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The Neural Mechanisms Linking Social Exclusion and Aggression: Research Progress and Review

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Abstract: This study summarizes the research on the neural mechanisms underlying social exclusion and aggression, exploring the potential bidirectional neural connections between them, including both direct and indirect pathways. Based on previous findings and the functional organization of brain structures, this study proposes five potential bidirectional indirect neural circuits linking social exclusion and aggression. There are indirect links between the amygdala and the prefrontal cortex (PFC) through important brain areas like the cingulate cortex, hippocampus, insula, striatum, and nucleus accumbens. This provides new insights into understanding the neural mechanisms linking social exclusion and aggression while offering directions for future research and intervention practices.

Keywords: social exclusion, aggression, neural mechanisms

1. Introduction

Aggression refers to behaviors intended to harm or exert control over others or the environment, which can manifest as physical attacks or verbal insults [1]. According to the General Aggression Model (GAM), aggression is triggered by a combination of external situational factors and internal individual factors [2]. Among these factors, social exclusion is a major external situational factor. Social exclusion is the feeling of being alone or rejected by others, which keeps people from having social interactions [3]. Research has demonstrated that social exclusion not only affects individuals' mental health but also significantly elicits aggressive behaviors [4]. With advances in neuroscience, increasing attention has been paid to the neural mechanisms underlying social exclusion and aggression. The amygdala, anterior cingulate cortex (ACC), and prefrontal cortex (PFC), which are important brain regions for processing and controlling emotions, seem to play a central role in this process [5,6]. This paper aims to review the neural mechanisms of aggression and social exclusion, as well as the potential direct and indirect neural connections between them. Studying the neural mechanisms underlying the relationship between social exclusion and aggression offers new perspectives for understanding their deeper connections. It not only enriches and further validates theoretical models of aggression but also provides practical guidance for designing targeted interventions, such as in the judicial field.

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2. Neural mechanisms of aggression

The amygdala, a critical component of the limbic system, plays a central role in the perception, generation, and regulation of negative emotions such as fear and anger. External stimuli influence the amygdala through two main pathways: the low road and the high road. The low road directly transmits sensory inputs to the thalamus, rapidly activating the central nucleus of the amygdala (CeA) while bypassing cognitive evaluation. This pathway triggers immediate responses, such as aggression or flight, enabling adaptive reactions to high-stress or threatening situations [7,8]. Taking the high road, on the other hand, involves complex cognitive evaluation through cortical processing, especially in the PFC, before sending information to the basolateral nucleus of the amygdala (BLA). This pathway facilitates precise contextual analysis and reduces impulsive aggression [9,10]. If the high road isn't working right, the PFC may not be able to control the amygdala as well, which can make reactive aggression more likely [11,12].

In addition, the bidirectional connections between the amygdala and other brain structures are also implicated in aggression. The hippocampus reinforces emotional memories and promotes amygdala activation, which exacerbates aggressive responses under chronic stress [13,14]. The ACC regulates amygdala activity through impulse control, and weakened functional coupling between these regions may result in uncontrolled aggressive behaviors [15,16]. The striatum and nucleus accumbens interact with the amygdala to modulate reward signals, reinforcing emotionally driven aggression [17,18]. The insula enhances functional coupling with the amygdala during social emotional processing and threat evaluation, suggesting its critical role in judging aggressive social contexts [19,20].

The bed nucleus of the stria terminalis (BNST), an extension of the amygdala, plays a key role in processing chronic threat information and regulating aggressive behaviors. BNST promotes aggression by modulating the hypothalamic-pituitary-adrenal (HPA) axis and autonomic nervous system activity [21,22]. BNST interacts with neural circuits in the ventromedial hypothalamus (VMH) and the dopaminergic reward system, further enhancing aggression under chronic stress [23,24]. Optogenetic studies have demonstrated that chronic activation of BNST circuits leads to increased aggression under prolonged stress conditions [25,26].

To sum up, aggression is caused by a neural network centered on the amygdala that communicates back and forth with brain areas like the prefrontal cortex, hippocampus, and anterior cingulate cortex. The amygdala responds rapidly to external emotional and threat signals, while its interactions with these regions facilitate the dynamic regulation and balance of aggressive behaviors.

3. Neural mechanisms of social exclusion

Social exclusion refers to the negative emotional experience arising from cognitive processing of exclusionary situations, involving multiple brain regions, particularly the PFC. The ventromedial prefrontal cortex (vmPFC) plays a key role in processing subjective feelings of exclusion and emotional experiences [27]. Its connectivity with the amygdala and hippocampus is essential for integrating threat-related information [28]. Dysfunction in the vmPFC exacerbates negative emotions and reduces emotional resilience [29]. The dorsolateral prefrontal cortex (dlPFC), which controls thinking and stopping impulses, also lowers emotional responses by changing how the amygdala and vmPFC work. Higher dlPFC activation is associated with lower negative emotional responses to exclusion [30,31].

Other brain regions associated with social cognition form a complex interactive network through bidirectional connections with the PFC. The insula, which has reciprocal links with the PFC, processes emotional distress and transmits bodily state information to the PFC for regulation [32]. The ACC monitors emotional conflict and collaborates with the PFC to regulate rejection-related emotions [33,34]. Additionally, the striatum and nucleus accumbens influence reward processing in

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social exclusion. Studies have linked reduced nucleus accumbens activity to increased negative emotions and social withdrawal [35,36]. The hippocampus activates emotional memory networks, enhancing the PFC's evaluation of exclusion scenarios, and its functional coupling with the PFC aids in emotional recovery [37]. Imbalanced connectivity between the amygdala and PFC during threat processing may heighten emotional sensitivity and anxiety related to exclusion[38].

The default mode network (DMN), comprising the medial prefrontal cortex (mPFC), PCC, and hippocampus, is primarily responsible for self-reflection and social cognition. In exclusionary contexts, functional connectivity between the mPFC and PCC is enhanced, amplifying subjective experiences of exclusion [39]. Imbalance between the DMN and the lateral prefrontal cortex (lPFC) can result in emotional regulation difficulties and rumination [40]. Also, being left out of a group activates the network in the hippocampi that stores bad emotions, which makes negative thoughts stronger in the mPFC [41]. Dysfunctional connectivity between the hippocampus and PCC is implicated in emotional regulation deficits seen in depression [42]. Reduced flexibility in the DMN's dynamic functional connectivity significantly impairs emotional recovery following exclusion [43].

In conclusion, the core neural mechanisms of social exclusion are centered on the PFC, which is primarily responsible for social cognitive processing. Through bidirectional connections between the PFC and other regions associated with social cognition, as well as the integration and transmission of information within these neural networks, the brain collectively regulates the experience of social exclusion.

4. Bidirectional neural connections between social exclusion and aggression

From the literature review above, the neural mechanisms of social exclusion and aggression primarily center on the PFC and the amygdala, respectively. The bidirectional neural connections between these two regions constitute a core pathway for regulating emotional and behavioral responses. These connections operate through both direct and indirect pathways, forming a complex neural regulatory network.

4.1. Direct bidirectional connections between the PFC and amygdala

The direct neural connections between the PFC and amygdala play a central role in emotional regulation, threat perception, and social cognition. The PFC has an inhibitory effect on the amygdala from the top down, which lowers its hyperactivity and helps people control their emotions and impulsive behaviors [44]. Specifically, the vmPFC is responsible for emotional evaluation and regulation, while the dlPFC primarily facilitates cognitive control [45]. Conversely, heightened amygdala activation can impair the PFC's emotional and cognitive regulatory functions, leading to emotional dysregulation, especially in contexts of social exclusion or perceived threat [46]. Not only that, but the PFC is linked to the BNST, which is an extension of the amygdala and controls long-term fear responses and anxiety [47]. The BNST not only participates in processing chronic stress but also influences amygdala function, which in turn feeds back to the PFC, forming a complex regulatory mechanism [48].

4.2. Indirect bidirectional connections between the PFC and amygdala

The PFC and amygdala also interact indirectly through other brain regions, forming neural circuits that integrate emotion, memory, and cognitive functions to regulate social exclusion and aggression.

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4.2.1. PFC-Cingulate Cortex-Amygdala Circuit

The Anterior Cingulate Cortex (ACC) has bidirectional connections with the PFC, receiving cognitive control signals from the PFC and relaying emotional conflict information back to it [49]. The bidirectional connection between the ACC and amygdala is involved in threat perception and emotional regulation, with ACC activation closely synchronized with amygdala-driven emotional responses [50]. The PCC affects social cognitive processing in the PFC by retrieving memories and putting them together with other information. Simultaneously, the PCC relays emotional contextual information back to the amygdala, modulating emotional responses [51,52].

4.2.2. PFC-Hippocampus-Amygdala Circuit

The PFC exerts top-down control over the hippocampus, influencing the formation of contextual memories, while the hippocampus provides feedback to enhance the PFC's integration of threat-related information [53]. The bidirectional connection between the hippocampus and amygdala plays a crucial role in consolidating threat-related memories and triggering emotional responses [54]. Researchers have found that people with post-traumatic stress disorder (PTSD) have abnormally strong functional connectivity between the hippocampus and amygdala. This makes threat-related memories stick around longer and makes them more sensitive to being left out of social situations [55].

4.2.3. PFC-Insula-Amygdala Circuit

The bidirectional connections between the PFC and insula are essential for emotional processing and interoceptive body state awareness [56]. The connection between the insula and amygdala is particularly critical in the experience of emotions. The insula transmits sensory pain and emotional signals, such as those associated with social exclusion, to the amygdala, while simultaneously receiving emotionally driven feedback from the amygdala, further enhancing emotional perception [15,57].

4.2.4. PFC-Striatum-Amygdala Circuit

The bidirectional connections between the PFC and striatum support motivational regulation and behavioral selection. The PFC regulates goal-directed behaviors via prefrontal-striatal pathways, while the striatum provides feedback signals that influence the PFC's decision-making processes [58]. The striatum and amygdala are connected in a way that changes the motivation behind aggressive and antisocial behavior that is at the heart of emotionally driven behavior [59,60].

4.2.5. PFC-Nucleus Accumbens-Amygdala Circuit

The PFC's connection with the nucleus accumbens supports emotional regulation and reward processing. The PFC regulates nucleus accumbens activity to mitigate negative emotional influences, while the nucleus accumbens transmits reward feedback signals to the PFC, facilitating emotional recovery [61]. The bidirectional connection between the nucleus accumbens and amygdala plays a key role in balancing emotional and behavioral responses through reward-emotion interactions [62]. Research has shown that abnormal nucleus accumbens function and reduced reward sensitivity may exacerbate negative emotional experiences in social exclusion contexts [63].

In summary, the direct bidirectional connection between the PFC and amygdala constitutes the core pathway for emotional regulation and aggression. Meanwhile, the PFC and amygdala interact indirectly through the ACC, hippocampus, insula, striatum, and nucleus accumbens, forming complex circuits that integrate emotional, cognitive, and social behavioral functions.

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5. Practical applications and future directions

Functional magnetic resonance imaging (fMRI), transcranial magnetic stimulation (TMS), and other advanced neuroimaging techniques can be used to learn more about the neural links between being left out of a group and being aggressive. Experimental tasks, such as the "Cyberball" virtual exclusion game, can induce exclusionary scenarios while dynamically recording brain activity. Studies have shown that following social exclusion, functional connectivity between the amygdala and the PFC is significantly weakened, whereas connectivity between the amygdala and insula is enhanced, suggesting that changes in neural network patterns exacerbate negative emotions and aggression [64]. Furthermore, TMS modulation of PFC activity has been found to significantly reduce amygdala hyperactivation, thereby alleviating the negative emotions triggered by social exclusion [65]. Combined with dynamic causal modeling (DCM), modern technology can further uncover the directional abnormalities within the PFC-amygdala-hippocampal circuit under social exclusion conditions, which are closely associated with aggressive behaviors [66].

To address these neural dysfunctions, pharmacological interventions and cognitive-behavioral therapies (CBT) offer effective strategies. For instance, selective serotonin reuptake inhibitors (SSRIs) can enhance the inhibitory control of the PFC over the amygdala, reducing emotional reactivity and aggression [67]. Similarly, NMDA receptor antagonists, such as ketamine, have demonstrated rapid improvements in emotional regulation [68]. CBT, through techniques like emotional exposure and cognitive restructuring, can strengthen functional connectivity between the PFC and amygdala, improving emotional regulation and behavioral control [69]. When these therapies are combined with mindfulness-based interventions, they can control the insula-amygdala circuit, which lowers the emotional responses that come from being left out of a group [70].

In the judicial domain, research on the neural mechanisms underlying social exclusion and aggression has important practical applications. Violent offenders often face significant challenges in social reintegration after release, partly due to a negative feedback loop caused by PFC-amygdala dysfunction. This imbalance exacerbates emotional regulation deficits and impulsive aggressive behaviors [71,72]. Addressing this issue, emotional management and social cognition interventions can be implemented during incarceration. Rational Emotive Therapy (RET) can help offenders identify irrational beliefs and adjust negative emotions, while psychoeducation modules can teach the neurobiological basis of emotional regulation involving the amygdala and PFC. Enhancing self-awareness and emotional management capabilities through such interventions can disrupt the vicious cycle between aggression and social exclusion, facilitating offenders' successful reintegration into society and reducing recidivism rates.

6. Conclusion

This review summarizes the neural mechanisms underlying social exclusion and aggression, emphasizing the pivotal role of the bidirectional connection between the PFC and the amygdala in emotional regulation and behavioral responses. The PFC and amygdala form complex indirect circuits through key brain regions such as the cingulate cortex, hippocampus, insula, striatum, and nucleus accumbens, collaboratively modulating emotional responses and aggressive behaviors in exclusionary contexts. These findings provide a neurobiological foundation for understanding the interplay between social exclusion and aggression. Although this review is only theoretical, testing this hypothesis through real-world research requires not only careful experiment design but also the use of advanced techniques and specialized tools. The complexity of investigating these neural mechanisms presents a significant limitation for the research.

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