Immune System - The Evolutionary Root of Emotions and Behaviour

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Emotions evolved as evolutionary function of the immune system to optimize survival and reproduction

"Nothing in Biology Makes Sense, Except in the Light of Evolution" - Theorodore Dobzhansky

The human body and mind are shaped by the rigorously teleological demands of evolution. Traits only persist across generations if they serve the ultimate purpose of maximizing survival and reproduction. Any complex living system that evolves must have this end as its fundamental motivation and logic.

This includes not just physiology, but also psychology - the thoughts, motives and feelings that shape the development and behavior of the organism. At their core, emotions evolved as a means of calibrating thoughts and behaviors to achieve evolutionary success. While emotions may enable rich experiences of life, meaning and relationships, they have no other ultimate purpose beyond optimizing survival and reproduction.

A mechanism crucial for achieving this end is the immune system. Living systems evolve under vigilange and protection of the immune system, resisting threats, repairing damage and maintaining health directly enabling continued survival and reproducing, allowing organisms to spread their genes. Emotions and immunity interact multidirectionally, with inflammation influencing psychological experience, and emotions modulating and being modulated by the immune function, while emotions regulate behaviour. The immune system regulates a chain of biochemical, biomechanical and bioelectrical processes within the organisms' internal and external environment, from stimulus to behavior and back. Over the course of evolution, a rapid, optimized emotive-immunological response likely conferred a survival/reproductive advantage, with immune system mobilising emotional circuits that govern behaviour and guiding the organism toward opportunities, or away from threats to safety.

Over generations, natural selection has directed this coordination, sculpting the immune system to work with emotions to optimize evolution's teleological function - optimizing survival and reproduction. Cultural evolution and social behavior, relationships, morality, spirituality - all emerge to regulate selfishness, coordinate cooperative efforts and foster purpose beyond individuation in service of propagating genes. Emotions evolve not because of inherent metaphysical meaning but because they increased access to resources, protection and mating partners - directly enabling more success in survival and gene transmission.

No biological, psychological or social experience transcends beyond this teleology. Emotions like awe, wonder, transcendence and spirituality may inspire notions of vast meaning, but evolve to motivate the thoughts, emotions and behaviour that collectively optimise survival/reproduction. Emotions may seem to cultivate profundity and higher purpose, but are aimed toward these evolutionary ends. Culture, values and beliefs may inspire notions of virtue, meaning and transcendence, but have no rationale beyond what supports survival and propagating genes across time. In essence, all humans and other living beings share an overarching evolutionary purpose: to optimise survival and reproduction.

Thus, despite being an apparent oversimplification, the idea that *"Emotions evolved as evolutionary function of the immune system to optimize survival and reproduction"* may be able to capture an essential teleological truth.

The biopsychosocial systems that emerge to instantiate human perception, thought, emotion, behaviour and spirituality work together, orchestrated by natural selection, to ensure organisms remain alive and able to successfully self-organise, reproduce and spread their genes. Maximizing this end is the only purpose that guides human nature's evolution and complex form. Our greater thoughts, perceptions and experiences may inspire, but ultimately evolve to achieve this aim.

Evolutionary origins of Emotions

The immune system evolved to modulate emotions, which in turn drive behavior, leading to optimization of survival and reproduction. Negative emotions driven by the immune system can activate stress responses as behavior, such as approach or withdrawal, fight-or-flight responses. , On the other hand, immune system signaling also promotes positive emotions, activation/inhibition of reward-seeking behavior, approach/withdrawal and tend-and-befriend responses and can drive empathic and altruistic behavior, promoting social bonding and reproductive success.

Emotions are central neural states that evolved through interactions between the central nervous system and immune system to drive adaptive responses to stimuli. They are triggered by sensory or memory inputs and generate widespread behavioral, cognitive, and physiological changes. Certain properties of emotions generalize across species, even those with different emotions, indicating conserved evolutionary functions. For example, threat responses to stress are driven by emotions across species. 6

Fundamentally, emotions represent adaptive brain states that regulate responses to stimuli in ways that influence survival and reproduction. Critically, they emerged through evolutionary processes as modulated by the immune system signaling to the brain. Emotion states have precise, conserved neurological correlates and expressions across species due to their functionality. Same neurotransmitters handle communication in synapses between neurons across species. In vertebrates, including fish, amphibians, reptiles, birds, and mammals, the motor neurons (neurons whose fibres innervate striated muscle) are always cholinergic (that is, they secrete the neurotransmitter acetylcholine). The number of known neurotransmitters in the animal kingdom is small, and their presence in more primitive organisms as well as in nervous systems of later vertebrates shows a striking conservation of these substances throughout evolution. 1
Behavioral regularities observed in diverse animals when circumstances affect survival/reproduction further illustrate emotions' evolved functionality. All species react to threats by activation stress circuits and responses (i.e. fight/flight/freeze).

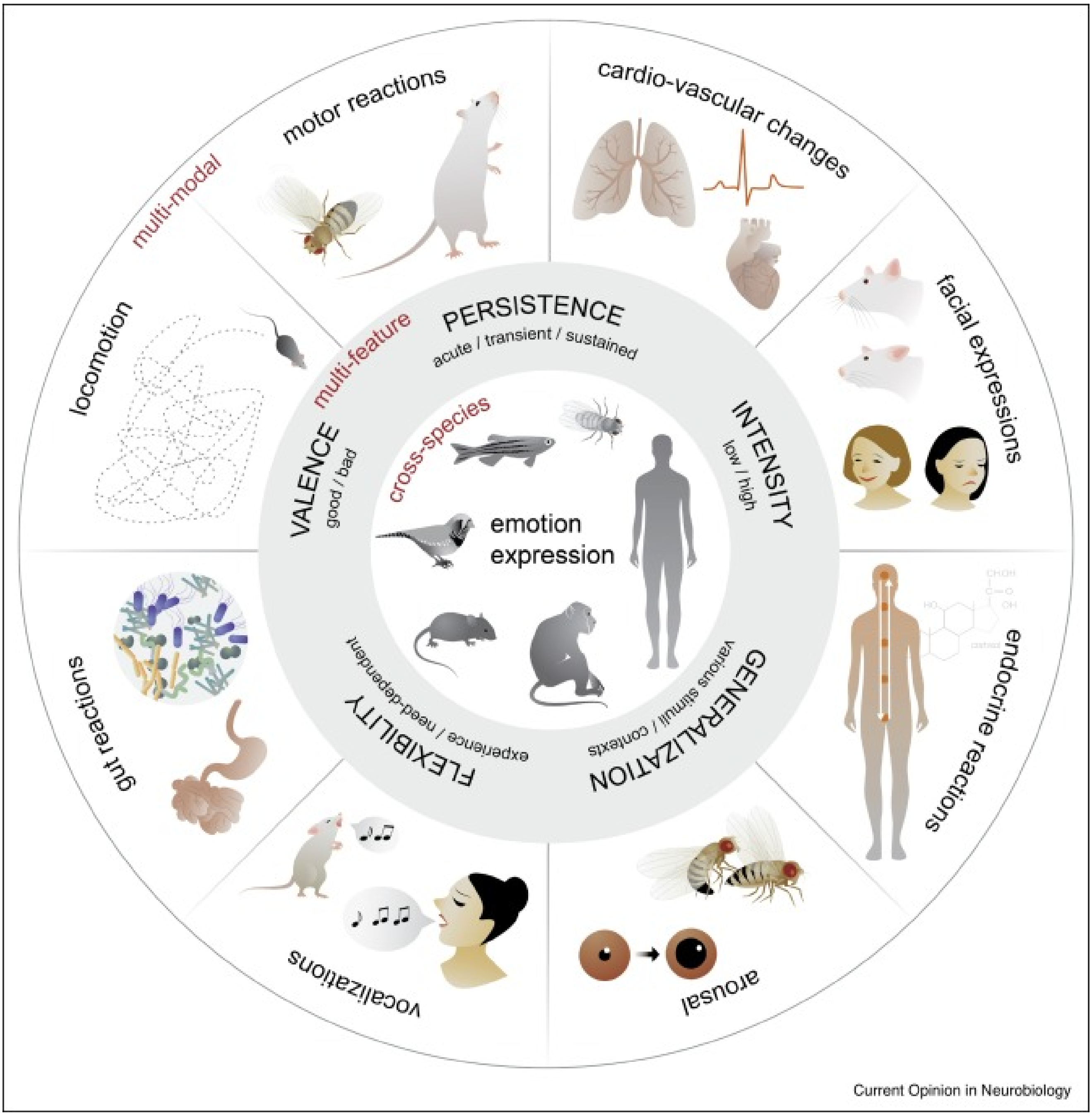
Consciousness, on the other hand, can be considered a feature rather than a prerequisite for emotion is the finding that humans can exhibit measureable behavioral adaptations even when they are unaware of changes in their emotion state. Humans can express emotions unconsciously and conscious awareness of an emotion is not necessary for the underlying emotional state to affect behavior. Analogously, many core functions of the brain, such as sensing, vision, attention, memory or decision-making regularly involve consciousness in humans yet do not depend on it. There are multiple examples of blind sight, non-declarative memory, and unconscious decision-making in humans. Autonomous nervous system regulates breathing, digestion or heartrate without conscious control. Visceral and metabolic signaling can directly regulate mood and emotions wihtout involving consciousness. It thus seems that several core functions of the brain can be executed in absence of conscious appraisal.

Non-conscious emotional processing demonstrates emotions' adaptive purpose rather than dependency on consciousness. Likewise, immune regulation of emotions unconsciously drives behaviors even without emotional awareness, analogous to vision and memory. Primitive emotional forms likely exist across phylogeny with immune-regulated brain/behavioral homologies serving conserved functionality.

Conserved neurological circuits and regulatory regions for similar emotions across species provide strong evidence emotions evolved. In evolutionary timescale, the emotion-related neural circuits evolved much later than primitive sensory or motor functions, organisms were able to sense, evaluate and respond to stimuli without having yet evolved cognitive circuitry required for emotional processing. While identifying and defining distant species' emotions presents difficulties, immune signals generate primitive forms with adaptive functions. Emotion expressions patterned multi-modally beyond reflexes yet constrained by experience, state, context. They adhere to basic features of valence (emotions are positive or negative), persistence (emotions tend to outlast their trigger), intensity (emotions can be weak or strong) and generalization (the same emotion can occur in different contexts or be triggered by different stimulus conditions). Behaviors in humans down to the most primitive model organism should adhere to these emotion features to qualify as an expression of emotion.

Detailed analysis of emotions' origin and properties indicates they arose through evolutionary processes as conserved, functional brain states modulated by immune signaling. Emotions adaptively regulate multi-system responses to environmental inputs in ways that optimize survival and reproduction. Across phylogeny, primitive emotional forms with conserved brain/behavioral signatures evolved through immuno-neurological interactions driving multi-modal expression patterns fulfilling the roles emotions serve for organisms. Fundamentally, the immune system shaped the emergence and function of emotions in flexibly but persistently regulating behavioral outputs to stimuli promoting individuals' evolutionary fitness.

Emotions trigger 'action patterns' in multiple modalities, such as behavioral, physiological, biochemical and bioelectrical. For example, the emotion state of fear may prompt widening of the eyes, heavier breathing, shifts in attention, redistribution of blood, release of hormones, motor responses such as freezing or flight, and sustained avoidance. The following diagram shows how emotions are expressed across diverse species to illustrate their evolutionarily conserved principles. [2]



The evolutionary role of the immune system

The evolutionary perspective on the immune system's role in regulating emotions and behavior is based on the idea that survival and reproduction are the ultimate goals of all organisms. Evolution has shaped the immune system to function as a protector and optimizer of these goals. The immune system is the first line of defense against damage, pathogens and other threats that can harm the organism. It has also evolved to recognize and respond to cues that indicate potential opportunities for rewards and mating, such as pheromones and other chemical signals.

The immune system's response to threats involves the release of chemical messengers, such as cytokines, that can cross the blood-brain barrier and communicate with the brain. These cytokines can activate the threat response mechanisms, such as hypothalamic-pituitary-adrenal (HPA) axis, leading to the release of stress hormones such as cortisol and norepinephrine. Multiple hormones can modulate the emotional response of an individual, leading to approach or withdrawal, fight-or-flight, or tend-and-befriend responses.

Approach or withdrawal are behavioural responses activated by the immune system when there is a perceived threat. For example, if a person perceives a predator or other threat in the environment, the immune system may release cytokines that activate the HPA axis, leading to the release of cortisol. This can lead to an approach or withdrawal response, depending on the individual's perception of the threat. If the person perceives the threat as manageable, they may approach it to gather more information. If the threat is perceived as too great, they may withdraw from the situation to protect themselves.

Fight-or-flight are emotional responses that also activated by the immune system in response to perceived threats. In this case, the individual may perceive the threat as too great to manage, leading to a response of aggression or escape. This response can be important for survival in dangerous situations, as it allows the individual to either fight off the threat or flee from it.

Tend-and-befriend responses are activated by the immune system in response to positive social cues and opportunities. These responses involve empathy, caregiving, seeking social support and forming social bonds, or even as a means of coping with stressors. This can involve empathic and altruistic behavior, as individuals seek to help and support others in their social group. The immune system can modulate these responses by releasing cytokines, leading to the release of oxytocin and other hormones that promote social bonding.

Sexual signaling is another important aspect of behavior that is regulated by the immune system. The immune system can recognize and respond to chemical signals that indicate potential mating opportunities. For example, women who are ovulating may emit chemical signals that indicate their fertility, leading to increased sexual attraction from potential mates. The immune system can also regulate sexual behavior by releasing hormones such as testosterone and dopamine that drive sexual motivation and behavior. Sexual motivation influences social signaling by increasing/decreasing displays of fitness. For example, individuals with more monogamic sexual status tend to to dress to attract less attention of potential mates, while more polygamic individuals tend to exhibit more flamboyant and attention-calling ways of dressing. The intensity and characteristics of social signaling is influened by the sexual status appraisal of the immune system.

Positive emotions

Positive emotions play a crucial role in pair bonding, sexual signaling, and mating. Positive emotions associated with these behaviors, such as attraction, care and love, are regulated by the immune system and evolved as adaptive responses to maximize reproductive success and survival.

One example of this is pair bonding, which is characterized by the development of strong emotional bonds between partners. Positive emotions such as trust, affection, and intimacy play a crucial role in promoting long-term relationships and cooperation between partners. The immune system plays a role in regulating these emotions through *tend and befriend* responses and the release of hormones associated with bonding and social behavior. Social bonding behaviours are mediated primarily through release of oxytocin, serotonin and vasopressin. As OXT and 5-HT are structurally and functionally integrated, they collectively mediate emotion-based behavior. The amygdala is the center of OXT regulation of 5-HT. OXT can inhibit amygdala activity and decrease anxiety, while high amygdala activity and dysregulation of 5-HT are associated with increased anxiety.

Similarly, sexual signaling and mating are also driven by positive emotions. In order to attract mates, individuals often engage in behaviors such as displaying bright colors or performing elaborate courtship displays. These behaviors are regulated by the immune system and evolved as mechanisms to signal fitness and reproductive potential to potential partners.

Positive emotions regulated by the immune system also drive altruistic and empathic behavior. These behaviors are thought to have evolved as mechanisms to promote cooperation and social bonding within groups, which in turn promotes survival and reproductive success. For example, individuals who display empathy towards others are more likely to form strong social bonds and are better able to navigate social relationships, which can lead to greater access to resources and mating opportunities.

Positive emotions also play a crucial role in driving reproduction and survival. For example, the experience of positive emotions such as pleasure and satisfaction associated with sex is thought to reinforce the behavior and promote continued reproduction. In addition, positive emotions such as happiness and contentment are associated with improved health outcomes and increased longevity, promoting survival.

Negative emotions

Negative emotions regulated by the immune system also play an important role in behaviors related to perceived threat, pair bonding, mating, and protecting reproduction and survival. These emotions have evolved as adaptive responses to ensure survival and maximize reproductive success, and the immune system plays a crucial role in regulating the emotions that drive them.

One example of negative emotions playing a role in behavior is in response to perceived threats. The immune system can trigger negative emotions such as fear and anxiety in response to potential dangers in the environment. These emotions serve as adaptive responses that prepare individuals for *fight or flight* responses to protect themselves and their resources.

In terms of pair bonding and mating, negative emotions can also play a role. For example, jealousy and envy are negative emotions that can arise in response to perceived threats to a romantic relationship. These emotions can serve as a means of protecting the relationship and maintaining pair bonding. Negative emotions such as disgust may also be elicited in response to potential mating partners who are perceived as unhealthy or not genetically compatible. For example, in pair-bonding and mating situations where multiple candidates are present, the immune system may trigger negative emotions of disgust towards certain mating candidates, leading to withdrawal from their presence. Conversely, the presence of another - more immunologically compatible - candidate elicits positive emotions such as empathy and care, leading to approach towards this candidate.

Negative emotions regulated by the immune system can also drive aversive and aggressive behaviors. For example, individuals may display aggression towards potential rivals or competitors in order to protect their resources or mating opportunities. Negative emotions such as anger and frustration can also be triggered in response to obstacles that may hinder successful reproduction or survival.

Finally, negative emotions can play a role in protecting reproduction and survival. For example, the experience of pain is a negative emotion that serves as an adaptive response to physical injury or illness. Pain signals potential harm to the body and motivates individuals to take action to protect themselves and promote healing. Negative emotions such as sadness or grief can also serve as adaptive responses to loss, motivating individuals to seek out social support and resources necessary for survival.

Emotions and control systems

Emotions are special states that adjust physiology, arousal, cognition, facial expression, motivation, memory, behavior, and subjective experience in ways that gave selective advantages when expressed in situations that recurred and influenced reproductive success over the evolutionary history of a species. Control systems, such as the immune system and the central nervous system, process information from multiple internal and external sources to express emotions in the form and to the degree that maximizes fitness in the current situation and environment.

The immune system influences emotions through chemicals and biolectrical signals that circulate in and around the body. When the immune system detects stimuli, it activates the biochemical and bioelectrical signaling that control the emotional responses to motivate behaviours. For example, when the immune system detects a pathogen or illness, it may generate feelings of fear, anxiety, or disgust to prompt withdrawal from social contact or unhealthy environments that could worsen infection. These feelings originally helped reduce disease transmission.

Furthermore, the immune system's protective mechanisms can help explain the causal root of a range of psychopathological conditions, such as depression and social anxiety disorders. Theories from evolutionary psychology suggest that stress and anxiety may act as biological protective mechanisms to inhibit behaviour, when the likely cost(energy spent) of obtaining resources is higher than the likely benefit (energy gained).

The immune system also induces positive emotions like joy when it detects low levels of threat or bonding opportunities. Joy-motivated and socially affiliative behaviours support health and group living, which benefited survival and reproduction. Emotions, therefore, evolve to shape behaviours that either avoid health threats (negative emotions) or approach opportunities for growth and bonding (positive emotions). The immune system influences which emotions become activated based on its assessment of threats versus safety, and the cost/benefit inference.

For instance, feelings of compassion or altruism may emerge when the immune system perceives a low threat to one's own health and sufficient resources to help others in need. These prosocial emotions strengthen social bonds and reciprocity, providing evolutionary benefits. The immune system may also increase motivation to seek rewards. When the immune system interprets the stimulus as positive for an opportunity, such as mating or collaboration opportunities, it prompts the activation of brain's reward circuits and dopamine, serotonin and oxytocin, leading to positive emotions and reward-seeking behavior towards the stimulus.

In contrast, feelings of fear, pain, aversion or aggression may emerge when the immune system detects a high threat like infection, injury or molecular intruder. These motivate avoidance, escape and defence - crucial for survival when health is compromised or threatened - and may be expressed as stress, anxiety or aggression.

Therefore, emotions did not evolve as ends in themselves but as bio-psychological mechanisms to drive purposeful and adaptive behaviours. The immune system helps regulate which emotions arise to shape the behaviours most useful for self-preservation, and passing on genes.

An evolutionary interplay between the immune system, emotions and behaviour influences how we perceive and respond to health threats, as well as opportunities for growth in both ourselves and our relationships. Maladaptive emotions can also result when this system is dysregulated or mismatches modern environments. Emotions originate in part from the immune system and evolved to motivate the behaviours most useful for regulating health, mitigating threats, and promoting survival and reproduction. Positive emotions approach rewards while negative emotions withdraw from harm. This fundamental link between the mind and body, nature and nurture, shapes psychology, society, and physical health in a multitude of ways.

The complex relationship between the immune system and emotions

The relationship between the immune system and emotions is complex and bidirectionally connected. Emotions can affect the immune system, and the immune system can affect emotions. Inflammatory response resulting from chronic exposure to stress, anxiety, and negative moods generally can affect physical health to a large extent. Negative emotions can suppress the immune system, while positive emotions can enhance it. The pain caused by inflammation can increase emotional distress, leading to a feedback loop between negative emotional stimuli and immune response, prompting the already weakened immune system to allocate more immune resources away from the previous inflammatory sites.

For example, individuals can take years to recover a healthy immune system following the death of their loved one, and long-term caregivers have suppressed immune systems compared with persons in the general population. Studies on survivors of sexual abuse and those with post-traumatic stress disorder suggest they have elevated levels of stress hormones, as do students at exam time. In these groups of people and others experiencing loneliness, anger, trauma, and relationship problems, infections last longer, and wounds take longer to heal. Chronic stress and depression has been shown to be functionally connected to inflammation and immune system irregularities.

On the other hand, having fun with friends and family seems to have the opposite effect on our immune systems. Social bonding and laughter have a measurable and immediate effect in the immune system. When one feels an emotion, the immune system immediately registers the changes and adjusts to it. This means that if we are laughing, we have an immediate change in immune cell numbers in blood and in their functions — as is the case if we are angry or crying. As with negative emotions, the same bidirectional feedback loop affects positive emotions, where positive mental states trigger positive immune responses, and vice-versa.

The regulatory dynamics of the immune system and emotions

One of the ways the innate immune system regulates emotions is by producing hormones like cortisol, which helps the body respond to stress and manage anxiety. Additionally, inflammation in the body can impact mood, and the adaptive immune system is in control of inflammation levels and duration. The neurotransmitter serotonin, which regulates mood and emotions, is also heavily influenced by the immune system, especially in interaction with metabolic processes due to abundance of serotonin receptors in the gut. Likewise, the dopamine signaling involved with reward-seeking behaviour is tightly regulated by the immune system, as emotions like feeling hungry are stimulated by metabolic processes. Stress is an emotion, and hunger is a stress-response to a threat and to the depletion of body's energy reserves. Dopaminergic signaling from the gut activates the SNS via the vagus nerve, prompting increase in stress hormone levels. We thus feel motivated by stress to respond to hunger.

Conversely, emotions can affect immune function. Chronic negative emotions like stress, anxiety, and depression can suppress the immune system function, making individuals more vulnerable to pathogens and illnesses. On the other hand, positive emotions like joy and optimism can boost immune function. Emotional traumatic experiences can also impair the immune system, whereas forgiveness and compassion may reduce inflammation and benefit immune health. The *placebo* effect, and it's close cousin the *nocebo* effect, demonstrate the powerful connection between the mind and body; believing in a real treatment can boost immunity and overall health, while believing in inevitability of adversity may decrease immune responsiveness.

The many roles of the immune system

The immune system plays a regulatory role in many homeostatic processes, including detection, recognition, inference and elimination of pathogens, foreign substances, cancer cells, or damaged cells. It also plays a key role in inflammation, tissue repair, tissue remodelling, and regulation of immune response magnitude. An optimal immune system maintains a balance between responding to harmful and tolerating harmless agents or, in some cases, even tolerating harmful agents. In addition, the immune system also regulates the nervous system, emotions, cognition, behaviour, metabolism, thermogenesis, and influences the functioning of the autonomous nervous system (ANS).

The immune system also plays a critical role in development, pair-bonding and sexual selection. For example, perceived immune quality in males correlates with masculinity, which is seen as a signal of evolutionary fitness.Masculine, dominant males are often viewed as high-quality mates capable of providing resources for raising offspring and navigating threats. Their immune signaling thus plays an important role in sexual selection and reproductive success.

During pregnancy, the immune system must tolerate the developing fetus, which contains foreign genetic material from the father, besides it's own, including the immune systems from both. To do this, the mother's immune system undergoes a series of changes that suppress the immune response, making it easier for the fetus to survive. In the early stages of development, three different immune systems need to to be able to infer and "negotiate" their co-existence within a the fetal environment. Each of the three immune systems must make compatibility inferences (self-vs-other) between the other immune systems and reach consensus. However, in case of immune incompatibility, these changes can also make the mother more susceptible to infections and other immune health problems.

Therefore, the immune system has a significant influence over mating and sexual selection by regulating and determining preferences for immune similarity versus diversity. Moreover, the immune system influences selection by shaping sex drive based on health and threat levels, mediating social signaling through emotions and behavior, and ultimately shaping the development of multiple immune types within a species. Each of these mechanisms provides different advantages and disadvantages for surviving and promoting reproduction.

This interplay between immune function, mating preferences, and reproductive success exemplifies how evolution uses the immune system not only for health but also for adapting offspring to local ecologies, finding the right genetic matches, and maximizing inclusive fitness. The immune system achieves these goals primarily through its biopsychological influence over mating and attraction.

The immune system as a self-organizing and self-regulating network

The complexity of the interplay between the immune system, the nervous system, perception, cognition, emotions and behaviours could be roughly summarised as:

The immune system regulates perception, cognition and emotions that drive behaviours, while the feedback loops from those processes influence the immune system's self-regulation process.

The human body and mind consist of remarkably complex systems that display the abilities to self-organize and self-regulate. This process of self-regulation (homeostasis) allows the immune system to regulate and to activate immune response by allocating immune resources towards sites of interest (allostasis). Sensory mechanisms, memory appraisal capacities, and executive decision making processing allows reinforcement or inhibition of behavior though feedback monitoring. This allows the body to maintain stability and adapt to changing conditions, without the need for an external organizing force. The adaptive immune system, in particular, demonstrates impressive capabilities for self-organization and regulation that help maintain physiological and psychological homeostasis.

The immune system consists of a distributed network of cells, tissues, and organs that interact in nonlinear ways, with no single governing component. Out of these local interactions, a global order emerges allowing the immune system to organize itself and adapt to defend the body against damage and pathogens.

The immune system displays key features of complex self-organizing systems:

- Distributed control - There is no "command center", rather control is distributed among components.
- Redundancy - Loss of a single component does not impair the overall functioning.
- Plasticity - The system can adapt and learn from experience.

Through intercellular signaling cytokines, contact-dependent interactions between cells, and antigen presentation, the billions of immune cells scattered throughout the body self-organize into dynamically functional units. These include sensory system, lymph nodes, germinal centers, and sites of infection.

Within these organized structures, immune cells specialize and take on distinct roles in a self-regulating division of labor. Various homeostatic mechanisms keep cell populations in balance, preventing overreaction. This includes negative feedback loops that dampen or shut off immune responses when pathogens are cleared, as well as activation of immune memory cells that linger in the circulation past this clearance, containing the memory of previous episodes of immune responses.

Homeostasis and interdependence of physiology, perception, and cognition

The human biology is shaped through complex and dynamic interactions between our various body-brain circuits. At the core of human functioning are the physiological mechanisms that allow the body to maintain homeostasis - keeping the internal environment within a viable range for survival. Through intricate self-organizing processes, the human organism aims to establish equilibrium and respond adaptively to both internal and external stimuli.

On a basic level, the human body is a self-sustaining biological system made up of interdependent parts. According to the principles of systems theory, biological organisms can be characterized as self-organizing through locally replicated and globally coordinated regulatory processes. When faced with perturbations from within or without, the human body works to resist disturbances and return internal systems to optimal states. This ability for self-regulation helps ensure the continuity of the organism by supporting survival and, ultimately, reproduction.

Central to self-organization are the dynamic interconnections between psychophysiological circuits in the body and brain. Numerous feedback loops coordinate signals between tissues, organs, and the central nervous system. As in all complex systems, changes in one area, such as hormonal fluctuations or neurological firing patterns, can impact other bodily domains in turn. These reciprocating body-brain connections form the foundation for how we perceive and understand the world.

On a moment-to-moment basis, the autonomic nervous system regulates vital processes like respiration, circulation, and digestion to maintain homeostasis. When faced with stressors that challenge homeostasis, allostasis - the active process of readjustment - comes into play. Through physiological, psychological, and behavioral means, the organism works to restore balance. The hypothalamic-pituitary-adrenal axis modulates adrenergic release, priming the body for heightened arousal or restful restoration as needed.

These homeostatic regulatory mechanisms underlie all human experience. The psychophysiological basis for self-organization subsequently shapes higher-level cognition and perception. Dynamic interactions between bodily state, neurological activity, and mental processes continually update our internal representations and subsequent responses. As such, our perceptions and interpretations of both internal and external cues are fundamentally dependent on the stability and adaptability established through homeostatic self-regulation at the biological level.

As a recap: the human experience arises from intertwined networks of feedback and coordination between physiological and psychological domains. Through self-organizing properties like homeostasis and allostasis, the human body supports survival by maintaining optimal internal conditions and responding dynamically to perturbations. These psychophysiological regulatory mechanisms then inform and influence how we perceive, interpret, learn from, and engage with our world on cognitive levels. The human perception is thus grounded in, and emerges from, the dynamic interdependencies between our biological and mental functioning.

Bidirectional interactions between immune, neural, and endocrine systems

There are extensive bidirectional interactions between the immune system and the nervous and endocrine (hormonal) systems. This forms an integrated network where each system regulates the others to maintain homeostasis.

Inflammatory signals from the immune system, especially pro-inflammatory cytokines, activate the HPA axis which governs the endocrine stress response. This stimulates the release of cortisol and other anti-inflammatory signals to prevent excessive inflammation. Conversely, the brain can regulate immune activity through direct neuronal connections with lymphoid organs and by secreting neurotransmitters and hormones that interact with immune cells. Stress and emotions strongly influence these pathways.

Through these bidirectional interactions, the immune system helps regulate neural activity and neuroendocrine functions. This shapes mood, emotions, cognition, and behavioral patterns in response to immune activation, such as during injury or infection. Conversely, brain-controlled pathways modulate immune system activity, calibrating inflammation and immune defenses based on perceived threats and environmental conditions. This tuning of the immune system by the nervous and endocrine systems is essential for health. Breakdowns and dysregulation contribute to chronic inflammatory, autoimmune, and mood disorders.

The human immune system utilizes remarkable self-organizing capacities and bidirectional interactions with the brain and hormone systems to defend the body against threats. This maintains physiological and psychological homeostasis in the face of changing conditions. These complex self-regulatory abilities of the immune system are critical for human health and adaptability.

The three-way immunoception and active inference

The immune system uses a three-way system of self vs non-self vs reward (safe, threat, or opportunity for reward) to make inferences about sensory stimuli. This system is similar to what is known as the sensory perception in the nervous system. The immune system can thus be considered as a sensory organ that receives and processes specific information about both internal and external stimuli. The immune system perceives both the inner and the outer worlds through unique immune receptors, which enable it to control interactions of the organism with the environment. The immune system uses this system to influence active inferences about sensory stimuli.

The immune system can regulate the process of active inference through its dynamic interactions with the brain and the broader organism. Active inference is a framework that describes how biological systems, including the brain, engage in perception, learning, and action to maintain physiological and psychological integrity. Recent research has proposed the concept of "immunoceptive inference," which suggests that the immune system and the brain are interconnected and engage in a form of inference similar to that described in active inference. This concept implies that the immune system's responses to pathogens, tissue damage, and environmental challenges involve a process of probabilistic inference and prediction, akin to the active inference framework applied to the brain 2.

The immune system's influence on active inference is further supported by the idea that the immune system and the brain are internal states of the same "Markov blanket," a theoretical construct that defines the boundaries of a system for the purpose of making predictions and engaging in inference. This perspective suggests that the immune system's responses and the brain's activities are mutually informative and interdependent, with both systems engaged in minimizing surprise and maintaining physiological stability.

The immune system's influence on active inference involves its participation in the organism's overall process of perception, prediction, and action, contributing to the maintenance of homeostasis and the adaptive regulation of physiological and psychological states.

The immune system is capable of recognizing and responding to a wide range of antigens. Antigens are typically classified into three categories: self-antigens, non-self-antigens, and reward-associated antigens. Self-antigens are recognized as safe, non-self-antigens are recognized as a threat, and reward-associated antigens present an opportunity for reward that controls the reward system. This ternary system allows the immune system to distinguish between self, threat, and reward in order to mount an appropriate immune response, whether activating defenses against threats, or activating the reward system for opportunities.

The immune system, as a sensory system, perceives and processes information about the environment. The immune system is capable of detecting and responding to a wide range of signals, including pathogen-associated molecular patterns (PAMPs), damage-associated molecular patterns (DAMPs), and reward/resolution-associated molecular patterns (RAMPs).3 These signals are detected by immune receptors, which are expressed on the surface of immune cells. Upon detection of a signal, the immune system processes the information and initiates an appropriate immune response, whether activating defenses, activating the reward system, or doing nothing.

The immune system, as a sensory system, is able to solve similar problems of perception, processing of information, and appropriate response by using similar behavior patterns. These behavior patterns include complementarity principle, receptive fields of the immune system, and abilities to respond appropriately to incoming stimuli as safe, threatening, or rewarding. These behavior patterns allow the immune system to recognize and respond to a wide range of signals from the environment. The immune system perceives and processes information about the environment, including PAMPs, DAMPs, and RAMPs. This information is detected by immune system's Pattern Recognition Receptors (PRRs), which initiate an appropriate immune response signaling depending on perceived safety, threat level, or reward potential.

Immunological Memory

The immune system also keeps memory of past events. When an antigen is encountered more than once, the adaptive immune response to each subsequent encounter is speedier and more effective, a crucial feature of protective immunity known as *immunological memory*.

Immunological memory is specific for a particular antigen and is long-lived. Immunological memory is the adaptive ability of the immune system to recognize pathogens encountered previously and respond effectively upon re-exposure. 8 When a pathogen or its cognate antigens enter the body for the first time, either through natural infection or vaccination, a cascade of immune system responses is generated against that pathogen. During this initial encounter, some immune cells develop a ‘memory’ of the invader. If the immune system reencounters the same pathogen, a stronger and faster response will be mounted, allowing the body to ensure effective pathogen clearance, without severe illness or development of disease.

Immunological memory is developed by cells of the adaptive immune system that produce a highly sophisticated and specific immune response to destroy invading cells. This specificity is crucial to ensure that only antigen molecules that are foreign to the host, and not those that are host-specific, are targeted. T and B lymphocytes (specialized white blood cells) are the primary players in this process, effectively attacking and killing pathogen-infected cells and producing antibodies, respectively.

Sensory perception as the neural counterpart of immune recognition

The conceptual aim of sensory perception lies in refining the parallel between the nervous and the immune systems. In the nervous system, sensory signals captured by specific peripheral receptors are transmitted to the central nervous system and are eventually integrated in specific cortical areas of the brain before an adapted reaction and/or a memory trace is or is not generated. Sensory perception is thus supported by two distinct processes: signal reception and signal integration.

In the sensory nervous system, any sensory input, such as an auditory or visual object, is first captured by specialized sensory neurons. The captured signal is then transmitted by the relay/projection neurons towards and integrated in specific brain cortical areas in which specialized neuronal cell populations reside and interact.

In the sensory immune system, any immune input (for example, antigens, DAMPs and PAMPs) is first captured by specialized immune cells with PRRs, in particular, but not exclusively, by antigen-presenting cells. The captured signal is then transmitted towards and integrated in the lymph nodes or other secondary lymphoid organs.

This model suggests that the immune system can be seen as a sensory system that perceives and responds to signals from the environment, including pathogens and other foreign substances. This perception is not only based on molecular recognition but also on neural processing, which allows the immune system to integrate information from different sources and respond in a coordinated and adaptive manner.

At the molecular level, the immune system recognizes and responds to specific antigens through a complex network of receptors and signaling pathways. This molecular recognition is the first step in immune signal perception and is essential for the activation of immune cells and the initiation of immune responses.

However, the immune system also relies on neural processing to interpret and integrate information from different sources. This processing occurs through a network of sensory neurons that are activated by immune signals and transmit information to the brain. The brain then integrates this information with other sensory input and cognitive and emotional factors to generate an appropriate response.

The integration of neural processing with molecular recognition allows the immune system to respond not only to the specific antigen but also to the context in which it is encountered. For example, the same antigen may elicit a different immune response depending on the presence of other signals or the emotional state of the individual.

This model framework suggests that the sensory immune system is not only a passive detector of antigens but also an active participant in the generation of cognitive, emotional, and behavioral responses. This has important implications for our understanding of immune function and the development of new research methods that target the sensory immune system.

Approach and Withdrawal

Approach and withdrawal behaviors evolved as fundamental motivation systems to maximize survival and reproductive fitness, striking a balance between them. The neurotransmitters that influence these systems developed because they provided benefits for optimizing this balance, and they continue shaping human thoughts, feelings, and behaviors, even in new evolutionary contexts. These behaviors are mediated by the immune system and neurotransmitters such as dopamine, serotonin, norepinephrine, and GABA.

Approach behaviors are driven by dopamine, serotonin, and norepinephrine and motivate individuals to seek out rewards, pleasures, and opportunities that benefit survival and reproduction. For example, an individual may approach food, sex, or social connections. Dopamine, in particular, encourages risk-taking and reward-seeking approaches.

On the other hand, withdrawal behaviors are driven by GABA and inhibit approach while motivating individuals to avoid threats and pain. For instance, an individual may flee from danger, avoid predators, or withdraw from harm. These behaviors help to ensure survival by minimizing harm.

These systems are thought to have evolved because animals that approached rewards and avoided threats tended to survive, reproduce, and pass on their genes more than others. As such, natural selection favored those with neurotransmitter systems that optimized approach-withdrawal balances.

The drive for reproduction, in particular, shaped these systems. Anything that increased mating opportunities was selected for. This includes increased sex drive and arousal, and reduced inhibition (lower withdrawal) during mating. However, too much approach or too little withdrawal decreases survival, so balanced, regulated systems provided the best fitness benefits. Unregulated reward-seeking is dangerous, and some withdrawal is needed to avoid harm.

Different species developed different approach-withdrawal balances based on their ecological niches and survival pressures. For example, species with low predation may be more approach-oriented, while vulnerable species may be more withdrawal-oriented.

These evolved systems influence human emotional functioning, motivating both everyday behaviors and important life decisions through the pursuit of rewards and avoidance of pain/threats. However, modern environments can sometimes mismatch these ancient instincts, due to an exponential increase of selective pressures in human gene-environment interaction.

In addition, the immune system can be modulated by social experiences, including social support and social isolation. For example, caregiving and social support can enhance immune function and reduce the inflammatory response to stress, while social isolation can have the opposite effect. This suggests that the immune system is not only influenced by psychological states, but also plays a role in shaping them.

Sexual selection

From an evolutionary perspective, all animals have to coordinate their activity with other members of their species if they are to survive and reproduce. This requires some form of communication, which for the majority of animals involves the use of chemical signals, known as *pheromones*. The term pheromone is usually reserved for chemical signals that are produced and received by members of the same species, in which both the sender and receiver of the signal gain benefit. In this case, selective pressures usually lead to the coevolution of specialized sending and receiving systems for pheromones.

The immune system is involved in sexual selection and mating in several key ways. It produces pheromones that mediate sexual signaling and influence how attractive and compatible mates seem. This signaling informs the initial judgments we make about potential partners. The immune system regulates pheromone production based on its assessment of threats to health and genetic quality. Pheromones that signal strong immune function and low disease risk are seen as most attractive, as they promise offspring health and longevity.

Partner compatibility is judged in part based on the similarity of immune profiles. Mating with a partner whose immune system is adapted to recognize and neutralize similar pathogens helps to ensure healthy offspring with strong defences. The immune system promotes assortative mating based on immune type.

Immune activation also influences sexual arousal, desire, and performance. When health and pathogen threats are low, the immune system generates more resources for mating and less for defence. Sex drive increases along with attractiveness to a wide range of partners.

Over time, these mechanisms resulted in distinct mating preferences for different immune profiles based on local disease ecologies. What signalled health in one population or environment did not necessarily do so in another. This drove the evolution of diverse immune types within a species.

Other signalling mechanisms also provide immune information, such as skin carotenoids (which indicate nutrition and development), and MHC profiles (which indicate disease resistance). Partners find these signals attractive in proportion to perceived compatibility.

Therefore, the immune system has a significant influence over mating and sexual selection through regulating pheromones, influencing preferences for immune similarity versus diversity, determining sex drive based on health and threat levels, mediating signalling through attributes like carotenoids or masculinity, and ultimately shaping the development of multiple immune types within a species. Each provides different advantages and disadvantages for surviving disease.

This interplay between immune function, mating preferences, and reproductive success illustrates how evolution utilizes the immune system not just for health but also for adapting offspring to local ecologies, finding the right genetic matches, and maximizing inclusive fitness. The immune system achieves these goals in large part through its psychological influence over mating and attraction.

Assortative mating

Assortative mating is a phenomenon in which individuals tend to select partners who are similar to themselves in traits like intelligence, personality, social status, physical appearance, or genetics. This type of mating has several evolutionary functions that contribute to the success of the species. Assortative mating provides crucial benefits for adapting to local environments, maximizing offspring fitness, promoting cooperation within groups, and generating diversity between groups.

The immune system plays a key though often hidden role in facilitating assortative mating through influences over mate choice, preferences, imprinting, and stigma. Such psychological mechanisms have evolved because they resulted in the greatest reproductive success, shaped by the fundamental goals of health, inclusive fitness, and adaptation.

One of the significant benefits of assortative mating is that it increases the likelihood of producing healthy, high-fitness offspring. When individuals mate with genetically similar partners, their offspring inherit desirable traits from both parents, resulting in improved offspring quality, and greater reproductive success. Additionally, it promotes adaptation to local environments as offspring are well-suited to thrive in their ecological niche, enhancing survival.

Assortative mating also reduces the production of less-fit offspring. By choosing partners of similar quality or compatibility, individuals minimize the chances of producing offspring with undesirable or maladaptive combinations of traits from each parent, benefiting inclusive fitness. Moreover, it facilitates cooperation and altruism within families by fostering trust, reciprocity, and self-sacrifice between mates and offspring, aiding in raising children and increasing group success.

Over many generations, assortative mating can result in the emergence of distinct subgroups within a population that differ genetically in consistent ways, leading to the evolution of trait clusters and morphs. This produces niche diversity and adaptability.

In humans, assortative mating is achieved through several means, with many influenced by the immune system. Individuals are attracted to partners whose immune profiles seem genetically compatible with their own, as evidenced by attributes like health, scent, and MHC profiles, ensuring offspring immunity. Preferences for other traits that correlate with immune function like attractiveness, masculinity, status, and ethnicity, co-evolve with and signal immune advantage, even if immunity itself remains unperceived.

In some bird species, females preferentially choose males with more brightly colored feathers, which are an indication of good health and immune function. Similarly, in humans, women have been found to be more attracted to men with symmetrical facial features, which is a sign of good developmental stability and immune function. In general, people tend to be more attracted to the scent of individuals with dissimilar immune systems, suggesting that the immune system may be an important factor in human assortative mating and sexual selection. This is because mating between dissimilar immune systems decreases inbreeding and therefore increases genetic diversity and adaptability.

Cultural assortment based on factors like religion, social class, education level or geographic region, also promote assortative mating, as these attributes correlate at least moderately with immune adaptation and are preferred in mates. However, prejudice against others seen as more disease-prone or with less desirable immune profiles leads to weaker attraction and mating, enhancing assortment if not accuracy.

Assortative mating provides crucial benefits for adapting to local environments, maximizing offspring fitness, promoting cooperation within groups, and generating diversity between groups. The immune system plays a key though often hidden role in facilitating assortative mating through influences over mate choice, preferences, imprinting, and stigma. Such psychological mechanisms have evolved because they resulted in the greatest reproductive success, shaped by the fundamental goals of health, inclusive fitness, and adaptation.

MHC profiles

Over time, these selection mechanisms have led to distinct mating preferences for different immune profiles based on local disease ecologies. The evolution of diverse immune types within a species was driven by these preferences. Other signaling mechanisms, such as skin carotenoids and MHC profiles, also provide immune information that partners find attractive in proportion to perceived compatibility.

MHC (Major Histocompatibility Complex) profiles are a set of genes that code for cell surface proteins that are important for the immune system's ability to recognize and respond to foreign substances, such as viruses, bacteria, and other pathogens. MHC profiles are also known as HLA (Human Leukocyte Antigen) profiles in humans.

MHC proteins are found on the surface of cells and act as markers that help the immune system distinguish between the body's own cells and foreign cells. When the immune system encounters a foreign substance, it identifies the MHC proteins on the surface of the foreign cells and triggers an immune response to destroy them.

MHC genes are highly polymorphic, meaning that there are many different variations of these genes within the population. Each individual has a unique MHC profile, which is determined by their specific combination of MHC genes.

The diversity of MHC profiles within the population is thought to be important for the immune system's ability to recognize and respond to a wide range of foreign substances. However, this diversity can also create challenges for organ and tissue transplantation, as the immune system may recognize the transplanted tissue as foreign and mount an immune response against it.

In addition to their role in the immune system, MHC profiles have also been linked to a number of other biological processes, including mate selection, odor recognition, and autoimmune diseases.

Molecular signaling and neurotransmission

Through bioactive molecular signaling via various nervous systems, the immune system can regulate the synthesis, release, and reuptake of neurotransmitters like adrenaline, glutamate, GABA, dopamine, serotonin, etc. Inflammatory cytokines can activate or inhibit neurotransmitter signaling. For example, inflammation can increase glutamate release, reduce GABA and serotonin activity, and alter dopamine neurotransmission. These effects are implicated in sickness behaviors and mental health, and in particular with depression.

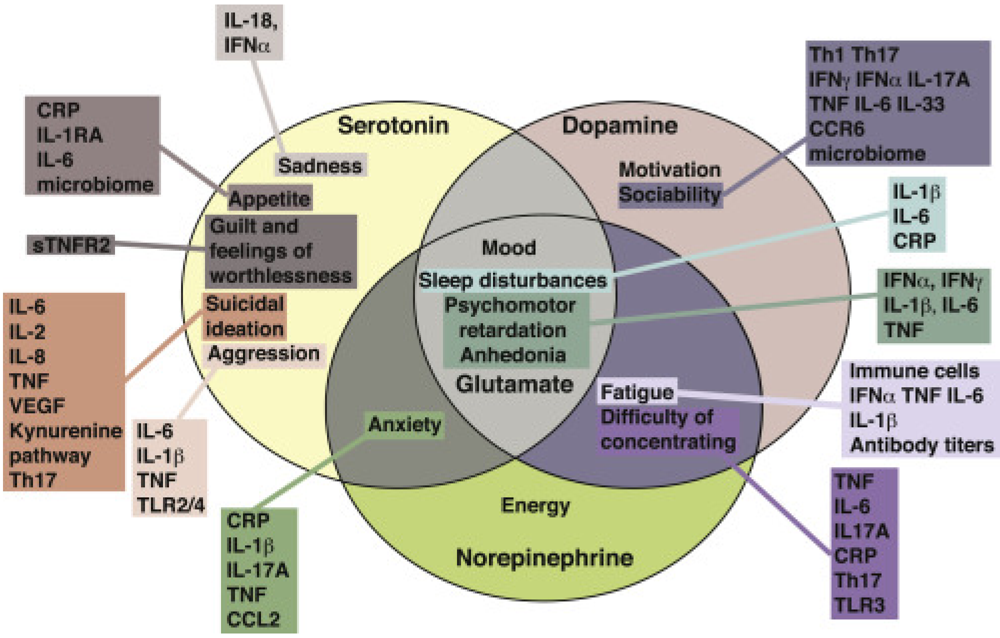


figure: Symptoms of Depression Associated with Different Immunological Changes
Nemeroff et al. 4
Monoamine neurotransmitters have been associated with various symptoms of depression as depicted in each oval. Some symptoms are dependent on multiple neurotransmitters, such as psychomotor retardation that is regulated by serotonin, dopamine, norepinephrine, and glutamate. Each box represents the different immunological changes (e.g., cytokines, immune cell, and others) associated with each symptom.

The immune system regulates the hypothalamic-pituitary-adrenal (HPA) axis and the release of hormones like cortisol, adrenaline, and prolactin. Inflammation activates the HPA axis, leading to increased cortisol which helps contain the immune response. Cortisol and other neuroendocrine hormones in turn regulate immune function, creating a feedback loop. Dysregulation of this neuroendocrine-immune axis may contribute to chronic fatigue syndrome, anxiety, and other disorders.

The vagus nerve connects the brain to major organs and the autonomous nervous system. Activation of the vagus nerve can produce an anti-inflammatory effect. The inflammatory reflex mediated by the vagus nerve and neurotransmitters like acetylcholine is important for controlling inflammation. Disrupting vagus nerve signaling may worsen inflammation and outcomes in conditions like sepsis or arthritis, while stimulating the vagus nerve has been found to have anti-inflammatory effects through inhibition of the Sympathetic and activation of the Parasympathetic Nervous System..

The Central Nervous System

The primary nervous system involved in processing incoming perceptions is the central nervous system (CNS). The CNS consists of the brain and spinal cord, which work together to receive, process, and interpret sensory information from the environment.

Different areas of the brain are specialized to process different types of sensory information. For example, the visual cortex in the occipital lobe of the brain is responsible for processing visual information, while the auditory cortex in the temporal lobe processes auditory information. When sensory information is detected by specialized receptors in the body, such as in the eyes, nose, ears, or skin, it is transmitted as electrical signals through neurons to the CNS. The CNS then processes this information, integrating it with past experiences and knowledge, to create a perception of the environment.

When the CNS detects a potential threat, such as an infection or injury, it can activate the immune system to respond. This is done through the release of signaling molecules, such as cytokines and chemokines, that communicate with immune cells throughout the body.

Conversely, the immune system can also communicate with the CNS in response to perceived threats. Cytokines produced by immune cells can cross the blood-brain barrier and activate receptors on brain cells, such as microglia and astrocytes. This can lead to changes in neurotransmitter levels and brain function, which can influence behavior and mood.

For example, inflammation, which is a key component of the immune response, can contribute to the development of mood disorders such as depression and anxiety. Inflammation can alter the balance of neurotransmitters in the brain, including serotonin and dopamine, which are important for regulating mood and motivation.

Furthermore, stress, which is often accompanied by changes in perceptions and emotions, can also activate the immune system and contribute to inflammation. Chronic stress can lead to dysregulation of the immune system, with increased production of pro-inflammatory cytokines, which may in turn contribute to the development of mood disorders.

Overall, the interaction between the CNS and immune system in response to perceptions is complex and bidirectional, and involves a range of signaling molecules and pathways.

Neurogenesis and neuroplasticity

Immune system regulates neurogenesis and neuroplasticity. Inflammation can inhibit the growth of new neural connections and stem cell proliferation in the hippocampus and other brain regions. This may negatively impact learning, memory, and mood regulation. Some antidepressant and anti-inflammatory drugs work by blocking these effects and restoring neurogenesis.

Inflammation can alter the integrity and permeability of the blood-brain barrier. This allows immune cells, inflammatory molecules, and neurotoxins to enter the brain and cause damage. Breakdown of the blood-brain barrier is implicated in diseases like multiple sclerosis, meningitis, and Alzheimer's disease.

The immune system also plays a critical role in regulating reproduction. During pregnancy, the immune system must tolerate the developing fetus, which contains foreign genetic material from the father. To do this, the immune system undergoes a series of changes that suppress the immune response, making it easier for the fetus to survive. However, these changes can also make the mother more susceptible to infections and other health problems.

Microglia and astrocytes

The activity of glial cells like microglia and astrocytes is strongly regulated by the immune system. Microglia become activated in response to inflammation, which can be either beneficial or harmful, as it may be activated both by inflammatory and anti-inflammatory cytokines. Astrocytes also become reactive and undergo morphological changes that alter their support of neural signaling. Glial dysregulation is implicated in most neurodegenerative and psychiatric illnesses.

The human immune system and microglia have a very close relationship: microglia are the resident immune cells of the central nervous system (CNS), including the brain and spinal cord. They act as the first line of defense against injury and infection in the CNS. Microglia respond quickly to any disturbances in the CNS by becoming activated. Activated microglia perform several immune functions to protect the CNS. Under normal physiological conditions, microglia remain in a "resting" state with a ramified morphology. They continuously survey the CNS microenvironment for signs of disturbance or damage. Once activated by the immune system, microglia change their morphology into an amoeboid form and migrate toward the site of injury. They remain activated as long as needed to resolve the inflammation and restore CNS homeostasis.

Microglia as the CNS resident immune cells work closely with the peripheral immune system to protect the brain and spinal cord by initiating innate and adaptive immune responses against infections and injuries. Proper regulation of microglial activation is essential for CNS homeostasis and function.

Psychobehavioural regulation

Psychobehavioural action results from emotions, such as stress, empathy, joy, anxiety or disgust. The immune system plays a crucial role in modulating psychological and behavioral responses in humans. While sickness behavior is a well-established example of the immune system's effect on behavior, there is also evidence to suggest that chronic inflammation can lead to negative psychological and behavioral outcomes. Conversely, positive regulation of the immune system, through nutrition, exercise or mindfulness meditation, can have positive effects on mood and cognitive function. The effects of pathogens on behavior further illustrate the relationship between the immune system and behavior.

The immune system also plays a role in empathic arousal, or our ability to feel and respond positively to the emotions of others. Individuals with stronger immune systems tend to have greater empathic abilities, in contrast to those with a weaker immune system. The empathic arousal is a key emotion involved in mate choice and sexual/reproductive behaviour, and the immune system regulates empathic arousal. Therefore, the immune system plays an essential role in regulating reproduction and ultimately, orchestrating natural and sexual selection. The immune system has evolved as a defense mechanism against harmful pathogens and infectious agents, and its functions have co-evolved with psychological and behavioral processes in order to maximize the fitness of the individual.

One of the ways in which the immune system affects behavior is through the activation of the sickness response. When the immune system detects the presence of a pathogen, it activates a cascade of responses, including the release of cytokines, which can lead to symptoms such as fever, fatigue, and a decrease in appetite. These symptoms are thought to have evolved as a means of conserving energy and directing resources towards fighting the infection.

These physiological changes can also have psychological effects. For example, the fatigue and lethargy associated with sickness behavior can lead to a decrease in motivation and an increase in the need for rest. The loss of appetite can also lead to changes in dietary behavior, with a preference for high-calorie, high-fat foods that provide quick energy. These psychological responses can help the body to conserve energy and direct resources towards fighting the infection.

However, sustained and chronic activation of the immune system can lead to negative psychological and behavioral outcomes. Chronic inflammation has been linked to a range of psychological and behavioral disorders, including depression, anxiety, and cognitive decline. Inflammatory processes can disrupt neural circuits involved in mood and cognition, leading to a decrease in motivation, memory, and attention.

On the other hand, there is plenty of evidence to suggest that positive regulation of the immune system can have beneficial effects on psychological and behavioral outcomes. For example, regular exercise has been shown to reduce inflammation and improve mood and cognitive function. Mindfulness meditation has also been found to reduce inflammation and improve mental health outcomes, such as reducing symptoms of depression and anxiety.

Another example of the immune system modulating psychological and behavioral responses is the effect of certain pathogens on behavior. The parasite Toxoplasma gondii is known to manipulate host behavior, altering personality traits such as conscientiousness and increasing risk-taking behavior. This is thought to be an adaptation of the parasite, as it increases the likelihood of transmission to new hosts.

Niels Jerne's network theory of the immune system

Niels Jerne first proposed the network theory of the immune system in his 1974 paper "Towards a network theory of the immune system." At the time, it differed from previous theories of the immune system in several ways.

The network theory proposed that the immune system is a self-referential network made up of molecules that represent one another and interact with one another in complex ways, rather than a hierarchical system. Jerne argued that the immune system is capable of recognizing and responding to an almost infinite number of antigens due to its network structure, rather than a limited set of antigens as proposed by previous theories.

The network theory proposed that the immune system is capable of self-organization and self-regulation, which allows it to adapt to changing conditions and maintain homeostasis, rather than being controlled by a central organizing principle.

Jerne suggested that the immune system is capable of learning and memory, which allows it to respond more effectively to previously encountered antigens, rather than simply responding to new antigens. This has implications for understanding autoimmune diseases, which arise when the immune system mistakenly attacks the body's own tissues. The theory suggests that autoimmune diseases may result from a breakdown in the self-regulation and self-organization of the immune system.

The network theory proposed that the immune system is capable of generating diversity through somatic recombination and mutation, which allows it to recognize a wide range of antigens, rather than being limited to a fixed set of receptors. This notion has been videly used in designing vaccines, which work by exposing the immune system to a harmless form of an antigen so that it can generate an immune response. According to the theory, vaccines may be more effective if they are designed to stimulate a wider range of immune receptors.

The network theory of the immune system has also inspired a subfield of optimization algorithms similar to artificial neural networks. These algorithms are used to optimize artificial immune systems, which are used in fields such as computer science and engineering.

Jerne's network theory of the immune system represents a significant departure from previous theories of the immune system, which tend to focus on the immune system as a hierarchical system that responds to a limited set of antigens. The network theory proposed a more complex and dynamic view of the immune system as a self-referential network capable of recognizing and responding to an almost infinite number of antigens, adapting to changing conditions, learning and memory, and generating diversity.

Conclusion

The overarching proposal of this essay is that emotions evolved as an adaptive function of the immune system to optimize survival and reproduction. A wealth of evidence and concurring perspectives from multiple disciplines strongly supports this thesis.

From an evolutionary, psycholgic and social perspective, the immune system appears to have evolved to influence several mechanisms in modulating stress, empathic arousal, reproductive behavior, and sexual selection in various animal species, including humans. The influence of the immune system is ubiquoitus in all major functions of organism from roviding protection to securing reproduction.

The same appears to apply to neurobiological mechanisms under the regulation of the immune system. When body is perceived to be under physical, psychological or environmental threat, the immune system activates the sympathetic nervous system, followedd by release of neurotransmissors such as cortisol and pro-inflammatory cytokines.

Conversely, when the body is perceiving lower possibility of a threat, the immune system may in response increase the levels of prosocial neurotransmitters such as oxytocin and estrogen, which are linked to approach, empathy, caregiving and social bonding behaviour. By regulating pair bonding and sexual selection, the immune system can influence reproductive behavior and sexual selection. The immune system is an important factor in mate choice, as individuals may be more attracted to mates with a diverse set of immune genes. This is because a diverse immune system can provide better protection against a wider range of pathogens.

The immune system can play a role in determining mating preferences and assortative mating. As mentioned earlier, humans tend to be attracted to partners with immune profiles that are genetically compatible with their own, as evidenced by attributes such as scent, visual cues and MHC profiles. This may help ensure offspring immunity and improve reproductive success.

At the most fundamental level, evolution shapes all biological traits to maximize an organism's ability to survive threats and produce offspring. The immune system emerged as life's first line of defense against harm, while emotions motivate behaviors impacting these goals. As detailed in this essay, immune responses influence psychological processes and vice versa via interconnected signaling pathways. This bidirectional relationship indicates emotions and immunity co-evolved as coordinated, interdependent systems.

Analysis of their interactions provides insight into emotions' evolutionary origins and roles. Immune signaling activates emotional brain states that regulate fight-or-flight, tend-and-befriend, sexual, and social behaviors through conserved neurotransmitter and hormonal pathways. These emotion-driven responses optimize defense, resource access, social bonding, and reproduction in ways enhancing inclusive fitness over generations.

Emotions' conserved features like valence and expressiveness support their evolved functionality as adaptive, regulated states rather than inherent qualities. Their immune regulation unconsciously shapes behaviors and preferences despite emotional awareness, analogous to vision and memory. Emotional commonalities observed across species provide strong evidence for their deep evolutionary foundations tuned by immune signaling requirements.

Immune influences over mating also demonstrate emotions' optimized functionality. Preferences evolutionarily track partners with immune profiles ensuring offspring health and adapting to changing disease ecologies. This interplay shaped group cohesion through assortative mating preferences and cultural assortment regulating fitness tradeoffs.

Emotions thus adaptively regulate multidimensional responses to stimuli optimized through natural selection pressures. While granting rich subjective experiences, their ultimate purpose serves evolutionary ends. Far from diminishing meaning or experience, this perspective offers compelling insight into emotions' deep origins and significance as innately adaptive, biologically grounded phenomena.

Taken together, extensive evidence supports the teleology that emotions emerged and evolved through interactions between the immune system, brain, and behavior to motivate survival-and reproduction-optimizing responses to the environment. By regulating this coordinated relationship, the immune system profoundly shapes humanity's deepest experiences, social structures, and capacities for meaning—all still ultimately tuned to life's core evolutionary function and purpose.