Review

Growing pains and pleasures: how emotional learning guides development

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The nervous system promotes adaptive responding to myriad environmental stimuli by ascribing emotion to specific stimulus domains. This affects the salience of different stimuli, facilitates learning, and likely involves the amygdala. Recent studies suggest a strong homology between adaptive responses that result from learning and those that emerge during development. As in motivated learning, developmental studies have found the salience of different classes of stimulus (e.g., peers) undergoes marked fluctuation across maturation and may involve differential amygdala engagement. In this review, by highlighting the importance of particular stimulus categories during sensitive periods of development, we suggest that variability in amygdala response to different stimulus domains has an active and functional role in shaping emerging cortical circuits across development.

Emotion facilitates adaptive responding

A primary function of the central nervous system is to match behavior optimally with environmental conditions. An important modulator of this process is emotion. Emotion can be construed as the synergistic response of multiple independent body systems in response to a stimulus [1]. Emotion induction enables both an orchestrated response and flexible attribution of salience to environmental stimuli. Importantly, differential emotional responses can be tailored to match the internal state of the organism with the stimulus or context in which it is encountered [1–3]. Thus, an emotional response is an intrinsic signal ascribed to a stimulus that flexibly signals its importance. Another important function of emotion is that it facilitates learning by enhancing sensory experience, focusing attention, and promoting long-term consolidation of sensory experience [4–6]. Emotional responses also promote expression of optimal responses to emotion-eliciting stimuli [7] that can be rapidly executed during subsequent encounters.

Such emotional mediation effects are typically studied in a learning context where relatively rapid shifts in both emotion and behavior occur. Another process in which response tendencies are crafted by environmental conditions to optimize the match between individual and environment is development [8] (Box 1). Indeed the similarities between learning and development are such that they are often considered analogous processes [9] (Box 2, but see Box 3). Many studies have demonstrated that, in development, as in learning, emotional experiences induced by particular stimuli can act as a key modulator of stimulus impact and profoundly influence maturational outcome [10–13]. Thus, just as in learning, emotional responses to stimuli in development have an important role in highlighting the significance of different stimuli and promote an ideal match between organism, behavior, and environment.

A key aspect of developmental adaptations is that the timing of stimulus encounters is important. Development progresses through a series of sensitive periods or time windows during which particular classes of stimulus (or stimulus domains) are influential in affecting the course and trajectory of maturation [14,15]. This time-sensitive and domain-specific property of development highlights the importance of maximizing the impact of relevant experiences during developmentally appropriate periods. Although there are several factors that influence the potency of discrete classes of stimulus across development, here we suggest that differences in emotional response are an important, and often overlooked, means of heightening the salience of environmental features at specific sensitive periods.

Based on a similar role in learning paradigms, we suggest that an important neuronal hub in this process is the amygdala. The amygdala is thought to be a key region for the orchestration of emotional responding and for the flexible attribution of salience to different stimuli in the environment. In addition the amygdala is a critical site for emotional facilitation of memory [3,16,17]. Several recent studies have revealed systematic differences in patterns of amygdala activity across development [18–23] and differential consequences of amygdala damage incurred at discrete periods of development have also been observed [24,25]. These findings suggest that shifting amygdala-mediated affective processes are a key component of development. We suggest that differential emotional reactivity

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Box 1. Development: a dance between nature and nurture

Although the central nervous system is one of the earliest organ systems to emerge during gestation, maturation is a protracted process. Indeed, in humans, neural development is now thought to extend well beyond puberty, into early adulthood [30]. Over the first several years of life, brain development is marked by neurogenesis and the establishment of new synaptic contacts. This expansion is then followed by a gradual refinement process, which comprises synaptic pruning and myelination [27,30]. This refinement process follows a developmental sequence, from phylogenetically conserved regions involved in sensory and motor processes to regions involved in more complex functions, such as multisensory integration and socioperceptual functions [27,30,32].

The extent to which developmental refinement is driven by intrinsic maturational processes or constructed primarily as a consequence of experiential inputs has been a source of considerable debate [92]. Over the past several decades, a pendulum has swung from nativist intrinsic explanations, to constructivist empirical explanations, which emphasize environmental contingencies. More recently, models have begun to characterize development as a culmination of the inseparable interaction between biological and environmental factors [8,11]. These models suggest that, although there is a loosely defined sequence, timeline, and process associated with maturation of the nervous system, the output of this maturation is largely influenced by the environmental context in which development occurs. Some models also suggest a differential susceptibility to environmental influence [8].

There are many examples that illustrate how developmental outcomes are shaped by interactions between biology and environment. A classic example is language. Although language acquisition is a milestone of normative development, the specific language acquired is completely dependent on the context in which maturation occurs [44,93]. Similar examples of this principle are found across many domains and include ‘programming’ the dynamics of the hypothalamo–pituitary–adrenal axis, where early stress can alter the homeostatic balance of cortisol detection and release [11,85]; tuning of sensory and perceptual sensitivity, where discrimination of subtle elements becomes more or less sensitive with early life exposure [12,41,45]; acquisition of parental behavior patterns, which are influenced by patterns of one’s own parental behavior [63]; and even adoption of preferred characteristics for subsequent mate preferences [43]. Therefore, for most neural circuits, the final maturational outcome depends completely on an interaction between genes and experience.

Box 2. Neurobiological mechanisms of learning and development: strengthening connections

Over the past several decades, great strides have been made in delineating the molecular mechanisms that mediate learning [94]. Much of this research is guided by models of simple associative conditioning that demonstrate that synaptic strength between two weakly connected cells increases when they fire simultaneously [94]. A key molecular component of this strengthening is activation of the glutamate NMDA receptor. This receptor acts as a ‘coincidence detector’ that strengthens connectivity of co-active cells by opening calcium ion channels, which ultimately induces protein-based cellular changes responsible for long-term stabilization of circuits [82,95]. Inhibitory GABAergic connections may also have an important modulatory role in this strengthening process. Given that GABA exerts tonic inhibitory control on some NMDA circuits, modulation of GABA input is thought to be an important precursor for NMDA-mediated learning under some circumstances [67,82,96].

Likewise, in development, circuit strength is refined through patterns of synaptic activity that are affected by environmental context [27]. The early stages of this refinement are characterized by a highly dynamic phase of formation and retraction of synaptic contacts on newly formed dendritic spines [95]. In a manner similar to synaptic strengthening implicated in traditional Hebbian learning, activity within these nascent synaptic contacts is stabilized and maintained via activation of NMDA receptors, influx of intracellular calcium ions, induction of transcription factors, and neurotrophin release [95]. Moreover, recent evidence indicates that inhibitory GABA inputs may also help to tune receptive fields and gate neuronal sensitivity to environmental input across development [96]. Thus, in both maturation and traditional learning, synaptic and circuit stabilization is a process of amplifying and strengthening connections that are weakly co-active. Mechanistically, this depends on glutamate NMDA receptors, a cascade of events triggered by intracellular calcium influx, and GABA-mediated inhibition of competing influences.

During critical developmental phases, rapid synaptic refinement occurs in specific circuits. Thus, environmental contexts that induce synapse-specific neuronal activity may have a particularly strong influence on specific circuit function. At a systems level, sensory processing has been used to model the effects of environment on brain organization across development. This work demonstrates that the experience of visual, auditory, or somatosensory stimuli during specific developmental windows is critical for the organization of cortical circuitry, parcelation of cortical space, and functional responsivity [36,37,97]. These models of sensory development may serve as more general models of experiential influence during sensitive periods.

and amygdala responses in particular have an important role in highlighting developmentally relevant features of the environment. Such a fluctuation in amygdala sensitivity may serve to orient the organism to important features of the environment during sensitive maturational periods.

Periods of sensitivity and insensitivity in development: timing is everything

In broad terms, there are two components involved in the development of the nervous system. The first is an organizational framework that is primarily mediated by intrinsic factors, such as gene expression, which spur the generation and elaboration of neurons and determine the general spatial organization of neural tissue [26,27]. In the second phase, the organizational framework is fine-tuned. This fine-tuning is based on use-dependent preservation or elimination of neural circuits, which ultimately results in an extensive network of differentially weighted neural networks [28]. This second, fine-tuning process is affected to a greater extent by the environmental context than is establishment of the initial organizational framework [27,28].

The developmental tuning process is both protracted and serial. Recent findings indicate that the brain does not complete developmental maturation until early adulthood, and development proceeds in a piecemeal fashion with phylogenetically newer regions undergoing maturation subsequent to older regions [29–32]. Thus, the fine-tuning phase of development proceeds through a serial pattern of distinct sensitive periods and these are likely to extend from the first few years of life well into the third decade in humans [15,29,33–35].

The pattern of sensitive periods was first demonstrated in the visual system of nonhuman primates and cats by the Nobel prize-winning work of Hubel and Wiesel, where restriction of visual input for a brief period of development resulted in dramatic alterations in the maturation of the visual system at cellular, morphological, and functional levels [26]. Many of these alterations persist throughout life despite normative exposure to stimuli through late development and maturity. Similar phenomena have also been observed in humans in the development of the visual