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PREDICTIVE PROCESSING AND EMBODIMENT IN EMOTION

Fiorella Del Popolo Cristaldi, Suzanne Oosterwijk, and Lisa Feldman Barrett

Introduction

Imagine that you are cycling home. Suddenly you see a right-turning car from the corner of your eye. The car will hit you if you don't act. Your brain immediately prepares your body for action: your heart pumps faster; your hands grip the bars of the bicycsle. You squeeze the brakes and skid to a full stop. You feel scared. The car turns without noticing you. You feel anger.

In this chapter we will introduce the theory of constructed emotion (Barrett 2017b, 2022; Barrett and Lida, 2024), a brain-based, context-sensitive theory of emotion that hypothesizes that past experience (e.g., of cycling around the city) is continuously being used to plan action (e.g., the viscero- and skeletomotor movements for braking) and predict experience (e.g., the incoming sense data from the body and the world that result in the percept of a car), including the creation of instances of emotion (e.g., fear, anger). We explain that all actions and experiences begin as prediction signals that are, in effect, ad hoc conceptual categories that the brain constructs in a situated, embodied way. Incoming sense data from the body and the world help select and confirm prediction signals, in effect categorizing those signals. Every instance of emotion, like every mental event, is a combination of these embodied concepts (i.e., the remembered past) and incoming signals to the brain (i.e., the sensory present). We also discuss how interoception (i.e., the brain's modeling of the sensory state of the body) is related to the affective features of consciousness and gives instances of emotion their characteristic affective feel (e.g., pleasure, discomfort, activation). Finally, we address how perceiving instances of emotion in others (e.g., observing someone else being almost hit by a car and perceiving them as being afraid) is produced by the same embodied predictive process.

A predictive model of emotion

Predictive processing and the theory of constructed emotion

The theory of constructed emotion (Barrett 2017b, 2022; Barrett and Lida, 2024) is a predictive processing account of brain function (e.g., Clark 2013; Seth and Friston 2016;

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Hutchinson and Barrett 2019) hypothesizing that past experience is continuously being used to predictively guide action and construct experience. In order to reduce uncertainty and conserve metabolic resources for growth, survival and reproduction, the brain runs an internal model of actions coupled with continuously arriving signals from the body's sensory surfaces (e.g., retina, cochlea, glucose receptors, etc.) to anticipate the body's energetic needs and try to meet them before they arise (called allostasis; Sterling 2012; Barrett 2017b; Pezzulo, Zorzi and Corbetta 2021). Running an internal model of the body in the world, thus, serves to regulate that body in the world.

Predictive processing accounts dismiss the idea of a reactive brain that processes all incoming information bit by bit, because such a system would quickly drain all metabolic resources (e.g., Sterling and Laughlin 2015). A predictive brain, instead, minimizes the processing costs of new information by using previous experience (based on features of equivalence) to generate visceromotor and skeletomotor control signals that plan upcoming, situated action as well as predict the sensory consequences of those actions. Incoming sensory signals are thought to confirm or correct the sensory predictions as a means of coordinating and controlling action. Discrepancies between ongoing prediction signals and incoming sensory signals (i.e., *prediction errors*) provide the brain with an opportunity to update its internal model (i.e., learn) (Den Ouden, Kok and De Lange 2012; Clark 2018). In part, the decision to update or adjust ongoing predictions depends on *precision signals* (i.e., attentional control) that modulate the strength of the prediction signals (as priors) as well as the incoming sensory prediction errors with regard to their relevance for allostasis (e.g., reward-prediction errors).

The theory of constructed emotion (Barrett 2017b) draws on the predictive computational architecture of the brain as the core biological substrate in which instances of emotions (as well as other mental phenomena) unfold. Emotions are not represented in distinct, dedicated neural circuits, but are hypothesized to be created through the activation of multiple spatiotemporal neural patterns serving the general purpose of predicting and correcting to maintain allostasis and skeletomotor control (Barrett and Simmons 2015; Chanes and Barrett 2016; Barrett 2017b; Kleckner *et al.* 2017; Katsumi *et al.* 2022, 2023). A crucial and paradigm-shifting consequence of these assumptions is that instances of emotion can no longer be considered "reactions to the world". People are active constructors of their emotions rather than passive receivers of sensory inputs (Barrett 2017a).

Predictions as concepts

When a brain constructs prediction signals, it is in effect constructing an *ad hoc*, *situated* and *embodied* conceptual category (see Barrett 2017a, 2017b for a discussion of ad hoc categories; see Barsalou 1983; Barsalou *et al.* 2003; Casasanto and Lupyan 2015). A category consists of a reassembly of a group of past events that share features of equivalence with the current state of the body and the world (Radulescu, Shin and Niv 2021). The brain continuously constructs these complex assemblies of prediction signals in order to coordinate and control motor actions, thereby explaining the cause of those actions and disambiguating the meaning of associated sensory signals (Barrett 2017a, 2017b and references therein). Precision signals and incoming sensory signals help to select (or correct) this assembly of prediction signals. In other words, based on past experiences with similar features, the brain runs an internal model to estimate the state of its body in the present world,

thereby constructing situated categories tailored to the goals and functional requirements of the present.

Categories can be assemblies of low-level sensory and motor features with high dimensionality or assemblies of compressed, multi-modal summaries of those sensory and motor features, i.e., abstract mental features (for discussion, see Barrett 2017b, 2022; Barrett and Finlay 2018). Abstract conceptual categories, such as emotion categories, are constructed when the brain assembles abstract mental features of equivalence, such as "protect against threat" (i.e., a multi-modal summary of past events with a similar goal to protect oneself) and "arousal" (i.e., a multi-modal summary of past events similarly experienced as arousing) (for neural details, see these papers and references therein: Barrett and Simmons 2015; Chanes and Barrett 2016; Barrett 2017a, 2017b; Hutchinson and Barrett 2019; Katsumi *et al*. 2021, 2022). It is these abstract mental features that make instances of an emotion similar across situations. Abstract mental features can reflect plans for visceromotor and motor action (i.e., abstract action concepts; Barrett and Finlay 2018), but also the goals associated with actions (e.g., to protect yourself), appraisals of the situation (e.g., novelty) and affective features (e.g., feeling aroused). An instance of an emotion is thus a mental event, in which the brain has selected a pattern of features (i.e., an emotion category constructed specifically for that situation) that confirms (or corrects) incoming sensory signals, thereby guiding action and giving psychological meaning to those incoming signals.

Previous experiences begin to be assembled as multi-modal, compressed, embodied representations of "the body in the world" (Barrett and Simmons 2015) and then become decompressed as they cascade along various architectural gradients in the brain to create the motor and sensory particulars of a situation-specific representation (for a review, see Barrett 2017b; Katsumi *et al*. 2022, 2023, and references therein). Part of this process involves predicting and integrating ascending signals from the visceral organs, the immune system and endocrine system, referred to as *interoception* (Critchley *et al*. 2004; Craig 2015; Kleckner *et al*. 2017). Thus, the brain not only predicts incoming signals from the external world (creating what you see, hear, smell and so on), but also generates interoceptive predictions about how the body reacts to the world. These embodied predictions have both sensory and motor aspects: they make up part of a brain's efforts to maintain allostasis while at the same time the efferent copies of those allostatic (i.e., visceromotor) control signals are sensory "simulations" (Barrett 2017b; Katsumi *et al*. 2022).

Let's apply this to our cycling example. As you are cycling home, your brain is continually reassembling (i.e., remembering) events from the past that are similar to the present (e.g., past experiences of cycling around the city, watching other people cycle or hearing stories about cycling) as a way of predicting what to do next. If predictions come from past instances of *fear* that you have experienced, read or heard about, then your brain is constructing an ad hoc, situated conceptual category for *fear*. These predictions take the form of visceromotor plans that may change your physiology (e.g., accelerate your heart rate, quicken your breath, release cortisol) to support planned skeletomotor movements, and sensory prediction signals that anticipate what you will see (the car), hear (screeching tires) and feel (activated). These prediction signals (e.g., what will happen if the car hits you), when confirmed by the incoming signals from the body's sensory surfaces, give psychological meaning to those sensory signals, including the abstract mental features (e.g., a goal to protect yourself) that are commonly experienced in similarly situated instances of fear. If predictions are constructed from prior instances of *anger* (including, for example, the

abstract mental feature to punish someone), then the resulting sensations and actions are experienced as a situated instance of *anger*.

Importantly, in our predictive approach, it is the brain's preparation for action that guides perception (the visual percept of a car coming too close) and experience (the subjective experience of anger and fear). Thus, perception and experience *arise from* action (Barrett 2022). Even before you see the car, your brain is preparing actions to handle the situation. This information is sent to sensory regions of the brain, predicting the sensory consequences of those skeletomotor changes. If there is a car dangerously approaching you, the predictions are confirmed and the motor plans to handle the situation are executed. If the car stays in its lane, your brain might ignore the prediction error and execute the motor plans anyway, particularly in this situation where your life may be at stake. If the brain encodes the prediction error, you might have a slight swerve and keep going, or keep pedaling with no change in speed, but might feel the affective changes nonetheless, because the ascending interoceptive prediction error to correct the interoceptive predictions is slow.

A predictive functional architecture of the brain

One of the main strengths of the theory of constructed emotion is that it is based on the structural and functional architecture of the brain (for reviews, see Barrett and Simmons 2015; Kleckner *et al*. 2017; Katsumi *et al*. 2021, 2022). It leans on evidence demonstrating that there is no consistent one-to-one mapping between specific emotion categories and any neural and physiological correlates (Lindquist *et al*. 2012; Touroutoglou *et al*. 2015; Siegel *et al*. 2018; Westlin *et al*. 2023). Instead, situated variation in the sensory and motor features of instances within the same emotion category is a core feature of our framework (Barrett 2009, 2017b, 2022; for a discussion, see Barrett and Satpute 2019).

Here we will introduce three large-scale, distributed brain networks that are suggested as the neural substrates for the construction of embodied predictions (Seth and Friston 2016; Barrett 2017b; Katsumi *et al*. 2022). First, we hypothesize that the *default mode network* (DMN) constructs compressed, multi-modal summaries (i.e., prediction signals with a relatively high level of abstractness). This role of the DMN is supported by meta-analyses showing consistent activation of this network during emotional experience (Lindquist *et al*. 2012; Satpute and Lindquist 2019), emotion regulation (Wager *et al*. 2008) and subjective affective ratings (Wilson-Mendenhall, Barrett and Barsalou 2013). These summaries then cascade and become particularized into signals that predict specific sensory and motor details. Second, we hypothesize that the *salience network* estimates the precision for prediction errors relative to which are most relevant for allostasis and which can safely be ignored as noise (for discussion, see Barrett 2017b; Katsumi *et al*. 2022). This function of the salience network is consistent with its general role in interoception (Critchley *et al*. 2004), and with its common involvement in emotion perception and experience (Lindquist *et al*. 2012; Oosterwijk *et al*. 2012; Zaki, Davis and Ochsner 2012; Touroutoglou *et al*. 2015). Third, we hypothesize that the *frontoparietal control network* is involved in generating precision signals that estimate the priors of prediction signals (Barrett 2017b). It also tunes internal models with prediction errors by supporting top-down control activity in response to feedback. Therefore, we hypothesize that all these regions and networks, and the functions they support, play a pivotal role in upholding embodied prediction construction (Katsumi *et al*. 2022).

It is important to note that the brain networks presented here are domain general. That is, these networks serve general psychological functions across a range of mental phenomena, including emotion, (social) cognition, perception and memory. For example, the DMN plays a role in emotion, but also in other instances of the mind (see for an overview Buckner and DiNicola 2019), including self-relevant thought (e.g., Northoff *et al.* 2006), internal mentation (Andrews-Hanna *et al.* 2010), and understanding the minds of other people (Spreng and Grady 2010). We argue that what unifies these different psychological domains is the general role of these networks in the construction of embodied predictions in the service of allostasis.

The fundamental role of context

If emotions derive from *ad hoc*, *situated* and *embodied* conceptual categories, it follows that the specific situation in which they unfold, as well as what the brain is doing in the meantime, may influence how an embodied prediction yields an instance of an emotion. Simply put, emotions cannot be understood separately from the context in which they occur. Crucially, by "context" we mean not only what happens *outside* the brain while an emotion is being constructed (i.e., the *external context*), but also what happens *inside* (i.e., the *internal* or *neural context*).

The impact of the *external context* is well illustrated by research demonstrating that neural activation for the same emotion category differs as a function of the situation in which the emotion is experienced. For example, Wilson-Mendenhall *et al.* (2011) found that anger and fear showed different patterns of neural activation depending on the situational context in which they were categorized (e.g., situations describing physical danger engaged the salience network more than situations involving social evaluation). Furthermore, recent work has shown that experiencing certain vs. uncertain stimuli predictability (that is, probabilistic context) modulates pre- and post-stimulus cortical processing of positive and negative affective pictures (Del Popolo Cristaldi *et al.* 2021). In addition, external contextual factors related to previous experience were found to shape subjective affective ratings (see Del Popolo Cristaldi, Gambarota and Oosterwijk 2022b). The *neural or internal context* (i.e., what the brain is doing while an instance of emotion is constructed) is another crucial factor shaping the way in which an instance of emotion is constructed. Within this view lies evidence suggesting that the brain's functional connectivity at rest may predict affective processes such as the construction of affective predictions (Del Popolo Cristaldi *et al.* 2022a), emotional face processing, social cognition and the expression of emotions (Kong *et al.* 2019), and even pain sensitivity (Spisak *et al.* 2020). Further, bodily states measured as peripheral physiological activity may also modulate embodied predictions and the associated subjective experience of emotion (e.g., MacCormack and Lindquist 2019; for a comprehensive review, see Pace-Schott *et al.* 2019).

Prediction and embodiment in emotion perception

If subjective emotional experience can be understood as the product of a predictive process, then predictions may also be fundamental to representing emotion in perception (e.g., perceiving fear in someone else; Chanes *et al.* 2018), cognition (e.g., thinking about your partner's anger), memory (e.g., retrieving a happy memory), imagination (e.g., imagining a threatening situation; Oosterwijk *et al.* 2017) and language (e.g., reading about a disgusting

experience; Oosterwijk *et al.* 2015). Indeed, several recent perspectives have positioned predictive processing as central to social cognitive processes (e.g., Gallagher and Allen 2018; Tamir and Thornton 2018; Shamay-Tsoory *et al.* 2019). Moreover, predictive processing may not only be fundamental in understanding the emotional states of other people, but also in aligning one's own emotional state with the state of psychologically close others (Shamay-Tsoory *et al.* 2019).

The idea that embodied predictions underlie social cognition resonates with embodied simulation theories that propose that observing actions, sensations and emotions in other people engages the same neural circuits as experiencing actions, sensations and emotions in the self (e.g., Bastiaansen, Thioux and Keysers 2009). Furthermore, it is consistent with views that propose that the conceptual system for emotion is grounded in sensorimotor and bodily states (Barsalou 1999; Niedenthal 2007; see for empirical support Oosterwijk *et al.* 2009, 2015; see for an overview Winkielman, Coulson and Niedenthal 2018). According to these views, multi-modal systems in the brain and body *simulate* experiential states in order to represent online instances of emotion (e.g., observing someone who is frightened) and offline instances of emotion (e.g., reading about a frightening event), even in the absence of direct sensory or bodily stimulation. Similar to "embodied cognition" accounts, we propose that people explain the external world, including the thoughts, feelings and actions of the other people in it, by constructing embodied predictions that anticipate the sensory signals that arise from the actions or words of others. In other words, we use our own internal model of our body in the world to predict what other people think, feel and do.

Neuroimaging work supports the idea that predictions based on an individual's own lived experience lie at the core of understanding other people. For example, neuroimaging experiments demonstrate neural overlap when people experience and observe emotions (Jabbi, Bastiaansen and Keysers 2008) or pain in other people (Zaki *et al.* 2016). Furthermore, vicarious experience is seen as an important component of empathy (Keysers and Gazzola 2014) and involves activation in the previously discussed salience network (e.g., Decety 2011; Fan *et al.* 2011). Moreover, there is an abundance of findings in the social neuroscience literature that demonstrates that the DMN network is involved when people make attributions about the content of other people's mental state (e.g., Van Overwalle and Baetens 2009; Yeshurun, Nguyen and Hasson 2021) or engage in other tasks that require a high level of abstraction (Satpute and Lindquist 2019).

To illustrate how a predictive process lies at the core of different emotion phenomena, we give an example from our own lab (Oosterwijk *et al.* 2017). In this study, participants imagined emotion-related actions (e.g., pushing someone away), interoceptive sensations (e.g., an increased heart rate) and situations (e.g., being alone in a park at night); and engaged in other-focused understanding of emotion-related actions (i.e., how does this person express his/her emotions?), interoceptive sensations (i.e., what does this person feel in their body?) and situations (i.e., why does this person feel an emotion?). Consistent with the idea that embodied predictions underlie imagery (Barrett 2017b), we found that imagining actions, interoceptive sensations and situations involved the salience network and DMN. Furthermore, using a classifier trained on the imagery task, we could accurately decode whether participants focused on actions, interoceptive sensations or situations when understanding the emotions of other people. Thus, the brain generates similar embodied predictions when imagining "experiencing" an action (or sensation or situation) and when understanding an action (or sensation or situation) in someone else.

Future directions

In summary, our constructionist framework connects a range of emotional phenomena by proposing that emotional experience and perception share a predictive process that dynamically adapts to the context at hand. Although some progress has been made in answering questions about how instances of emotion are grounded in the brain, body and situational context, there are still many questions that call for further investigation.

First of all, we know relatively little about how cultural differences impact the generation and implementation of predictions, even though people from different cultures differ in emotional expression and experience (e.g., Boiger and Mesquita 2012; Jack *et al*. 2012). Future research could focus on how culturally shared and culturally different emotion knowledge guides embodied predictions in interactive social contexts. A second topic for future research is the development of predictions across the lifespan. Although there is work that emphasizes the importance of shared allostatic experiences between children and parents in fine-tuning the internal model of "the body in the world" (e.g., Atzil and Gendron 2017), we know relatively little about how people continue to update their internal model in adulthood. For example, it is an open question how people build predictions not only on their own lived experience, but also on the lived experience of other people, for example through the consumption of TV shows, movies and books (see Hoemann and Barrett 2019). And finally, in order to capture emotions as they unfold in real life, affective research should start coming out of the labs and design more ecologically valid studies that can complement and overcome the limitations of traditional lab-based experiments. In the effort to do so, we call for a combined investigation of the neural, behavioural and subjective level in the experience of emotion, with the end goal of explaining emotion in all its complexity.

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