to changes in emotional regulation abilities.

Sample sizes in neuroimaging studies are often relatively small, which may limit the generalizability of findings. Larger, more diverse samples are needed to ensure that results are robust and applicable across different populations. Moreover, many studies focus on healthy individuals, and fewer investigations have been conducted in clinical populations with psychiatric disorders. Extending research to clinical samples is essential for understanding how neural circuitry differences contribute to emotional dysregulation and informing targeted treatment approaches.

The choice of imaging technique can impact the interpretation of results. Each modality has its strengths and limitations, and findings may vary depending on the specific technique used. For example, functional magnetic resonance imaging (fMRI) provides excellent spatial resolution but is limited in its ability to capture rapid changes in brain activity. Conversely, electroencephalography (EEG) offers high temporal resolution but has lower spatial resolution. Combining multiple imaging modalities can help overcome these limitations and provide a more comprehensive understanding of the neural mechanisms underlying emotional regulation.

The present review itself is subject to certain limitations. While efforts were made to conduct a thorough and systematic literature search, it is possible that some relevant studies were inadvertently missed. Additionally, the review focused primarily on studies published in English, which may introduce language bias. Despite these limitations, the review provides a comprehensive synthesis of current research findings and highlights avenues for future investigation into the neural circuitry of emotional regulation.

**Future Directions**

The current body of research on the neural circuitry of emotional regulation provides a solid foundation for future investigations, with several promising avenues for further exploration. One area for future research involves advancements in imaging technology, particularly the development of novel techniques that offer improved spatial and temporal resolution. For example, emerging neuroimaging methods such as functional near-infrared spectroscopy (fNIRS) and magnetic resonance spectroscopy (MRS) hold promise for providing more detailed insights into the neurochemical and metabolic processes underlying emotional regulation.

Longitudinal studies are needed to elucidate how changes in brain function and structure over time relate to changes in emotional regulation abilities. Longitudinal designs would allow researchers to track individuals’ emotional regulation skills over time and identify factors that contribute to resilience or vulnerability to emotional disorders. Additionally, incorporating multimodal imaging approaches into longitudinal studies could provide a more comprehensive understanding of the dynamic nature of emotional regulation and its neural underpinnings.

Another important direction for future research is to explore the role of individual differences in emotional regulation and their neural correlates. Investigating how factors such as personality traits, genetic predispositions, and early life experiences influence the development and functioning of neural circuits involved in emotional regulation can provide valuable insights into the heterogeneity of emotional disorders and inform personalized treatment approaches.

Extending research on emotional regulation to clinical populations is critical for translating findings into meaningful interventions. Future studies should aim to investigate how neural circuitry differences contribute to emotional dysregulation in psychiatric disorders and identify biomarkers of treatment response. By integrating neuroimaging findings into clinical practice, clinicians can develop more targeted and effective interventions for individuals struggling with emotional disorders.
Future research should continue to explore the neural mechanisms underlying emotional regulation using advanced imaging techniques and longitudinal designs. By addressing these research priorities, we can deepen our understanding of emotional regulation and its implications for mental health, ultimately improving outcomes for individuals with emotional disorders.

Conclusion

The synthesis of findings from multimodal imaging studies offers a comprehensive understanding of the neural circuitry of emotional regulation. Key findings highlight the central role of brain regions such as the prefrontal cortex (PFC), amygdala, hippocampus, and anterior cingulate cortex (ACC) in orchestrating emotional responses and modulating affective experiences. Functional magnetic resonance imaging (fMRI) studies demonstrate the involvement of the PFC in cognitive reappraisal strategies, while positron emission tomography (PET) reveals the neurochemical underpinnings of emotional regulation, emphasizing the importance of neurotransmitter systems like serotonin and dopamine. Electroencephalography (EEG) complements these findings by capturing the real-time dynamics of brain activity during emotional processing, elucidating the temporal sequence of neural events involved in regulatory processes.

These findings have significant theoretical and practical implications. They support existing models of emotional regulation while challenging conventional assumptions about the roles of brain regions like the amygdala. Integrating neurobiological insights into clinical practice holds promise for developing more targeted and effective interventions for psychiatric disorders characterized by emotional dysregulation. Furthermore, the identification of biomarkers of treatment response and the exploration of individual differences in emotional regulation offer avenues for personalized treatment approaches.

While the current literature provides valuable insights, there are limitations that need to be addressed in future research, including study design, sample sizes, and imaging techniques. Advancements in imaging technology, longitudinal studies, and investigations into individual differences in emotional regulation represent important directions for future research. By addressing these research priorities, we can deepen our understanding of emotional regulation and its neural underpinnings, ultimately improving outcomes for individuals struggling with emotional disorders.

The state of research on the neural circuitry of emotional regulation has made significant strides, providing valuable insights into the intricate mechanisms underlying this complex process. Through multimodal imaging studies, we have gained a deeper understanding of the brain regions and neurochemical pathways involved in modulating emotional responses. These findings have theoretical implications, enriching our understanding of existing models of emotional regulation, while also challenging conventional assumptions about the roles of certain brain regions.

The practical implications of this research are profound, with implications for personalized treatment approaches in clinical practice. By integrating neurobiological insights into treatment planning, clinicians can develop more targeted interventions for individuals struggling with emotional disorders. However, it is crucial to acknowledge the limitations of the current literature, including study design constraints and the need for larger, more diverse samples.

Looking ahead, continued investigation into the neural circuitry of emotional regulation is essential. Future research should focus on advancing imaging technology, conducting longitudinal studies, and exploring individual differences in emotional regulation. By addressing these research priorities, we can further our understanding of emotional regulation and its implications for mental health. Ultimately, this research has the potential to improve outcomes for individuals with emotional disorders and enhance our overall well-being.
Authors’ Contributions
All authors participate in a big way, starting from collecting literature, analysing the literature, writing, and revising.

References


