Received: 10 July 2020 | Accepted: 10 June 2021

DOI: 10.1111/infa.12420

INFANCY THE OFFICIAL JOURNAL OF THE INTERNATIONAL CONGRESS OF INFANT STUDIES WILEY

RESEARCH ARTICLE

Exploring emotional face processing in 5-month-olds: The relation with quality of parent–child interaction and spatial frequencies

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Funding information
Dutch Ministry of Education, Culture, and Science and the Netherlands Organization for Scientific Research, Grant/Award Number: 024.001.003

Abstract

It is unclear whether infants differentially process emotional faces in the brain at 5 months of age. Contradictory findings of previous research indicate that additional factors play a role in this process. The current study investigated whether five-month-old infants show differential brain activity between emotional faces. Furthermore, we explored the relation between emotional face processing and (I) stimulus characteristics, specifically the spatial frequency content, and (II) parent, child, and dyadic qualities of interaction characteristics. Face-sensitive components (i.e., N290, P400, Nc) in response to neutral and fearful faces that contained only lower or higher spatial frequencies were assessed. Quality of parent–child interaction was assessed with the Manchester Assessment of Caregiver Infant Interaction (MACI). The results show that, as a full group, none of the components differed between emotional expressions. However, when splitting the group based on median MACI scores, infants who showed high quality of interaction (i.e., more attentiveness to caregiver, positive and negative affect, and liveliness) processed emotions differently, whereas infants who showed low quality did

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not. These results indicate that a sub-group of infants show differential emotional face processing at 5 months of age, which seem to relate to quality of their behavior during the parent–child interaction.

1 | INTRODUCTION

Facial emotional expressions provide crucial information for children's social interactions. The ability to discriminate between facial expressions develops rapidly in the first year of life (for a review see Leppänen & Nelson, 2009). The field usually considers 7 months as the age at which infants respond differently to facial emotional expressions. At this age, neural responses measured using electroencephalography (EEG) differ for instance between fearful and neutral expressions (e.g., Yrttiaho et al., 2014; for an overview see van den Boomen et al., 2019). Yet whether differential emotional face processing is possible at 5 months of age is less well established: Three out of five EEG studies with infants of this age indicated that infants show differential processing of emotional faces (Rigato et al., 2010; Xie et al., 2018; Yrttiaho et al., 2014), whereas two other studies found no difference in brain activity between expressions (Hoehl & Striano, 2010; Peltola et al., 2009). Discrepancies between studies could be due to multiple factors including characteristics of the children as well as the stimuli involved. Although these factors are confirmed to influence emotional face processing in older children and adults (for reviews see e.gJeantet et al., 2018; Leppänen & Nelson, 2009), their role in young infants is unknown. An increased understanding of what affects emotional face processing in five-month-olds would be relevant to the clinical field and parenting, as it can help shaping the optimal environment for children but also help to detect infants that might be at risk for atypical development of emotional face processing. Furthermore, knowledge about relevant factors aids shaping theoretical models regarding influences very early in the developmental trajectory (e.gJohnson, 2015; Leppänen & Nelson, 2009). Therefore, the current study sets out to investigate the role of two (clusters of) factors in emotional face processing at 5 months of age that tap on child-related factors, namely the quality of interaction between parents and children, and stimulus characteristics. As such, this is a first step to integrate two factors that are traditionally studied in separate research fields.

The quality of interaction between parents and children is of interest because emotional face processing is thought to depend on the quantity and quality of input (e.g., Leppänen & Nelson, 2009). Most young infants receive much facial input (average 15 min per h), but only from a few persons (Jayaraman et al., 2015), which most plausibly are their parents. The facial expressions of the parent are likely to be affected by characteristics of both the parent and the child, as well as the dyadic interaction between them. Think for instance about the difference a crying or laughing baby makes for the look on the parent's face, and what effect a soothing or desperate parent might have on the subsequent response of the infant. Consequently, parent and child characteristics could affect the emotional face processing of infants. Indeed, previous research showed that infants' ability to process emotional faces relates to their parent's personality and behavior, and thus, the input parents provide to their infant. For instance, 5-month-old infants of depressed mothers (Bornstein et al., 2011) and 7-month-old infants with mothers who scored low on positivity or sensitivity (de Haan et al., 2004; Taylor-Colls & Pasco Fearon, 2015) showed smaller or even no differences between processing happy and neutral or fearful faces. These studies did not investigate the behavior of the child. However, the role of the child itself was studied as defined by temperament: Infants with low scores on fearfulness or soothability showed less to no differential responses between fearful and happy or neutral faces (de Haan et al., 2004; Taylor-Colls & Pasco Fearon, 2015). Nevertheless, other infant characteristics, such as the quality of their behavior during interaction with the parent, might also affect the ability to process emotional faces: possibly, infants who show a higher quality of social interactions (e.g., show more attentiveness to the caregiver, positive and negative affect, and liveliness) also might have more experience with emotional expressions which could promote their discrimination abilities. In the present study, we investigate three characteristics of interaction between infants and parents that possibly relate to emotional face processing: parent, infant, and dyadic qualities of interaction.

Emotional face processing could also depend on the stimulus properties. An often-investigated stimulus property in older children and adults is the spatial frequency (SF) content of the face (for a review see Jeantet et al., 2018). Specific ranges of SF support processing of specific information in the face: Lower spatial frequencies are suggested to support, more than higher spatial frequencies, the processing of the global configuration of the face. In contrast, higher spatial frequencies are suggested to support, more than lower spatial frequencies, the encoding of detailed visual information such as sharp edges present in a face (Goffaux & Rossion, 2006; Morrison & Schyns, 2001). The SF content affects processing of aspects such as identity, gender, and emotional expression (Jeantet et al., 2018). For the current study, the SF content is relevant for two reasons: Firstly, the SF content might differ between stimuli presented in previous studies and thus partly explain discrepant findings. More specifically, the SF content depends on the size at which a stimulus is presented and might also differ between face stimulus sets (e.g., due to differences in models and in quality of images). However, the stimulus size was similar between studies that did and did not find differential processing of emotional faces in five-month-old infants (e.gPeltola et al., 2009; Yrttiaho et al., 2014) and is thus unlikely to explain the discrepant results. However, the specific stimulus sets differed and might partly explain differences in findings. The second relevance of the SF content is that studies in older children and adults suggest that specific SF content is used to process emotional expressions (Jeantet et al., 2018). Event-related potential (ERP) studies revealed that although adults show differential responses when only LSF are presented (Pourtois et al., 2005; Vlamings et al., 2009), 7- and 10-month-old infants do this when only HSF are presented (van den Boomen et al., 2019; Di Lorenzo et al., 2021; Jessen & Grossmann, 2017). No studies have investigated the role of specific SFs in emotional face processing in infants below 7 months of age. In such young infants, it is revealed that the SF content plays a role in general face processing: Newborns seem to process faces based on LSF information (de Heering et al., 2008). However, it is unknown what SF content five-month-olds require and whether the specific use of HSF for emotional face processing is already present at 5 months of age.

Interestingly, there are even suggestions for an interaction between the quality of interaction and the role of the SF content. While most previous studies investigated either spatial frequency content or parent–child interaction in relation to emotional face processing, there are a few studies in older children (10-month-old infants: Di Lorenzo et al., 2021; 3- to 4-year-olds: Vlamings et al., 2010) indicating that these two factors interact. More specifically, these studies investigated children at familial high likelihood for or diagnosed with autism spectrum disorder (ASD), a disorder characterized by atypical social interaction (American Psychiatric Association, 2013). Both studies revealed that these children differed from controls in the role of spatial frequency content in emotional face processing. Infants at high likelihood for developing ASD did not show differential brain activity between fearful and neutral faces, whereas infants at low likelihood did for faces containing high spatial frequencies. In addition, toddlers diagnosed with ASD showed differential brain activity between emotional faces containing high spatial frequencies, while toddlers without ASD showed this for low spatial frequency filtered faces. As such, these studies suggest a possible link between child characteristics and the role of spatial frequency content. However, this link is indirect, because the behavior of the child was not analyzed in relation to the brain activity. Combining analyses of child behavior and manipulation of spatial frequencies within one study can reveal a direct relation.

Thus, discrepancies in findings on emotional face processing in five-month-olds suggest that other factors influence this ability. Research in older children suggests that stimulus characteristics, particularly SF, play an important role. It is however unknown whether there is a transition in the use of specific stimulus characteristics (SF) around 5 months of age, and whether there individual differences in this ability. Furthermore, even though parental behavior affects emotional face processing of infants (e.g., Bornstein et al., 2011), the role of the infant itself is less well understood. Therefore, the current study investigated whether infants at 5 months of age show differential brain activity between fearful and neutral faces when either LSF or HSF are available, and whether this relates to quality of parent–child interaction characteristics (child, parent, and dyad interactive behaviors). We hypothesized that the presence of differential responses between emotions relates to specific characteristics of parent–child interaction: Infants who themselves, whose parents, or dyads show high quality of interaction are expected to show larger differences between fearful and neutral faces compared to those with low quality of interaction. We also hypothesize that a more mature use of spatial frequency (involvement of HSF in emotional face processing as can be seen in 7 months old) is related to a high quality of interaction.

2 | METHODS

2.1 | Participants

The final sample consisted of 43 infants (23 males; mean age: 153 days, 5.1 months, range 121–180 days, SD 16 days) and their parents (37 mothers, six fathers). Note that the main findings presented in this paper are the same for infants participating with their mother or father. An additional 37 infants were tested, but excluded from the analyses due to insufficient data quality (observation of the parent–child interaction: $N = 3$; EEG: $N = 34$; the criteria for sufficient data quality are described in the data analysis section). Infants were born full-term (>37 weeks) with a birth weight above 2500 g and no developmental delays or abnormalities in visual or auditory processing, as reported by the healthcare system. Race of the parents and children was not registered. However, based on observation most participants were Caucasian. The Medical Ethical Committee of the University Medical Centre of Utrecht approved the study protocol. The study is conducted in accordance with the Declaration of Helsinki. Parent(s) of the infant gave written informed consent prior to participation.

2.2 | Emotional face processing

2.2.1 | Stimuli

Face stimuli consisted of photographs of 10 faces taken from the MacBrain Face Stimulus Set.[1] Face images included five males and five females, of which six European-American, three African-American, and one Asian-American model. Face pictures were trimmed to remove external features (neck, ears, and hairline). Using Photoshop, all faces were cropped, turned into gray-scale, and

[1]Development of the MacBrain Face Stimulus Set was overseen by Nim Tottenham and supported by the John D. and Catherine T. MacArthur Foundation Research Network on Early Experience and Brain Development. Please contact Nim Tottenham at tott0006@tc.umn.edu for information concerning the stimulus set.

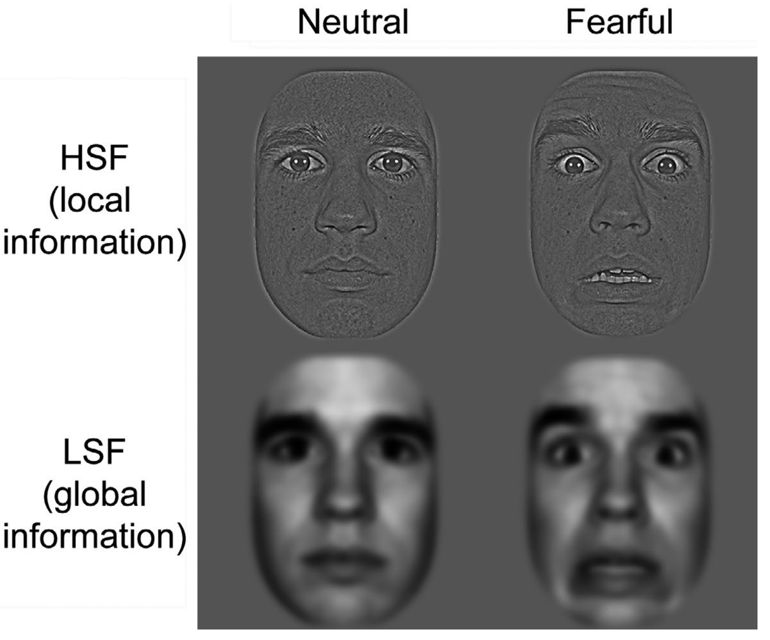

FIGURE 1 Examples of the fearful and neutral face stimuli containing HSF or LSF information

matched for size (19.4° by 14.0° of visual angle at a viewing distance of 57 cm). Similar to the papers of Di Lorenzo et al. (2021), van den Boomen et al. (2019), and Vlamings et al. (2010), faces had a fearful or neutral facial expression. In addition, similar to these papers the faces were either filtered with a low-pass spatial frequency filter (<2 cycles per degree) and contain only lower spatial frequencies (LSF; large-scale luminance variations), or filtered with a high-pass spatial frequency filter (>6 cycles per degree) and contain only higher spatial frequencies (HSF; small-scale luminance variations). The LSF and HSF stimuli differed in terms of root mean square (RMS) contrast (LSF: 25 cd/m^2; HSF: 8 cd/m^2). This created a 2 (expression: fearful, neutral) × 2 (SF: LSF, HSF[2]) condition design, resulting in four versions of the 10 faces (Figure 1).

2.2.2 | Procedure

The data collection took place at the Child Research Centre of Utrecht University. Infants were seated in a quiet and dimly lit room in a car seat positioned at eye level 57 cm from the computer screen, while wearing the EEG cap. There were in total 160 stimuli presented: 40 stimuli for each of the four conditions (i.e., each face stimulus was mirrored and both the normal and mirrored face were presented twice). Stimuli were presented in two blocks (in each block all conditions were presented an equal number of times), on a 23-inch screen with a resolution of 1920 × 1080 pixels, and a refresh rate of 60 Hz. Each trial consisted of a jittered inter-stimulus interval between 700 and 1000 ms followed by a face stimulus for 800 ms. A video camera was placed on top of the screen for online observation. When the infant was not looking at the screen, the experiment was paused and attention

[2]No unfiltered faces were presented in the current study. Based on previous literature and an unpublished pilot study, a maximal of four conditions can be included in an EEG study with 5-month-old infants due to their limited attention span. The current four conditions are necessary to answer the research question on the relation between emotional face processing and spatial frequency content.

was reoriented by a sound played by the computer or a moving stimulus on the screen. Stimuli were presented until the infant became too fussy or bored to attend. Video recordings were additionally used for offline coding of attention. Unattended trials (i.e., not looking with at least one eye to the stimulus, blinking, and/or eyes not visible on the video during the first 500 ms of stimulus presentation) were discarded from analyses. The average number of attended trials was 104 (range: 61–139) for included participants.

2.2.3 | Data reduction

ERP recording

EEG data were recorded with 32 electrodes (Active Two system, Biosemi) positioned at standard recording locations in a cap according to the international 10/20 system. During recording, EEG was sampled at a rate of 2048 Hz. Two extra electrodes, the CMS (common Mode Sense) and DRL (driven Right Leg), provided an active ground.

Preprocessing

Using Brain Vision Analyser software (Brainproducts GmbH) and Matlab (The Mathworks), data were pre-processed. Data were re-sampled offline to 512 Hz and filtered with a high-pass filter of 0.1 Hz (24 dB/oct), a low-pass filter of 30 Hz (24 dB/oct), and a notch filter of 50 Hz. In order to compute ERPs, epochs of 100 ms pre-stimulus (baseline) until 1000 ms post-stimulus were extracted from the continuous data. The data were demeaned, with baseline defined as 100 ms pre-stimulus until stimulus onset. Trials were removed in *single electrodes* if it contained artifacts. Artifacts were defined as amplitudes below −200 or above 200 μV, a difference of more than 200 μV within 100 ms, a difference of less than 3 μV within 200 ms, or a voltage change of more than 50 μV per sampling point. An electrode was rejected if it contained less than five artifact-free trials. Trials were removed *in all electrodes* if the stimulus was unattended or contained an eye blink between 0 and 500 ms after onset (manually detected in the videos), or if more than 16% of electrodes contained artifacts as described above (based on previous research on face processing in infants, e.g., Halit et al., 2003). Activity was referenced to the average of all included electrodes. For each stimulus condition, an average of the ERP was created. Based on previous research in infants (e.gKobiella et al., 2007; Leppänen et al., 2007), participants were included in data analyses if at least 10 segments per condition were included in the average of each of the electrodes of interest (i.e., P3, PO3, O1, Oz, O2, PO4, P4, Cz, Fz, C3, C4, F3, F4, FC1, FC2). The average number of included segments per condition and per electrode of interest was 23.

ERP component analyses

The components of interest were the N290, P400, and Nc. Mean activity within a time window of 200–300 ms (N290), 300–500 ms (P400), and 300–700 ms (Nc) was exported for further analyses on the amplitude of these components. Electrodes of interest were based on previous research, which were for N290 and P400 the P3, PO3, O1, Oz, O2, PO4, and P4. For the Nc, electrodes of interest were C3, Cz, C4, FC1, FC2, F3, F4, and Fz. Although based on previous research some additional electrodes of interest could be identified, those electrodes were excluded based on low data quality in most of the participants (i.e., P7, P8, T7, T8) or unclear components of interest (i.e., Pz). To limit the number of statistical comparisons, analyses were performed for the average amplitude over all electrodes of interest. Data inspection showed that the electrode with the largest difference in amplitude between emotions differed across participants, thus the effects of emotion seem not limited to specific electrodes.

2.3 | Parent–child interaction

2.3.1 | Procedure

During the same day, an unstructured play interaction between parent and child was video recorded. The parents were instructed to engage in play as they would normally do at home for two times 3 min, using, if they wished, a supplied set of developmentally appropriate toys. In between were 6 min of structured play, which was not used in the present study. Parent and infant sat on a floor mat in the laboratory, during the first 3 min the infant was seated in a rocker. Recording was interrupted for six of the included participants because the infant was distressed for an extended time, needed to nap, change a diaper, or needed to be fed. The recordings were completed at a later moment that day.

2.3.2 | Data reduction

Quality of parent–child interaction was assessed with the Manchester Assessment of Caregiver Infant Interaction (MACI; version 2; Wan et al., 2016). The MACI consists of global rating scales, particularly developed for use in infants (3–10 months). Please see Table 1 for an overview of the scales. A randomly selected subsample (44%; $N = 19$) was independently blind rated by another trained rater to test inter-rater reliability. Using intra-class-correlations (two-way mixed, absolute agreement, single measures), adequate to high agreement (ICC > 0.60) was demonstrated for all scales, which is similar to the reliability reported by Wan et al. (2016). To limit the number of statistical comparisons, composite scores (i.e., average rating on the scales) were computed for parent, infant, and dyadic quality of the interaction characteristics (parent: sensitive responsiveness and nondirectiveness; infant: attentiveness to the parent, liveliness, and positive affect and reversed coded negative affect; dyadic: mutuality and engagement intensity). The inter-correlations between scales were similar to the psychometrics reported by Wan et al. (2016). That is, within the parent and dyad quality characteristics, there was a significant correlation between the scales ($p < 0.001$). For the infant quality characteristics, there was a significant correlation between some (attentiveness and positive affect; negative affect and positive affect; $p < 0.05$) but not all scales (all other pairs; all ps > 0.05). There was a significant correlation between composite scores and all scales for the parent, infant, and dyad quality characteristics (all ps < 0.001).

2.4 | Statistical analyses

Main interest was in a main effect of emotion (neutral, fearful), in relation to the three characteristics of parent–child interaction (i.e., parent, infant, and dyad), and in interaction with SF (LSF; HSF). The main effect of emotion and the interaction between emotion and SF was investigated using a repeated measures ANOVA per ERP component (N290, P400, Nc) with ERP mean amplitude as dependent variable, and emotion and SF as independent within-subject variables.

Parent–child interaction scores have been analyzed in two ways in previous literature: (1) as continuous scores, by adding the scores as covariates in the ANOVA (Taylor-Colls & Pasco Fearon, 2015);

TABLE 1 Brief description of the used MACI scales (adapted with some changes from Wan et al. (2016))

Scale	Description	Rating anchor: Brief label
Parent		
Sensitive responsiveness (SR)	Appropriate, timely responding to infant behavior (or lack thereof) at the service of meeting the infant's immediate, interactive and developmental needs; an attentive attitude, warmth, and appropriate engagement, support, and structuring	1. Minimal SR 2. Occasional SR 3. Scattered SR 4. Some SR 5. Fairly consistent SR 6. Consistent SR 7. High SR
Nondirectiveness	A behavioral and mental "acceptance" of and focus on the infant's experience, rather than using directiveness, which includes implicit and explicit demanding and intrusive behaviors, and negative comments	1. Highly directive 2. Directive 3. Moderately directive 4. Somewhat nondirective 5. Mainly nondirective 6. Nondirective 7. Highly nondirective
Infant		
Attentiveness to caregiver	Interest in the caregiver through direct eye contact or joint activity, acceptance of and interest in caregiver, face/body orientation, and other references to caregiver activity, such as imitation	1. Inattentive/ minimally attentive 2. Generally inattentive 3. Slightly attentive 4. Slightly to somewhat attentive 5. Somewhat attentive 6. Generally attentive 7. Highly attentive

(Continues)

TABLE 1 (Continued)

Scale	Description	Rating anchor: Brief label
Positive affect	The overall amount and degree of (voluntary) positive emotional affective display by the infant, as shown in their vocal, facial, and gestural/bodily expression	1. No positivity 2. Minimal positivity 3. Slight positivity 4. Slight to some positivity 5. Some positivity 6. Some to substantial positivity 7. Substantial positivity
Negative affect	The overall amount and degree of (voluntary) negative emotional affective display by the infant, as shown in their vocal, facial, and gestural/bodily expression	1. No negativity 2. Minimal negativity 3. Slight negativity 4. Slight to some negativity 5. Some negativity 6. Some to substantial negativity 7. Substantial negativity
Liveliness	Amount and level of physical activity, particularly those behaviors initiated by the infant spontaneously	1. Unlively 2. Somewhat unlively 3. Slightly unlively 4. Moderately unlively 5. Lively 6. Very lively 7. Extremely lively
Dyad		
Mutuality	Amount and level of reciprocity, attunement and "togetherness," including shared attention, infant acceptance of caregiver involvement, playing together, flow and body orientation	1. Very low mutuality 2. Low mutuality 3. Quite low mutuality 4. Some mutuality 5. Clear mutuality 6. Quite high mutuality 7. Consistently high mutuality

(Continues)

TABLE 1 (Continued)

Scale	Description	Rating anchor: Brief label
Engagement intensity (only rated when engagement is present)	Degree of intensity of engagement by both parties at its optimal point, directly or through mutual object focus, including the degree of interest, arousal, and positivity/excitement	1. Almost no engagement 2. Very low intensity 3. Low intensity 4. Low-medium intensity 5. Medium intensity 6. Intense engagement 7. Very intense engagement

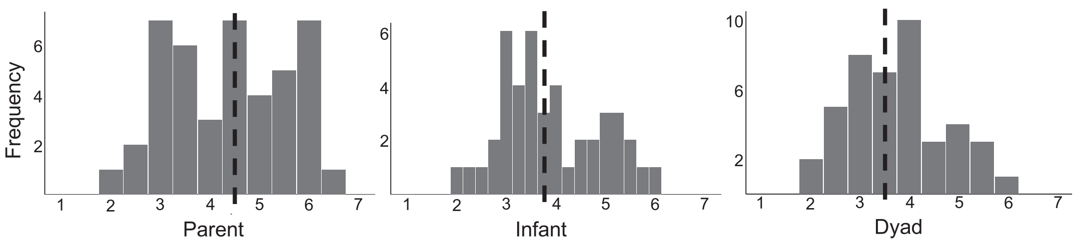

FIGURE 2 Histograms of parent, infant, and dyad interaction scores. Dotted black lines represent median scores

or (2) by splitting the scores into two groups, based on the median score, and then adding the group as between-subject variable in the ANOVA (de Haan et al., 2004). In the current study, we initially choose for a continuous score because this approach preserves more information about individual variation. However, during data inspection we observed that two groups were present in the infant and possibly the parent scores (see Figure 2). This would be a reason to split the data in two groups. We then computed the median scores and observed that these approximated the split-score between the groups (parent median = 4.5; infant median = 3.75; dyad median = 3.5). Moreover, the median scores approximated the middle of each scale (which ranges from 1 to 7), suggesting that the two groups could be interpreted as those with relatively low versus high quality of interaction. We decided to use both ways of treating the parent–child interaction scores in the current study, because the median-split groups fitted better to observed distribution of the parent and infant scores but the continuous scores were the planned analyses. Moreover, both ways of treating the scores provide valuable and complementary information: The median-split groups indicate whether a group of infants differentiates between emotional faces when they show a high (or low) quality of interaction. Analyses between and within the median-split groups have relatively more power to detect differential responses to emotions within a group and could be used to investigate whether some 5-month-olds do show differential brain activity between emotions and others do not. The continuous scores indicate whether infants' neural activity differentiates more between emotional faces when there is a higher quality of interaction. This provides insight in subtle individual differences and could be used to interpret the quality of interaction as a continuum.

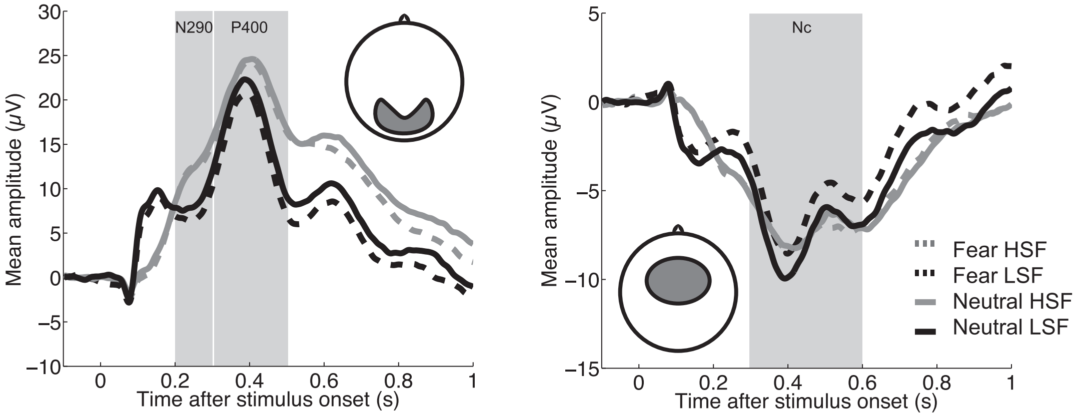

FIGURE 3 Event-related potential waveform for the N290, P400, and Nc electrode clusters, with the time windows shaded in gray, separately for the emotional (fearful and neutral) and spatial frequency (lower (LSF); higher (HSF)) conditions

Consequently, to study the relation of the parent–child interaction with emotion and SF processing, we run the above-described repeated measures ANOVAs again: first with the median-split groups as independent between-subject variables, then with infant, parent, and dyad continuous scores as co-variates. If interaction effects were found, we further analyzed interactions of parent, infant, or dyad with emotion or with emotion and SF. Note that the effects of parent–child interaction scores were analyzed in a separate ANOVA from the main and interacting effects of emotion and SF, because the two options for treating the PCI scores differently influence the results on emotion and SF effects.

For all analyses, the alpha value was set at 0.05 and all post hoc analyses are corrected for multiple testing using Bonferroni correction.

3 | RESULTS

3.1 | Differential processing of emotions, and the relation to specific spatial frequencies

Figure 3 shows the grand average ERPs and Figure 4 shows topographic representations of activity evoked by fearful and neutral faces filtered to contain either LSF or HSF information.

For the N290, P400, and Nc, there was no significant main effect of emotion (N290: $F(1, 42) = 1.140$; $p = 0.292$; $\eta^2 = 0.026$; P400: $F(1, 42) = 3.005$; $p = 0.090$; $\eta^2 = 0.067$; Nc: $F(1, 42) = 3.097$; $p = 0.086$; $\eta^2 = 0.069$). At all components, there was also no interaction between SF and emotion (N290: $F(1, 42) = 0.701$; $p = 0.407$; $\eta^2 = 0.016$; P400: $F(1, 42) = 0.764$; $p = 0.387$; $\eta^2 = 0.018$; Nc: $F(1, 42) = 3.462$; $p = 0.070$; $\eta^2 = 0.076$). At the N290 and P400, there was a main effect of SF revealing more negative activity evoked by LSF than HSF stimuli (N290: $F(1, 42) = 35.097$; $p < 0.001$; $\eta^2 = 0.455$; P400: $F(1, 42) = 21.602$; $p < 0.001$; $\eta^2 = 0.340$), but this effect was absent at the Nc ($F(1, 42) = 1.701$; $p = 0.199$; $\eta^2 = 0.039$).

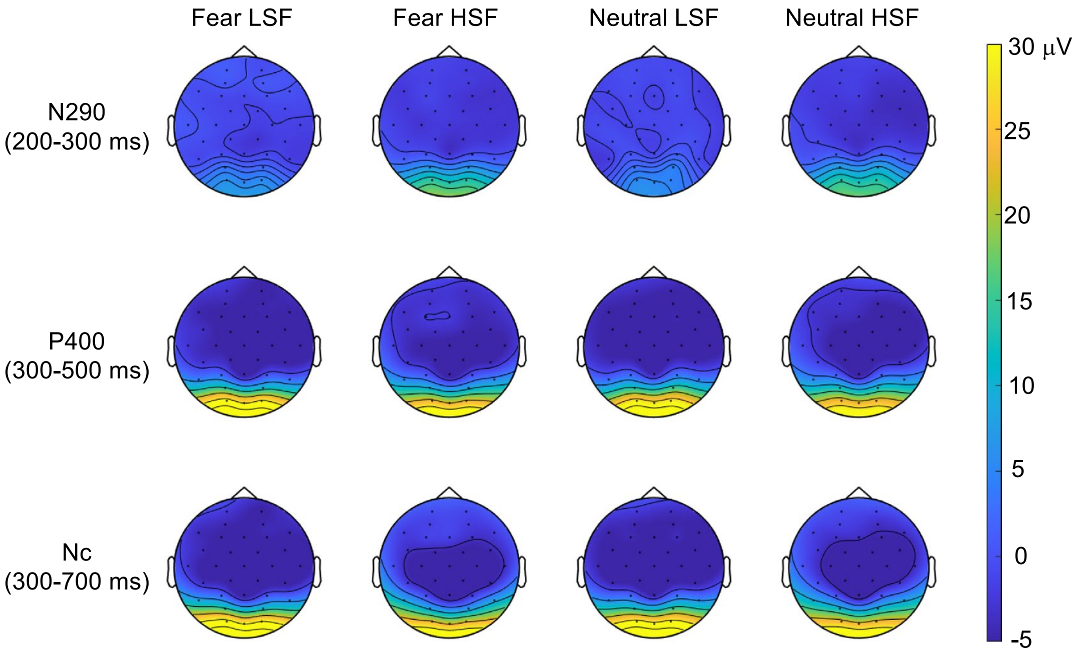

FIGURE 4 Topographical representations of activity during the time windows of the N290, P400, and Nc components, separately for the emotional (fearful and neutral) and spatial frequency (lower (LSF); higher (HSF)) conditions

TABLE 2 Sample size, age in days, and gender of infants

		Infant		Parent		Dyad	
	Total	Low	High	Low	High	Low	High
N	43	24	19	26	17	22	21
Age (SD)	153 (16)	151 (17)	156 (15)	152 (17)	154 (14)	151 (16)	155 (15)
Boy/Girl	23/20	14/10	9/10	14/12	9/8	13/9	10/11

Note: The "Total" column describes the full group, the "Infant" column the infants divided based on whether they score lower or higher than median on the infant PCI scales, the "Parent" column the infants divided based on whether their parents score lower or higher than median on the parent PCI scales, and the "Dyad" column based on lower or higher than median scores on the parent-child dyad scales.

3.2 | Relation between emotional face processing and quality of social interaction

3.2.1 | Parent–child interaction scores as two groups

Table 2 shows the characteristics of the infants scoring lower or higher than the median score for each of the parent–child interaction measures. Figure 5 shows the ERP mean amplitudes per component and emotion, for infants scoring lower or higher than median on the infant scales. At the N290 component, there was a significant interaction between emotion and infant scale score ($F(1, 39) = 5.756$; $p = 0.021$; $\eta^2 = 0.129$). Follow-up tests (against alpha of 0.025) revealed no difference between emotions for the group of infants showing below-median quality of interaction ($t(23) = 1.4$;

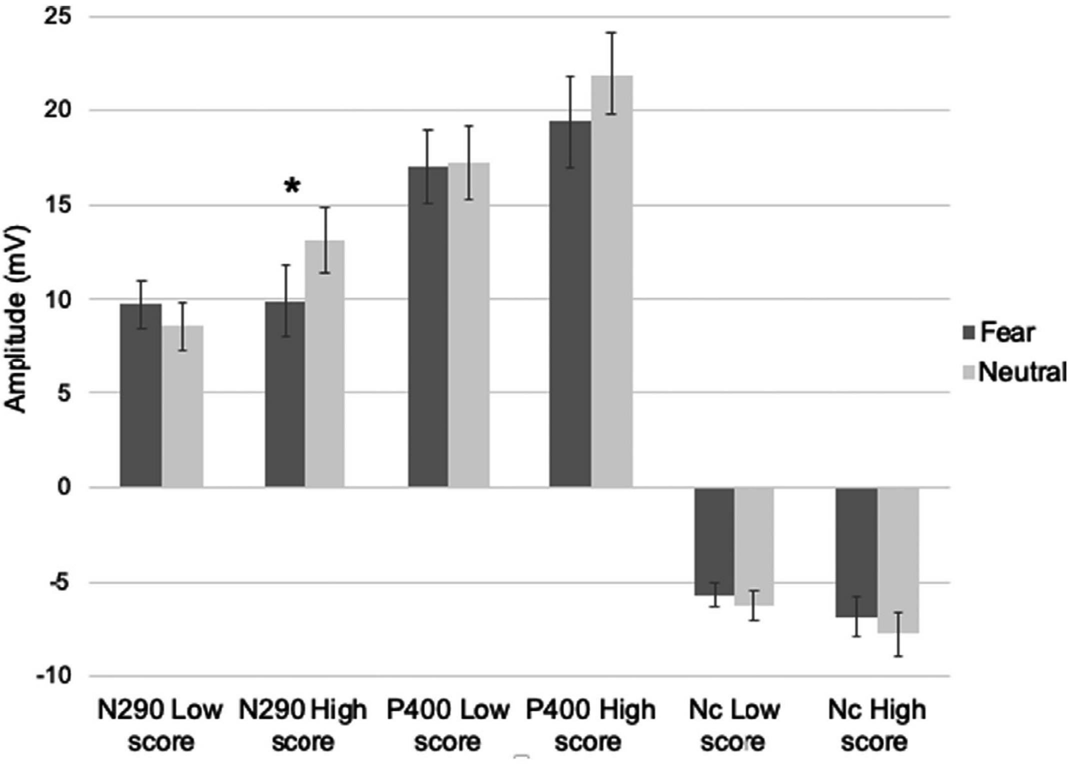

FIGURE 5 ERP mean amplitude per component and emotion, averaged over HSF and LSF conditions, for infants scoring lower or higher than median on the infant scales. Infants with high scores show a significantly different response to fearful versus neutral faces at the N290 component, whereas infants with low scores do not show this difference

$p = 0.169$), but more positive amplitudes evoked by neutral than fearful faces in the group showing above-median quality of interaction ($t(18) = -2.95$; $p = 0.009$; Cohen's $d = 0.41$). The interaction between emotion and infant score was in the same direction, but not significant at the P400 component ($F(1,39) = 2.916$; $p = 0.096$; $\eta^2 = 0.070$). There were no other interactions of the PCI scores with emotion or emotion and SF at the N290, P400, or Nc (all $p > 0.1$). Figure 6 shows the ERP grand averages and Figure 7 the topographical representations of activity evoked by fearful and neutral faces in these two sub-groups.

3.2.2 | Parent–child interaction scores as covariates

There were no interactions of the parent–child interaction scores with SF, emotion or emotion and SF at the N290, P400, and Nc (all $p > 0.1$). However, as described above, when splitting the parent–child interaction scores into high versus low groups, there is an effect of infant scores on the difference between responses to emotions at the N290 component. To explore whether this relation would in any way be observable in the continuous scores, we exploratively computed the correlation between infant scores and the difference between N290 amplitudes evoked by fearful versus neutral faces. This revealed a significant correlation (Kendall's tau = −0.272; $p = 0.012$). The correlation suggests that the higher the infant score, the more positive the amplitudes evoked by neutral faces compared to fearful

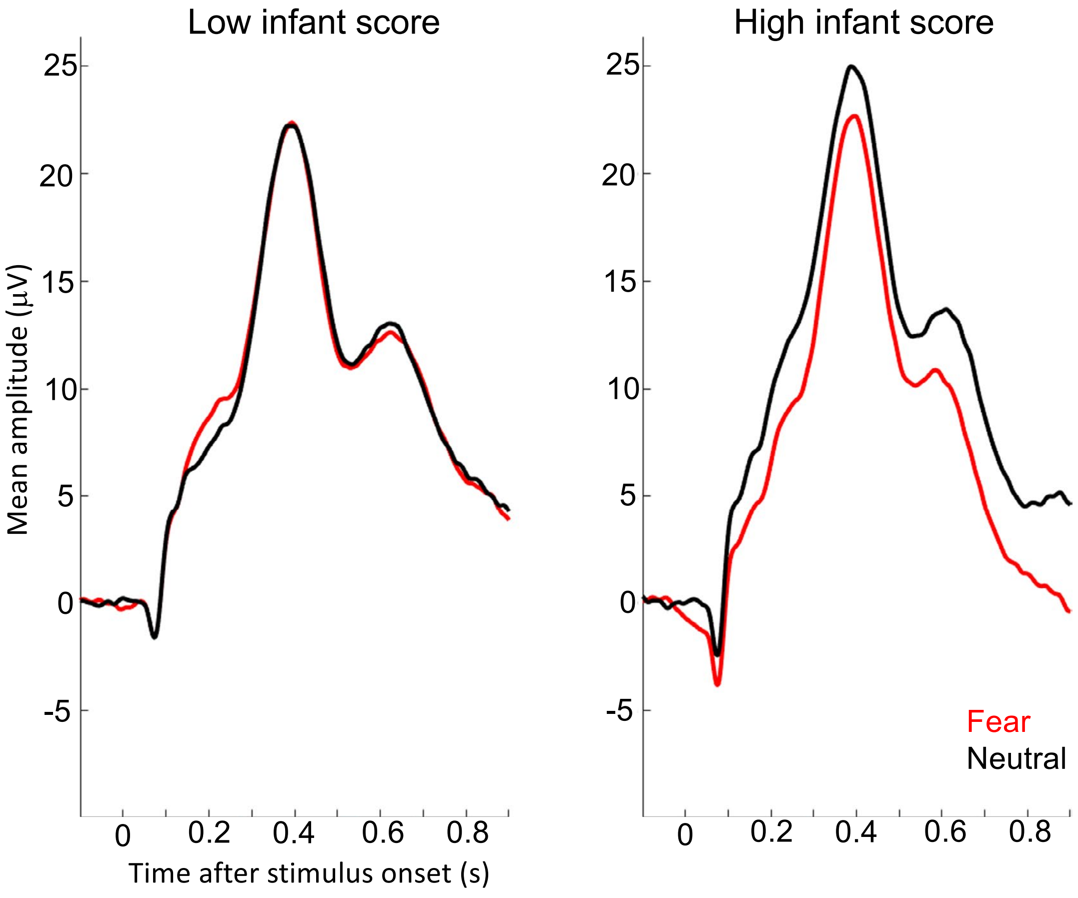

FIGURE 6 Event-related potential waveform for the N290 and P400 electrode clusters, separately for the emotional (fearful and neutral) conditions and the sub-groups of infants scoring lower or higher than median on the infant scales

faces. In other words, the higher the infant quality of interaction, the more is the emotion effect in the direction described in the median-split analyses.

4 | DISCUSSION

It is unclear from previous research whether brain activity of five-month-old infants differs between facial emotional expressions. The current study investigated whether differential brain responses between emotions are related to the presence of specific visual information: higher (HSF; related to detail perception) or lower spatial frequencies (LSF; related to perception of global information). In addition, we investigated whether individual differences in neural responses to emotional faces relate to the quality of parent–child interaction (parent, child, and dyad scores). Results revealed that as one group, infants did not show differential brain activity evoked by fearful versus neutral facial expressions, regardless of the presence of HSF or LSF information. However, there seemed to be a relation between emotional face processing and infants' behavior during the parent–child interaction: The subgroup of infants with high scores during parent–child interaction (i.e., who are more attentive, lively, showing more positive and less negative affect) showed differential responses between emotions,

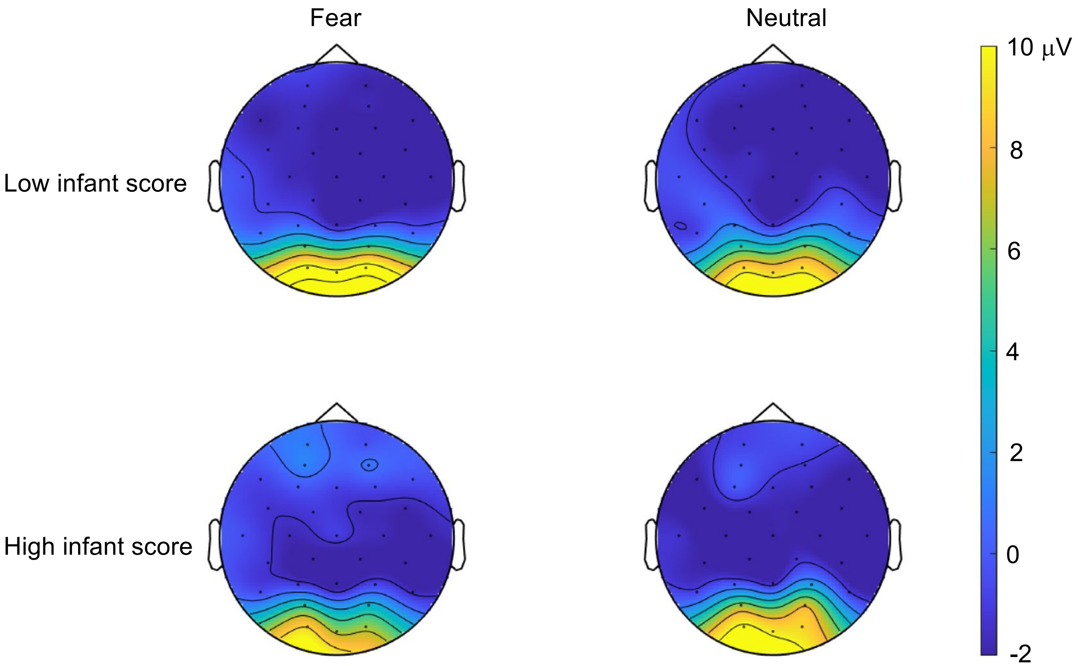

FIGURE 7 Topographical representations of activity during the time window of the N290 component, separately for the emotional (fearful and neutral) and the sub-groups of infants scoring lower or higher than median on the infant scales

whereas the sub-group with low scores did not. When dividing the infants based on the quality of parent or dyad scores, no differences in neural responses were observed between groups. Moreover, a relation between infant characteristics and emotional face processing was not revealed when the infant characteristics were added as a continuous variable. Overall, the results reveal that when looking at the full group there are no differential responses to fearful versus neutral faces at 5 months of age, but indicate that the sub-group of infants with high quality of interaction differentially process emotional faces whereas those with low quality cannot.

The absence of differential neural responses to emotional faces in the total group adds evidence to previous findings suggesting that such responses are not yet present at 5 months of age (Hoehl & Striano, 2010; Peltola et al., 2009). However, it is in contrast to other research that did suggest emotion discrimination (Rigato et al., 2010; Yrttiaho et al., 2014; Xie et al., 2018). Individual differences between infants might explain these discrepancies. Possibly, the studies that did report differential responses to emotions (i.e., Rigato et al., 2009; Yrttiaho et al., 2014; Xie et al., 2018) coincidentally included more infants with high quality of interaction compared to studies that did not show an effect (Hoehl & Striano, 2010; Peltola et al., 2009). Moreover, the absence of differential processing of emotions regardless of SF content indicates that neither HSF nor LSF information are singly sufficient for this process in five-month-old infants. This finding is in contrast to 7- and 10-month-olds, at which age expressions evoked differential brain activity when only HSF but not only LSF information was presented (van den Boomen et al., 2019; Jessen & Grossmann, 2017). It should be noted that Jessen & Grossmann applied different settings while filtering the face stimuli (i.e., Jessen & Grossmann: LSF < 0.6 cpd and HSF > 3.2 cpd; current study: LSF < 2 cpd and HSF > 6 cpd). Therefore, comparison of the results should be careful as any differences could also be due to differences in image characteristics. Nevertheless, this difference between age-groups might relate to the development of neural pathways involved in processing of SF. The dual-route model of face processing describes two interconnected pathways via which emotional faces could be processed: a subcortical route including the amygdala, and a cortical route via the primary visual cortex to the fusiform face area (Johnson, 2005, 2015). Both routes send information to the cortical areas of the emotion processing network, that eventually discriminates between expressions (Leppänen & Nelson, 2009). The subcortical route is thought to be activated by LSF, whereas HSF supposedly activate the part of the cortical route that leads to the fusiform face area. The developmental differences might indicate that the cortical visual pathway shows an important maturation between 5 and 7 months of age: At 5 months, processing HSF information by the cortical pathway seems not sufficient to differentiate between emotions, whereas it might be at 7 months.

When relating neural responses to quality of infant interactive behavior, the results depend on how the infant characteristics are used in the analyses. A relation between infant characteristics and emotional face processing is revealed when splitting the infants into two groups, but not when the characteristics were added as a continuous variable. What could be explanations for and interpretations of these different results? There are at least two explanations: First, the presence of two groups might have obscured the results of the continuous analyses. Second, the different results might reflect a power difference between the two approaches. Previous research already showed low test–retest reliability of the emotion effects at the N290, P400, and Nc in 10-month-olds (Munsters et al., 2019). High amount of measurement error could mask a (not very strong) relation between the concepts of interest, particularly in low-powered analyses. Indeed, the power might be higher in the median split than the continuous analyses: Splitting the group creates two behaviorally more homogeneous groups. When this homogeneity is also reflected in brain activity, variation between participants is reduced which increases the chance to find an effect.[3] Moreover, analyses were conducted separately per parent, infant, or dyad characteristic in the median-split analyses but all at once in the continuous analyses. Including all three instead of one characteristic can also reduce the power, because the results are corrected for more analyses. This suggestion is supported by the explorative finding that there is a correlation between continuous infant scores and difference in brain activity evoked by fearful versus neutral faces, when only these two variables are included in the analyses. Therefore, even though the effect size of the group difference suggests a medium to large effect, the results might not be very strong and need to be confirmed by future research. Nevertheless, the current combination of findings can be interpreted as follows: On a group level, there is a difference in emotional face processing between infants that show high versus low quality of interaction, but subtle individual differences seem absent.

A closer look at current sub-groups and previous findings on the relation between emotional face processing and parent–child interaction gives rise to new hypotheses. It could be suggested that infant characteristics might influence emotional face processing at an earlier age and for more negative emotions than parent characteristics, in non-clinical populations. That is, the current findings reveal that only infants with high quality of interaction show different responses to fearful versus neutral faces already at 5 months of age, but that there is no influence of parent quality of interaction on this ability. Parental influences on 5-month-old infants are only observed in clinical populations, where infants of clinically depressed mothers did not respond differently to happy versus neutral faces, whereas controls could (Bornstein et al., 2011). In non-clinical populations, such parental influences are observed at 7 months of age: Low positive affect or low sensitivity of the mother relates to less or even an absence of discriminating responses between happy versus neutral or fearful faces (de Haan

[3]Note that even though splitting the group also decreases the number of participants and thus the power, the number of participants per group was still sufficient to find a statistically significant effect.

et al., 2004; Taylor-Colls & Pasco Fearon, 2015). Infant and parent characteristics might even affect differential processing of specific emotions: Infant characteristics seem to relate to processing of fear versus neutral emotions, but not happy versus neutral emotions (Taylor-Colls & Pasco Fearon, 2015; current study). On the contrary, parent characteristics related to differential processing of happy versus neutral faces, but not to that of fearful versus neutral ones (Bornstein et al., 2011; Taylor-Colls & Pasco Fearon, 2015; current study). As such, infants and parents might play specific roles in infants' development of emotional face processing.

In addition, the presence of differential emotional face processing in some infants confirms that in certain cases or circumstances emotions can be perceived at an earlier age than the often-reported 7 months. Previous research already revealed that the circumstance of more information in a stimulus can lead to emotion discrimination in 5-month-olds, such as dynamic instead of static faces (e.g., Heck et al., 2016) or audio-visual instead of only visual information (e.g., Flom & Bahrick, 2007). This could imply that more salient emotional information can be detected by younger infants.[4] As already suggested by Leppänen and Nelson (2009), a potential underlying neural mechanism could be the emotional face-processing network receiving more information from such salient stimuli, consequently becoming more and hence sufficiently activated to show differential activity between emotions. The current findings add that even static unimodal emotions could be processed by 5-month-olds, but that there are individual differences in this ability. Possibly, the emotional face-processing network is further developed in some individuals and as such requires relatively few information to discriminate between expressions. Such individual differences in responses of the network are previous reported in adults (e.gEtkin et al.,.., 2004; Stein et al., 2007). The individual differences at 5 months of age might suggest that the emotional face-processing network develops differently between individuals from an early stage onwards, confirming previous reports on individual differences in neural responses to social stimuli in this young age group (e.gBraukmann et al., 2017; Lloyd-Fox et al., 2013).

The discussed suggestions raise several questions to be answered in future research, such as to find the specific circumstances under which 5-month-olds can differentiate between emotional faces, the causes, and consequences of individual differences, and how these can be applied to aid emotional face processing in young infants. For instance, individual differences likely have consequences for the child's social development. The neurosconstructivism theory poses that seemingly small differences early in life could result in cascading effects in multiple domains later in development (D'Souza & Karmiloff-Smith, 2017). So-called "social-first theories" specify this further: they suggest that reduced social information processing of an infant, such as absence of emotion discrimination or reduced stimulation by the parents, could lead to less engagement with social stimuli, such as parents, which could lead to reduced or abnormal social cognition and communication (Elsabbagh & Johnson, 2016). Consequently, it is important for future research to confirm the relation between infant quality of interaction and emotional face processing, to reveal possible other factors leading to differences in these abilities, and to eventually identify and help those infants with abnormalities in emotional face processing.

While interpreting the results of the current study, it is crucial to ensure that the stimuli were visible to the subjects. That is, sensitivity to HSF is absent at birth and develops during the first year of life (for a review see van den Boomen et al., 2012). When focusing on 5-month-olds there are several papers on sensitivity to LSF, but the number of studies on HSF is more limited (van den Boomen et al., 2012). The one study including 6 cpd gratings indicates that this information is at the threshold of perceivable at 6 months of age (Gwiazda et al., 1997). However, this conclusion is based on behavioral responses, and to our current knowledge, no studies investigated neural responses to HSF stimuli in

[4]note that it is not motion in itself, but the moving *emotional* face that leads to discrimination (Heck et al., 2017).

5-month-olds. Therefore, we checked after the first participants whether the neural responses indicated that the HSF stimuli were perceived: If infants would not perceive the HSF stimuli, there would be no or a very small ERP response. On the contrary, the presence of an ERP response would indicate that infants could see the HSF stimuli. As can be seen in Figure 3, infants did show an ERP response to the HSF stimuli, indicating they could perceive them. The finding that a selection of infants even differentiated between fearful and neutral faces, regardless of the SF content, further supports the conclusion that infants were able to perceive the HSF stimuli.

In conclusion, the current study revealed that infants as a group do not differentially process fearful and neutral facial expressions at 5 months of age when only LSF or HSF information is present. However, when splitting the group based on infant behavior during social interaction, those infants with high quality of interaction do show differential processing whereas those with low quality of interaction do not. These findings have important consequences for early detection of infants who might be at risk for atypical social development.

ACKNOWLEDGMENT

The authors thank parents and children for participating in the study. We also are grateful to all employees at the KinderKennisCentrum of Utrecht University for their help in set-up of the study and data collection. The Consortium on Individual Development (CID) financed this study. CID is funded through the Gravitation program of the Dutch Ministry of Education, Culture, and Science and the NWO (Grant No. 024.001.003). The authors declare no conflicts of interest with regard to the funding source for this study.

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How to cite this article: van den Boomen, C., Munsters, N. M., Deković, M., & Kemner, C. (2021). Exploring emotional face processing in 5-month-olds: The relation with quality of parent–child interaction and spatial frequencies. *Infancy*, 00, 1–20. https://doi.org/10.1111/infa.12420