Emotional Information Processing in Infants: Cognitive Developmental Characteristics and Neural Mechanisms

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Abstract

The emotional information conveyed by vocal prosody and facial expressions constitutes the foundation for humans to interpret others' emotions and engage in interpersonal interactions. Investigating infants' perception, discrimination, and evaluation of emotional information transmitted through these two modalities facilitates deeper understanding of the characteristics of infant cognitive development and its underlying neural mechanisms. This article systematically reviews research on infant emotion, revealing that the temporal and frontal cortices play crucial roles in the processing of emotional vocalizations and facial expressions in infants; although infant emotional processing involves both cerebral hemispheres, it has already preliminarily exhibited a right-hemisphere advantage similar to that observed in adults. Infants can discriminate emotional information within the first week after birth and demonstrate a processing bias toward positive emotions. Around 6 months of age, infants' emotional processing bias gradually shifts from positive to negative. By 12 months, infants' negative emotion bias becomes essentially stable, and they can comprehend the emotional meaning conveyed through emotional vocalizations and facial expressions, using this understanding to guide their own behavior. Based on these findings, we propose the "Emotion Bias Development Theory." Furthermore, audio-visual cross-modal information plays a positive role in infants' discrimination and understanding of specific emotions.

Full Text

Preamble

Emotional Information Processing in Infants: Cognitive Developmental Characteristics and Neural Mechanisms

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Abstract: The emotional information conveyed through vocal prosody and facial expressions forms the foundation for human interpretation of others' emotions and facilitates interpersonal interactions. Investigating how infants perceive, discriminate, and evaluate emotions embedded in these two modalities deepens our understanding of infants' cognitive development and neural mechanisms. This paper comprehensively reviews emotion processing in infants, revealing that the temporal and frontal cortex play crucial roles in processing emotional speech and facial expressions. Although emotional processing involves both brain hemispheres, infants initially show a right-hemisphere advantage similar to adults. Within the first week after birth, infants can distinguish emotional information and exhibit a processing bias toward positive emotions. This bias gradually shifts to favor negative emotions around six months of age. By twelve months, infants' negative emotional biases stabilize, and they can understand and respond to emotional cues from speech and facial expressions. Based on these findings, we propose the "Developmental Theory of Emotional Bias." Importantly, cross-modal visual-auditory information significantly enhances infants' ability to discern and understand specific emotions.

Keywords: infant, emotion processing, speech prosody, facial expression

Understanding others' emotions helps us infer their intentions, predict their behaviors, and guide our own adaptive actions (Devereux et al., 2009). The period from birth to 28 days is defined as the "neonatal" stage, while the period from 29 days to 12 months constitutes the "infant" stage. Research has found that during early developmental stages, learning to recognize and differentiate others' emotional expressions forms the foundation for infants to establish social relationships and is crucial for their rapid adaptation to the environment and the development of other abilities such as language (Levine et al., 2016). Newborns are well-prepared for rapid development of emotion perception abilities at birth, showing heightened attention to social stimuli, particularly faces and voices. Through attending to these social stimuli, they acquire information that facilitates later discrimination and recognition of emotional expressions. Within the first week after birth, newborns exhibit extreme sensitivity to social, familiar, and positively valenced vocal and facial stimuli, gradually forming stable emotional processing biases over time.

In auditory processing, previous research has primarily used emotional prosody as material. Emotional prosody refers to the dynamic changes in various acoustic cues within speech—such as pitch, duration, intensity, stress, and intonation —that speakers use to express and convey emotions (Brück et al., 2011). Studies indicate that newborns can discriminate emotional prosody within 24 hours after birth and show greater sensitivity to positive than to negative emotions (Liu et al., 2021). Beyond the auditory system, infants also demonstrate sensitivity to facial expressions and show discrimination and processing biases for different emotional faces during visual system development. For example, Farroni et

al. (2007) found that when viewing happy and fearful facial expressions, newborns looked longer at happy than at fearful faces, suggesting that newborns may discriminate between these two emotional expressions early on and show a preference for positive emotions. Regarding cross-modal emotional processing, infants can reliably match and identify emotional information from face-voice audiovisual materials by at least 7 months of age (Grossmann, 2010). Neuroimaging studies have found that infant emotion processing relates to resting-state functional connectivity in a brain network centered on the amygdala. Increased positive emotion in infants is associated with decreased amygdala-salience network connectivity and enhanced amygdala-executive control network connectivity (Phillips et al., 2021), while decreased negative emotion relates to increased amygdala-orbitofrontal cortex connectivity (Banihashemi et al., 2023). White matter microstructure in the left terminal stria (a fiber bundle connecting frontal and temporoparietal cortex) at 1 month of age relates to both current fear levels and later changes in fear (Planalp et al., 2023). These studies demonstrate that humans possess emotion-processing brain networks similar to adults from birth, enabling infants to respond to various emotional information in their environment.

Given the important role of vocal prosody and facial expression information in infant emotional development, this paper will respectively elaborate on cognitive neuroscience research regarding the development of emotional information in the auditory speech system and visual face processing, reveal the cognitive developmental characteristics and neural mechanisms underlying infants' processing of emotional information from speech and faces, and provide constructive prospects for future research in this field.

2 Infant Processing of Emotional Faces

Discrimination and differentiation of emotional faces constitute an important channel for human nonverbal communication. The emotional information conveyed by faces serves as a medium for infants' social communication, enabling them to recognize caregivers' emotional states and behaviors through identification of subtle changes in facial expressions. This is critically important for infants, not only facilitating information exchange with parents but also improving their adaptation to the survival environment and other aspects (Bayet et al., 2021). Adult studies have found that differentiation of facial emotions typically occurs in a "facial emotion processing" network that includes the superior temporal sulcus, amygdala, and orbitofrontal cortex (Leppänen & Nelson, 2009). Infants appear to share similar functional networks with adults. Rotem-Kohavi et al. (2017) used electroencephalography to examine the functional brain organization for emotional face processing in 8- to 10-month-old infants and adults. Through graph-theoretic analysis of functional connectivity, they compared global and local brain network organization underlying perception of negative and positive dynamic facial expressions (happy and sad). The results revealed that dynamic emotional face expression processing involves multiple

brain regions in both infants and adults. At the global level, infants showed higher brain network density than adults, indicating that the overall brain organization related to emotion perception is not yet fully mature during infancy. In contrast, at the local level, the functional characteristics of frontal and parietal nodes were similar between infants and adults, suggesting that region-specific brain networks for emotion perception are already established during infancy. Additionally, occipital, parietal, and temporal nodes appeared to have the greatest influence on information flow within brain networks. Overall, these results indicate that although the global brain organization for happy and sad emotion perception is still developing in infants, the basic local functional brain networks are already established early in infancy and are nearly comparable to those of adults.

During the first year after birth, infants' ability to recognize faces and interpret facial expressions develops rapidly. Shortly after birth, newborns can discriminate limited facial expressions. Field et al. (1982) examined discrimination and imitation of facial expressions in newborns with an average age of 36 hours. The results showed that newborns could not only differentiate happy, sad, and surprised facial expressions but also imitate these expressions through facial movements of the eyebrows, eyes, and mouth. Farroni et al. (2007) examined facial expression discrimination ability in 2-day-old newborns and found that they could not differentiate neutral and fearful faces but could distinguish happy from fearful faces. Moreover, 2-day-old newborns can also discriminate dynamic facial expressions. Research has found that after habituating to dynamic happy and disgusted faces, newborns could successfully discriminate between them (Addabbo et al., 2018). A cross-sectional study by Bayet et al. (2017) found that from 3.5-month-old infants to all age groups (6 and 12 months), they more easily detected fearful faces (compared to happy faces) when presented in noisy backgrounds. Safar et al. (2020) further found that 3-month-old infants gave more attention to fearful faces (compared to happy faces) in a visual paired-comparison (VPC) task. Five-month-old infants can differentiate happy and neutral faces (Bornstein et al., 2011), show stronger sustained attention to dynamic fearful faces than to non-fearful faces (happy and neutral faces), and demonstrate stronger temporal region activity in response to fearful faces (Heck et al., 2016). At this stage, the occipital region already shows sensitivity to face processing and exhibits right-hemisphere advantage in facial emotion processing (DiLorenzo et al., 2019), though the brain network for facial expression processing appears not yet fully developed (Nakato et al., 2009). Six-month-old infants can reliably differentiate happy and angry faces of varying intensities (Striano et al., 2002). Infants aged 6.5 to 7.5 months already show categorical perception, discriminating between emotional expressions across face categories but not within categories when presented with a happy-fear face expression continuum. Additionally, infants can discriminate happy and fearful faces and, after habituating to fearful faces, show longer looking times to happy than to fearful faces (Cong et al., 2019). Previous research by Kotsoni et al. (2001) also found categorical perception of emotional faces in infants after habituating to happy

faces. Seven-month-old infants can discriminate angry and fearful faces, with angry faces eliciting larger N290 amplitudes and smaller P400 amplitudes compared to fearful faces (Andrea et al., 2008). These components are considered precursors to the adult face-sensitive N170 component (de Haan et al., 2003). Furthermore, 7-month-old infants are highly sensitive to dynamic facial expressions. Quadrelli et al. (2019) examined differences in processing dynamic versus static facial expressions in 7-month-old infants and found that the negative central component (Nc) in infant EEG could not differentiate facial emotions when viewing static expressions. However, when facial expressions were presented dynamically, happy and angry expressions elicited larger Nc amplitudes over right central regions than neutral faces. This finding highlights the facilitating effect of dynamic facial expressions on infant emotion recognition. Eight- to ten-month-old infants gradually develop the ability to understand facial expressions. A series of studies using the violation-of-expectation paradigm have examined infants' understanding of facial expressions by testing whether they can match facial expressions with corresponding events. Hepach and Westermann (2013) found that 10- and 14-month-old infants expected expressers to show happiness rather than anger when playing with plush toys. Subsequently, Skerry et al. (2014) found that 8- to 10-month-old infants expected others to express happiness rather than sadness after completing a goal. This indicates that infants older than 8 months can match positive facial expressions with positive events, suggesting they understand the emotional meaning of positive facial expressions. However, the ability to match negative emotions with negative events emerges later. Reschke et al. (2017) examined infants' sensitivity to consistent and inconsistent emotional reactions to positive and negative events. Researchers showed 12-month-old infants three types of interpersonal events (giving a toy, breaking a toy, fighting over a toy) and then presented emotional expressions (happy, sad, angry) that were consistent or inconsistent with the event outcome, observing infants' looking durations to each emotional reaction. The results showed that in the giving condition, infants looked longer at angry than at happy expressions; in the fighting condition, they looked longer at happy than at angry and sad expressions. This indicates that infants showed sensitivity to inconsistent emotional reactions in giving and fighting events and provides evidence for infants' understanding of facial expression meaning. More importantly, this study provides the earliest evidence to date of infants' sensitivity to negative event emotions.

In summary, infants' ability to perceive and differentiate various facial expressions shows a certain level from the neonatal period and develops steadily throughout the first year after birth. Through reviewing existing literature, we have preliminarily found that within just 36 hours after birth, newborns already possess the ability to discriminate and imitate facial expressions, demonstrating sensitivity to and interactive capacity with facial expressions from the surrounding environment. Two-day-old infants can basically differentiate various facial expressions such as happy, sad, surprised, and fearful. As time progresses, 3- to 4-month-old infants can more reliably differentiate various facial expressions.

By 5 months, infants begin to discriminate different types and forms of expressions and can reliably differentiate different dynamic facial expressions. After 6 months, infants show categorical perception of emotional faces. By 7 months, infants are highly sensitive to dynamic facial expressions. Infants 8 months and older begin to show understanding of emotional facial expressions, with understanding of positive emotions emerging earlier than that of negative emotions. Although the global brain network for infant facial emotion perception is not yet fully mature at this time, local specific brain networks have already formed and are almost comparable to those of adults.

3 Infant Processing of Emotional Speech

Compared to other sensory modalities, audition plays a more important role in early human emotion processing (Caron et al., 1988), as infants' visual functions are extremely immature (for example, they have almost no color perception during the first half year after birth). Research has found that infants can discriminate and differentiate emotional speech in the early period after birth. Cheng et al. (2012) were the first to use brain observation techniques to examine infant processing of emotional speech and found that infants could discriminate emotional speech within 1-5 days after birth. Fearful prosody (compared to neutral and happy prosody) elicited larger mismatch response components (MMR; the early form of adult mismatch negativity MMN) in the right frontal region, suggesting that infants may have a right-hemisphere advantage for emotion processing. Zhang et al. (2014) also found that infants aged 0-6 days could differentiate fearful and angry prosody. Subsequently, Zhang et al. (2019) further found that when 0-4-day-old newborns heard emotional speech prosody expressing happiness, fear, and anger, their right temporal lobe showed more significant activation compared to neutral prosody. Additionally, the right parietal region was more sensitive to fearful prosody than to happy and neutral prosody, highlighting the importance of the right hemisphere in neonatal emotional prosody perception. These studies demonstrate that newborns can not only differentiate different types of emotional speech to some extent but also show a right-hemisphere advantage for emotional speech prosody processing.

Research has found that 2-month-old infants show greater activation in the left temporal-parietal cortex in response to happy speech (compared to neutral speech), with the left superior temporal gyrus being more sensitive to happy speech (than to angry speech), indicating that left brain regions play an important role in processing positive emotions in 2-month-old infants (Shekhar et al., 2019). At 4 months, when infants hear emotional speech (compared to non-emotional speech), the right temporal lobe is significantly activated (Minagawa et al., 2011). At 5 months, Grossmann et al. (2005) found that infants' left temporal cortex showed responses to different emotional sounds, with response intensity decreasing from happy to angry to neutral. At 6 months, Graham et al. (2013) found that infants showed increased activation in the left dorsolateral prefrontal cortex when listening to happy emotional speech (compared

to neutral speech). At 7 months, Grossmann et al. (2005) found that infants' right temporal cortex was sensitive to angry prosody. Compared to happy and neutral prosody, infants showed larger amplitudes of the negative component (Nc) in temporal brain regions when listening to angry speech, indicating that infants at this stage allocate more attentional resources to negative emotions. Similarly, Blasi et al. (2011) also found that 7-month-old infants showed increased activation in voice-sensitive regions of the right temporal cortex when hearing emotional sounds, being more sensitive to sad sounds (compared to happy and neutral sounds). However, some studies have not observed brain lateralization in prosody processing. For example, Zhao et al. (2019) found that 6-month-old infants' bilateral temporal cortex showed enhanced responses to emotional speech. Specifically, angry prosody (compared to neutral prosody) elicited stronger responses in the left anterior superior temporal cortex, while happy prosody (compared to angry prosody) led to enhanced activation in the right superior temporal cortex. This finding suggests that infant processing of emotional speech involves both brain hemispheres.

In summary, infants can perceive and differentiate different emotional speech to some extent during the neonatal period, and this ability gradually becomes more mature with age. Through reviewing existing literature, we have preliminarily found that within the first week after birth, infants show considerable sensitivity to emotional speech and can basically discriminate emotional speech, which helps increase their opportunities for interaction with others. Two-month-old infants can differentiate happy speech from neutral speech and are more sensitive to happy speech. At 5 months, infants can differentiate happy, angry, and neutral speech and are more sensitive to happy speech. At 7 months, infants can differentiate happy, sad, angry, and neutral speech, being more sensitive to angry and sad speech at this point. Overall, the core brain region for infant emotional speech processing is the temporal cortex, involving both brain hemispheres, though the right hemisphere appears to have an advantage. However, existing research has not yet reached consistent conclusions regarding brain lateralization in infant emotional speech processing.

4 Cross-Modal Processing of Emotional Information in Infants

Infants' cross-modal processing of emotional information refers to their ability to simultaneously utilize multiple sensory channels (e.g., visual and auditory) when perceiving and processing emotional information. This process is crucial for infants' emotional development and social interaction. Research indicates that developing circuits in the infant brain are essentially multisensory (Hyde et al., 2011). Three-and-a-half-month-old infants can successfully match emotional speech (happy or sad) with appropriate static facial images, but this ability is limited to familiar persons (mothers) (Montague et al., 2001). Vaillant-Molina et al. (2013) had 3.5- and 5-month-old infants listen to and watch dynamic facial expressions and voices of other infants expressing positive and negative emotions,

finding that only 5-month-old infants could match facial expressions consistent with the vocal emotion. Walker-Andrews et al. (1997) had 2- to 7-month-old infants view emotional faces while listening to matching or mismatching emotional speech, finding that 2-month-old infants could not yet match emotional sounds with facial expressions; 4-month-old infants could only match faces and voices when both expressed happiness; while 7-month-old infants could achieve audiovisual information matching under different emotional conditions, indicating that infants' ability to process emotional information cross-modally develops with age. Additionally, Bahrick et al. (2004) found that when experiencing emotional events in bimodal sensory modalities, 5-month-old infants could also detect rhythmic and prosodic changes in the events.

Palama et al. (2018) explored whether 6-month-old infants could transfer non-sensory modality information (i.e., information independent of sensory modality) from emotional speech to emotional faces. Researchers presented 24 infants with continuous emotional stimulus sequences (transferring sounds or facial expressions from one sensory modality (auditory) to another (visual)), constituting cross-modal transfer. Each sequence contained an emotional (angry or happy) or neutral sound, followed by simultaneous presentation of two static emotional faces (angry or happy, consistent or inconsistent with the emotional sound). The results showed that after listening to neutral or angry sounds, infants showed no significant difference in looking time at happy or angry faces. However, after hearing happy sounds, infants looked longer at angry faces inconsistent with the emotional sound (particularly at the mouth region), indicating that for 6-month-old infants, cross-modal transfer (from auditory to visual) may only occur after hearing happy sounds. This study demonstrates that 6-month-old infants can recognize emotions across sensory modalities. Soken et al. (1992) found that 7-month-old infants showed larger late negative components under conditions of consistent audiovisual emotional information, representing the acquisition of emotionally consistent information—that is, they could capture common emotional information from faces and voices and became sensitive to the consistency of facial expressions and emotional tone of voice. Later, Grossmann et al. (2006) observed that 7-month-old infants recorded larger early negative components (Nc) when facial and vocal emotional information was inconsistent, indicating they allocated more attention to inconsistent information. Hepach and Westermann (2013) found that when watching actors perform with positive or negative emotions, 10-month-old infants could not yet make selective responses to scenes where emotions and behaviors were consistent, while 14-month-old infants could match emotional information with social interaction scenes, suggesting that 10-month-old infants may not yet fully understand the meaning of emotions in social interactions, but this ability gradually develops with age, becoming evident by 14 months.

In summary, infants demonstrate the ability to process emotional information cross-modally, showing they can match emotional information across channels and transfer emotional information across sensory modalities. These abilities gradually improve with age. Based on existing research, we have preliminar-

ily observed that at 3.5 months, infants can already match emotional sounds and static faces of familiar persons (mothers); at 5 months, infants can match emotional sounds with consistent facial expressions and can use bimodal sensory information to perceive changes in emotional information. At 6 months, infants can recognize emotions across sensory modalities, possessing the ability to transfer emotion information independent of sensory modality from auditory (speech) to visual (faces). By 7 months, infants can stably capture common emotional information from audiovisual stimuli. After 10 months, infants can adjust their attention to facial information based on changes in emotional prosody and gradually deepen their understanding of emotions, thereby recognizing and understanding emotions through cross-modal channels in social interaction scenes.

5 Processing Biases in Infant Emotion Processing

By reviewing research on emotion processing in infants of different ages, we find that infants show processing biases toward emotions, and these biases manifest differently at different developmental stages. Early research found that happy prosody attracted more attention from newborns than negative prosody, eliciting more eye-opening responses (Mastropieri et al., 1999). Two-day-old newborns looked longer at happy than at fearful faces, indicating a preference for positive facial expressions in newborns. Newborns aged 0-4 days showed stronger brain responses to positive than to negative prosody (Zhang et al., 2019). One- to five-day-old newborns were more sensitive to fearful prosody, showing stronger brain responses when hearing fearful prosody (compared to neutral and happy prosody) (Cheng et al., 2012). At 2 months, infants' sensitivity to positive emotions increased, showing stronger brain responses to happy speech (compared to neutral and angry prosody) (Shekhar et al., 2019). Around 3 months, infants were more sensitive to fearful faces (compared to happy faces) (Bayet et al., 2017; Safar et al., 2020). Four-month-old infants looked longer at happy than at angry faces (LaBarbera et al., 1976) and could only match faces and voices when both expressed happiness (Walker-Andrews et al., 1997), suggesting a preference for positive emotions when using visual or cross-modal processing. At 5 months, infants showed stronger brain responses to happy speech prosody (compared to angry prosody) (Grossmann et al., 2005) but were more sensitive to fearful faces (Heck et al., 2016). Six-month-old infants could recognize happiness across sensory modalities but not neutral or angry emotions (Palama et al., 2018), suggesting greater sensitivity to positive emotions in cross-modal processing. At 7 months, infants were more sensitive to angry (Grossmann et al., 2010) and sad (Blasi et al., 2011) speech prosody, showed stronger brain responses to angry prosody (Grossmann et al., 2005), looked longer at fearful than at happy faces, and fearful faces elicited stronger brain responses (Hoehl & Striano, 2010; Peltola et al., 2009). Numerous other studies have consistently found that 7-month-old infants show greater bias toward fearful than happy facial expressions (Geangu et al., 2016; Krol et al., 2015; LoBue et al., 2010; Miguel et al., 2019; Safar et al., 2017). These studies indicate that infants' negative bias in emotion processing is relatively stable by 7 months of

age.

In summary, existing research has not yet reached consistent conclusions regarding processing biases in infant emotion. Emotional bias manifests differently at different stages of infant development. Infants' emotion processing is dominated by positive bias during the first 6 months, but gradually develops into a stable negative bias after 6 months. Accordingly, we propose the "Developmental Theory of Emotional Bias" : human emotional processing bias shifts around half a year of age, with infants aged 6 months and below showing positive bias, while infants aged 6-7 months and beyond show increasingly stable negative bias. From a cognitive developmental perspective, infants' brains prioritize processing stimuli relevant to their developmental stage. For infants aged 6 months and below, more positive responses to positive emotions may help establish positive connections with parents and thus obtain more care, so infants at this stage prefer positive emotions. Infants older than 6 months gradually develop motor abilities such as crawling, walking, and running, and begin to actively explore the world. At this stage, they need to be more sensitive to threatening information to protect themselves from harm, so infants at this stage prefer negative emotions. Currently, scholars have basically reached consensus that infants older than 6 months show negative bias in emotion processing. However, evidence for positive bias in infants younger than 6 months is relatively scarce, and more research is needed in the future.

6 Summary and Outlook

In summary, infant emotion processing primarily relies on speech, facial expressions, and cross-modal processing between the two. In infant emotional speech processing, the temporal cortex is the core brain region; while in emotional face processing, the temporal and frontal cortices are core regions. Although infant emotion processing involves both brain hemispheres, the right hemisphere appears to have an advantage. Within days after birth, infants can already preliminarily discriminate and differentiate emotional speech and faces and show emotional bias. This emotional bias manifests differently at different developmental stages. Infants' emotion processing is dominated by positive bias during the first 6 months, but gradually develops into negative bias after 6 months. This shift in processing bias may be related to infants' adaptation to the environment and accumulation of experience. Compared to emotional processing of speech and faces, infants' cross-modal emotion processing abilities show later development. Overall, with increasing age, infants' emotion processing gradually becomes more sophisticated, encompassing multiple levels from discrimination and differentiation of emotions, to capturing emotional changes, to understanding and applying emotions. Currently, research on processing visual, auditory, and cross-modal emotional information during infancy has made considerable progress and established a relatively solid foundation. However, several issues remain to be resolved:

First, there is currently insufficient evidence regarding the developmental

changes in emotion processing bias during the first year after birth. Most existing studies adopt age-split designs with infants from specific age ranges or conduct cross-sectional comparisons with infants from specific age groups, lacking longitudinal studies on the development of infant emotion processing. To address this issue, future research could adopt longitudinal tracking designs to conduct systematic studies on infants' emotion processing from early infancy to toddlerhood, constructing a complete developmental timeline to deeply reveal characteristics of infant emotional development and shifts in bias. During tracking, it is recommended to collect infant emotion processing data regularly at multiple time points to more accurately capture developmental trajectories. Additionally, researchers should not only focus on changes at specific ages but also deeply understand dynamic changes across different developmental periods to provide a more comprehensive understanding of temporal changes and continuity in infant emotion processing.

Second, the emotion labels (anger, fear, happiness) used in most studies are typically determined by adult participants. It should be noted that this does not necessarily mean infants have the same understanding of the emotions reflected by these labels (Zhang et al., 2017). Infants' sensitivity to a particular emotional material does not necessarily mean they can conceptually understand these emotions (Leppänen et al., 2009). Enhanced responses to certain emotional prosodies and faces may reflect processing of low-level differences present in emotional sounds and physical feature changes in the faces themselves, rather than emotion processing per se (Belin et al., 2010). Future research should verify emotional information from the infant' s own perspective as much as possible. Although infants cannot provide direct verbal feedback, their emotional experiences can be inferred through observation of their behavior, facial expressions, and physiological responses to ensure the accuracy and appropriateness of emotion labels. Moreover, future studies could carefully control for physical feature changes in emotional sounds and faces in experimental designs to exclude potential interference from these changes on infant responses. This would help ensure that observed enhanced responses are more likely results of emotion processing rather than caused by low-level differences in sounds and physical feature changes in faces. Finally, future research could integrate multiple sensory information through multimodal approaches, such as sound, faces, and physiological indicators (heart rate, respiration, and brain responses), to more comprehensively understand infants' emotional reactions. This would help distinguish whether physiological and behavioral responses elicited by specific emotional materials reflect conceptual understanding.

Third, current research on emotion categories is relatively limited, mainly focusing on basic emotions such as happiness, fear, anger, and disgust. Whether existing findings can be generalized to other more complex emotion categories remains an unanswered question. Future research could appropriately introduce complex social emotions, such as guilt, anxiety, and shame, as stimulus materials based on existing research, using established experimental paradigms to explore infants' processing of more complex social emotions. This would help

further enrich and expand theories of infant emotion processing. Additionally, social performance is an important indicator for measuring children's psychological development (彭小凡 et al., 2020). In-depth research on infants' processing of social emotions can provide valuable references for them to develop better social abilities as they grow.

Fourth, differences in experimental materials or paradigms often lead to inconsistent or even contradictory results. For example, using static versus dynamic faces in emotional face research may yield opposite results. Future research could use multiple materials and paradigms within the same experiment to compare the same group of participants, ensuring reliability and stability of research results. Additionally, multiple research methods could be combined, such as behavioral observation, neuroimaging, and physiological measurement, to comprehensively understand multiple aspects of infant emotion processing. This integrated approach not only helps provide reliable research results but also facilitates the establishment of a more comprehensive model of emotion processing development, providing more convincing evidence for revealing its cognitive development and neural mechanisms.

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