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The infant brain combines emotional information from faces and action kinematics

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ABSTRACT

Converging evidence suggests that infants can extract and integrate emotional content from multiple sources (e.g., faces, body postures, and voices). Yet this evidence is mostly based on static representations of emotions, such as photographs, whereas in everyday life, infants are primarily exposed to dynamic input, particularly others' actions. This study investigates whether infants can link emotional information conveyed in action kinematics and facial expressions. To address this issue, we used an ERP priming paradigm in which 12-month-olds were presented with video primes of actions performed with happy or angry kinematics, followed by target images of faces displaying happy or angry facial expressions. Results revealed a P400 congruency effect over the right hemisphere. Specifically, happy faces elicited a larger P400 than angry faces when they followed an incongruent emotional action. Moreover, the P400 was larger for incongruent than for congruent happy facial expressions. Results suggest that bodily kinematics provide infants with crucial contextual and emotional cues that bias their perception of facial expressions from early in life.

Introduction

Being able to detect and identify others' emotions accurately is essential for successful interpersonal relationships. It allows us to infer others' internal states, predict their upcoming actions, and adjust our behavior accordingly (Horstmann, 2003). Traditionally, researchers have considered facial expressions to be the main way of communicating emotions in humans (Ekman & Oster, 1979). Evidence shows that, early in life, human infants are capable to discriminate, recognize, and learn emotional cues from faces, a vital competence for navigating social interactions (Addabbo et al., 2018; Geangu et al., 2011; Hoehl & Striano, 2008; Hunnius et al., 2011; Mermier et al, 2022; Nava et al., 2016). However, facial expressions alone do not capture the richness of emotional cues that are communicated in everyday life. Facial expressions are embedded in a social context (Aviezer, Ensenberg, & Hassin, 2017) in which various other emotional cues such as vocal tones, body postures, or body movements are also important sources of emotional information.

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Several behavioral and neurophysiological studies indicated that infants' ability to discriminate emotional content is not confined to faces but extends to body postures (Geangu & Vuong, 2020; Missana et al., 2014) and vocal tones (Grossmann, 2010). In addition to being able to extract emotional content from different modalities (e.g., visual and auditory) and different forms of emotional expressions (e.g., body postures and faces) independently, infants are capable of integrating emotional information across modalities and forms. Several studies examining infants' looking times suggested that they can match emotional faces and body movements with the corresponding vocal tones (i.e., for happy and angry emotions; Heck et al., 2018; Palama et al., 2018; Zieber et al., 2014) and detect the correspondence between emotions from static body postures and faces (i.e., for happy, sad, and angry emotions; Hock et al., 2017).

Studies using event-related potentials (ERPs) have also provided neural evidence in support of intermodal matching. Infant research has shown that ERP components, including the Nc, Pc, N290, and P400, are not only modulated by emotional facial expressions (Grossmann et al., 2006; Hoehl & Striano, 2008; Kobiella et al., 2008; ; Quadrelli et al., 2019) but also indicate intermodal matching (Grossmann et al., 2006). That is, Grossman and colleagues (2006) investigated changes in the amplitude of the Nc and Pc components in 7-month-old infants in response to simultaneous presentations of matching and mismatching face-voice pairings involving angry and happy emotions. Results indicated an enhanced Pc in response to matching face-voice pairings and an enhanced Nc amplitude in response to mismatching face-voice pairings. Thus, infants detected the common emotion expressed by faces and voices in the matching condition and allocated more attention when the two emotions were mismatched.

One commonly used paradigm in ERP studies is the priming paradigm, which allows researchers to explore whether infants can extract a shared attribute, such as emotion, between two stimuli. For example, Rajhans and colleagues (2016) used a priming paradigm in which 8-month-old infants first observed fearful or happy body postures, followed by matching or mismatching facial expressions. Although they did not find any modulation of the P1, N290, and P400 components, a difference in the Nc and Pc showed distinct neural processing of the different emotions when body posture and facial expression were matching. No difference was found for mismatching stimuli. According to the authors, these results suggest that observing mismatched emotional body expressions impaired the subsequent neural discrimination of emotional faces, preventing infants from differentiating between happy and fearful faces. In another study, matching and mismatching audio-visual emotional displays were contrasted in a priming paradigm (Vogel, Monesson, & Scott, 2012). When emotional sounds (crying/laughing) were presented before an emotional facial expression, 5-month-old infants' Nc was larger for emotionally matching displays compared to mismatching displays. Interestingly, at 9 months of age, the neural activations for sound/face congruency shifted to the posterior face-sensitive ERP components (N290, P400). Specifically, the N290 peaked faster for incongruent versus congruent sound/face pairs, while the P400 showed faster latencies for incongruent compared to congruent face/sound pairs. Noteworthy, congruency effects on the infant P400 have also been observed in studies examining how infants encode the relationship between objects and hand gestures. These studies reported larger P400 amplitudes in response to congruent objects/gestures pairings at 8 months (Gredebäck et al., 2010; Bakker et al., 2015), and to incongruent pairings at 13 months (Melinder et al., 2015). Previous evidence shows that the context provided by voice and body posture modulates infants' neural allocation of attention to emotional faces. These findings suggest infants' neural processing reflects the integration of emotional information across modalities (e.g., visual and auditory; Grossmann et al., 2006; Vogel et al., 2012) and types of emotional expressions (e.g., facial expressions, body postures; Rajhans et al., 2016). It is important to acknowledge that differences in research design across studies investigating infants' sensitivity to cross-modal emotional incongruency may account for inconsistencies in both the ERP components associated with the congruency effect and the observed patterns of their activation.

While several studies have explored infants' ability to integrate emotional information across modalities, most research has focused on static representations of emotions, such as photographs of faces or body postures. However, in everyday life, infants are primarily exposed to dynamic rather than static input, particularly through the actions of others. Infants observe adults performing actions whose kinematics (e.g., velocity, acceleration, and jerkiness) noticeably reflect the agent's emotional state (Pollick et al., 2001), attribute greater saliency to actions performed in an emotional context rather than a neutral one (Addabbo & Turati, 2020). Moreover, 8-month-old infants can extract emotional information from body postures, as evidenced by their differential neural response to dynamic point-light displays of happy, angry and fearful body expressions (Missana & Grossmann, 2015). However, only a few studies – specifically two – have investigated infants' sensitivity to emotional cues conveyed through the kinematic properties of human actions. Addabbo and colleagues (2020) recorded facial electromyographic (EMG) activity in 11-month-old infants while they watched video clips of an agent moving an object using either happy or angry kinematics. Infants matched facial expressions to the different emotional kinematics they observed (i.e., increased *zygomaticus* activity in response to happy kinematics, and increased *corrugator* activity in response to angry kinematics). Using a similar EMG procedure, Schröer and colleagues (2023) found that infants' sensitivity to others' emotional action kinematics is associated with their caregivers' emotional expressivity, suggesting an important role of experience for infants' sensitivity to these emotional cues.

While these results suggest that infants can extract the emotional content of actions based on kinematic properties, they do not provide any information on whether and how infants potentially integrate emotional action information with other sources of emotional information, such as emotional facial expressions. Being able to extract the emotional content of these different sources (e.g., faces and kinematics) and integrate them can provide important additional cues and facilitate the understanding of others' emotional states. Our study investigated whether infants are able to integrate the emotional content conveyed by action kinematics and facial expressions. By examining infants' ERP responses, we aimed to tap into the perceptual, attentional, and memory processes underlying this association.

To address this question, we used a priming paradigm in which 11- to 12-month-old infants were presented with video primes of actions performed either with happy or angry kinematics, followed by target images of faces displaying happy or angry facial expressions. We chose to test 11- to 12-month-old infants based on the findings of Addabbo and colleagues (2021), which suggest that by this age, infants are capable of extracting emotional information from action kinematics. This is also consistent with recent research showing that 12-month-old infants make use of action kinematics to extract emotional information directed at objects in their visual exploration of those objects (Rutkowska et al., 2025). In line with previous research on infants' emotional processing and intermodal matching using priming paradigms, we expected congruency effects on attentional components such as the Nc and Pc. Specifically, we anticipated a larger Nc for incongruent kinematic/face pairs, indicating increased allocation of attention when emotions across modalities did not match. Further, we expected a larger Pc when facial expressions were primed with emotion-congruent actions compared to emotion-incongruent ones, showing that, at later stages of processing, infants detected the common emotion conveyed in kinematics and faces (Grossmann et al., 2006). Lastly, we expected congruency effects on face-sensitive components, such as the N290/P400 complex, with increased activity in response to incongruent compared to congruent kinematic/face pairings (Melinder et al., 2015; Vogel et al., 2012).

Methods

Participants

The final sample consisted of 28 healthy 11- to 12-month-old infants (11 females; M = 369.5 days; SD = 23.6 days), born full-term (37–42 weeks of gestation) and with normal birthweight (> 2500 g). An additional 23 infants were tested but excluded from the final sample due to the fussiness of the infant who refused to continue participation, resulting in not enough trials watched (N = 11), excessive artifacts (N = 8), or technical errors (N = 4). A minimum of 5 artifact-free trials per condition was required to proceed to further analysis (Xie & Richards, 2017). Participants were recruited via written invitation based on birth records of xxxx and neighbouring cities. Written informed consent was given by the caregiver before testing. The protocol followed the ethical standards of the Declaration of Helsinki (BMJ 1991; 302:1194) and was approved by the ethical committee of xxx *(omitted for blinding purposes)* (Protocol number: 421).

Stimuli

Priming stimuli consisted of videos of actions performed with angry or happy emotional kinematics, followed by target photographs of faces expressing anger or happiness. Emotions of anger and happiness were chosen for their distinct kinematic properties (higher peak velocity, acceleration, and jerkiness for anger than happiness; Sawada et al., 2003), and based on previous research suggesting that infants reliably discriminate them when displayed by faces or body movements (Xie et al., 2019; Missana & Grossmann, 2015). Emotional kinematic videos were taken from the stimulus set used by Addabbo and colleagues (2020) and depicted a female actress picking up an object from one side of a table to move it into a box on the other side of that table (Fig. 1). The actress, whose face was not visible, was seated behind the table on which the object and the box were placed. The action was carried out by two different models selected based on high recognition rates (average recognition rate of 84 % for happy kinematics, and 96 % for angry kinematics; Addabbo et al., 2020), each model moving two different objects in the box. The direction of the movement (i.e., objects moved from right to left, or left to right) was counterbalanced for both angry and happy emotional kinematics. The videos taken from Addabbo and colleagues' study were cut to have a shorter total duration of 1700 ms.

Face stimuli were coloured photographs of women expressing happiness or anger. Photographs were taken from the validated BU-3DFE database (Yin et al., 2006), and three different female models were selected, based on high recognition rates (average recognition rate of 100 % for happy faces, and 86 % for angry faces). Similar to previous studies, the photographs were cropped using Adobe Photoshop software so that only the internal features of the face were visible within an oval shape (Rajhans et al., 2016).

Design

We adapted Rahjans and colleagues' design (2016). Infants were first primed with videos of actions performed with either happy or angry kinematics, followed by photographs of faces expressing either congruent or incongruent emotions (Fig. 2). Thus, the congruent condition encompassed angry kinematics followed by angry faces, as well as happy kinematics followed by happy faces. Inversely, the incongruent condition encompassed angry kinematics followed by happy faces, as well as happy kinematics followed by angry faces. For each emotion, the action was carried out by two different models, and each model performed the movement in two different directions, leading to 4 possible action videos. As for the photographs of emotional faces, each emotion was expressed by 3 different models. All possible combinations of emotional actions and emotional faces were presented, leading to 12 combinations per subcondition (e.g., 12 combinations of angry kinematics followed by angry faces). Thus, 24 combinations were presented for the

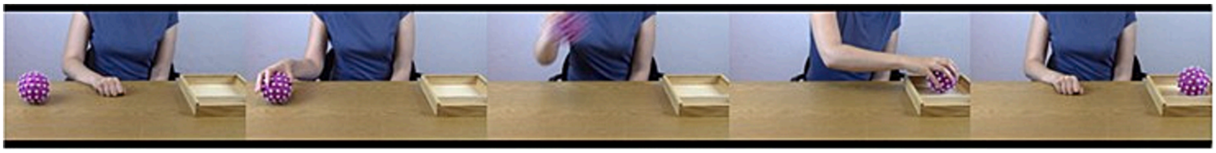

Fig. 1. Example of frames from the priming videos depicting an actress picking up an object from one side of a table to move it into a box on the other side of that table.

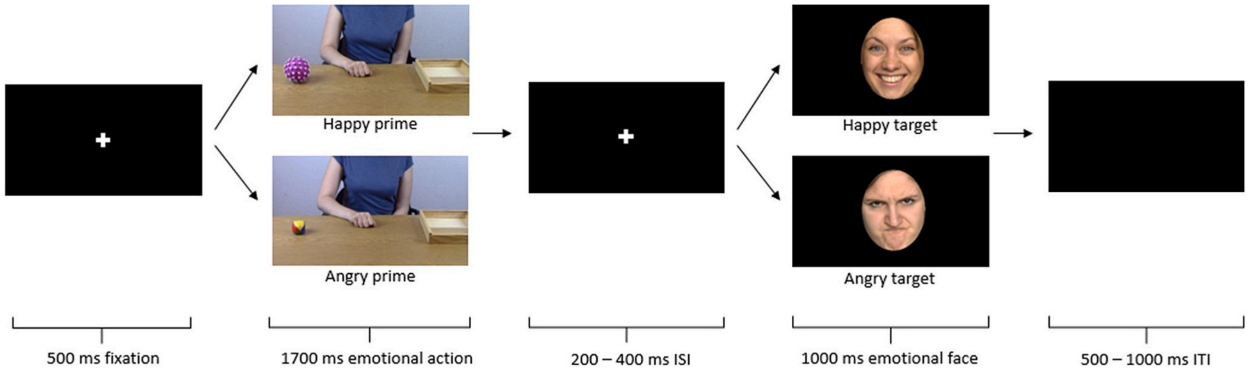

Fig. 2. Example of the priming design and stimuli used in the study. Infants were first primed with actions performed with happy or angry kinematics, and were then presented with target photographs of faces expressing either congruent or incongruent emotions.

congruent and incongruent conditions, resulting in a total of 48 combinations. Each of these combinations was presented up to four times, leading to a maximum of 192 trials, or until the infant became inattentive and looked away for 5 consecutive trials.

Each trial started with the display of a white fixation cross on a black background for 500 ms, followed by the presentation of the prime video for 1700 ms. A fixation cross was then displayed for a random duration of 200 to 400 ms, followed by the presentation of the static emotional face for 1000 ms. The inter-trial interval consisted of a black screen, displayed for a random duration of 500 to 1000 ms (Fig. 2). All stimuli were presented in a random order, with the constraint that the same sub-condition could not be presented more than twice in a row. Further, the association between the object used and the emotional condition was counterbalanced across trials.

Procedure and apparatus

Infants were seated on their caregiver’s lap, in an electrically shielded and sound-proofed cabin. Stimuli were displayed on a 24-inch monitor positioned at approximately 60 cm from the infant’s eyes using the software E-Prime v2.0 (Psychology Software Tools Inc., Pittsburgh, PA). Before the stimulus presentation, caregivers were instructed to avoid talking to their infant and pointing to the monitor and to remain as still as possible throughout the entire procedure. The infant’s face and body were recorded during the whole experiment using an infrared video camera hidden over the monitor, which fed into the data acquisition computer and TV monitor located outside the cabin. This allowed the experimenter to orient the infant’s attention back to the monitor by displaying an attention-getter (i.e., a moving colored fixation point) whenever they were distracted.

EEG data acquisition and processing

We recorded the electroencephalograms (EEG) using a 128-electrode HydroCel Geodesic Sensor Net (Electrical Geodesic Inc., Eugene, OR). The data was referenced online to the vertex electrode (Cz) and amplified through an EGI NetAmps 300 amplifier at a sample rate of 500 Hz. An online band-pass filter of 0.1–100 Hz was applied. Before stimulus presentation, impedance values were inspected so that any channel exceeding a threshold of 50 kΩ could be adjusted before data collection. Data processing was carried out with the NetStation software v4.6.4 (Eugene, OR). Continuous signals were bandpass filtered at 0.3–30 Hz and segmented into epochs comprising 100 ms of baseline (i.e., fixation cross period preceding the emotional face picture) and 1000 ms of the target stimulus presentation. Automatic artifact detection was first performed on segmented data to reject any signal exceeding ± 200 μV in a sliding window of 80 ms. Data were then visually inspected to eliminate any remaining artifact by rejecting channels containing muscle artifacts, blinks, eye movement artifacts, or drift (Hoehl & Wahl, 2012; Xie et al., 2019; Rajhans et al., 2016). Any segments identified as bad were excluded from all further analyses. Also, any trial containing more than 15 % of the channels marked as bad was excluded from further analysis. Among the included trials, channels containing artifacts were replaced using spherical spline interpolation. However, if clusters of three or more nearby channels with artifacts were detected, then the entire trial was excluded from the analysis. Further, video recordings were used to exclude trials in which the infant did not look at the cue/target or did not keep fixation on the screen at least until the target offset. The final data were then re-referenced to the average reference. An average of 17.82 trials (SD = 6.48) were retained for the congruent condition (M = 8.82 for angry prime–target pairs and M = 9.00 for happy prime–target pairs), and 18.10 trials (SD = 6.60) for the incongruent condition (M = 9.03 for angry prime followed by a happy target, M = 9.06 for happy prime followed by an angry target). The mean number of trials watched by the infants was: M = 24.5 (SD = 4.87) for the happy congruent condition, M = 24.4 (SD = 4.69) for the happy incongruent condition, M = 24.31 (SD = 4.69) for the Angry congruent condition, and M = 24.51 (SD = 4.70) for the Angry incongruent condition. Overall, this procedure resulted in the exclusion of 37.0 % of the trials in the Happy congruent condition, 36.8 % in the Happy incongruent condition, 36.3 % in the Angry congruent condition, and 36.8 % in the Angry incongruent condition.

Inspection of the grand-average waveforms over fronto-central regions revealed a well-defined Nc attentional component and a well-defined Pc component (Fig. 3). Similar to previous studies (Rajhans et al., 2016), two clusters of electrodes were selected, over the left (20, 24, 28, 29, 30, 36, 37, 42) and right fronto-central regions (87, 93, 104, 105, 111, 117, 118, 124) (Fig. 3). More temporal electrodes were excluded due to excessive artifacts near the ear region of the infant. Time windows were selected based on previous studies and are also consistent with the waveform observed in the current sample (Grossmann et al., 2006; Quadrelli et al., 2019; Rajhans et al., 2016). Specifically, time windows of respectively 350–600 ms and 600–750 ms were selected. Well-defined N290 and P400 face-sensitive components were also observed over the occipital electrodes. Similar to previous studies (Bakker et al., 2015; Melinder et al., 2015), one cluster of electrodes in the left (58, 59,64, 65, 66, 70, 71) and right (76, 83, 84, 90, 91, 95, 96) occipital region was selected (Fig. 3). Following previous infant ERP studies (Leppänen et al., 2007; Quadrelli et al., 2019), a time window of 200–300 ms was chosen for the N290 component, and 300–500 ms for the P400 component. Mean amplitude (μV) values were extracted for each of these five components, and mean-minus-trough corrections were then calculated (Bettoni et al., 2021; Xie et al., 2019; Xie & Richards, 2017). The mean ERP for the Nc was defined as the mean amplitude between 350 and 600 ms, minus the preceding positive component at 250–350 ms, and the Pc was defined as the mean EEG between 600 and 750 ms, minus the preceding Nc interval. The mean ERP for the N290 was defined as the mean EEG between 200 and 300 ms, minus the preceding P1 component at 100–200 ms, and the P400 was defined as the mean EEG between 300 and 500 ms, minus the preceding N290 interval (Fig. 4). This mean-minus-trough correction was calculated to mitigate the carry-over effects of preceding activity on these components and has been employed in different ERP studies with infants (e.g., Bettoni et al., 2021; Xie et al., 2019; Xie & Richards, 2017).

Data analysis

Statistical analyses were performed using the software Jamovi (version 1.6.15; https://jamovi.org). All statistical tests were

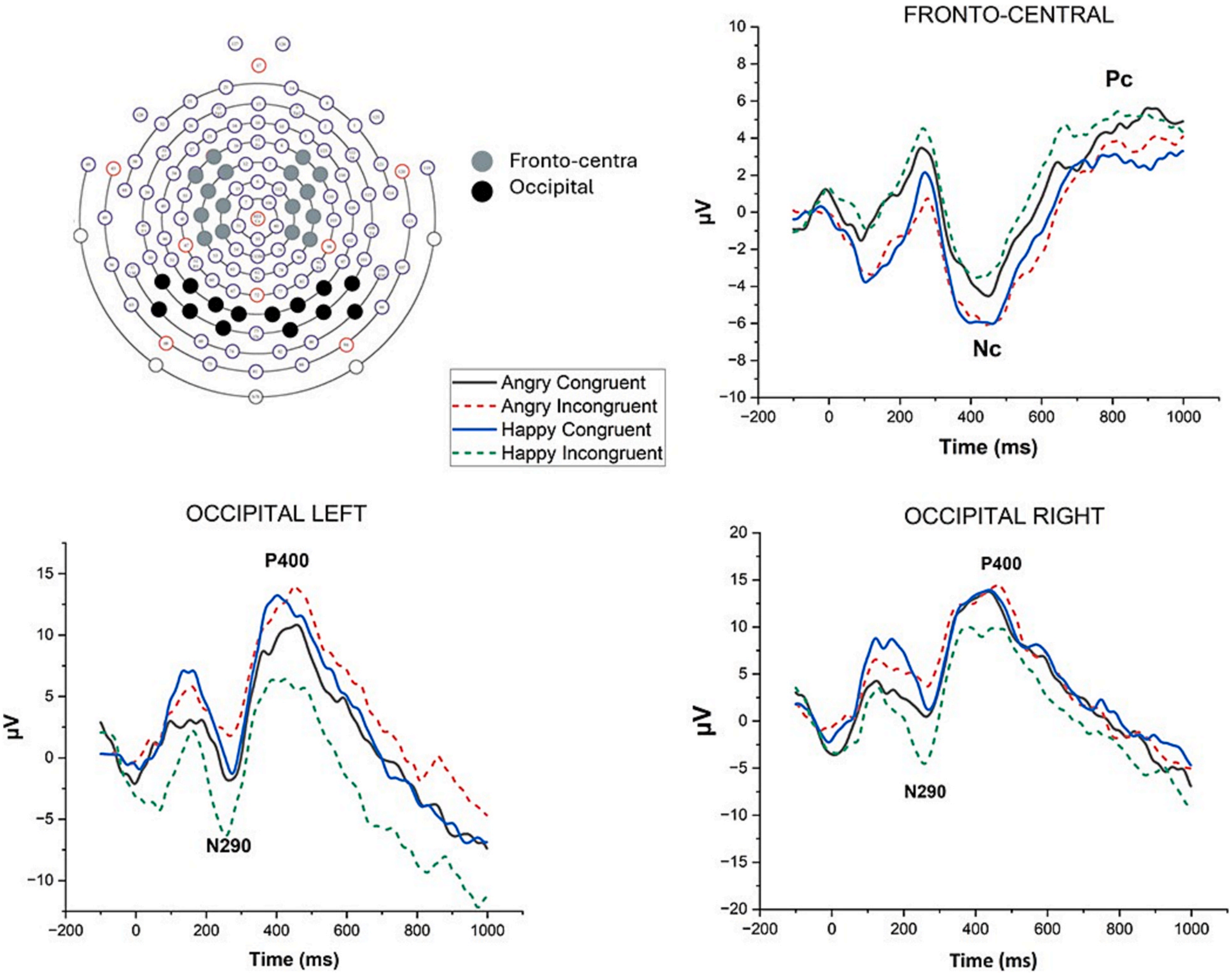

Fig. 3. Electrode clusters (Occipital and Fronto-central) and Grand average waveforms depicting ERP components (N290, P400, Nc, Pc) at occipital (separately for left and right hemisphere) and fronto-central electrode sites in response to angry faces primed with angry kinematics (Angry Congruent), angry faces primed with happy kinematics (Angry Incongruent), happy faces primed with happy kinematics (Happy Congruent), and happy faces primed with angry kinematics (Happy Incongruent).

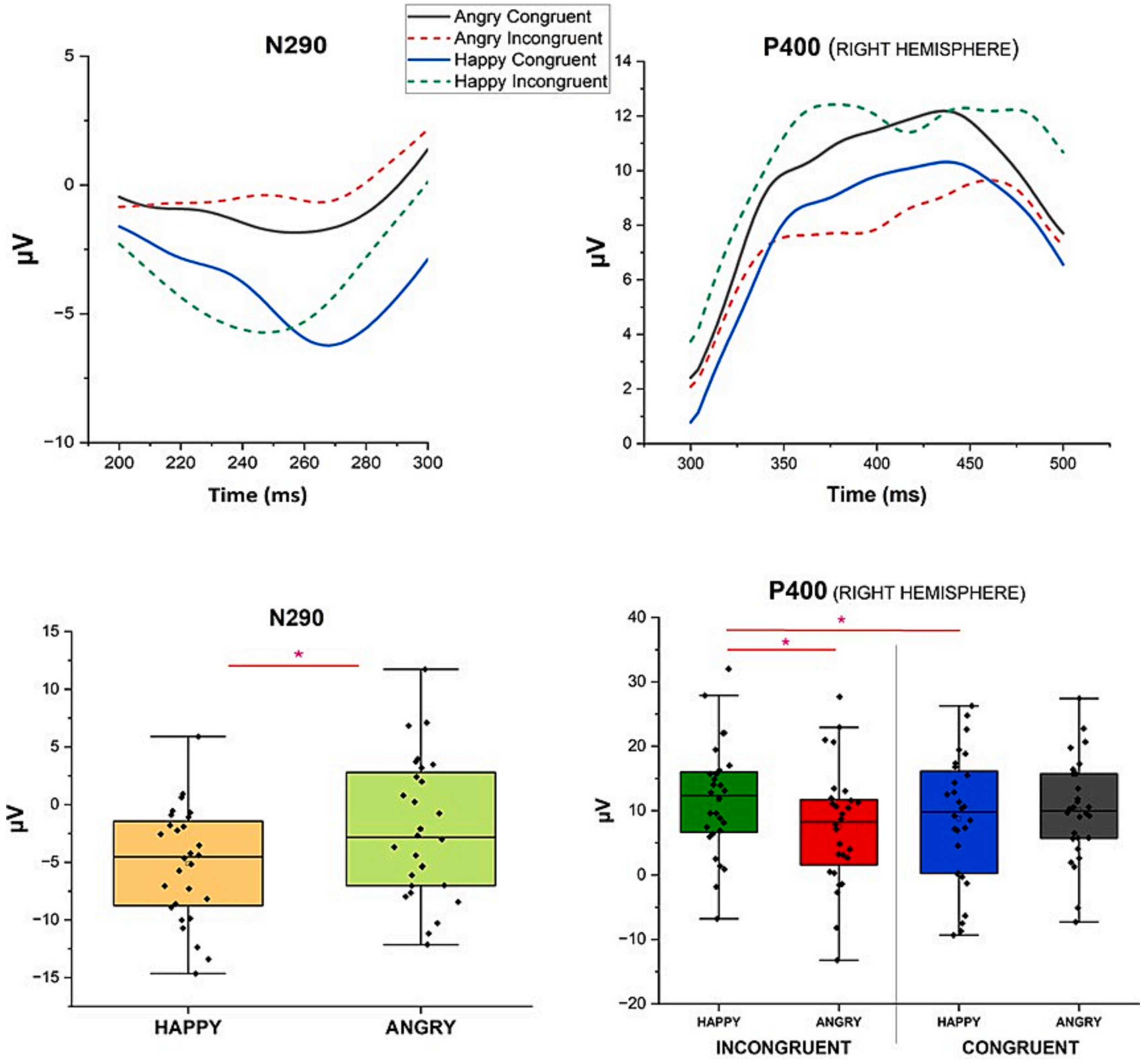

Fig. 4. Mean-minus-through ERP activity at occipital electrode sites. The upper panel displays the corrected mean-minus-through waveforms for the N290 and P400 components. In the lower panel, the left side shows increased N290 responses to happy compared to angry facial expressions. The right side illustrates enhanced P400 responses to happy incongruent compared to angry incongruent, and happy congruent faces in the right hemisphere.

conducted on a two-tailed.05 level of significance. Pairwise comparisons were performed using t-tests with the False Discovery Rate control procedure (Benjamini & Hochberg, 1995). The Greenhouse-Geisser correction for non-sphericity was applied when appropriate (Abdi, 2010), and effect sizes were estimated using the partial eta square measure (η_p^2). Mean amplitudes of the Nc, Pc, N290, and P400 components were analyzed in separate 2x2x2 repeated measures Analyses of Variance (ANOVAs) with the target emotion (anger, happiness), condition (congruent, incongruent), and hemispheres (left, right) as within-subject factors. Data are reported as the mean and the standard deviation (SD). We focused our analysis on mean amplitudes because this measure is less sensitive to noise than peak amplitude and latency and is recommended for infant EEG recordings (Picton & Taylor, 2007).

Results

Nc

The ANOVA performed on the Nc component at anterior electrode sites did not reveal any significant main effects or interactions (all $ps > .17$).

Pc

The ANOVA performed on the Pc component revealed a significant Congruency x Hemisphere interaction, $F(1,27) = 5.92$, $p = .02$, $\eta_p^2 = .18$. However, follow-up t-tests did not show any significant differences (all $ps_{corr} > .32$).

N290

The ANOVA performed on the N290 component revealed a significant main effect of Emotion, $F(1,27) = 10.47$, $p = .003$, $\eta_p^2 = 0.28$ indicating that infants showed greater N290 amplitudes in response to Happy ($M = -5.11$ µV; $SD = 4.87$) compared to Angry ($M = -2.14$ µV; $SD = 6.05$) facial expressions (Fig. 3). No other main or interaction effects were detected.

P400

The ANOVA performed on the P400 component revealed a Congruency x Emotion interaction, $F(1,27) = 4.28$, $p = .048$, $\eta_p^2 = .14$. Follow-up comparisons showed no significant differences across conditions (all $ps_{\text{corr}} > .09$).

A significant Congruency x Emotion x Hemisphere interaction, $F(1,27) = 6.19$, $p = .019$, $\eta_p^2 = .19$, also emerged. Follow-up comparisons were corrected for multiple testing using the False Discovery Rate control procedure (Benjamini & Hochberg, 1995). Results indicate that infants showed a greater P400 response to Happy ($M = 11.7$ µV; $SD = 8.6$) compared to Angry ($M = 7.5$ µV; $SD = 9.2$) emotions in the right hemisphere in the incongruent condition ($t(27) = 4.14$, $p_{corr} = .008$). Further, P400 was greater in response to incongruent Happy ($M = 11.7$ µV; $SD = 8.6$) compared to congruent Happy ($M = 8.7$ µV; $SD = 10.01$) emotions in the right hemisphere ($t(27) = -2.85$, $p_{corr} = .03$) (Fig. 3). No other comparison reached significance (all $ps_{\text{corr}} > .09$).

Discussion

The current study investigated infants' capacity to bind emotional information across action kinematics and facial expressions. To integrate affective information across modalities, infants should be able to extract the meaningful, common emotional information expressed in action kinematics and emotional expressions. Here, we have found that infants discriminated between happy and angry facial expressions as indexed by differential N290 activity for the two emotions, and detected the incongruency between kinematics and facial expressions: A congruency effect was evident for the P400 ERP component, typically considered a face-sensitive component. In particular, our results showed that only when emotional faces were primed with incongruent emotional kinematics, the P400 over the right hemisphere showed enhanced amplitude in response to happy compared to angry faces. Further, the P400 showed enhanced responses to happy faces in the incongruent compared to the congruent condition. Thus, from an early age, the emotions conveyed in action kinematics can influence the neural processing of faces.

Confirming previous findings (Xie et al., 2019), the modulation of the N290 indicates that infants were able to differentiate between happy and angry facial expressions. Notably, only the P400 was affected by the emotion congruency between action kinematics and faces. This suggests that infants detected the incongruency between emotional content conveyed by action kinematics and faces at later stages of visual processing, with happy faces preceded by angry kinematics appearing more salient than angry faces preceded by happy kinematics and from happy faces preceded by happy kinematics. Importantly, there was no evidence that congruency effects involved attentional anterior components such as the Nc and Pc, in contrast with previous evidence from younger infants (Rajhans et al., 2016; Grossmann et al., 2006). The study by Vogel and colleagues (2012) suggests that, between 5 to 9 months of age, neural responses to sound/face congruency shift from the anterior attentional Nc component to the posterior face-sensitive ERP components (N290, P400). Therefore, differences across studies might be attributed to the age of the participants. Infants at the end of the first year, like those in our study, may rely less on sustained attentional processes to detect emotional incongruency across modalities compared to younger infants. However, the small sample size may have limited our ability to detect more robust effects over the Nc/Pc complex, highlighting the importance of future research with larger sample sizes to better understand the role of these attentional components in processing crossmodal congruency.

Interestingly, the modulation of the P400 is in line with a body of literature exploring infants' ability to detect the congruency/incongruency between object locations and hand gestures (i.e., pointing, grasping; Bakker et al., 2015; Gredebäck et al., 2010; Melinder et al., 2015). While in younger infants – 8-month-olds – the P400 amplitude was enhanced in response to congruent vs incongruent object/hand gesture pairing, in older infants – 13-month-olds – the P400 was larger to incongruent compared to congruent pairs (Melinder et al., 2015). Thus, previous evidence suggests that the P400 might be sensitive to congruency effects in a wide range of different social signals, including faces and gestures. Our results with 11-month-old infants support previous findings with older populations (Melinder et al., 2015), showing increased P400 activity in response to incongruent vs. congruent conditions, but only when infants were presented with happy facial expressions. Our findings indicate that the P400 congruency effect emerged specifically when happy facial expressions followed angry body movements, but not when angry faces followed angry body movements. This selective pattern argues against a general attentional explanation, in which any angry action would broadly heighten attention and modulate subsequent face processing. Instead, the effect is more consistent with the integration of emotional cues across modalities, suggesting that infants are sensitive to the valence mismatch between body kinematics and facial expressions. At the same time, the asymmetry emerging from our data can be interpreted in different ways. One possibility is that the shift from negative kinematic cues to a positive facial expression may elicit a sense of emotional relief, potentially engaging reward-related neural mechanisms and thereby enhancing the salience of the happy face. Another interpretation is that a positivity bias may be at play, with happy faces constituting a more familiar or more deeply processed emotion in infancy, making them more susceptible to modulation by a preceding negative context. More generally, such asymmetries are not uncommon in emotion research, as different emotions are known to recruit partly distinct neural processing pathways (Kesler et al., 2001). Future studies are needed to disentangle these alternative and speculative interpretations and to clarify which mechanisms primarily drive infants' sensitivity to mismatches in response to happy facial expressions.

Overall, our results show that 11- to 12-month-olds rely primarily on perceptual-based processes to detect emotion commonalities across kinematics and faces rather than on their attention-based system. However, a recent study identified common neural sources—specifically the PCC/Precuneus and temporal regions—for both the P400 and Nc components, suggesting that they may reflect shared attentional mechanisms involved in infants' face processing (Xie et al., 2019). Future studies might explore the neural sources of the P400 activity to better understand the nature of such activation within a priming paradigm and provide insight into the processes behind it.

It is important to acknowledge some limitations of the present study. First, the high attrition rate (45 %). This level of data loss is not unexpected given the relative length of the trials, which each included a dynamic prime followed by a target stimulus. Such extended trial structures are more demanding for infants and can naturally contribute to higher attrition. However, the attrition rate observed in the present study is in line with what has been reported in previous infant ERP research (e.g., Stets et al., 2012). Second, future research could benefit from including a neutral condition, which would provide a critical baseline for interpreting emotional effects more precisely. This would allow for clearer differentiation between facilitatory and inhibitory processes underlying the observed differences.

Our findings offer the first indication that, from very early in life, action kinematics provide infants with contextual emotional cues that can alter the neural processing of emotional facial expressions. In real life, faces can sometimes be out of sight or highly ambiguous. The ability to rely on bodily contextual information to better decipher others' facial expressions is essential from the very first stages of development and could have important implications for socio-emotional development. Indeed, the ability of infants to process and combine emotional cues from different sensory modalities, such as facial expressions and bodily kinematics, might serve as a cornerstone for developing social understanding. By coordinating emotional information across sensory channels, infants enhance their capacity to interpret and respond to the emotional dynamics of their environment, especially within caregiver interactions. Early sensitivity to cross-modal emotional congruency may play a key role in the development of socio-emotional abilities, including forming secure attachments, using others' emotional responses for guidance, and responding empathetically.

CRediT authorship contribution statement

M. Addabbo: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J. Mermier:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J. Rutkowska:** Writing – review & editing, Methodology, Conceptualization. **M. Meyer:** Writing – review & editing, Methodology, Conceptualization. **S. Hunnius:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **C. Turati:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **H. Bulf:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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