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Emotion and allostatic control: An active inference account of emotion regulation

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ABSTRACT

Emotions are a central aspect of human experience and they serve as inherently regulatory processes that play a crucial role in supporting allostasis and the adaptive regulation of bodily and physiological states. Here, we propose a novel comprehensive account of emotion regulation — encompassing both implicit and explicit processes — and its role in allostatic control, within the active inference framework. First, we discuss empirical evidence highlighting the roles of emotion regulation in supporting allostasis and the preservation of organismal integrity. Second, we introduce active inference and discuss how emotions have been characterized within it. We emphasize that within active inference, emotions are closely tied to allostatic control, serving as multimodal inferential strategies that support adaptive responses to environmental stressors while preserving biological integrity – through the minimization of interoceptive, proprioceptive and exteroceptive prediction errors, or more formally free energy. Third, we present a novel account of emotion regulation through active inference, that links implicit and explicit regulation to two non-mutually exclusive types of free energy minimization – retrospective/variational free energy and prospective/expected free energy – that underpin distinct regulatory processes. In addition, our proposal systematically maps the core strategies of Gross's process model of emotion regulation to active inference constructs, while also extending this model to incorporate missing elements. Finally, we briefly discuss how linking emotion regulation to active inference offers a novel perspective on maladaptive emotional behavior in psychopathology.

1. Introduction

The word “emotion,” from the Latin *emovere* — a combination of *e*- (variant of *ex*, meaning “out of” or “from”) and *movere* (“to move”) — reflects that the essence of emotional experience lies in dynamic changes of bodily and sensorimotor states.

Emotions are complex, multidimensional, and dynamic phenomena, comprising experiential, behavioral (e.g., bodily, facial), and physiological responses (e.g., respiration, heart rate) that support adaptive behaviors and promote survival, wellbeing, and species preservation (Barrett and Finlay, 2018; Caria, 2023; DeSteno et al., 2013; Panksepp, 2010; Zych and Gogolla, 2021). Influential models of emotion, such as the modal model of emotion (Gross, 1998, 2015), explicitly distinguished emotion generation from its regulation by illustrating specific regulation strategies individuals use to alter the trajectory of an emotion at different points in the emotion generative process. In a similar fashion, appraisal models of emotion consider regulatory actions as a distinct component of the generative process (Lazarus, 1991; Scherer et al., 2001). On the other hand, psychological constructivist models of emotion integrated emotion regulation into the emotion construction process itself, involving manipulating critical elements that in combination constitute emotion (Barrett, 2017b; Barrett et al., 2025; Barrett and Russell, 2015; Russell, 2003). Constructivist theories build upon a large body of research supporting the view that emotions are inherently *regulatory* processes (Cole et al., 2004; Gross and Barrett, 2011). As emotion in its essence, independently of its categorization, is a dynamic physiological change by which the organism responds to the environment, it can be viewed as an inherent regulatory process, where generation and regulation are interdependent processes. Within this perspective, emotion regulation represents an intrinsic continuous feature of emotion that shapes the unfolding of emotional responses (Campos et al., 2004; Gross and Barrett, 2011). Building on this assumption, we will here provide a comprehensive characterization of emotion regulation as predictive and enactive process within active

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inference perspective. As generally acknowledged, we refer to emotion to express a specific, short-term, and intense reaction to a particular event, whereas we refer to affect to express the broad, often non-conscious, and underlying feeling state.

Emotion regulation - defined as “those processes by which individuals exert influence over the emotions they have, when they have them, and how they experience and express them” (Gross, 1999), see also (Thompson, 1994) — can be achieved through a spectrum of strategies, either explicit or implicit (Gross and Barrett, 2011). For instance, the spontaneous rise of fear and its associated physiological responses’ modulation, such as increased heart rate in dangerous contexts, denotes that regulation operates *implicitly* and without conscious awareness. Conversely, feeling sad but smiling and adopting a more positive attitude in a social situation denotes an explicit strategy to temporarily counteract a negative emotional state.

The leading Gross’s conceptual model of emotion regulation (Gross, 1998a, b), that maps onto the modal model of emotion generation, illustrates a series of strategies individuals use to alter the trajectory of an emotion at different points in its emotion-generating process. In particular, the Gross’s process model of emotion regulation distinguishes five non mutually-exclusive emotion regulation strategies: *situation selection, situation modification, attentional deployment, cognitive change* and *response modulation* (Gross, 1998a, b), that can be instantiated either before (antecedent-focused) or after stimulus appearance (response-focused) (Bonanno, 2005; Isaacowitz et al., 2006; Koole and Jostmann, 2004; Koole et al., 2015; Mauss et al., 2007b; Mauss et al., 2006; Zhang et al., 2017; Zhang and Lu, 2012). These regulatory strategies, crucial to shape the unfolding of emotions, are usually described as mostly explicit perceptual, evaluative and modulatory processes; though, their implicit instantiation has been also illustrated (Etkin et al., 2015; Mauss et al., 2007a).

We assume that emotion regulation, as commonly intended – modulating an emotional trajectory – is closely connected to allostasis: ”a brain-centered, predictive mode of physiological regulation that requires *anticipating* needs and preparing to satisfy them *before* they arise“ (Schulkin and Sterling, 2019; Sterling, 2012). In this perspective, metabolic and energy regulation — associated with behavior, physiology, and brain processing — are central concerns for biological organisms. To manage them, the brain does more than simply react to external perturbations: it orchestrates anticipatory (allostatic) strategies to optimize energy allocation and regulate physiological states in relation to both current demands and anticipated future needs (Barrett and Simmons, 2015b; Cohen and Atzil, 2026; Niven and Laughlin, 2008; Palumbo et al., 2026; Pezzulo et al., 2022; Theriault et al., 2025). Unlike homeostatic regulation, which operates through reactive mechanisms to correct deviations of physiological variables from a set point and maintain them within stable ranges, allostatic regulation (see Table 1) entails anticipatory and feedforward processes. These mechanisms proactively adjust physiological parameters in response to changing or anticipated environmental demands, maintaining their variation within biologically adaptive boundaries.

The conceptualization of emotion regulation as an allostatic process arises from the observation that emotional responses and their regulation involve widespread modulation across autonomic and sensorimotor systems. These coordinated adjustments reflect the dynamic allocation of physiological resources required to manage internal and environmental perturbations. The instrumental role of emotions in mediating allostasis is also evident at the neural level, as there is a significant overlap between the mechanisms underlying allostasis and the generation and regulation of emotions (Barrett and Simmons, 2015b; Craig, 2003; Critchley and Harrison, 2013; Katsumi et al., 2022b; Theriault et al., 2025; Wass, 2023). Notably, individual differences in emotion regulation, which are at the core of personality traits models (Friedman et al., 1980; Hoyle, 2010; Hughes et al., 2020), also reflect intrinsic physiological regulation (or dysregulation) mechanisms (Thayer and Lane, 2000; Yoneda et al., 2023). Conversely, disruption of approriate regulation of our somatic and physiological processes, can lead to allostatic overload (condition in which physiological systems are chronically overactivated or inefficient) and trigger inflammatory processes (Ganzel et al., 2010; Hughes et al., 2020; Lenart-Bugla et al., 2022; McEwen, 1998, 2000; Moriarity et al., 2023; Ng et al., 2024). Furthermore, dysfunctional emotion and allostatic regulation is commonly observed in a variety of psychiatric and neurological disorders (Ng et al., 2025; Paulus et al., 2019; Santamaria-Garcia et al., 2025). This latter evidence further highlights a close relationship between the (dys)regulation of emotions and allostatic mechanisms.

Table 1
Key concepts.

Emotion Regulation: those implicit and explicit processes by which individuals exert influence over the emotions they have, when they have them, and how they experience and express them-

Allostasis: a predictive mode of physiological and energy regulation that requires anticipating needs and preparing to satisfy them before they arise

Allostatic regulation: the process by which the brain and body maintain stability through anticipatory change, adjusting physiological systems (e.g., autonomic, endocrine, metabolic) to meet predicted demands rather than reacting only after disruption occurs.

Stress: the condition in which environmental or internal demands exceed or threaten to exceed the organism’s regulatory capacity, activating coordinated neuroendocrine, autonomic, immune, and behavioral responses to preserve stability.

Allostatic load: the “wear and tear” on the body and brain resulting from repeated cycles of stress response activation and inefficient regulation of physiological systems.

Allostatic overload: the state in which the cumulative burden of stress and allostatic load surpasses the organism’s capacity for adaptation, resulting in functional impairment or disease.

Mitochondrial stress: a cellular condition in which mitochondrial integrity, bioenergetics, or signaling pathways are disrupted, triggering adaptive responses such as oxidative stress responses and metabolic reprogramming.

Free Energy: free energy is a functional that measures the discrepancy between an agent’s internal model of the world and its sensory inputs. It provides an upper bound on surprise (i.e., the improbability of sensory observations given the model) and thus quantifies how poorly current beliefs align with incoming sensory data.

Variational free energy: a functional that measures how well an agent’s current internal beliefs align with its present (and past) sensory inputs.

Expected free energy: a functional that measures how well a sequence of action (or policy) is expected to minimize free energy *in the future*, hence it is more prospective compared to variational free energy. It is optional and used for planning, i.e., to evaluates candidate policies in terms of both preference fulfillment and uncertainty reduction.

Policy: belief about a sequence of regulatory actions (or control states) that an agent believes it could pursue over time, used to predict and select future behavior.

Predictions: beliefs about hidden states of the world, causes of sensations, future observations, given the agent’s generative model. They answer the question: “What do I expect to happen?”

Preferences: in active inference, these are encoded as prior beliefs over outcomes or observations, representing which sensory states are expected or desirable for the agent to occupy. They answer the question: “Which outcomes should occur? and thus guide which predictions are worth realizing by acting.

Prediction error: the difference between predicted and actual sensory input, signaling a mismatch between the brain’s expectations and incoming evidence. The minimization of prediction error (or more formally free energy) drives belief updating to improve future predictions and action selection.

Precision weighting: a mechanism that estimates the reliability of predictions and prediction errors, thereby prioritizing the minimization of the most precise errors, possibly linked to neuromodulatory and attentional processes. More informally, it refers to the assignment of confidence (inverse uncertainty) to sensory evidence and prior beliefs during inference.

Belief updating: the process by which an agent revises its internal beliefs about the world, the body, or itself in response to new sensory evidence or prediction errors. Belief updating allows an organism to reduce uncertainty and minimize free energy by continuously aligning its internal model with changing internal and external states. Note that learning can be formally treated as a form of belief updating (about the parameters of the generative model).

Emotion and allostatic regulation have been previously described in the framework of predictive processing and active inference (Barrett, 2017a; Barrett and Finlay, 2018; Barrett and Simmons, 2015a; Parr et al., 2022; Pezzulo et al., 2015a; Seth, 2013; Seth and Friston, 2016). According to active inference, humans — like all living organisms — survive by actively maintaining a limited set of biologically preferred states, such as drive and goal states, which reduce stress on the organism and prevent it from experiencing intolerable perturbations (Parr et al., 2022). Crucially, in active inference, these preferred states can be formally characterized as priors or states that the organism "expects" – and conversely, maladaptive states are those that the organism does not expect and are "surprising". In this technical sense, for a fish, being out of water is "surprising". Within active inference, therefore, living organisms constantly strive to minimize their prediction errors or 'surprise' — or more formally, free energy—, which indexes the discrepancy between predicted and actual sensory input, signaling a mismatch between the brain's expectations and incoming evidence and driving belief updating to improve future predictions. This is accomplished through two complementary strategies, *perceptual inference*, which involves updating internal generative models to better predict sensory input (changing beliefs to fit the world), and *action*, which involves modifying sensory input to match predictions (changing the world to fit beliefs).

Within this perspective, emotions are posited to essentially depend on predictive processes that orchestrate the temporal unfolding of physiological, experiential, and behavioral responses. One could argue that emotion generation is more closely aligned with the perceptual side of active inference, whereas emotion regulation aligns more with the action side; but in active inference, they are not separate processes — they are two sides of the same inferential loop. Emotional states arise from the minimization of *interoceptive* prediction errors, which signal mismatches between interoceptive predictions generated by internal generative models of physiological and emotional processes and incoming interoceptive and exteroceptive evidence (Barrett, 2017a; Barrett and Simmons, 2015a; Seth and Friston, 2016).

Interoceptive models of emotion, generalizing the 'appraisal' theories of emotion (Lazarus, 1991; Scherer et al., 2001), proposed that emotions emerge from inferring the causes of interoceptive signals through interoceptive prediction errors' minimization (Barrett and Simmons, 2015a; Pezzulo, 2014; Seth, 2013; Seth and Friston, 2016). Complementarily, Barrett's theory of constructed emotion similarly conceived of emotional states as arising from actively inferred generative models of the causes of interoceptive afferents, although it assumed that such inference is shaped by culturally embodied concepts that allow for the categorization of core affect, reflecting the current allostatic state of the organism (Barrett, 2017b; Barrett et al., 2025; Barrett and Russell, 2015; Russell, 2003; Theriault et al., 2025). This model emphasizes allostasis as a fundamental process for emotion, in which the instantiation of predictive representations of current and future physiological states effectively supports allostatic regulation, that is, the proactive regulation of the internal environment (e.g. metabolic resources) to anticipate and meet the organism's needs (Barrett et al., 2016; Seth and Friston, 2016; Smith et al., 2019a; Smith et al., 2019b; Sterling, 2012; Tschantz et al., 2022). Affect and emotion are intrinsically linked to generative models that continuously predict future action outcomes and, crucially, whether these are good or bad for the organism. These (low dimensional) generative models are crucial for allostasis and adaptive interoceptive processing and the management of metabolic cost – and when maladaptive, can cause psychopathological conditions.

Despite their appeal, these previous predictive processing and active inference accounts of emotion did not capture the full range of the mechanisms of implicit and explicit regulation of emotion and their relevance to its generative process and organism's allostasis, nor did they systematically integrate with psychological models of emotion regulation, such as the Gross's model (Gross, 1998a, b).

The main goal of this work is to fill a gap in current theories by proposing a novel and comprehensive account of emotion regulation aligning with previous predictive models of emotions which conceives both implicit and explicit regulation as crucial processes for allostatic regulation. Within the active inference framework, we postulate that free energy minimization is the overarching principle of emotion regulation that allows us to promote probabilistically viable physiological states that preserve wellbeing and survival through the adaptive regulation of physiological variables and their related emotional responses. We thus assume that emotion regulation essentially relies on neural mechanisms that continuously evaluate physiological priorities and anticipate fluctuations in biochemical and physiological resources in relation to environmental contingencies (Katsumi et al., 2022b; Schulkin and Sterling, 2019; Sterling, 2012). In short, we propose an active inference model of emotion regulation that fully integrates emotions and their regulation with allostatic mechanisms, as they jointly converge to reduce physiological uncertainty, optimize resource allocation and energy expenditure, and ensure adaptive behavior and overall survival.

The remainder of this paper is organized as follows. In the "Implicit and explicit emotion regulation and allostasis" section, we review the literature to describe emotion and its regulation as primarily (though not exclusively) implicit processes that support allostasis and the preservation of organismal integrity. In the"Active inference and emotion" section, we introduce active inference theory and discuss how emotions have been characterized within it. We emphasize that emotions are closely tied to interoceptive inference and allostatic control, framing them as multimodal inferential and regulatory strategies that support adaptive responses to environmental stressors while preserving biological integrity, through free energy minimization. Then, in the subsequent "Emotion regulation as active inference" section, we present a novel account of emotion and its regulation through active inference (see Fig. 1). Mapping emotion and its regulation onto this framework allows us to make two key contributions. First, we link implicit and explicit regulation to two non-mutually exclusive types of free energy minimization, distinguishing retrospective (*variational free energy*) from prospective (*expected free energy*) processes (see Table 1), and highlighting the need to engage different types of generative models—simpler models versus more complex models with "temporal depth," capable of predicting the outcomes of future actions or policies to select the most effective one. Second, we reframe and extend the cognitive and behavioral strategies of Gross's process model of emotion regulation within active inference. Unlike Gross's modular, stage-wise framework, we propose that emotion regulation strategies emerge from a continuous inferential process that dynamically optimizes beliefs and actions. Finally, in the last "Active inference and dysfunctional emotion regulation" section, we conclude discussing how linking emotion and its regulation to active inference offers a novel perspective on maladaptive and dyfunctional emotion regulation.

2. Implicit and explicit emotion regulation and allostasis

As outlined in the Introduction, emotions are assumed inherently regulatory as the implicit deployment of a physiological response to an emotional stimulus is an intrinsic regulatory process. Accordingly, emotion regulation is tightly linked to allostasis, the brain's predictive regulation of physiological parameters through anticipatory adjustments, that maintain stability by changing set points adaptively (McEwen, 2000; Schulkin and Sterling, 2019; Sterling, 2012). Emotion regulation and allostatic regulation (see Table 1) are largely overlapping processes by which the brain efficiently coordinates multiple bodily systems to meet predicted future demands in response to environment. As such, emotion regulation involves learned patterns of preparatory and reactive responses of multiple physiological systems, including cardiovascular, metabolic, immune, neuroendocrine and sensorimotor systems, that are triggered by environmental cues. In this section, we review the literature on *implicit* and *explicit* strategies of emotion regulation and its relationship with allostasis, and then discuss a leading attempt to systematize these strategies in Gross's model (Gross, 1998a,

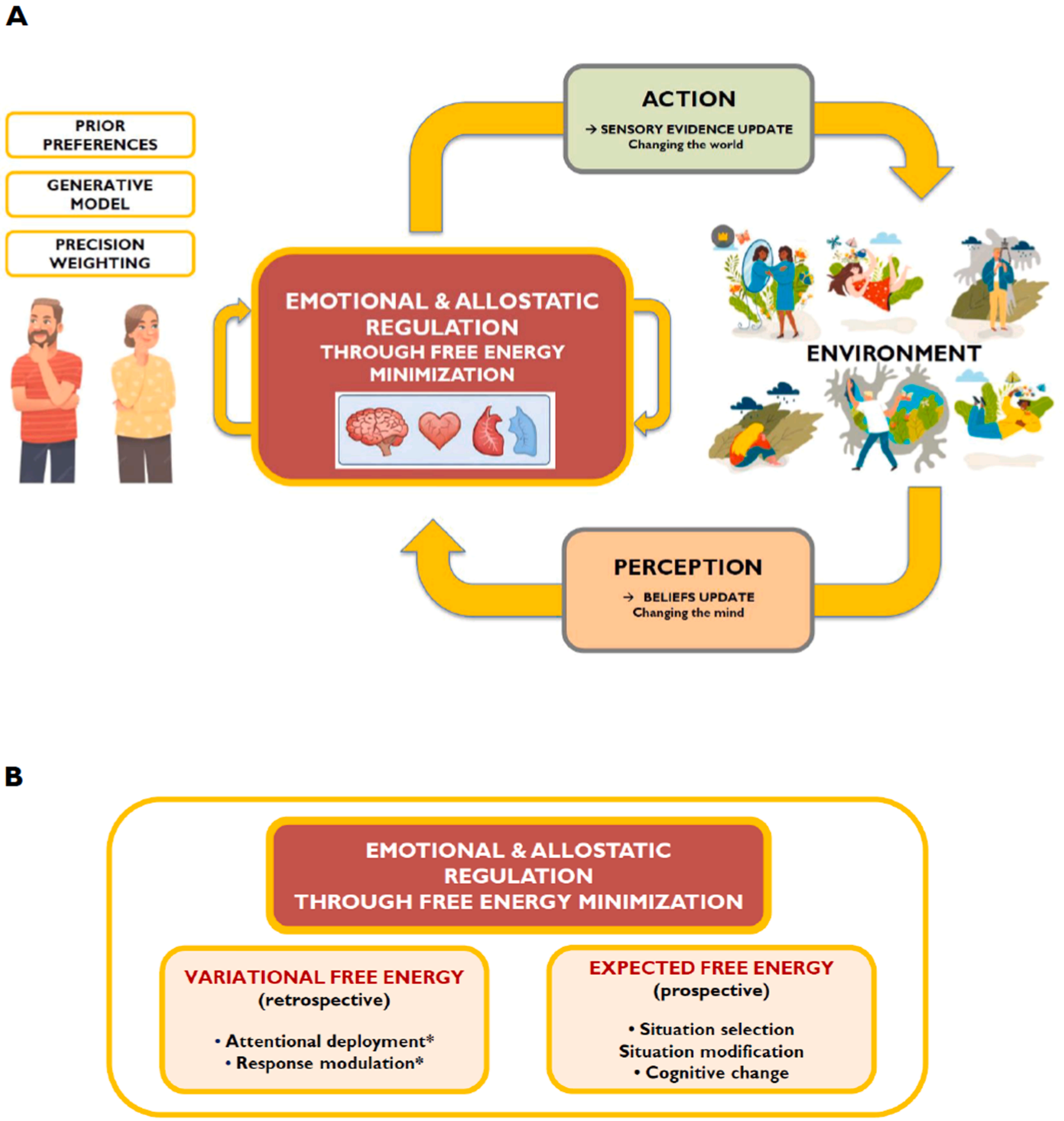

Fig. 1. Integrated model of emotion regulation and allostasis within the active inference framework. A. Emotion generation and regulation emerge from probabilistic beliefs about emotional events and the predictive regulation of physiological states (allostasis) through sequences of autonomic and goal-directed actions and policies. Active inference minimizes exteroceptive, proprioceptive, and interoceptive prediction errors – or more formally, free energy – through both perceptual inference (e.g., beliefs update through perception) and action-based strategies (e.g., active sensing, engagement of autonomic reflexes through action). Perception and action influence, and are reciprocally influenced by, emotion-related allostatic processes which aim at optimizing energy and physiological demands in relation to environmental contingencies, both present and future (predicted). Active inference acquires flexibility through "precision weighting": a mechanism that estimates the reliability of predictions and prediction errors, prioritizes the minimization of the most precise errors, and is possibly linked to neuromodulatory and attentional processes. The large arrows illustrate the action perception loop, while the small arrows illustrate the emotional and allostatic regulation cycle involving the dynamic modulation of the autonomic, endocrine, and sensorimotor systems and their related interoceptive, proprioceptive, and exteroceptive signals. B. Active inference during emotion regulation corresponds to free energy (prediction error) minimization that occurs through implicit and explicit strategies, which map to the two types of free energy. There are two types of free energy minimization in active inference: *variational free energy* minimization is always, while minimization of *expected free energy* is optional and occurs during planning. Retrospective forms of autonomic control map primarily to the minimization of *variational free energy*, whereas the prospective management of uncertainty and physiological costs map primarily to the minimization of *expected free energy*. The distinction between variational and free energy minimization also provides a formal perspective to conceptualize different types of emotion regulation strategies, as defined by the Gross's process model of emotion regulation (see Table 2). *Denotes emotion regulation strategies potentially involving either variational or expected free energy depending on previous subjective experience and learning.

b).

2.1. *Implicit emotion regulation*

Emotion regulation is typically operated through *implicit* processes. Implicit emotion regulation refers to the automatic, unconscious modulation of emotional experience and expression that occurs without deliberate intent or awareness. It works through habitual physiological response patterns, automatic goal activation, and incidental regulatory effects of other cognitive processes. Automatic forms of emotion regulation are efficient without direct awareness or effortful intent, in contrast to explicit (effortful) forms that demand conscious, deliberative application.

Implicit emotion regulation represents a central aspect of emotion (Inzlicht et al., 2021; Koole and Coenen, 2007) and is necessary for fast and adaptive emotional responses to environmental events (Hopp et al., 2011; Koole and Rothermund, 2011; Koole et al., 2015). Direct evidence of implicit regulation of emotion is manifested by the unfolding of different states such as happiness, rage, fear or anxiety, all involving a broader emotional dimension such as the arousal (excitation of the central nervous system). These emotional states are generally associated with automatic modulation of physiological systems – in response to, or anticipating environmental stimuli – including autonomic responses such as sweating, heart beat increase as well as motor contraction, hands and voice tremors, compulsory walking or moving, reflecting increased emotional arousal. At the same time, these sympathetic nervous system responses also promote gradual reduction of excessive emotional arousal and muscle tension (balancing excitation and inhibition (Froemke, 2015; Marin, 2012; Murray et al., 2014; Sohal and Rubenstein, 2019), and support maintaining the organism within viable operational states. Similarly, crying, resulting from either happiness- or sadness-related intense responses, entails activation of both sympathetic and parasympathetic nervous system and involves complex automatic regulation of neurochemical systems including the release of oxytocin, vasopressin, and endogenous opioids, which can improve mood and reduce pain (Bylsma et al., 2019). Crying can signal positive and negative overwhelming arousal but equally mediates its decrease so as to preserve wellbeing, and elicits prosocial behaviors in conspecifics that in turn can promote well-adjusted physical and psychological regulation. Clearly, implicit emotion regulation can extend beyond arousal, including other dimensions such as valence, dominance (the perceived ability to influence, control, or cope with a situation), agency (who or what is perceived as causing an event or emotional state), novelty (how new, unexpected, or unfamiliar a stimulus or situation is) etc. – all involving dynamically coordinated engagement of multiple physiological systems. Implicit regulation can shape emotional responses by operating at various timescales and at multiple brain levels involving dynamic modulation of several exteroceptive and interoceptive signals including neurotransmitters, neuropeptides and hormones (Etkin et al., 2015; Hopp et al., 2011; Koole et al., 2015; Phillips et al., 2008; Quadt et al., 2022; Williams et al., 2009).

A growing number of studies demonstrated that implicit processes support most idiosyncratic emotional reactions (Etkin et al., 2015; Gyurak et al., 2011; Hopp et al., 2011; Koole and Rothermund, 2011; Schwager and Rothermund, 2014). Indeed, both positive and negative emotions are associated with the involuntary regulation of central and peripheral physiological responses, , enabling fast and well-tuned responses to emotional events (Hopp et al., 2011; Koole and Rothermund, 2011; Koole et al., 2015). Notably, implicit regulatory processes associated with emotional expressions and actions also represent (involuntary) social signals through which individuals convey information about their internal state to others and to influence how others perceive and interact with them (Hareli and Hess, 2012; Oatley and Johnson-Laird, 1987, 2011). Such involuntary intersubjective communication has an inherent evolutionary survival value as it can encourage mutual prosocial actions that can in fact exogenously support allostatic regulation, or simply discourage aggressive or unfair behaviors, and thus promote organism's preservation.

The automatic implicit emotion regulatory strategies typically depend on a historical repertoire of context-dependent responses shaped by several factors such as regulatory mechanisms acquired during development through attuned parental behavior (Kerr et al., 2019; Morris et al., 2017), individual overlearned habits and previous experiences, implicit motivational goals, as well as explicit or implicit social norms, which generally conform emotional responses to sociocultural models (Gyurak et al., 2011; Koole et al., 2015). For example, in certain social contexts overt emotional expressions such as hand clapping, knocking on a desk, and stomping or tapping the feet are different cultural-specific way to communicate positive emotions and to discharge increased excitement. The embedding of certain regulatory (or dysregulatory) schemas, mainly resulting from parental imprinting during childhood (Adrian et al., 2011; Cole et al., 2020) as well as from consecutive recurrent exposure to emotional contingencies during adulthood (Kerr et al., 2019; Morris et al., 2017), ultimately leads to encoded representations of adaptive (or maladaptive) implicit responses to emotional stimuli (emotional schemas), (Dickie et al., 2024; Drummond and Gatt, 2018; Edwards and Wupperman, 2019; Faustino and Vasco, 2020; Izard et al., 2008; Nicol et al., 2020; Pilkington et al., 2024). The automatic implementation of a specific regulatory mechanism will then be based on the available representations.

Importantly, the fact that implicit emotion regulation is automatic does not mean that it is merely reactive: instead, it can imply predictive or anticipatory aspects. In an allostatic perspective, any regulatory process is assumed to anticipate rather than merely react to an organism's physiological state and its dynamic perturbations. Accordingly, a number of studies demonstrated that implicit emotion regulation can anticipate expected emotional events. For example, the autonomic nervous system can adjust heart rate and arousal in the presence of anticipated emotional cues, without conscious awareness (Schumacher et al., 2015). In this case, a sort of neurovisceral priming leads to physiological tuning based on predictive information and prior experience. Physiological regulation can be also induced by prior emotional experiences that are reactivated in memory and influence anticipatory emotional states (e.g., calmness before a familiar situation) or by unconsciously adjusting expectations for a potentially stressful event so as to reduce emotional intensity when it occurs. In this latter case, implicit predictions automatically simulating future emotional outcomes leads to adjustment of emotional setpoints. Modulation of hormonal responses, such as cortisol secretion, can also adjusts arousal and attentional readiness in anticipation of emotionally salient stimuli, without conscious appraisal (Erickson et al., 2003). Similarly, implicit cognitive and behavioral strategies can be deployed in anticipation of emotional scenarios (Mauss et al., 2007a). In summary, all these examples demonstrate that implicit emotion regulation instantiates expressions of allostatic regulation, because regulating emotions involves largely the same predictive, physiology-balancing mechanisms the brain uses to regulate the body.

2.2. *Explicit emotion regulation*

We have so far described how emotion regulation can operate automatically through implicit processes that support fast and efficient response to environmental contingencies. On the other hand, emotion regulation can also occur through explicit and deliberate strategies that enable individuals to adaptively shape their emotional trajectory (Engen and Anderson, 2018; Gross, 2015; Gross and Ford, 2024). One of the most effective explicit strategies is *cognitive reappraisal*, which involves reinterpreting the meaning of an emotional stimulus in order to change its impact. For example, a student might view a negative performance review as constructive feedback rather than personal failure. Research consistently shows that reappraisal reduces negative affect, enhances positive emotion, and is associated with healthier psychological outcomes (Gross, 2002; Troy et al., 2018). Contrasting regulation approaches are expressive *suppression* or *avoidance*, the deliberate inhibition of outward emotional behavior, or the elusion of emotionally charged situations, thoughts, or feelings to prevent distress. An individual may, for instance, force oneself to smile when sad during social interactions or inhibit the urge to make negative comments when angry, or even decide to avoid the unpleasant situation. While *suppression* may be socially useful in certain contexts, evidence suggests it often increases physiological arousal and impairs memory. Similarly, *avoidance* appears strongly linked to anxiety disorders, depression, and reduced psychological flexibility (Blackledge and Hayes, 2001). Another explicit strategy is *attentional deployment*, where individuals consciously shift their focus away from emotionally charged aspects of a situation. For example, diverting attention to neutral details during a medical procedure can reduce distress. Although useful for short-term relief, overreliance on distraction can resemble avoidance and hinder long-term emotional processing (Walker et al., 2023). In addition, problem-solving represents a proactive form of regulation in which individuals address the source of emotional distress. Confronting a conflict directly or improving preparation for a challenge can reduce negative emotions by altering the stressor itself. This strategy is most effective in controllable situations but less helpful when circumstances cannot be changed. Finally, explicit *physiological/response modulation* involves deliberate manipulation of bodily state instead of changing thoughts (as in reappraisal) or behaviors (as in suppression), For instance, individual may practice slow, deep breathing or progressive muscle relaxation to reduce autonomic arousal and improves emotional outcome.

Notably, although explicit emotion regulation is typically effortful, in certain situations it is more effective in supporting individuals to adjust and counteract dysfunctional regulation processes compared to implicit emotion regulation. In some occasions, explicit regulatory mechanisms are used to appropriately modulate emotional responses when implicit processes, either reactive or predictive, are inefficient and maladaptive (Baumeister et al., 1998; Derakshan et al., 2007; Hoid et al., 2020; Liu et al., 2018).

Cognitive emotion regulation is extensively applied in psychological and psychiatric disorders characterized by dysfunctional emotion regulation (Aldao et al., 2010; Sheppes et al., 2015). In these conditions, the re-instantiation of more adaptive emotion regulation can be moderately attained through behavioral and cognitive strategies, such as reappraisal, acceptance, and problem solving (Aldao et al., 2010; Gross, 2015; Naragon-Gainey et al., 2017; Sheppes et al., 2014; Sheppes et al., 2015). Interestedly, such explicit emotion regulation strategies often correspond to those implicit regulatory schemas that are successfully deployed by healthy individuals to adaptively respond to emotional scenarios (Koole et al., 2015).

While we discussed implicit and explicit emotion regulation processes separately, they are not mutually exclusive but can operate interdependently to modulate emotional responses. For example, initial implicit regulation can trigger explicit regulatory strategies, in particular in case of maladaptive emotional responses. In addition, the relearning of adaptive emotional responses, which entails adopting novel regulator actions, typically occurs explicitly. Learning (relearning) of successful explicit emotion regulation strategies ultimately lead to an update of regulatory schemas through the incorporation of processes, actions and policies that proved beneficial for adaptive responses, and ultimately for allostasis. Furthermore, the repeated deployment of more adaptive explicit regulatory schemas during learning (re-learning) may in turn become again automatic and implicit (Mauss et al., 2007a).

Taken together, all the above-mentioned strategies illustrate the different ways individuals can shape their emotional responses through implicit and explicit allostatic regulation that ensures adaptive functioning in response to internal or external demands.

2.3. The Gross's model

A leading attempt to systematize emotion regulation is due to Gross (1998a, b), who built a comprehensive framework including well-defined, empirically validated and clinically applicable regulation strategies. In contrast to more narrowly structured appraisal models (Lazarus, 1991; Scherer et al., 2001) and constructivist models (Barrett, 2017b; Barrett et al., 2025; Barrett and Russell, 2015; Russell, 2003), Gross's process model of emotion regulation systematically operationalizes regulatory strategies and describes them in relation to their temporal specificity and potential context-dependent efficiency. The Gross's model of emotion regulation is closely aligned with the modal model of emotion (Gross, 1998b, 2015; Gross and Ford, 2024), which links the experiential, behavioral, and physiological components of emotional dynamics to processes — both explicit and implicit — organized around a situation–attention–appraisal–response sequence.

2.4. Gross's emotion regulation strategies

The Gross's process model of emotion regulation provides a taxonomy of regulation strategies, distinguishing antecedent and response-focused regulation and identifying five non–mutually exclusive strategies: *situation selection*, *situation modification*, *attentional deployment*, *cognitive change*, and *response modulation*. The *situation selection* strategy of the Gross's model involves taking anticipatory actions to modify the likelihood of encountering situations associated with desirable or undesirable emotions, such as avoiding or approaching certain stimuli or situations. Similarly*, situation modification* entails direct actions to alter an emotional situation and adjust its impact to align with emotional expectations. This may include *problem-solving* strategies aimed at consciously addressing or eliminating emotional stressors. The *attentional deployment* strategy typically entails changing the emotional scenario by reallocating attentional resources, such as through distraction or shifting attention away from overwhelming stimuli or situations. On the other hand, *cognitive change* involves reappraising the emotional context to alter its impact. *Cognitive change* also includes *acceptance*, voluntarily choosing not to alter an emotional event and allowing the experience to unfold naturally (Messina et al., 2021; Wojnarowska et al., 2020); and also comprises *rumination*, where one repeatedly thinks about an emotional event or situation, often focusing on negative aspects (Smith and Alloy, 2009). Finally, *response modulation* targets the regulation of fully unfolded emotional responses by implicitly or explicitly modifying, or suppressing, the experiential, behavioral, or physiological components of an emotional response. Repressive coping and conscious suppression strategies - self-protective inhibition of overwhelming emotions, whether negative or positive - fall under *response modulation*. Notably, repressive coping and conscious suppression often represent maladaptive regulatory strategies resulting in discrepancies between external sensorimotor responses and autonomic reactions.

2.5. Implicit instantiation of Gross's emotion regulation strategies

Although Gross's model was originally developed to account for explicit, volitional forms of regulation, it can also encompass implicit strategies, which we consider fundamental for understanding emotion and its regulation. Several implicitly deployed mechanisms that often involve the regulation of autonomic signals fall into the Gross's *response modulation*, that entails modifications of ongoing emotional responses. For instance, studies reported that individuals may show bradycardia in anticipation of an aversive event, aimed at freezing and increasing attentional focus (Hagenaars et al., 2014). Automatic regulation of the parasympathetic system in the presence of learned safety cues (e.g., familiar environments) can reduce unnecessary vigilance and emotional reactivity. Affiliative interactions and social engagement activate the ventral vagal complex, and thus promote calm states (Porges, 2007). Slow, deep breathing indeed supports vagal afferent signaling, which in turn modulates emotion regulation and autonomic stability. When repeatedly exposed to emotional images or sounds, electrodermal activity appeared to be automatically down-regulated indicating that habituation occurs without conscious effort (Lang et al., 1997). Individuals with social training may implicitly suppress peripheral blushing responses (Bogels, 2006; Hartling et al., 2016; Mulken et al., 2001).

In addition, implicit *response modulation* can also involve modulation of neurotransmitters, neuropeptides and hormones. Studies showed that increased serotonergic tone reduce automatic amygdala reactivity to threat, and hence attenuate emotional responses without conscious control (Crockett et al., 2008). Oxytocin has been shown to facilitate automatic emotion regulation in social context by reducing amygdala activation in response to social threats (Kirsch et al., 2005). The endogenous opioid system can also decrease negative physical and emotional states without conscious awareness, by automatically modulating affective components of pain and social rejection (Hsu et al., 2013; Zubieta et al., 2005). Additional evidence is also revealed by norepinephrine modulation that can boost sensory processing and enhance attention to threat-related stimuli under emotionally salient contexts (Mather et al., 2016).

On the other hand, implicit instantiation of alternative regulatory schemas such as *attentional deployment, situation selection* and *situation modification*, can also occur. For example, individuals who are repeatedly exposed to emotionally negative stimuli can develop an implicit tendency to avoid attending to those stimuli, effectively downregulating emotional responses without conscious strategy (Gyurak et al., 2011). This reflects attentional deployment as a form of implicit emotion regulation. Behavioral tendencies like avoidance or approach can be also triggered by contextual cues without conscious emotion regulation goals, effectively modifying future exposure to emotional stimuli (Bargh and Williams, 2006). Individuals may adjust environmental cues — turning on soothing music, altering lighting, or changing location — without deliberate emotion-regulation goals, thereby modifying the affective quality of a situation implicitly (Tamir and Mauss, 2011).

In short, both implicit and explicit forms of emotion regulation can use the same strategies identified by Gross, but have different characteristics and demands in terms of effort, awareness and resources. Optimal functioning of emotion regulation is thus based on a dynamic integration of automatic mechanisms and conscious control (Gyurak et al., 2011).

3. Active inference and emotion

In this Section, we briefly summarize the main concepts of the active inference framework and how emotion is conceptualized within it. This overview thus serves to introduce the key ideas that we will build on in the subsequent section to advance our perspective on emotion regulation.

3.1. Active inference

Active inference is a computational framework originally introduced to explain perception and action under the common imperative of free energy minimization (Friston, 2009, 2010; Parr et al., 2022) (see Table 1). In the active inference framework, free energy is a formal quantity that measures the discrepancy between an agent's internal model of the world (and of the body in it) and the sensory observations—exteroceptive, interoceptive and proprioceptive. It provides an upper bound on surprise (i.e., the improbability of sensory observations given the model) and thus quantifies how poorly current beliefs explain incoming sensory data. By minimizing free energy through perceptual inference (updating beliefs), and action (updating sensory evidence), an agent actively supports the alignment of its model and the environment and achieves adaptive behavior (see Table 1). The central idea is that the brain employs a generative model — a probabilistic model of the world and of the body within it — that encodes probabilistic beliefs about how "hidden states" of the world and the body (called "hidden" since they must be inferred from sensory observations) give rise to sensory observations. Probabilistic beliefs concerning external states of the world may encompass elements such as the presence of obstacles on a path or the location of a goal, and are inferred mainly (although not exclusively) through exteroceptive and proprioceptive sensations, whereas those pertaining to the state of the body may include factors such as current heart rate, body temperature, or levels of hydration, and are inferred mainly (although not exclusively) through interoceptive sensations. These probabilistic beliefs continuously generate predictions about external events and the outcomes of actions. The predictions are then compared against sensory observations — exteroceptive, proprioceptive, and interoceptive — and the resulting prediction errors indicate the extent to which the brain's current hypotheses deviate from reality and require updating during inference. Minimizing such errors (or more formally, *free energy*) constitutes the organism's overarching objective.

Perception and action both contribute to this minimization, albeit in complementary ways. Perception updates probabilistic beliefs to bring predictions into closer alignment with observations, ensuring that the organism's hypotheses remain accurate ("changing the mind"). Action, in turn, modifies the world so that sensory inputs better match predicted outcomes ("changing the world"). At each moment, the balance between whether to "change the mind" or "change the world" depends on the so-called precision-weighting: a mechanism, possibly linked to neuromodulatory and attentional processes, that estimates the reliability of predictions and prediction errors, thereby prioritizing the minimization of the most precise errors (see Table 1). Crucially, the organism's preferred states are encoded as high-precision prior beliefs in the generative model — for example, an implicit interoceptive expectation of not being hungry or thirsty, or, in the case of a fish, an expectation of being in water. Acting to fulfill these high-precision priors — such as eating when hungry or remaining submerged for a fish — constitutes goal-directed behavior that realizes the organism's preferences. Conversely, states that deviate from such high-precision priors (e.g., hunger, or a fish being out of water) generate prediction errors that must be resolved for survival. The encoding of preferred states as high-precision priors ensures they are prioritized. In sum, active inference views perception and action as cooperative processes that continuously update the generative model to form approximate posterior beliefs about the most likely causes of sensory states. By minimizing free energy, these beliefs help align the model with reality and guide adaptive behavior that fulfills the organism's prior expectations.

3.2. Variational free energy and expected free energy

In active inference, a fundamental distinction is made between two types of free energy: *variational free energy* and *expected free energy* (Parr et al., 2022) (see Table 1). *Variational free energy* is the core quantity minimized during inference. It can be decomposed into two complementary terms: *accuracy* and *complexity*. Minimizing *variational free energy* involves a trade-off, with posterior beliefs updated to provide the most accurate account of the data while maintaining the simplest (least complex) explanation. An equivalent decomposition expresses *variational free energy* as the sum of *divergence* and *evidence*, which, from a psychological perspective, map onto the complementary sub-objectives of perception and action. Minimizing *divergence* ensures that posterior beliefs approximate the true causes of sensory data, corresponding to perception. Once divergence is minimized, *variational free energy* becomes an approximation to the (negative log) *evidence* of the data — or *surprise* — which measures the model's explanatory power relative to the observations. This quantity can be also minimized by changing observations through action. Importantly, the minimization of *variational free energy* is *retrospective*, in the sense that it only considers present and past observations.

There is also a second, prospective form of free energy — *expected free energy* — which underlies more advanced (and optional) processes such as deliberation, planning and *policy* selection (i.e., choosing future courses of regulatory actions), where policies are beliefs about a sequence of regulatory actions (or control states) that an agent believes it could pursue over time, used to predict and select future behavior.

Expected free energy provides a way to evaluate the quality of alternative policies in relation to the future states and outcomes they are expected to bring about: the lower the *expected free energy* of a policy, the better its quality and the higher its probability of being selected. *Expected free energy* can be decomposed into two complementary components: *pragmatic value* (utility maximization) and *epistemic value* (uncertainty minimization). Balancing these two terms means selecting policies that optimally trade off achieving preferred outcomes, encoded as priors in the generative model (the *pragmatic* imperative), and gaining information to reduce uncertainty (the *epistemic* imperative). These imperatives are tightly interdependent; for instance, a hungry agent may wish to consume food (*pragmatic* imperative), but this may first require discovering where the food is located (*epistemic* imperative).

In sum, active inference entails a fundamental, retrospective process of *variational free energy* minimization and an additional (and optional), prospective process of planning and policy selection through the scoring of the *expected free energy* associated with each policy. Minimizing *variational free energy* is the fundamental operation of all living organisms, regardless of the degree of sophistication of their generative models. Indeed, *minimizing free energy* is possible even if the organism is endowed with a relatively simple generative model that considers only present and past states and observations – and it typically results in engaging relatively simple forms of action. For example, when an organism detects interoceptive prediction errors, it may infer that its body temperature is higher than the preferred level encoded in the generative model—thereby generating a negative feeling of discomfort — and engage autonomic reflexes such as sweating to restore balance. In addition to these reactive regulation strategies, which only occur after a prediction error is sensed, relatively simple generative models can also support basic forms of anticipatory regulation strategies, which operate even before prediction errors are sensed. For example, they may initiate "anticipatory cooling," activating autonomic reflexes before a rise in body temperature is actually sensed, when predictive sensory cues signal an impending increase (Tschantz et al., 2022).

In contrast to *variational free energy*, calculating *expected free energy*, as required for planning and policy selection, is fundamentally a prospective process, necessitating consideration of future states and observations, not just present and past ones. Since future states and observations cannot, by definition, be directly observed, the organism must endogenously generate them — predicting them through its generative model. This, in turn, requires advanced generative models — referred to as *temporally deep* generative models—that can operate offline and estimate which states and observations are more likely under each policy. These advanced generative models enable sophisticated capabilities; for example, they could allow a runner who is not currently thirsty to decide to bring a bottle of water (with the necessary amount of liquid), anticipating a future need to drink a specific quantity to restore body temperature and satisfy thirst later during the run (Tschantz et al., 2022).

The distinction between (retrospective) *variational free energy* and (prospective) *expected free energy* — and the fact that the latter, but not the former, requires advanced, temporally deep generative models — will become particularly important in the next Section, where we will discuss implicit and explicit strategies for emotion regulation. Before that, in the remainder of this section, we briefly review how emotion, interoceptive processing, and allostatic control are currently conceptualized within active inference and introduce our novel perspective.

3.3. Emotion, interoceptive processing and allostatic control within active inference

Previous theoretical accounts of emotion as *active interoceptive inference* inherently assumed the dynamic nature of emotion (Barrett, 2017a; Barrett et al., 2025; Barrett et al., 2016; Ben-Ze'ev, 2001; Seth and Friston, 2016; Theriault et al., 2025). According to these models, emotional experience emerges from active (interoceptive) inference about the causes of bodily sensations. This involves interactions between descending (top-down) projections that convey predictive representations of the probabilistic conditions that generate emotional responses — primarily autonomic, hormonal, and somatic signals — and ascending (bottom-up) interoceptive and exteroceptive prediction errors. Interoceptive predictions can be resolved either by updating beliefs about the state of the body or by acting to modify the body itself and the ensuing sensations. In both cases, changes in predictive representations — or in the body state itself — translate into changes in emotional experience. In particular, the "interoceptive inference" model proposed by Seth conceptualizes emotions as the result of predictive inference about interoceptive signals (Seth and Critchley, 2013), whereby the brain continuously generates predictions about bodily states and updates them based on incoming visceral sensory input. Emotions arise when the brain infers the causes of interoceptive changes, integrating bottom-up bodily signals with top-down expectations. A key feature of this model of emotions is the role of precision weighting: emotions are shaped by how much confidence is assigned to interoceptive prediction errors versus prior beliefs. The interoceptive inference model, generalizing 'appraisal' theories that view emotions as emerging from cognitive evaluations of physiological changes (Lazarus, 1991; Scherer et al., 2001), focuses specifically on extending predictive coding to interoception, with emphasis on how this informs emotion and embodied selfhood. On the other hand, Barrett's theory of constructed emotion delineates a comprehensive brain-based computational account proposing that emotions are constructed experiences, emerging from the integration of core affect (valence and arousal derived from interoceptive signals) with conceptual knowledge and contextual information. Rather than discrete, hardwired emotion circuits, the brain categorizes ongoing interoceptive and exteroceptive sensations into emotion concepts (e.g., fear, anger) through predictive processing. Emotions therefore depend on prior experience, language, and learning, and vary across individuals and contexts (Barrett, 2017a; Barrett and Simmons, 2015a; Pezzulo et al., 2015a; Seth, 2013; Seth and Friston, 2016). Barrett's model therefore places more emphasis on explaining emotion as emerging from categorizing interoceptive predictions using learned concepts, and provides a functional account of why the brain constructs emotions with central emphasis on allostasis – also emphasizing that the interoceptive / allostatic system sits at the core of the brain hierarchy (Katsumi et al., 2022a; Theriault et al., 2025; Zhang et al., 2025). Both models imply that emotion regulation operates primarily by altering predictions about bodily states rather than suppressing emotional responses after they occur. In Seth's framework, regulation is primarily achieved by recalibrating interoceptive predictions or adjusting the precision assigned to bodily signals, thereby reducing persistent prediction errors. In Barrett's framework, regulation primarily involves reshaping the concepts and interpretations applied to interoceptive sensations — through reappraisal, learning, and contextual reframing — allowing the same bodily state to be experienced as different emotions. Crucially, both models predict that early, predictive regulation of interoceptive inference is more efficient and less physiologically costly than late-stage response modulation, aligning emotion regulation with allostatic control.

Furthermore, some studies have attempted to formalize computational models of key components of emotion within the framework of the free energy principle. It has been proposed that the dynamics of free energy over time may be linked to emotional experience and valence (Joffily and Coricelli, 2013): a decrease in free energy (or its anticipation) might correspond to positive valence, whereas its increase might correspond to negative valence. More recently, emotional valence has been formalized as the variation of confidence (expected precision) in agent's action model based on free energy (Hesp et al., 2021). Furthermore, a model associating free energy with arousal potential and its variations has been proposed to explain emotional valence (Smith et al., 2019b; Yanagisawa et al., 2023).

Summing up, previous accounts of predictive processing and interoception highlighted important aspects of emotion regulation, but some points remain unclear, such as under which condition emotion regulation processes are more implicit or explicit, and when it implies changing what is predicted (e.g., the content of interoceptive priors) versus changing the confidence (or precision) in such predictions, which is important to characterize the distinction between — for example — reappraisal (content change) from attention or mindfulness (precision change). Furthermore, the above accounts of predictive processing and interoception did not comprehensively address the emotion regulation strategies identified by Gross. For example, less attention in the literature has been devoted to the fact that many effective regulation strategies operate by actively changing the world, not the mind (but see (Barca and Pezzulo, 2020)), and much remains to be understood about the embodied strategies that we use for emotion regulation and environmental restructuring. Finally, although predictive processing theories of interoception and emotion highlight allostasis, much remains to be understood about how to quantify energetic costs of sustained regulation, cumulative allostatic load (see Table 1), the trade-offs between short-term regulation and long-term stability, and how whole-body and exposomic factors contribute to adaptive and maladaptive cognitive and emotional processing (Engelen et al., 2023; Ibanez et al., 2025; Kleckner et al., 2017; Paulus et al., 2019; Paulus and Stein, 2010).

4. Emotion regulation as active inference

Extending previous predictive models of emotion, here we model emotion regulation as the synergistic process of continuously inferring the physiological condition of the body and the effective management of bodily resources to ensure allostasis, thereby reducing free energy (see Fig. 1). We thus conceive of implicit and explicit emotion regulatory processes as evolutionarily preserved physiological mechanisms that promote allostasis and adaptation to environmental contingencies, mediate the dynamic allocation of resources to address internal and external perturbations, maintain variations within biological limits, minimize physiological resource expenditure while maximizing benefits of the organism, and ultimately ensure species survival by minimizing free energy (Barrett and Finlay, 2018; Parr et al., 2022). As such, they rely on anticipatory representations of emotional states and the trajectories of autonomic responses, sensorimotor actions, and regulatory policies. This involves the continuous prediction and assessment of dynamic variations, primarily in interoceptive signals, but also in proprioceptive and exteroceptive ones. Crucially, different regulatory strategies can modify bodily states and emotional experiences to reduce prediction errors, ranging from implicit (automatic) to explicit (volitional), and supported by generative models of varying complexity. At one end of the spectrum, simple generative models can recruit implicit autonomic responses that implement automatic strategies for resolving prediction errors within certain limits (e.g., sweating, shaking or trembling to reduce emotional arousal). At the other end, more advanced generative models support sophisticated, prospective regulatory policies — implicit, explicit, or combinations thereof — that manage interoceptive prediction errors more indirectly, thereby facilitating allostasis and emotional beahvior. Examples include deliberately slowing one's breathing to reduce arousal or avoiding a party to prevent social anxiety and its associated bodily sensations.

The simplest forms of implicit regulation correspond to adaptive physiological responses and behaviors shaped through evolution, elicited largely automatically to minimize sudden interoceptive — as well as proprioceptive and exteroceptive — prediction errors. These processes can be understood as instances of variational free energy minimization, guiding immediate autonomic actions based on present and past observations and relying only on simple generative models lacking temporal depth (i.e., the capacity to predict the consequences of actions). While simple, these strategies are nevertheless powerful and may include basic anticipatory aspects, as in the case of the "anticipatory cooling" before a run introduced in Section 3. In addition, other forms of emotion regulation — implicit or explicit — can be conceived as more prospective forms of active inference, which involve anticipating the future consequences of alternative emotion and allostatic regulation policies, and selecting the one with the lowest associated expected free energy. Unlike immediate responses, such regulatory policies require generative models with temporal depth, capable of generating probabilistic predictions about the evolution of states and action outcomes under different policy choices. Policy selection under expected free energy prioritizes strategies most likely to achieve preferred physiological and emotional states (or those proven effective in the past, in the case of habits), while considering the entire trajectory of future states generated by each policy.

It is noteworthy that, emotion regulation, that is shaped by the energetic capacity, stress tolerance, and interoceptive signaling upon which neural regulation of emotion depends, relies heavily on activity of mitochondria (Picard and McEwen, 2018). Mitochondria by linking cellular energy metabolism, stress physiology, and neural signaling can set the biological limits and biases within which regulation operates. They can influence the quality of interoceptive signals that contribute to emotional experience by implementing allostasis at the cellular scale. In active inference mitochondria might contribute to constrain precision weighting by setting physiological limits. Furthermore, on a larger brain scale, the hypothalamus plays a key role in integrating allostasis and emotion regulation by coordinating physiological adjustments. It receives inputs from limbic and cortical regions (Zhang et al., 2025) and orchestrates autonomic, endocrine, and behavioral responses via the HPA axis and autonomic nervous system, enabling anticipatory regulation of bodily states. Through this function, the hypothalamus links emotional processing to energy balance and stress regulation, making it an important hub where emotion regulation is implemented as allostatic control (Barrett and Simmons, 2015a; Goel et al., 2025; Ulrich-Lai and Herman, 2009), and thus substantially influencing socioemotional behavior (Caria, 2023). It is also important to note that neurons in the hypothalamus (in the lateral nuclei) can generate multiple signals that encode expectation, appreciation, and uncertainty in appetitive and aversive contexts (Noritake and Nakamura, 2019, 2023).

4.1. Connecting the strategies of emotion regulation of the Gross's model and active inference

We now examine in more detail the range of implicit and explicit strategies for emotion and allostatic regulation recasting in active inference terms the strategies identified in Gross's model (Gross, 1998a, b). There are some fundamental theoretical similarities between the conceptual underpinnings of Gross's model and the formal machinery of active inference. From an active inference perspective, emotion regulation strategies that shape the intensity, duration, and quality of emotional experience rely on a close interplay between generative models predicting emotional states and trajectories, and incoming sensory streams. When seen in this perspective, the strategies described in Gross's process model of emotion regulation can be understood as goal-directed policies that act on bodily states, sensory evidence, attention, or probabilistic beliefs at different levels of the generative model (e.g., higher-level beliefs about the meaning of a situation, or lower-level beliefs about interoceptive states) — or some combination of these. This highlights a fundamental mapping between what Gross calls "emotion regulation" – encompassing the strategies to influence one's own emotions – and goal-directed policies in active inference that influence subsequent emotional states and trajectories and associated physiological and allostatic processes. Another aspect of the extended Gross's model that aligns well with active inference is the concept of dynamic, valence-based valuation systems, which continuously evaluate representations of the current world against desired states (i.e., target emotional states) and trigger regulation when discrepancies are detected. In active (and interoceptive) inference, this mechanism is conceptually equivalent to prediction error: the mismatch between preferred and current interoceptive or emotion-related sensations, which in turn can elicit autonomic responses or more complex regulatory strategies.

Given these conceptual similarities, it is possible to map the five core strategies for emotion regulation identified by Gross into active inference mechanisms. We argue that *situation selection or modification,* which involve anticipating selection or modification to environmental contingencies to favor positive emotional responses or prevent undesired negative (unmanageable) emotions, could be linked in active inference terms to probabilistic generative models including representations of emotional scenarios and their associated implicit or explicit sensorimotor actions and policies that align with preferred prior beliefs. *Attentional deployment* could rely instead on priors of stimulus-response associations and employs attention-related mechanisms to avoid overwhelming and uncontrollable emotional states, and thereby achieving a preferred state. *Attentional deployment* could be linked to the modulation sensory precision via attention (precision weighting) that is key to minimize free energy efficiently. Both *situation modification* and *attentional deployment* involve active modifications of sensory observations, either through sensorimotor actions or attentional shifts. On the other hand, *cognitive change* (as well as *acceptance* and *rumination*) might primarily operate at higher representational levels, where beliefs at higher levels of the generative models are revised to influence the perception of interoceptive, proprioceptive and exteroceptive observations. Finally, *response modulation* might involve the active modulation of autonomic and motor outputs through sensorimotor actions and policies to suppress sensory, proprioceptive and interoceptive prediction errors.

In short, all regulatory actions and policies — whether evolutionarily predetermined or acquired during development — rely on generative models of emotion regulation that generate predictions about allostatic physiological outcomes and needs. These models encode probabilistic representations of goal-directed physiological and behavioral patterns, as well as cognitive and attentional strategies, aimed at dynamically suppressing interoceptive and emotion-related prediction errors — or, more formally, free energy. By minimizing free energy, the organism reduces uncertainty about both internal and external states, thereby maintaining physiological stability through anticipatory adjustments. The various emotion regulation strategies essentially correspond to predictive regulation mechanisms of internal physiological variables (e.g., arousal, metabolism, autonomic activity), that is precisely what defines allostasis. Therefore, free energy minimization through emotion regulation provides a comprehensive computational account by which allostasis could be implemented (Tschantz et al., 2022).

One might also consider that different types of strategies map differently to the notions of *variational* and *expected free energy*. Antecedent-focused strategies — such as *situation selection*, *situation modification*, and *cognitive change* — primarily involve prospective predictions about the unfolding of emotional experiences and therefore relate mainly to the notion of *expected free energy*. By contrast, response-focused strategies — such as *response modulation* — as well as some antecedent-focused strategies like *attentional deployment*, mainly rely on retrospective processes that integrate past and present experiences to reduce *variational free energy*. However, response focused strategies can also involve prospective aspects where contingent emotional response modulation relies on the knowledge of the dynamic consequences of a regulatory policy, hence linking to *expected free energy* (see Table 2 for more details). Thus, some emotion regulation strategies such as *attentional deployment and response modulation* may involve either variational or expected free energy depending on previous subjective experience and learning.

As this discussion exemplified, across physiological, behavioral, and cognitive domains—whether implicit or explicit — emotion regulation involves the continuous interaction between higher-level probabilistic beliefs within the generative model and lower-level autonomic and sensorimotor processes. These interactions give rise to reactive or anticipatory changes in physiology in response to emotional events, as well as modifications of the environment that elicits such responses. However, crucially, different strategies place varying emphasis on higher- versus lower-level processes and engage them with distinct temporal dynamics – which can be mapped to different non mutually exclusive mechanisms of active inference, as discussed above; see also Table 2 for a more detailed mapping of Gross's emotion regulation strategies onto the active inference framework and Table 3 for a specific example of how these strategies can be mapped onto active inference constructs in the context of social anxiety during public speaking.

Given that at each moment in time, many emotion regulation strategies are possible, how can a person select amongst them? From the normative perspective of active inference, theselection of the most effective regulatory strategy or schema (Engen and Anderson, 2018) depends on prior beliefs — implicit or explicit — about the efficacy of actions and policies in resolving discrepancies between preferred and current sensations, thereby minimizing free energy more effectively. Ultimately, the probability of pursuing a specific emotion regulatory policy depends upon a score assigned to each regulatory policy, either through deliberation (e.g., by considering their *expected free energy*) or more automatically (e.g., by engaging autonomic responses or habitual policies), where the best policies – or those expected to lead to the preferred emotional state transitions and interoceptive sensations – are assigned higher probability and hence prioritized. Precision weighting of interoceptive predictions and prediction errors — which prioritizes strategies that most effectively reduce these errors — thus represents a key mechanism for allostatic regulation and concurrent emotional response (Barrett and Simmons, 2015a; Pezzulo et al., 2015b).

4.2. Core features of the active inference account of emotion regulation

Our model aligns with functionalist models of emotion that view

Table 2
This table maps Gross's process model of emotion regulation into active inference concepts, summarizing how the five core strategies identified by Gross link to different types of free energy (*variational free energy* and/or *expected free energy)* and active inference mechanisms. *Denotes emotion regulation strategies potentially involving either variational or expected free energy depending on previous subjective experience and learning.

Emotion Regulation Strategy	Phase in Gross's Model	Description / Function	Type of Free Energy Involved	Mechanism in Active Inference Terms
Situation Selection	Antecedent-focused	Agent anticipates emotional outcomes and selects contexts that align with beliefs and preferences	○ *Expected free energy*	Prioritize policies that select contexts that match prior preferences about valuable outcomes and minimize uncertainty
Situation Modification	Antecedent-focused	Adjusting the situation to change predicted sensory inputs, aligning outcomes with emotional preferences	○ *Expected free energy*	Prioritize policies that change the environment, in ways that reduce mismatches with prior preferences and minimize uncertainty
Attentional Deployment *	Antecedent-focused	Modulates sensory precision via attention, minimizing surprise from threatening or emotionally salient cues	● *Variational free energy* *(○ Expected free energy)*	Precision-weighting of sensory inputs; redirecting attention
Cognitive Change (e.g., Reappraisal)	Antecedent-focused	Alters the agent's interpretation of the situation by modifying prior beliefs to better match emotional expectations	○ *Expected free energy*	Updating of emotion-related beliefs and prior preferences or hidden state inferences
Response Modulation*	Response-focused	Targets bottom-up sensory or interoceptive prediction errors via inhibitory control of emotional expressions	● *Variational free energy* *(○ Expected free energy)*	Modulation of autonomic/motor outputs to reduce prediction error

Table 3
A worked example: Social anxiety in public speaking. A university student with social anxiety is preparing to give a class presentation. The worked example illustrates how emotion regulation strategies (as categorized by Gross's process model) map onto active inference constructs in real-world scenarios.

Emotion Regulation Strategy	Behavioral Example	Active Inference Mechanism	Explanatory Notes	Allostatic impact	Allostatic risk
Situation Selection	Student chooses not to enroll in courses that require presentations	Selects policies minimizing exposure to predicted negative emotions or uncertainty	Reduces anticipated social threat and ambiguity about performance outcomes	Alters future predicted interoceptive states by avoiding high-cost contexts	It can lead to long-term allostatic overload via reduced learning and increased uncertainty
Situation Modification	Arrives early, picks seat near professor, prepares slides meticulously	Select policies that alter the external context to match emotional prior preferences (e.g., perceived safety)	Reduces uncertainty in social environment by shaping the presentation context	Reduces mismatch between expected and actual bodily demands	It becomes maladaptive if control is excessive or rigid
Attentional Deployment	Avoids looking at audience members who seem disinterested	Dynamically allocates attention to sensory cues that generate low surprise	Decreases prediction errors triggered by aversive social signals	Alters which bodily signals dominate inference	Sustained distraction suppresses error signals needed for learning
Cognitive Change (Reappraisal)	Tells self: *“They’re probably just tired, not judging me.”*	Updates beliefs about the (hidden) causes of sensory evidence (here, facial expressions)	Modifies belief about the interpretation of ambiguous social cues	Updates priors over bodily and environmental states	Limited unless reappraisal becomes unrealistic or invalidating
Response Modulation	Tries to control voice tremors and keep hands still	Inhibits autonomic/motor responses to minimize interoceptive (and optionally exteroceptive and proprioceptive) prediction errors	Suppresses mismatch between expected calmness and actual sympathetic arousal	Suppresses or amplifies bodily outputs without changing predictions	High energetic cost It increases allostatic load due to sustained autonomic activation

emotions as intrinsically regulatory and with predictive interoceptive models that conceive of emotions as predictive processes based on anticipatory visceromotor predictions and their confirmation through the recursive explanation of prediction errors and moving away from the representational/stimulus-response perspective (Friston, 2005). Unlike basic emotion theories, which view emotions as mechanistic fixed responses elicited by stimuli, predictive and constructionist approaches conceptualize emotions as dynamic inferential processes shaped by context, prediction, and bodily regulation. In active inference, the stimulus or the physiological response doesn't cause an emotion — it provides sensory evidence that the brain uses to update or confirm its already-ongoing emotional predictions. The emotion and its intrinsic regulation are the prediction itself, modified by prediction error if the sensory input doesn't match expectations. Within this perspective, our theoretical account complements and extends previous models by conceiving emotion regulatory processes as a central component for the active inference of emotions implying free energy minimization. In addition, we proposed that within active inference, the emotion regulation strategies of the Gross’s model map to distinctive aspects of generative models and policies that determine emotional states and trajectories and associated physiological and allostatic processes; furthermore, they differentially engage the minimization of *variational free energy*, *expected free energy*, or both.

Our account diverges from Gross’s process model of emotion regulation in two important ways. First, Gross’s framework assumes modular, stage-wise phases of intervention, where individuals selectively apply regulatory strategies to influence emotional outcomes. This view treats regulation as a secondary process, deployed in response to — or in anticipation of —emotional episodes. In contrast, the active inference perspective suggests seeing emotion regulation as a continuous inferential process that dynamically optimizes beliefs and actions (Table 4). Regulation is not a discrete, stage-based intervention but an emergent property of ongoing belief updating, precision modulation, and interoceptive and allostatic control. Sequential temporal “stages” cannot be clearly demarcated, as regulation unfolds continuously. Second, the Gross’s model of emotion regulation focuses primarily on explicit, volitional processes. Much of the emphasis is on effortful strategies — such as reappraisal or suppression — especially within experimental paradigms where participants are instructed to use them. By contrast, we emphasize that many crucial forms of regulation are implicit and automatic, often unfolding outside conscious awareness yet remaining fundamental to emotional experience and behavior.

In active inference, explicit volitional regulatory processes are supported by temporally deep generative models that include hierarchical predictions about events across multiple timescales — from milliseconds (sensory input) to hours, days, or longer (plans, narratives) that allow the human agent to predict future trajectories of emotional states and regulatory actions so as to adjust present actions accordingly. As explained in the previous Sections, it is only these temporally deep generative models that permit explicitly considering the *expected free energy* associated with each policy. However, importantly, temporally deep generative models can also support *implicit* regulation. Even strategies originally dependent on prospective planning can become automatized through learning: in active inference terms, this corresponds to policies acquiring strong habitual priors. Once established and embodied, such “habitized” policies might sidestep expected free energy calculations (Friston et al., 2016) and enable anticipatory regulation to be deployed automatically in familiar contexts. By contrast, when novel emotional scenarios are encountered and reliable prospective representations are unavailable, the system may fall back on retrospective inference — relying on past and present observations to reduce *variational free energy*. It is also worth reminding again that explicit and implicit emotion regulation strategies are not mutually exclusive but exist on a continuum, and can operate alternately or in parallel, within a hierarchical active inference scheme. Within this hierarchical scheme, higher levels support more explicit and deliberate control strategies and

Table 4
Summary of the main conceptual differences between Gross’s model of emotion regulation and our proposal grounded in active inference.

Gross’s Model	Our proposal
Regulation is mostly a deliberate, effortful intervention	Regulation is largely automatic, continuous, and often implicit
Modular: occurs at discrete stages (situation, attention, cognition, response)	Dynamic and distributed: no fixed stages, but depending on continuous inferential processes of belief and policy updating
Prioritizes conscious strategies (e.g., reappraisal)	Emphasizes sub-personal inference mechanisms, including the optimization of beliefs and precision weighting, while not disregarding that role of deliberate strategies
Separates emotion generation from emotion regulation	Emotion generation and regulation are inextricably linked in the same inferential process
Limited treatment of uncertainty and ambiguity	Explicitly incorporates uncertainty, precision modulation, and prediction error dynamics

lower levels support more implicit and automatic strategies – and these strategies can interact in many ways (Pezzulo et al., 2015b; Pezzulo et al., 2018). For example, lower level, implicit strategies can be fine-tuned (or contextualized) by higher layers, but also acquire some autonomy over time, in such a way that it can subsequently be engaged automatically without deliberation. At the same time, when implicit mechanisms fail to adequately support adaptive regulation — potentially increasing allostatic load (the cumulative strain on the body produced by elevated activity of physiologic systems under challenge, see Table 1) — explicit mechanisms can intervene. In such cases, the selection, adjustment, and optimization of regulatory strategies also promote learning, reflecting the updating of generative models and policy priors, so that the most adaptive strategies can be recruited more automatically in future situations. Overall, these examples illustrate the rich interplay between hierarchically arranged control mechanisms, from simpler to more sophisticated, that are responsible for the complex and multi-scale process of emotion and allostatic regulation in advanced living organisms.

5. Active inference and dysfunctional emotion regulation

Environmental challenges can disrupt well-tuned regulation, pushing the organism into dis-preferred physiological states and increasing free energy. Examples of dysfunctional emotional regulation include cases in which modulation of emotional responses reduces distress only in the short term but it is in long-term emotionally, physiologically or behaviorally dysfunctional, ultimately limiting flexibility and contributing to emotional disorders and psychopathology, or cases in which emotional responses is not at once context-appropriate and flexible, resulting in exaggerated, blunted, or poorly timed emotions that systematically interfere with adaptive functioning.

Our framework may help illuminate the pervasive and chronic dysfunctions in emotional regulation observed in psychological and psychiatric conditions. Psychopathological states such as pathological anxiety and depression have been previously modeled within the active inference framework as disorders characterized by dysfunctional homeostatic and allostatic regulation (Barrett et al., 2016; Maisto et al., 2021; McGovern et al., 2022; Santamaria-Garcia et al., 2025; Smith et al., 2021; Smith et al., 2020; Stephan et al., 2016). For example, both depression and anxiety have been proposed to result from altered interoceptive predictive processing — such as allostatic overload (see Table 1) or low interoceptive sensory precision — that impairs regulatory processes supporting homeostasis and allostasis (Barrett et al., 2016; Paulus et al., 2019; Santamaria-Garcia et al., 2025; Smith et al., 2020; Theriault et al., 2025). Additionally, depression and anxiety have been conceptualized as maladaptive prior generative models that overweigh uncertainty. Dysfunctional high-confidence assignments to unpredictable (Clark et al., 2018; McGovern et al., 2022) or negative outcomes (Badcock et al., 2017) may bias perception of the world negatively, leading to withdrawal and social isolation.

These earlier models can be extended by addressing more directly emotion regulation and dysregulation strategies – of the kind identified in the Gross's model – in psychopathology. As an example, from an active inference perspective, negative emotional states typical of depression and anxiety—such as anhedonia and apathy — could represent maladaptive regulatory strategies aimed at avoiding surprising (negative) states associated with increased free energy. In active inference, maladaptive regulatory predictions can operationally behave as preferences (a person who *values* emotional withdrawal because it minimizes interpersonal cost is expressing a preference, instantiated as a prediction), even though this has a detrimental effect. However, emotional dysregulation not only arise from unsuitable preferences (avoidance is valued) but also from maladaptive beliefs resulting from over-precise predictions (excessive confidence) acquired under adverse conditions (a person who avoids social interaction because they are certain it will be threatening is dominated by over-precise threat predictions). Dysfunctional regulation may be thus a consequence of maladaptive predictions (preferences) leading to pursuit low-cost but suboptimal physiological states, and of miscalibrated, pathological precision estimates (e.g., overly rigid priors about threat or arousal) leading to prediction errors overweighting, dysfunctional allostatic load, and more generally to organism's stress, that is any increase in metabolic resources that exceeds the stress response's capacity to mobilize energy (Kelley et al., 2025).

It is important to note that in clinical conditions, adaptive emotion regulation can be (re-)learned through psychotherapeutic interventions and behavioral training, that often leverage associative and non-associative learning strategies, resulting in long-term modifications of socioemotional behavior (Wright et al., 2024). In active inference context, interventions can either focus on changing predictions by reshaping what states are expected or valued (restructuring goals and meaning), or on relaxing pathological precision, restoring flexibility in belief updating (exposure-based therapies and pharmacological therapy can reduce precision of overly rigid priors, such as ill-conceived threat). Ultimately, (re-)learned regulatory policies that effectively reduce free energy correspond to adjusting probabilistic representations of regulatory schemas, so as to increase the priority of new adaptive policies while simultaneously reducing the priority of maladaptive ones.

In synthesis, emotion dysregulation can arise when predictive regulation is inefficient or maladaptive, leading to persistent prediction errors, elevated uncertainty, and allostatic load. As a result, emotional responses become exaggerated, inflexible, or poorly context-appropriate, reflecting a failure to minimize free energy effectively through adaptive allostatic control. Notably, increased free-energy and allostatic overload can arise from mitochondrial dysfunction altering precision weighting. For instance, changes in mitochondrial metabolism (Picard and McEwen, 2018), by affecting the quality of interoceptive signals can bias emotional inference toward threat, fatigue, or negative emotional valence and lead to emotion dysregulation. In general, stress exposure can lead to dysregulation of the mitochondrial information processing system (MIPS) (Kelly et al., 2024) and reduced metabolic efficiency (mitochondrial stress, see Table1), substantially affecting emotion regulation. The MIPS, which plays a key role in regulating cellular and systemic allostasis (Picard et al., 2014; Picard and Shirihai, 2022), can be altered by different forms of organisḿs stress in response to acute, chronic, or traumatic stressors. Acute stressors may lead to transient allostatic dysregulation and temporary emotional dysregulation, which are typically adaptive and resolve rapidly. In contrast, chronic or traumatic stressors can produce more detrimental and persistent consequences, including allostatic overload and severe emotional dysregulation (Kelley et al., 2025). Moreover, given the central role of the hypothalamus in integrating allostatic processes and emotion regulation, dysfunction within this region can propagate across physiological, affective, and cognitive domains. It follows that emotional challenges can be translated into chronic physiological strain, supporting the view that many mental disorders — including autism (Caria et al., 2020; Mahony and O'Ryan, 2022), bipolar disorder, depression and anxiety (Barrett et al., 2016; Chioino and Sandi, 2025; Hollis et al., 2015; Stephan et al., 2016; Ulgen et al., 2023) — can be conceptualized as conditions of dysfunctional cellular and systemic allostasis (Kelley et al., 2025; Santamaria-Garcia et al., 2025; Xia et al., 2025).

6. Concluding remarks

In our perspective, emotion regulation emerges as a multidimensional process that supports allostasis by dynamically allocating necessary physiological resources and maintaining balance in response to emotional stressors, and thus organism's operational efficiency, thereby minimizing free energy. Implicit and explicit regulatory processes ensure adaptive responses to both current and anticipated challenges by enacting retrospective and prospective forms of active inference, which minimize variational and expected free energy, respectively. While this novel proposal remains to be systematically developed and tested, it might help the cross fertilization between theories of emotion and its regulation developed within different traditions at different level of detail, conceptual or computational. A theoretical neural model of emotion regulation under active inference might be important to elucidate how signals associated with emotion-related free energy minimization during adaptive and maladaptive regulation are mapped onto different parts of an organism's generative models, and neurally implemented within cortical and subcortical structures. In general, our account integrating active inference, emotion regulation, and allostasis can be tested by combining computational modeling, interoceptive inference paradigms, and neurobiological measures. Emotion regulation tasks can be modeled within active inference to dissociate changes in priors, precision weighting, and policy selection, revealing for instance whether dysregulation reflects maladaptive predictions or inflexible precision control of regulatory strategies. Interoceptive inference paradigms can be used for direct manipulation of bodily uncertainty to test how miscalibrated precision contributes to emotion regulation instability and allostatic load. Neuroimaging and electrophysiology can then link these computational parameters to brain circuits involved in prediction error signaling and precision control. Critically, integrating these approaches with physiological markers of allostasis may enable validation of the framework by demonstrating that computational signatures of emotion dysregulation predict long-term allostatic load, rather than only subjective emotional experience.

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