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Spotlight

Emotion representations in context: maturation and convergence pathways

Shaozheng Qin [1,2,3,*]

How does the human brain develop stable emotion representations? According to recent work by Camacho *et al.*, neural representations of contextualized emotional cues are distinct and fairly stable by mid-to-late childhood and activation patterns become increasingly similar between individuals during adolescence. Here, I propose a framework for investigating contextualized emotion processing.

Emotions have a central role in adaptive behavior and mental health. Humans also require a shared conceptualization of others' emotions for successful social functioning. In cognitive neuroscience, localization of brain activation to static, context-independent, emotional stimuli has been the mainstay of approaches to understanding human emotions (Figure 1A). However, this approach offers limited insight into neural representations of contextualized emotion processing. To better understand contextualized emotional processing, researchers have begun to adopt more naturalistic (i.e., movie-watching) fMRI paradigms [1]. These approaches are also emerging as a powerful tool for exploring brain function and dynamic synchrony between individuals [1,2] (Figure 1B).

To date, few studies have used naturalistic movie-watching paradigms to explore the neurodevelopmental mechanisms of contextualized emotion processing. If these mechanisms are clarified, typical and atypical affective development could be more specifically targeted to improve health outcomes in children with socioemotional dysfunction. One fundamental question is how emotion concepts are learned from the environment and transformed into stable representations. Camacho *et al.* recently provided insights into this question by linking large-scale neural activity and synchrony to contextualized emotion cues during movie watching [3].

In a sample of 823 children (5–15 years of age), Camacho *et al.* found that widespread brain activation patterns to contextualized emotional cues were distinct and fairly stable by mid-to-late childhood: positive and negative emotions, as well as specific emotions (e.g., angry, excited, or fearful), were decodable from activation patterns throughout the brain in these children, with the most unique information represented in primary sensory regions and higher order associative areas in the frontal, temporal, and parietal lobes. Each emotion activation map provided moderate information predicting chronological age and puberty scores, suggesting modest changes in emotion representations across development. Intersubject neural synchrony also became increasingly similar between individuals during adolescence. Beyond specialized regions, Camacho *et al.* identified distinct and stable representations for different emotion concepts throughout the cortex, cerebellum, and caudate. Such distinct and stable patterns to each emotion may critically support children's ability to identify and distinguish different emotions. Camacho *et al.*'s observations regarding large-scale encoding emotion concepts do not deny

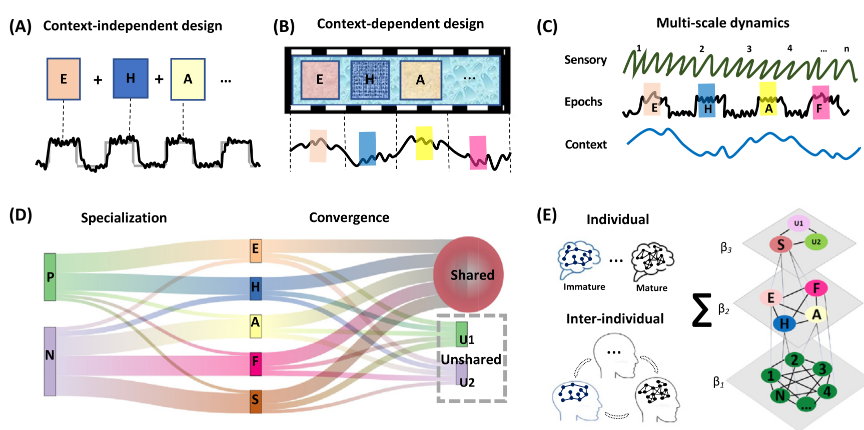

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Figure 1. fMRI experimental paradigms and the proposed framework for investigating maturation and convergence pathways to emotion representations in context. (A,B) Illustration of context-independent and context-dependent designs with fMRI signals for emotion research. Background color in the light blue rectangular (B) represents the context. (C) Neural dynamics at multi-temporal scales in response to sensory inputs, emotional cues during epoch events, and the context. (D) The proposed framework illustrates interactive specialization and convergence pathways to shared conceptualization of emotion representations between individuals and unshared representations linking to each individual's divergent experiences across development. (E) Schematic of the proposed framework for large-scale neural dynamics with multiple temporospatial scales that give rise to distinct, yet generalizable emotion representations in the developing brain. Such intricate dynamics are theorized to ensure an adaptive ongoing system for processing continuous epoch events that are embedded into a longer timescale of the narrative context, likely via a hierarchically organized manner. Testing neurocomputational models with simulations and developing new methods with high-resolution imaging are thus required when investigating maturation and convergence pathways to contextualized emotion representations. Abbreviations: A, angry; E, excited; F, fearful; H, happy; N, negative valence or avoidance; P, positive valence or approach; S, sad; U_1, U2, unshared or unique representations.

the existence of specialized circuits for discrete/basic emotions that some researchers believe are innate and sensitive reflections of the internal emotion state. For instance, recent findings from animal work demonstrate specialized circuitry for different facial expressions in mice [4]. Thus, representations of emotion concepts may engage both local microcircuits and large-scale brain networks.

Human brain systems need to not only maintain stable emotion representations, but must also use them flexibly and generalize them to new situations and environments. Future work should explore how representations of emotion concepts generalize and reorganize during development. Previous work has highlighted the population and compositional coding mechanisms through which certain neurons give rise to distinct representations for each task and also engage across multiple tasks [5]. One recent neuroimaging study also showed that domain-related information represented in the medial frontal cortex not only generalizes across mental states (i.e., pain, negative affect, and cognitive control), but also holds specific patterns to distinct psychological states [6]. Hence, neural modules may specialize during development to support specific emotions, yet also coexist in multiple modes to support generalizable emotion representations.

To address the neurodevelopment of shared emotion concepts between individuals, Camacho *et al.* computed the intersubject correlation of neural activity during movie watching and tested whether the similarity in activation across the video fitted one of three models of children's cognitive affective development: the nearest neighbor model expects that children proximal in maturity process the video similarly; the convergence model predicts that children process the video more similarly as they mature; whereas the divergence posits that children process the video less similarly as they mature with more divergent experiences. The convergence was the best fitting model, suggesting improved integration of multimodal information as children refine their shared understanding of emotional cues across development. This finding is striking, because it represents an important step by linking neural synchrony between individuals to shared emotion conceptualization. Emotion socialization may have a critical role in forming shared emotion conceptualization according to the theories of constructed emotion [7] and biobehavioral synchrony [2,8]. Future work should address how shared emotion conceptualization is reorganized with longitudinal designs in healthy and psychiatric populations, by considering the process of information accumulation and emotional inference during continuous events.

The dynamic analysis in conjunction with movie scenes used by Camacho and colleagues further revealed that scenes that required inferring negative emotional states elicited higher activation similarity in default mode network (DMN) in older than in younger children. The DMN is theorized as an active and dynamic 'sense-making' network that integrates current information into memory and forms a coherent understanding of discrete events during movie watching [1,9]. Given that inferring and segmenting continuous events are intertwined and driven by one's prior knowledge, future work should aim to disentangle the neural computations underlying these processes and how personal experiences and cognitive domains shape emotion representations. In addition, autonomic arousal and reactions to emotional events may have a role in the dynamic organization of large-scale encoding activity, raising the question of how autonomic reactions stimulate activation of neuromodulatory systems to shape emotion representations. Several factors should be considered, including the individual's physiological arousal, emotional feelings, and emotional inference within the whole narrative context. Valid and reliable methods are the cornerstone of progress in naturalistic fMRI. Testing models with simulations and developing new methods are also required to further clarify maturation and convergence pathways to emotion representations (Figure 1C–E).

One key open question is why contextualized emotion processing requires functional organization of large-scale brain networks. One possibility is that contextualized emotion processing involves a chain of ongoing cognitive processes that include multimodal integration of sensory inputs, selective attention, rapid detection, perception, and appraisal of emotional cues, as well as integrating information into a coherent understanding of the movie. These processes often deploy at different temporospatial scales, requiring recruitment of large-scale brain networks. Based on large-scale network accounts of brain function, human cognition involves dynamic integration of large-scale neural and neuromodulatory systems by converging onto a low-dimensional manifold that facilitates diverse task states [10]. This framework predicts that a network of core regions is active across multiple tasks with linear and/or nonlinear responses, and integrates specialized regions to support task-specific computations (Figure 1E). Thus, neural dynamics in large-scale network architecture are thought to support maximal information processing complexity [10] with multiple temporal modes: a slower mode is critical for accumulating narrative context over long timescales, whereas a fast mode supports information processing for transient events. Similar computational mechanisms are relevant to account for the convergence in shared emotion conceptualization as the brain matures during development (Figure 1C,E).

Although the multifaceted complexity of human emotions deserves further study, Camacho *et al.* make valuable inroads toward understanding contextualized emotion processing. Large-scale brain networks with multi-scale dynamics are computationally parsimonious to ensure an adaptive ongoing system for continuously epoch events that are embedded into a longer timescale of narrative contexts (Figure 1C,E). Delineating the computational principles of how emotion representations develop in the brain and converge into shared conceptualization between individuals will have important implications for not only emotion neurodevelopment in both healthy and psychiatric conditions, but also brain-inspired affective computing agents that aim to recognize, understand, and even simulate human emotions.

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Declaration of interests

None declared by the author.

[1]IDG/McGovern Institute for Brain Research & State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing, China
[2]Beijing Key Laboratory of Brain Imaging and Connectomics, Beijing Normal University, Beijing, China
[3]Chinese Institute for Brain Research, Beijing, China

*Correspondence:
szqin@bnu.edu.cn (S. Qin).

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