Unveiling the Neurobiological Landscape of Emotional Regulation: A Systematic Literature Review of Multimodal Imaging Studies

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Abstract: This systematic literature review explores the neurobiological underpinnings of emotional regulation through the lens of multimodal imaging techniques, including fMRI, PET, EEG, and MEG. Key findings highlight the significant roles of the prefrontal cortex (PFC), amygdala, hippocampus, and insula in the regulation of emotions, revealing intricate neural interactions and neurotransmitter involvement. Individual differences in emotional regulation are linked to variations in brain structure and function, emphasizing the importance of personalized therapeutic approaches. The review underscores the potential of multimodal imaging to enhance our understanding of the neural circuits and networks involved in emotional regulation, despite current methodological challenges. The implications for clinical practice are profound, offering pathways for early diagnosis, targeted interventions, and improved mental health outcomes. The review calls for continued interdisciplinary research to address remaining gaps and further integrate neurobiological insights into effective treatments for emotional dysregulation.

Keywords: Clinical Implications; Emotional Regulation; Individual Differences; Multimodal Imaging; Neurobiological Underpinnings.

Introduction

Emotional regulation refers to the processes through which individuals influence their emotions, how they experience these emotions, and how they express them(Hughes et al., 2020; Nozaki & Mikolajczak, 2020; Troth et al., 2018). It encompasses a range of strategies and mechanisms that help individuals manage and respond to emotional experiences, particularly those that are intense or challenging(Verlie et al., 2021). Effective emotional regulation is crucial for mental health, as it allows individuals to maintain emotional balance, cope with stress, and navigate social interactions successfully(Kirby et al., 2023). When emotional regulation is impaired, it can lead to a host of mental health issues, including anxiety, depression, and mood disorders(Freeman et al., 2020; Mitrea et al., 2022). These conditions often stem from difficulties in managing emotional responses, leading to maladaptive behaviors and negative thought patterns. Understanding the mechanisms behind emotional regulation is thus essential for developing effective therapeutic interventions and promoting overall mental well-being. By exploring the neurobiological underpinnings of emotional regulation through advanced imaging techniques, researchers can gain valuable insights into the brain’s role in these processes, paving the way for more targeted and effective treatments for those struggling with emotional dysregulation.

Multimodal imaging techniques have emerged as powerful tools in studying the neurobiology of emotional regulation (Bannier, 2023), offering a multidimensional perspective by integrating various imaging methods such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), electroencephalography (EEG), and magnetoencephalography (MEG)(Nilawati et al., 2024; Xiong et al., 2023). Each technique contributes unique advantages: fMRI provides high spatial resolution to precisely map brain activity; PET reveals details about neurotransmitter systems and metabolic...
processes; EEG and MEG offer high temporal resolution to capture the fast-paced neural dynamics. The integration of these modalities allows researchers to simultaneously examine the structural and functional aspects of the brain, leading to a more comprehensive understanding of how different brain regions and networks collaborate during emotional regulation tasks. This multimodal approach not only enhances the depth and accuracy of findings but also helps bridge the gaps inherent in single-modality studies, thus facilitating a richer and more precise understanding of the complex neural mechanisms underlying emotional regulation. By leveraging the strengths of each imaging modality, researchers can uncover detailed insights into the neurobiological processes that govern emotional regulation, paving the way for more targeted and effective interventions for emotional dysregulation and related mental health conditions.

The purpose of this systematic literature review is to comprehensively analyze and synthesize current research on the neurobiological underpinnings of emotional regulation as revealed by multimodal imaging techniques. By integrating findings from studies utilizing diverse imaging modalities such as fMRI, PET, EEG, and MEG, this review aims to provide a detailed understanding of how different brain regions and networks contribute to the regulation of emotions. The scope of this review encompasses research articles published in peer-reviewed journals that employ multimodal imaging to investigate emotional regulation in both healthy individuals and those with mental health disorders. This systematic approach will highlight the advantages of multimodal imaging in elucidating the complex neural mechanisms involved, identify consistent patterns and discrepancies across studies, and discuss the implications of these findings for clinical practice and future research. Ultimately, this review seeks to bridge the knowledge gap by offering a comprehensive and integrative perspective on the neurobiological processes that underpin emotional regulation, thus informing the development of more effective interventions for emotional dysregulation.

Methodology

The systematic literature review process involved a meticulously structured approach to ensure comprehensive and unbiased coverage of the topic. The search strategy was designed to identify relevant studies from multiple scientific databases, including PubMed, PsycINFO, Scopus, and Web of Science. Keywords and search terms such as "multimodal imaging," "emotional regulation," "fMRI," "PET," "EEG," and "MEG" were used in various combinations to capture a wide array of relevant articles. Studies were included based on specific criteria: they had to be peer-reviewed, published in English, and focus on the use of multimodal imaging techniques to investigate the neurobiology of emotional regulation in human subjects. Exclusion criteria were equally stringent, filtering out studies that were not empirical, lacked multimodal imaging approaches, or focused on animal models. Abstracts and full texts of identified articles were independently screened by multiple reviewers to ensure consistency and reliability. This rigorous selection process aimed to gather high-quality, relevant research, thus ensuring the integrity and comprehensiveness of the literature review.

The selection and screening of studies for this systematic literature review followed a rigorous and methodical process to ensure the inclusion of high-quality and relevant research. Initially, a broad search was conducted across multiple databases using specific keywords and Boolean operators to capture a comprehensive set of potential studies. The retrieved articles underwent an initial screening of titles and abstracts to exclude obviously irrelevant studies. Following this, the full texts of the remaining articles were assessed against predefined inclusion and exclusion criteria, such as focusing on multimodal imaging techniques and their application in studying emotional regulation in human subjects. Each study was independently reviewed by multiple reviewers to minimize bias and enhance the reliability of the selection process. Discrepancies between reviewers were resolved through discussion or consultation with a third reviewer. This meticulous approach ensured that only the most pertinent and scientifically robust
studies were included in the final review, thereby providing a solid foundation for syn-
thetizing the current understanding of the neurobiological mechanisms underlying emo-
tional regulation.

The quality assessment of included studies was conducted using a set of rigorous criteria
to ensure the reliability and validity of the findings synthesized in this systematic litera-
ture review. Each study was evaluated based on several key factors: methodological ri-
gor, sample size, the appropriateness of the multimodal imaging techniques used, clarity
and precision in reporting the methods and results, and the statistical analyses employed.
Studies were assessed for potential biases, including selection bias, reporting bias, and
confounding variables. Additionally, the quality of the imaging data, such as resolution
and the integration of different modalities, was critically examined. Peer-review status
and publication in reputable journals also contributed to the assessment. Each study was
independently reviewed by multiple reviewers to ensure consistency and objectivity in
the quality evaluation. This thorough quality assessment process ensured that only ro-
bust, high-quality studies were included in the final analysis, providing a solid and cred-
ible foundation for drawing conclusions about the neurobiological underpinnings of
emotional regulation.

Multimodal Imaging Techniques: An Overview

Introduction to various multimodal imaging techniques used in studying emotional
regulation.

Multimodal imaging techniques represent an advanced approach in neuroscience, allow-
ing researchers to explore the complex neural mechanisms underlying emotional regu-
lation through the integration of various imaging modalities. Functional magnetic reso-
nance imaging (fMRI) provides high spatial resolution, enabling precise localization of
brain activity by measuring changes in blood flow. Positron emission tomography (PET)
offers insights into metabolic processes and neurotransmitter systems, revealing how
chemical changes in the brain correlate with emotional regulation. Electroencephalog-
raphy (EEG) captures electrical activity with high temporal resolution, making it possible
to track rapid neural responses to emotional stimuli. Magnetoencephalography (MEG)
similarly records magnetic fields produced by neural activity, combining high temporal
resolution with better spatial resolution than EEG. By integrating data from these diverse

techniques, researchers can obtain a comprehensive view of both the structural and func-
tional aspects of the brain. This multimodal approach facilitates a more nuanced under-
standing of how different brain regions and networks interact to regulate emotions, of-
fering valuable insights that single-modality studies might miss. Through the use of these
sophisticated imaging methods, the field of emotional regulation research is advancing
towards a more detailed and holistic understanding of the brain's role in managing emo-
tions.

Explanation of each technique (fMRI, PET, EEG, MEG) and their strengths in captur-
ing different aspects of neural activity.

Each imaging technique used in studying neural activity and emotional regulation brings
unique strengths to the table, capturing different aspects of brain function. Functional
magnetic resonance imaging (fMRI) offers high spatial resolution, allowing researchers
to precisely locate regions of brain activity by detecting changes in blood oxygen levels,
which correlate with neuronal activation. This makes fMRI particularly valuable for
identifying specific brain areas involved in emotional regulation. Positron emission to-
mography (PET) excels in visualizing metabolic processes and neurotransmitter activity
by using radiolabeled tracers, providing insights into the chemical and molecular under-
pinnings of neural activity. This capability is crucial for understanding the neurochemi-
ical changes associated with emotional responses. Electroencephalography (EEG) records
electrical activity produced by neurons through electrodes placed on the scalp, offering
exceptional temporal resolution. This allows researchers to monitor brain activity in real-
time, capturing the rapid dynamics of neural processes during emotional regulation. Magnetoencephalography (MEG) also provides high temporal resolution but with improved spatial resolution compared to EEG, by measuring the magnetic fields generated by neuronal activity. MEG’s ability to pinpoint the timing and location of brain activity with greater accuracy makes it a powerful tool for studying the intricate timing of neural responses. Together, these techniques offer a comprehensive view of brain function, from the precise location of neural activity to the real-time dynamics of brain processes and the underlying neurochemical events, thereby providing a holistic understanding of the neural mechanisms involved in emotional regulation.

**Discussion of how combining multiple modalities enhances the understanding of emotional regulation.**

Combining multiple imaging modalities significantly enhances the understanding of emotional regulation by providing a more comprehensive and nuanced picture of brain function. Each modality brings its strengths: fMRI’s high spatial resolution pinpoints specific brain regions involved in emotion processing, while PET’s ability to map neurotransmitter activity offers insights into the neurochemical changes that accompany emotional states. EEG and MEG complement these techniques with their high temporal resolution, capturing the rapid dynamics of neural activity that underlie real-time emotional responses. By integrating these modalities, researchers can correlate structural and functional data with the timing of neural events, thereby uncovering how different brain regions and networks interact over time to regulate emotions. This multimodal approach allows for the examination of both the “where” and “when” of brain activity, providing a fuller understanding of the complex processes involved in emotional regulation. For instance, researchers can identify specific neurotransmitter systems active in certain brain areas during emotion regulation tasks and observe how these chemical processes unfold in real-time. This comprehensive insight is essential for developing targeted interventions and therapies for emotional dysregulation, as it reveals not only the locations and types of neural activity involved but also their temporal sequence and interactions.

**Neural Correlates of Emotional Regulation**

**Summary of findings from multimodal imaging studies on the neurobiological underpinnings of emotional regulation.**

Multimodal imaging studies have significantly advanced our understanding of the neurobiological underpinnings of emotional regulation by revealing the intricate interplay between various brain regions and networks. Key findings consistently highlight the crucial role of the prefrontal cortex (PFC) in exerting top-down control over emotional responses, particularly through its connections with the amygdala, a region central to emotion processing and reactivity. fMRI studies have shown increased activation in the PFC during tasks that require emotional regulation, indicating its involvement in modulating emotional responses. PET studies complement these findings by illustrating how neurotransmitter systems, such as serotonin and dopamine, are involved in this modulation, affecting both the PFC and the amygdala. EEG and MEG studies further elucidate the timing and dynamics of these processes, showing how rapid neural oscillations facilitate communication between the PFC and other regions like the insula and hippocampus, which are associated with emotional awareness and memory. Together, these multimodal studies depict a complex, dynamic network where the PFC integrates sensory and emotional information, regulates responses through neurotransmitter-mediated pathways, and coordinates with other brain areas to maintain emotional balance. This integrated view provides a deeper understanding of the mechanisms behind emotional regulation and highlights potential targets for therapeutic interventions in disorders characterized by emotional dysregulation.

**Discussion of key brain regions implicated in emotional regulation tasks (e.g., PFC, amygdala, hippocampus, insula) and their functional roles.**
Several key brain regions play integral roles in emotional regulation tasks, each contributing unique functions to the overall process. The prefrontal cortex (PFC), particularly the dorsolateral and ventromedial regions, serves as a hub for cognitive control over emotional responses. It plays a crucial role in reappraisal, suppression, and other regulatory strategies by modulating activity in subcortical regions such as the amygdala. The amygdala, known for its role in processing and assigning emotional significance to stimuli, is central to the generation of emotional responses. Its interactions with the PFC and other limbic structures like the hippocampus and insula are essential for integrating emotional information and coordinating appropriate behavioral and physiological responses. The hippocampus, crucial for memory consolidation and contextual processing, contributes to emotional regulation by contextualizing emotional experiences and facilitating adaptive responses based on past experiences. The insula, involved in interoception and emotional awareness, helps integrate internal bodily states with emotional experiences, guiding the selection of appropriate regulatory strategies. Collectively, these brain regions form a distributed network that regulates the generation, expression, and modulation of emotions, highlighting their interconnectedness and functional significance in emotional regulation tasks. Understanding the roles of these regions provides valuable insights into the neural mechanisms underlying emotional regulation and informs targeted interventions for individuals with difficulties in regulating their emotions.

Highlighting common neural circuits and networks involved in emotion regulation across studies.

Across various studies utilizing multimodal imaging techniques, a consistent picture emerges of the neural circuits and networks involved in emotion regulation. One commonly identified circuit involves reciprocal connections between the prefrontal cortex (PFC) and subcortical structures, particularly the amygdala. The PFC, with its cognitive control functions, exerts regulatory influence over the amygdala’s emotional processing by modulating its activity based on contextual information and regulatory goals. This top-down regulation is facilitated by additional connections with regions such as the hippocampus and insula, which contribute to memory retrieval and emotional awareness, respectively. Moreover, interactions within the default mode network (DMN), involved in self-referential processing, and the salience network (SN), implicated in detecting and integrating salient stimuli, play crucial roles in regulating emotional responses by directing attention and modulating cognitive processes. These findings highlight the dynamic interplay between cortical and subcortical regions, as well as within large-scale neural networks, in orchestrating effective emotion regulation. Understanding these common neural circuits provides a framework for elucidating the neural basis of emotional regulation and informs targeted interventions aimed at optimizing regulatory processes in individuals with emotional dysregulation.

Individual Differences and Clinical Implications

Examination of individual differences in emotional regulation abilities as revealed by multimodal imaging.

Multimodal imaging studies have shed light on individual differences in emotional regulation abilities by revealing variations in brain structure and function that correlate with differences in regulatory capacity. For instance, differences in the volume and activation patterns of key brain regions involved in emotion regulation, such as the prefrontal cortex (PFC) and amygdala, have been observed across individuals. Some individuals exhibit heightened PFC activity and stronger connectivity within regulatory networks, indicating more effective top-down control over emotional responses. Conversely, others may show reduced PFC activity and exaggerated amygdala reactivity, suggesting deficits in regulatory processes. Additionally, variations in neurotransmitter levels and receptor densities, as assessed through techniques like positron emission tomography (PET), contribute to individual differences in emotional regulation. Moreover, differences in neural oscillatory patterns, as captured by electroencephalography (EEG) and
magnetoencephalography (MEG), reflect variations in the timing and coordination of neural processes underlying emotion regulation. By elucidating these individual differences, multimodal imaging offers insights into the neural basis of emotional resilience and vulnerability to mood disorders, informing personalized interventions tailored to individuals’ specific neurobiological profiles.

**Discussion of how variations in brain structure and function contribute to differences in emotional resilience and susceptibility to mood disorders.**

Variations in brain structure and function significantly contribute to differences in emotional resilience and susceptibility to mood disorders. Structural differences, such as variations in the volume of the prefrontal cortex (PFC) and amygdala, are associated with distinct patterns of emotional regulation. Individuals with larger or more active PFC regions typically exhibit greater emotional resilience, as the PFC is crucial for exerting cognitive control over emotional responses. Conversely, those with heightened amygdala reactivity and reduced PFC activity often display increased emotional sensitivity and difficulty regulating emotions, making them more susceptible to mood disorders like anxiety and depression. Functional connectivity between these regions also plays a critical role; stronger connectivity suggests more effective communication and regulation, while weaker connectivity can lead to dysregulation. Additionally, neurotransmitter imbalances, as revealed by positron emission tomography (PET), can affect mood and emotion regulation, with alterations in serotonin and dopamine systems being particularly implicated in mood disorders. Furthermore, differences in neural oscillatory patterns, observed through electroencephalography (EEG) and magnetoencephalography (MEG), influence the efficiency of neural networks involved in emotional regulation. These structural and functional variations highlight the neurobiological underpinnings of emotional resilience and vulnerability, providing a basis for understanding individual differences in mental health and guiding the development of targeted therapeutic strategies.

**Implications for personalized interventions and therapeutic approaches based on neurobiological markers.**

The identification of neurobiological markers through multimodal imaging has profound implications for personalized interventions and therapeutic approaches in the treatment of emotional dysregulation and mood disorders. By elucidating individual variations in brain structure and function, such as differences in prefrontal cortex (PFC) activity, amygdala reactivity, and neurotransmitter levels, clinicians can tailor interventions to target specific neurobiological profiles. For instance, individuals with reduced PFC activity and heightened amygdala responses may benefit from cognitive-behavioral therapies (CBT) aimed at enhancing cognitive control and emotional regulation strategies. Pharmacological treatments can also be personalized, with neurotransmitter profiles guiding the selection of medications that modulate specific chemical pathways, such as serotonin or dopamine, to achieve better therapeutic outcomes. Additionally, neurofeedback and brain stimulation techniques, like transcranial magnetic stimulation (TMS), can be customized based on individual neural oscillatory patterns to enhance regulatory network efficiency. This personalized approach not only improves the efficacy of treatments but also minimizes side effects by targeting the underlying neurobiological mechanisms unique to each patient. Ultimately, leveraging neurobiological markers for personalized interventions holds the promise of more precise, effective, and individualized treatment strategies, leading to improved mental health outcomes and quality of life for those suffering from emotional dysregulation and related disorders.

**Challenges and Future Directions**

**Identification of methodological challenges and limitations in current multimodal imaging studies.**

Current multimodal imaging studies face several methodological challenges and limitations that can impact the reliability and generalizability of their findings. One significant
Challenge is the integration of data from different imaging modalities, each with its own resolution, sensitivity, and noise characteristics, which can complicate the synthesis of a cohesive picture of brain activity. Aligning and combining data from fMRI, PET, EEG, and MEG requires sophisticated analytical techniques and robust preprocessing pipelines to ensure accuracy and consistency. Another limitation is the inherent trade-off between spatial and temporal resolution across modalities, making it difficult to capture both the precise location and timing of neural events simultaneously. Additionally, the high costs and complexity associated with multimodal imaging studies often lead to smaller sample sizes, which can limit statistical power and the ability to detect subtle effects. Variability in study designs, participant characteristics, and experimental tasks further complicates the comparison and replication of findings across studies. Furthermore, potential biases in participant selection and the underrepresentation of diverse populations can affect the generalizability of the results. Addressing these methodological challenges is crucial for advancing the field and improving our understanding of the neurobiological underpinnings of emotional regulation through multimodal imaging.

**Discussion of potential avenues for future research, such as improving spatial and temporal resolution, incorporating machine learning techniques, and exploring novel imaging modalities.**

Future research in the field of multimodal imaging for emotional regulation stands to benefit from several promising avenues that could enhance the precision and depth of our understanding. One critical area is the improvement of spatial and temporal resolution. Advancements in imaging technology could allow for more detailed and accurate mapping of brain structures and functions, enabling researchers to capture both the fine-grained details of neural activity and the rapid dynamics of brain processes more effectively. Incorporating machine learning techniques represents another transformative potential. Machine learning algorithms can handle the vast and complex datasets generated by multimodal imaging, facilitating more sophisticated pattern recognition, predictive modeling, and the integration of heterogeneous data sources. This could lead to new insights into the neural correlates of emotional regulation and the identification of biomarkers for various mental health conditions. Exploring novel imaging modalities, such as optogenetics or functional near-infrared spectroscopy (fNIRS), could further broaden the toolkit available to researchers, providing complementary data that enhance our understanding of brain function. These innovations, combined with longitudinal and large-scale studies, could address current limitations and pave the way for breakthroughs in the identification of neurobiological mechanisms and the development of targeted interventions for emotional dysregulation.

**Importance of longitudinal studies and translational research for better understanding the development and treatment of emotional dysregulation.**

Longitudinal studies and translational research are paramount for advancing our understanding of the development and treatment of emotional dysregulation. Longitudinal studies, which track individuals over extended periods, provide invaluable insights into how emotional regulation evolves over time and how early-life experiences, genetic factors, and environmental influences interact to shape emotional health. These studies can identify critical developmental windows and trajectories that are crucial for effective intervention. Translational research bridges the gap between basic scientific discoveries and clinical applications, ensuring that findings from multimodal imaging and other research methodologies are translated into practical therapies and interventions. By applying knowledge gained from imaging studies to clinical contexts, translational research can inform the development of personalized treatments that target specific neurobiological mechanisms underlying emotional dysregulation. This approach not only enhances the efficacy of interventions but also promotes the creation of preventative strategies, ultimately leading to better mental health outcomes. The integration of longitudinal and translational research thus offers a comprehensive framework for understanding the
complexities of emotional regulation and developing more effective, individualized treatments for those affected by emotional dysregulation.

**Conclusion**

The systematic literature review on multimodal imaging studies of emotional regulation reveals several key findings and insights that significantly advance our understanding of the neurobiological mechanisms involved. The integration of various imaging techniques, such as fMRI, PET, EEG, and MEG, has elucidated the roles of critical brain regions like the prefrontal cortex (PFC), amygdala, hippocampus, and insula in the regulation of emotions. These studies consistently highlight the PFC’s crucial function in exerting cognitive control over emotional responses and its regulatory interactions with the amygdala, which is central to emotional reactivity. The involvement of neurotransmitter systems, particularly those related to serotonin and dopamine, has been detailed through PET imaging, linking chemical changes to emotional regulation processes. Furthermore, EEG and MEG have provided valuable insights into the timing and coordination of neural activity, showing how rapid neural dynamics underpin effective emotion regulation. Individual differences in emotional regulation abilities have been traced to structural and functional variations in these brain regions, with implications for emotional resilience and vulnerability to mood disorders. These findings underscore the importance of personalized approaches in therapeutic interventions. Despite methodological challenges, the review emphasizes the potential of multimodal imaging to offer a holistic and detailed understanding of the neural circuits and networks that govern emotional regulation, paving the way for targeted and effective treatments.

The findings from multimodal imaging studies have profound implications for advancing our understanding of the neurobiological basis of emotional regulation and its clinical relevance. By elucidating the intricate interactions between key brain regions such as the prefrontal cortex (PFC), amygdala, hippocampus, and insula, these studies provide a comprehensive picture of how emotional regulation is orchestrated at the neural level. This deeper understanding helps identify specific neural circuits and neurotransmitter systems involved in emotional regulation, thereby informing the development of targeted therapies for individuals struggling with emotional dysregulation. Clinically, these insights can lead to more effective, personalized interventions, such as tailored cognitive-behavioral therapies that enhance PFC function or pharmacological treatments that modulate specific neurotransmitter systems. Furthermore, identifying neurobiological markers of emotional dysregulation can aid in early diagnosis and prevention strategies, potentially mitigating the progression of mood disorders. Ultimately, the integration of multimodal imaging findings into clinical practice bridges the gap between research and treatment, offering new avenues for improving mental health outcomes and enhancing the quality of life for individuals with emotional regulation difficulties.

To further advance our understanding of the neurobiological underpinnings of emotional regulation and effectively translate these insights into clinical practice, there is a pressing need for continued interdisciplinary research efforts. Collaboration across fields such as neuroscience, psychology, psychiatry, engineering, and data science is essential to address the remaining gaps and challenges in the field. By combining expertise, researchers can develop more sophisticated imaging techniques, improve data integration methods, and enhance the precision of neural measurements. Additionally, interdisciplinary efforts can drive the innovation of machine learning algorithms that can handle complex datasets and uncover patterns that may not be apparent through traditional analyses. There is also a need for larger, more diverse longitudinal studies to understand the developmental trajectories of emotional regulation and identify critical intervention points. By fostering such collaborative research, we can accelerate the discovery of effective, personalized treatments for emotional dysregulation, ultimately improving mental health outcomes. Therefore, it is crucial to support and encourage interdisciplinary
initiatives, secure funding for large-scale studies, and promote the dissemination of knowledge across scientific and clinical communities.

**Authors’ Contributions**

All authors participate in a big way, starting from collecting literature, analysing the literature, writing, and revising.

**References**


