# This is me! Neural correlates of self-recognition in 6- to 8-month-old infants

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#### Abstract

Historically, evidence of self-recognition in development has been associated with the "rouge test"; however, this has been often criticized for providing a reductionist picture of self-conscious behavior. With two event-related potential (ERP) experiments, this study investigated the origin of self-recognition. Six- to eight-month-old infants (42 males and 35 females, predominately White, tested in the UK in 2022–2023) were presented with images of their face, another peer's face, and their mother's face (N=38, Exp.1), and images of their own face morphed into another peer's face (N=39, Exp.2). Results showed an enhanced P100 in infants' ERP response to their own face compared to others' faces (Exp.1 only), suggesting the presence of an enhanced attentional mechanism to one own's face as early as 6months.

The ability to distinguish self from others plays a fundamental role in the development of self-awareness, allowing infants to develop the skills necessary to emotionally and intentionally act in the surrounding environment. In particular, the ability to recognize one's own face is at the hallmark of selfhood and over the last 50 years, the question of whether and how humans and non-human primates possess the ability to recognize one's own mirror reflection has been a matter of extensive debate among philosophers and psychologists alike.

Self-recognition entails the ability to identify one's own facial features as being part of the self. It has been hypothesized that the ability to create a mental representation of the self develops with the emergence of overt self-directed behaviors, such as the display of emotions of embarrassment and coyness or stating one's own name in front of a mirror (Rochat, 2009). Indeed, historically psychologists have relied on an experimental paradigm that focuses on the presences of these behaviors to examine the emergence of self-recognition in infancy (Amsterdam, 1972; Bertenthal & Fischer, 1978). The mirror test of self-recognition-originally developed and tested with chimpanzees (Gallup, 1970)-consisted in marking the animal with red dye on their face and expose it to its mirror reflection. In the version of the test adapted to human infants (Amsterdam, 1972), the rouge mark is placed on their nose and the infants are tested as to whether they display a key set of marker behaviors (e.g., reaching for the mark, stating their name, showing self-conscious emotions), which are taken as evidence of self-recognition. Extensive use of the mirror test in developmental population suggests that, between 18 and 24 months of age, toddlers begin to clearly display these marker behaviors (Amsterdam, 1972; Bertenthal & Fischer, 1978; Johnson, 1983; Lewis & Brooks-Gunn, 1979), and as a consequence, it is now widely accepted that mirror self-recognition develops around this age.

Despite the widespread use of the mirror test in developmental psychology, this paradigm has been more recently challenged by conflicting evidence showing, for example, its susceptibility to cultural differences

Abbreviations: ERP, event-related potential; Nc, negative central.

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This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited. © 2024 The Authors. *Child Development* published by Wiley Periodicals LLC on behalf of Society for Research in Child Development. (Rochat, 2010) and its dissociation with neural markers of the self (Stapel et al., 2017). Importantly, the mirror test measures a behavioral response to the unusual situation of having something on the face when exposed to one's reflection. However, before infants are able to respond to such situation, they have to recognize the observed face as their own. In particular, evidence suggests that self-recognition might unfold over time and be dependent upon the familiarity that infants gradually gain with their own facial features during the first year of life (Filippetti & Tsakiris, 2018). That is, infants' ability to recognize their own face may be facilitated by the experience they obtain with their own mirror reflection, as well as with their primary caregivers (e.g., their parents) with whom they are likely to share a number of facial features.

Exposure to faces has been shown to influence infants' face perception. There is evidence in support to the hypothesis that visual preference for faces emerges as a result of prior experience to that face. Sai (2005) showed that neonates display a visual preference for their mothers' face, when exposed to both their mother's voice and face from birth. This finding is supported by a wealth of studies showing that the ability to distinguish a familiar from an unfamiliar face becomes more robust as a result of the extensive perceptual experience accumulated with other individuals within the first year of life. For example, infants' ability to distinguish the mother's face from a stranger's face becomes increasingly more robust between 3 and 10 months (Matsuda et al., 2012; Maurer & Salapatek, 1976), suggesting that progressively refined perceptual development allows infants to detect subtle features of the mother's face (Matsuda et al., 2012; Nakato et al., 2009). Similarly, newborns initially show a preference for faces displaying the emotional expression that they are likely to encounter more often in their visual environment, that is, happy faces (Farroni et al., 2007). As infants gain experience with different facial expressions (e.g., sad and fearful faces), they then begin discriminating among a variety of emotional faces (e.g., de Haan et al., 2004; Nelson & Dolgin, 1985; Peltola et al., 2009). Evidence that experience plays a crucial role in the development of face processing is also exemplified by the other-race effect (see Meissner & Brigham, 2001, for a review), whereby the faces observed in the daily encounters drive face preferences during infancy (e.g., Pascalis et al., 2002). Altogether, these studies support the idea that prior experience of faces is necessary for the development of a system for face recognition and warrant the question as to whether a similar mechanism might be in place in the context of self-face recognition.

Converging evidence from behavioral studies suggests that the ability to discriminate between self and other faces develops well before infants are able to pass the mirror test and might indeed be based on the ability to extract familiar facial features from the self (Bahrick & Moss, 1996; Legerstee et al., 1998; Rochat & Striano, 2002). As preferential looking behavior in infants is normally interpreted as a preference for the novel versus familiar stimulus (Hunter & Ames, 1988), evidence of a visual preference for the other (unfamiliar) face has been interpreted in light of a familiarity with the own facial features, possibly due to the amount of mirror exposure that infants experience in the first months of life (Bahrick & Moss, 1996). Visual preference for the unfamiliar other might also reflect familiarity with the own facial features because the own face looks more similar to that of caregivers. However, it is difficult to disentangle from these studies whether the self-face holds a special status or whether it is just a highly familiar stimulus.

In this sense, event-related potentials (ERPs) represent a good candidate for examining identity-specific from familiarity-specific effects. ERP studies are critical for investigating the neural time course of face processing before such skills can be observed in overt behavior (Richards, 2000), therefore not relying on the outcome of the processing (de Haan & Nelson, 1999). One of the most studied ERP components in adult face processing is the posterior (occipitotemporal) N170, which is enhanced in response to faces relative to other items including inanimate objects (e.g., Bentin et al., 1996; Stekelenburg & de Gelder, 2004). Interestingly, the N170 is also enhanced in response to the self-face compared to another person's face (Keyes et al., 2010), supporting the idea that we process our own face differently. Infant ERP studies have suggested that the processes underlying the adult N170 are evident as two distinct occipitotemporal components; a negative peak around 290 ms (N290) and a positive deflection around 400 ms (P400) after the presentation of a face stimulus (Halit et al., 2003). These components are thought to represent the N170 infant precursors because of their gradual reflection of face sensitivity in the first year of life (for a review see Hoehl, 2016). Infant ERP studies have also identified a further component that shows some sensitivity to faces, the negative central (Nc) component, which peaks between 400 and 800 ms after stimulus onset over frontal and central electrodes (Courchesne et al., 1981; Guy et al., 2016; Marinović et al., 2014; Parise et al., 2010). It is thought that Nc amplitude is associated with stimulus familiarity; however, the literature has shown mixed results. For example, de Haan and Nelson (1997) found that the infant Nc is enhanced in response to the mother's face compared to a novel face; however, larger Nc amplitude has also been reported in response to infrequent or novel stimulus presentation when compared with frequent or familiar stimulus presentations (e.g., Courchesne et al., 1981; Karrer & Ackles, 1987). While these findings may show divergent results, the enhanced Nc to the mother's face may reflect specific processes related to recognition of a face stored in long-term memory (de Haan & Nelson, 1997).

While a wealth of studies has examined the neural markers of face processing more generally, to the best of our knowledge, only one study investigated infant ERPs in response to the observation of the self-face compared to the face of others (Stapel et al., 2017). In 18-month-old infants, Stapel et al. (2017) found that the N290 showed an increased response to the self-face compared to the face of another infant. These findings are consistent with the pattern of activation found in the adult N170 in response to the self-face, that is, a larger N170 amplitude in response to the self-face compared to another person's face (Keyes et al., 2010), indicating the N290 as a potential precursor of the N170 for self-recognition processing. Interestingly though, Stapel et al. (2017) reported that such infant neural signature for self-face processing does not correlate with the outcome of the mirror test. The observation that a distinction between the neural response to self-face and to other-faces does not necessarily express itself in self-recognition behavior opens up the important question on when in development such neural signature emerges, independently from a behavioral response. Assuming that the behaviors displayed during the mirror test reflect self-awareness (Heyes, 1995; Suddendorf & Butler, 2013), it is possible that the way infants process their own face during mirror observation relies on a different set of information and task demands compared to when they simply observe their self-image in a static picture (as it is the case in Stapel et al., 2017). For example, a motivation to align to others (Kampis et al., 2021) or respond to the mirror image (e.g., in monkeys: Chang et al., 2015) can influence performance to the mirror test and be a contributing factor to falsenegative results reported in the literature (e.g., Courage et al., 2004). Thus, while the self-directed behaviors that children are able to display during the second year of life may be indicative of some form of mirror-self recognition, infants' processing of their own face might gradually unfold well before, and be at least partly independent to, these overt behaviors. Importantly, the findings from Stapel et al. (2017) suggest that 18-month-old infants can extrapolate information about the self from still images and use them to differentiate between self and other faces. These results thus suggest that the self-face might hold a special status and highlight a distinct neural signature that is specific to the self and that is already in place much earlier than previously thought. However, Stapel et al. (2017) did not directly test this hypothesis as in their study the infant Nc-a marker of familiarity (de Haan & Nelson, 1997)—was not examined. With this study, we aim to disentangle the relation between familiarity and own-face specificity by including observation of both the occipitotemporal face-sensitive components N290 and P400, as well as the frontocentral Nc.

Our pilot data (N=6) show that the face-sensitive P400 component is enhanced by self-face images compared to images of a peer's face in 6- to 8-month-old infants (see Pilot data section below). However, to the best of our knowledge, no study so far has conducted a systematic investigation of the neural correlates of self-recognition

in infants younger than 18 months of age. This is important because infant studies have only relied on visual preference paradigms to demonstrate the presence of a discrimination between self and other. These studies have shown that between the ages of 4 and 9 months, infants display a visual preference for the other-face, compared to the self-face (Bahrick & Moss, 1996; Legerstee et al., 1998; Rochat & Striano, 2002). Thus, in the search for precursors of self-recognition, in the current study, we recorded ERPs in response to self- and other-faces in 6to 8-month-old infants. We ran two distinct experiments where we presented infants with images of their face, another peer's face, and their mother's face (Exp.1), and images of their own face morphed into another peer's face (Exp.2). Given previous results from Stapel et al. (2017), those from our pilot study, as well as the suggestion from the literature that the adult N170 face-sensitive component emerges due to the integration of two distinct components (Halit et al., 2003), we investigated neural responses at both N290 and P400. To examine effects of familiarity, we also tested whether differences between self- and other-faces are present in the infant Nc.

Using the morphing procedure in Experiment 2, we contrasted the self-face with morphed faces that contain different percentages of self- and other-face (see Devue & Brédart, 2011, for a review). With this method, we aimed to examine at what point the self-face is no longer processed as self and instead starts to be processed as the other-face, and hence loses its self-specifying features.

# Predictions

For Experiment 1, our primary hypotheses were:

H1. Increased amplitude in the faceselective N290 and P400 for observation of the self-face compared to each other-face (peer and mother). We expected that the N290 and P400 ERP components would indicate ownface specificity, suggesting a distinct neural signature for infants' processing of their own face. These results would indicate that infants might process their own face differently over and above any familiarity effect.

**H2.** Increased amplitude in the frontocentral Nc for observation of the mother face compared to the self-face. The mother's face represents a visually familiar stimulus stored in long-term memory; thus, we anticipated that it would elicit a greater Nc amplitude compared to the self-face that is less visually experienced.

Our secondary hypothesis was:

**H3.** Increased amplitude in the frontocentral Nc for observation of the mother face compared to the peer face.

For Experiment 2, our primary hypothesis was:

H4. Increased amplitude in the faceselective N290 and P400 for observation of the self-face (100% self) compared to each morphed face (66% self and 44% self). If the N290 and P400 ERP components indicate own-face specificity, we expected that, as the percentage of other being incorporated into the self-image increases, amplitude of these ERP components would decrease. (Please note that we originally planned to contrast 100% self vs. 80% self vs. 60% self. Preliminary analyses of Experiment 1 were indicating that the manipulation we had planned for Experiment 2 could be too stringent. Based on infant behavioral, Nitta & Hashiya, 2021, and adult research, Sel et al., 2016, we therefore decided to adjust the percentages of morphing to 66% and 44% instead. This change in study design occurred before data collection for Experiment 2. The change received editorial approval on November 22, 2022.)

Our secondary hypothesis was:

**H5.** Increased amplitude of N290 and P400 for 66% self versus 44% self.

# Methods

# Participants

Based on the dropout rates of previous infant electroencephalogram (EEG) studies (estimated at 40%), we aimed to recruit 127 full-term, healthy 6- to 8-month-old infants to participate in the study. One hundred and thirty-eight full-term, healthy 6- to 8-month-old infants were recruited to participate in the study. Data collection began in March 2022 and ended in June 2023. According to the data exclusion criteria (see Data exclusion section), 61 participants were excluded due to 1 technical error (Experiment 1; N=8; Experiment 2; N=2), refusing to wear the EEG net (Experiment 2; N=1), fussiness (Experiment 1; N=13; Experiment 2; N=13), signal quality problems (Experiment 1; N=2; Experiment 2; N=17), and parental interference (Experiment 1; N=1; Experiment 2; N=2). Thus, the final sample was composed of 77 participants (Experiment 1: N=38 infants; 20 female;  $M_{age} = 208.61 \text{ days}$ , SD=19.98 days; Experiment 2: N=39 infants; 15 female;  $M_{age} = 203.51 \text{ days}$ , SD=15.59 days).

Due to the lack of previous electrophysiology studies on self-recognition in infancy, we determined sample sizes through power of analyses (G\*Power) using medium effect sizes and at least 80% power to detect a significant effect of Face Type on the ERP component, in Experiment 1 and 2 separately (alpha level=.017, N=38for each experiment). We aimed to counterbalance gender, although we decided to stop data collection once the stated sample of 38 infants per experiment would be reached. Infants were recruited through the database of interested participants from the University of Essex Babylab who were mostly based in or around Colchester (UK), were born no more than a month before their due date, had no birth complications or major health problems and no known hearing or vision difficulties. The majority of the recruited participants were White, although we planned to include participants of any ethnicity/race. Caregivers were compensated with a £5 voucher for their visit and were given a token gift (e.g., a Babylab bodysuit/t-shirt, bib or tote bag). Research was approved by the local research ethics subcommittee (ETH2122-0908).

# Stimuli and procedure

For Experiment 1, the experimental stimuli were images of the infant's own face, another peer's face, and their mother's face, whereas for Experiment 2, the images used were of the infant's face and their own face morphed into another peer's face. In both experiments, the peer face were from an infant taking part in the same study.

Pictures of the infants were taken against a white background while infants were sitting on a highchair in the Babylab reception room, with a standardized distance of 50 cm being set between the camera and the infant. Next, the photographs were uploaded to a Dell computer for editing. First, the experimental stimulus was chosen based on the quality of the photos (e.g., clarity of the image, infant keeping a neutral facial expression and gazing into the camera). Next, the photo was cropped and an ellipse shape was applied to exclude the background, hairline, ears, and the neck of the infant. Finally, the photo was converted to gray scale and mirror transposed. To ensure uniformity in image characteristics, luminosity of the room was kept consistent for all participants and luminance of images was equalized using an automated editing program (Keenan et al., 1999). As Experiment 2 also required a morphing procedure to be implemented, we used Abrasoft Fantamorph to produce a sequence of photos in which the participant's face was merged with another infant's face in a prespecified percentage of morphing transitions (66% and 44%; see Figure 1 for an example of stimuli).

The LED monitor used to display the experimental stimuli was 23" in size and located 90cm from the participant's eyes. Throughout the whole experiment, the NEURAL CORRELATES OF SELF-RECOGNITION IN INFANTS



**FIGURE 1** Illustrative example of the experimental stimuli for Experiment 2. Image editing used both for Experiments 1 and 2 includes cropping, application of ellipse shape to exclude external facial features, gray scaling, and mirror transposing. The morphing procedure used for Experiment 2 was implemented using Abrasoft Fantamorph using 66% and 44% morphing transitions.

infant's attention to the display screen was monitored via a video camera located under the screen. The session began with a color cartoon image presented in the middle of the screen for a random duration set between 1400 and 1800ms, which we used to attract the infant's attention to the screen. Next, the face stimuli were each presented for 1000ms in a pseudo-random order and for a total of 300 trials (100 trials for each stimulus). To control for equal exposition to the different faces, in the first 150 trials, infants were presented with 50 faces for each stimulus. In between each trial, a color cartoon image was displayed for a random duration between 800 and 1200ms. Stimulus presentation continued until the infant became fussy or bored.

Infants were tested in a dimly lit and sound attenuated room, and were sitting on their parent's lap. Infants were encouraged to watch the stimuli displayed on the monitor. Parents were asked to refrain from talking and interacting with the infant during the stimuli presentation unless the infant became fussy. The computer played the stimuli through Matlab (Mathworks), and a Macintosh computer recorded the EEG signal. The testing session lasted between 5 and 10min, depending on the infant's willingness to watch the stimuli. The whole visit took approximately 1h.

# Data exclusion

The decision to exclude each participating infant in subsequent analyses was made based on the following criteria:

- Refusing to wear the EEG net;
- Showing signs of distress (heavily fussing or crying);
- Parental interference (e.g., talking and interacting with the infant during the stimuli presentation) that led to fewer than the required number of valid trials;

- Signal quality problems (due to pulling on the EEG net, excessive movement, or poor contact with the scalp; objective criterion: minimum of 10 valid trials per condition);
- Experimental error, such as failing to record the EEG data or video.

# EEG recording and preprocessing

For both experiments, brain electrical activity was recorded via Hydrocel Geodesic Sensor Net (Electrical Geodesic Inc.), consisting of 128 electrodes evenly distributed across the scalp and referenced to the vertex. EEG was amplified with a 0.1–100 Hz band-pass filter and digitized at 500 Hz. The data were analyzed offline using NetStation 5.4.2 analysis software (Electrical Geodesic Inc.). Continuous EEG data were low-pass filtered at 30 Hz using digital elliptical filtering and segmented in epochs from 100ms before until 800ms after stimulus onset. Segments with eye movements and blinks were detected visually and rejected from further analysis. We manually excluded trials in which the infants were not attending and/or the caregivers were influencing the infants (e.g., by talking—see exclusion criteria). As in previous infant EEG studies, a minimum number of 10 trials per condition was required to carry out the baseline-corrected averaging analysis (e.g., Kobiella et al., 2008; Leppänen et al., 2007).

# Data analysis

Artifact-free data were baseline-corrected to the average amplitude of the 100 ms interval preceding stimulus onset, and re-referenced to the average potential over the scalp. For Experiment 1, statistical analyses of the ERP data targeted the examination of face type (self, other, mother) over the right and left occipital electrode sites (N290, P400) and over frontocentral site (a cluster of right, left, and medial electrodes) for the Nc. For Experiment 2, statistical analyses of the ERP data targeted the examination of morphing effects (100%, 66%, and 44%) over the same locations as for Experiment 1.

For both experiments, we performed three repeated measure ANOVAs for each dependent variable and applied a Bonferroni correction to control for multiple comparisons (alpha level=.017). Groups of electrodes were initially selected for analysis based on the pilot study (see section below) and this selection was then adjusted following visual inspection of the dataset to find where the components of interest were maximal. For the analyses of the occipitotemporal components, the electrodes included in the analysis were 76, 77, 84, 85 (right hemisphere); 67, 70, 71, 74 (left hemisphere). Waveforms from these electrodes were averaged to create left-hemisphere and right-hemisphere clusters for each condition. For the analyses of the Nc, the following frontocentral electrodes were selected: 103, 104, 105, 110, 111 (right frontocentral); 30, 35, 36, 41 (left frontocentral).

Over the occipitotemporal clusters, we detected the expected N290 and P400 components. The latencies of peak amplitudes were determined for each individual participant by visual inspection, and time windows were then chosen to include the temporal spread of peaks across participants. This results in the following time window selection: N290 between 190 and 410ms, and P400 between 340 and 510ms. Over the frontocentral clusters, we identified the expected Nc which was analyzed for the time window 420–520ms after stimulus onset.

# PILOT DATA

# Methods

# Participants

Nine healthy, full-term infants participated in the study. Of these, three were excluded from the analyses due to fussiness. The final sample included six 6-to 8-month-old infants (3 females, tested in the UK between February and March 2020). Infants were recruited and selected from the University of Essex Babylab database and lived in or around Colchester. The majority of the recruited participants were White, although we planned to include participants of any ethnicity/race. Prior to participation in the study, parents gave written informed consent. Parents received a small gift of a £5 Amazon voucher and an

"Essex Babylab Graduate" bib for their participation. Research was approved by the local research ethics subcommittee (MLF1805).

### Stimuli and procedure

The experimental stimuli consisted of images of the infant's own face and another peer's face. Photos were taken and edited as detailed in the *Stimuli and proce-dure* section of the planned study. The session began with a color cartoon image displayed in the middle of the screen for a random duration set between 1400 and 1800 ms. Next, the self- and other-face stimuli were each presented for 1000 ms in a random order and for a total of 200 trials (100 trials for each stimulus). In between each trial, a color cartoon image was displayed for a random duration between 800 and 1200 ms. The experiment ended once the total amount of trials was reached or if the infant became fussy or bored as judged by the experimenter.

Infants were tested in a dimly lit and sound attenuated room and sat on their parent's lap. Stimuli were presented using E-prime, and a Macintosh computer recorded the EEG signal. Brain electrical activity was recorded via Hydrocel Geodesic Sensor Net (Electrical Geodesic Inc.), consisting of 128 electrodes. The testing session lasted approximately 5 min.

# EEG data analysis

The EEG data were analyzed offline using NetStation analysis software (Electrical Geodesic Inc.). Continuous EEG data were low-pass filtered at 30 Hz using digital elliptical filtering and segmented in epochs from 100 ms before until 800 ms after stimulus onset. Segments with eye movements and blinks were detected visually and rejected from further analysis. The artifact-free data were then baseline-corrected to the average amplitude of the 100 ms interval preceding stimulus onset and re-referenced to the average potential over the scalp.

Statistical analyses of the ERP data targeted the examination of face type (self, other) effects over right and left occipitotemporal and frontocentral electrodes. Groups of electrodes were initially selected for analysis based on previous studies of infant face and body perception (e.g., de Haan et al., 2002; Gillmeister et al., 2019; Rigato et al., 2010) and this selection was adjusted following visual inspection to find where the components of interest were maximal in the present dataset. For the analyses of the occipitotemporal components, the electrodes included in the analysis were 76, 77, 84, 85 (right hemisphere); 60, 66, 67, 71 (left hemisphere). Waveforms from these electrodes were averaged to create left-hemisphere and right-hemisphere

clusters for each condition. For the analyses of the Nc, the following frontocentral electrodes were selected: 103, 104, 105, 110 (right hemisphere); 30, 35, 36, 41 (left hemisphere).

Over the occipitotemporal clusters, we detected the expected N290 and P400 components. The latencies of peak amplitudes were determined for each individual participant by visual inspection, and time windows were then chosen to include the temporal spread of peaks across participants. This results in the following time window selection: N290 between 240 and 400ms, and P400 between 370 and 570ms. Over the frontocentral clusters, we identified the expected Nc which was analyzed for the time window 400–600ms after stimulus onset.

#### Results

The ERPs were based on an average of 10.3 trials for the self-face condition, and 10 trials for the other-face condition. A  $2 \times 2$  repeated measures ANOVA was conducted for the N290 and P400 component, with the factors of face type (self-face, other-face) and hemisphere (left, right). A *t*-test between self-face and other-face was conducted for the Nc over the frontocentral clusters. Grand

average of ERP waveforms to self-face and other-face stimuli over occipitotemporal and frontocentral channels are displayed in Figure 2.

#### N290

With regard to N290 amplitude, we did not find a significant main effect of face type, F(1,5)=5.260, p=.070, nor hemisphere, F(1,5)=2.219, p=.196. No significant interaction was found between face type and hemisphere, F(1,5)=0.008, p=.930.

With regard to N290 latency, we did not find a significant main effect of face type, F(1,5)=0.721, p=.435, nor hemisphere, F(1,5)=0.381, p=.564. There was no significant face type x hemisphere interaction, F(1,5)=1.877, p=.229.

#### P400

With regard to P400 amplitude, we found a significant main effect of face type, F(1,5)=11.532, p=.019(self-face:  $M=24.09 \,\mu$ V; other-face:  $M=15.87 \,\mu$ V). This result demonstrates that the amplitude of the ERP component P400 showed an increased response to



**FIGURE 2** Results of pilot data showing the amplitude and latency of N290 and P400 event-related potential (ERP) components over the occipitotemporal channels (top-left) and the ERP component Nc (top-right) over the frontocentral channels for each condition. Left-hemisphere and right-hemisphere clusters of the occipitotemporal channels are displayed at the bottom of the figure. ERP waveforms for the self-face are displayed in black, whereas waveforms for the other-face are displayed in light gray.

the self-face compared to the other-face. There was, however, no main effect of hemisphere, F(1,5)=0.678, p=.448 and no significant interaction between the two factors.

With regard to P400 latency, we did not find a significant main effect of face type, F(1,5)=0.705, p=.439, nor hemisphere, F(1,5)=2.056, p=.211. There was no significant face type x hemisphere interaction, F(1,5)=3.092, p=.139.

#### Nc

We found no significant effect of face type over the Nc amplitude, t(5)=-.853, p=.433 (self-face: M=-7.64; other-face: M=-3.66).

#### RESULTS

#### Experiment 1

The average number of retained trials was 17.1 for the self-face condition, 16.3 for the mother-face condition, and 16.2 trials for the other-face condition.

#### N290/P400 components (H1)

A  $3 \times 2$  repeated measures ANOVA was conducted for the N290 and P400 component (amplitude and latency), with the factors of face type (self-face, mum-face, other-face) and hemisphere (left, right). The analyses of the N290 amplitude did not reveal any significant effect (face type: F(2,74) = 1.343, p = .267; hemisphere: F(1,37) = 0.119, p = .732; interaction: F(2,74) = 1.479, p=.235). The analyses of the N290 latency revealed a main effect of hemisphere, F(1,37) = 7.440, p = .010,  $\eta_{\rm p}^2$  = .17, showing an earlier peak over the left hemisphere  $(M=210.6\,\mu\text{V})$  than over the right hemisphere ( $M = 220.4 \,\mu\text{V}$ ). The main effect of face type and the interaction were not significant (face type: F(2,74) = 0.890, p = .415; interaction: F(2,74) = 0.208, p = .813). The analyses of the P400 amplitude did not reveal any significant effect (face type: F(2,74) = 1.103, p = .337; hemisphere: F(1,37) = 3.220, p = .081; interaction: F(2,74) = 0.240, p = .787). Similarly, there were no significant effects for the P400 latency (face type: F(2,74) = 1.223, p = .300; hemisphere: F(1,37) = 1.825, p = .185; interaction: F(2,74) = 0.204, p = .787).

#### Nc component (H2 and H3)

The analyses of mean amplitude of the Nc over the frontocentral electrode cluster did not reveal a significant effect of face type, F(2,74)=0.739, p=.460.

# Exploratory analysis

Visual inspection of the data revealed an early P100 peak in our sample, between 120 and 220ms from stimulus onset (see Figure 3). A  $3 \times 2$  repeated measure ANOVA showed a significant main effect of face type, F(2, 74) = 3.111, p = .05,  $\eta_p^2 = .08$ , driven by a significant difference between the self-face and motherface condition, t(37) = -2.518, p = .016, d = .38, with a larger P100 amplitude for self  $(M=9.95 \mu V)$  than mother ( $M = 7.65 \,\mu\text{V}$ ). There was also a trend for a face type x hemisphere interaction, F(2,74) = 2.711, p = .073,  $\eta_{\rm p}^2$  = .068, which revealed amplitude differences on the left hemisphere only, where P1 was larger for self-face  $(M=10.68 \,\mu\text{V})$  than both mother-face  $(M=7.55 \,\mu\text{V})$ , p = .003, d = .48t(37) = -3.221, and other-face  $(M=8.46 \,\mu\text{V}), t(37)=-2.078, p=.045, d=.35$ . However, this latter comparison did not survive FDR. Given the exploratory nature of these analyses, a cluster-based permutation test was additionally run. For both hemispheres separately, 5000 iterations were computed. The permutation revealed a significant difference between the mother-face and the self-face condition from 100 to 150 ms over channels 67, 70, and 71, p=.05. No other significant differences were found.

#### **Experiment 2**

The average number of trials retained for the analyses was 14.3 for the 100% self-face condition, 13.5 for the 66% self-face condition, and 13.2 for the 44% self-face condition.

#### N290/P400 components (H4 and H5)

A  $3 \times 2$  repeated measures ANOVA was conducted for the N290 and P400 component (amplitude and latency), with the factors of face type (100%, 66%, 44%)self-face) and hemisphere (left, right). The analyses of the N290 amplitude did not reveal any significant effect (face type: F(2,76) = 1.061, p = .351; hemisphere: F(1,38) = 1.442, p = .237; interaction: F(2,76) = 1.397, p = .254). The analyses of the N290 latency revealed a main effect of hemisphere, F(1,38) = 15.508, p < .001,  $\eta_p^2 = .29$  showing an earlier peak over the left hemisphere  $(M=203.8\,\mu\text{V})$  than over the right hemisphere ( $M = 222.9 \,\mu\text{V}$ ). The main effect of face type and the interaction were not significant (face type: F(2,76) = 0.977, p = .381; interaction: F(2,76) = 0.718, p = .491). The analyses of the P400 amplitude did not reveal any significant effect (face type: F(2,76) = 1.492, p = .231; hemisphere: F(1,38) = 0.016, p = .900; interaction: F(2,76) = 1.273, p = .285). Similarly, there were no significant effects for the P400 latency (face type: F(2,76) = 1.273, p = .286; hemisphere: F(1,38) = 0.071,



**FIGURE 3** Results of Experiment 1 showing the amplitude of P100, N290, and P400 event-related potential (ERP) components over the occipitotemporal channels (top-left) and the ERP component Nc (bottom-left) over the frontocentral channels for each condition. Left-hemisphere (LH) and right-hemisphere (RH) clusters of the occipitotemporal channels are displayed at the right side of the figure. ERP waveforms for the self-face are displayed in red, waveforms for the mother-face are displayed in blue, and waveforms for the other-face are displayed for each waveform.

p = .791; interaction: F(2,76) = 1.798, p = .173) (see Figure 4).

# DISCUSSION

The ability to distinguish self from others plays a fundamental role in the development of self-awareness and allows infants to develop the skills necessary to engage in social interactions. In particular self-recognition, that is, the ability to identify one's own facial features as being part of the self, is considered at the hallmark of selfhood (Morin, 2006). However, despite the important function that self-recognition serves for socioemotional development, its ontogenetic origin is a question surrounded by much controversy. A popular way of testing the emergence of self-recognition has been by using the mirror test (Amsterdam, 1972; Gallup, 1970). However, before infants can respond to such unusual situation, they have to recognize the observed face as their own. Converging evidence from looking behavior studies suggest that infants' ability to recognize their own face may develop well before infants are able to pass the mirror test. Yet, looking behavior studies cannot disentangle identityspecific from familiarity-specific effects. In other words, is the self just a highly familiar stimulus or does it hold a special status? With this registered report, we aimed

to disentangle the relation between familiarity and ownface specificity. We used ERPs to examine whether the infant's perception of self-face relies on distinct neural processes compared to other faces, even when compared to those faces that are familiar. In Experiment 1, we presented infants with images of their own face, another peer's face, and their mother's face, whereas in Experiment 2, we presented infants with images of their own face morphed into another peer's face (100% self vs. 66% self vs. 44% self).

One of the main results of the present study was that, in both experiments, the N290 and P400 components were not sensitive to the identification of the self-face. While these findings go against our primary hypotheses of both Experiments 1 and 2 (H1, H4, and H5), they are in line with previous adult ERP studies showing the lack of sensitivity of N170 for identifying the self-face and face familiarity (e.g., Alzueta et al., 2019; Bentin & Deouell, 2000; Eimer, 2000; Pierce et al., 2011; Sui et al., 2006; Tanaka et al., 2006). Our null findings provide further support to the hypothesis that the face-sensitive N170 component may reflect a mechanism responsible for face detection rather than being sensitive to own-face specificity (Alzueta et al., 2019; Bentin et al., 1996).

We also hypothesized that the frontocentral Nc examined in Experiment 1 would be sensitive to face familiarity, and therefore, our primary hypothesis (H2) was



**FIGURE 4** Results of Experiment 2 showing the amplitude and latency of N290 and P400 event-related potential (ERP) components over the occipitotemporal channels (top-left). Left-hemisphere (LH) and right-hemisphere (RH) clusters of the occipitotemporal channels are displayed at the bottom of the figure. ERP waveforms for the 100% self-face are displayed red, waveforms for the 66% self-face are displayed in green. Standard errors are displayed for each waveform.

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to find differences in Nc amplitude between mother-face and self-face. We reasoned that, as the mother's face is a stimulus more visually familiar than the self-face, it would elicit a greater Nc amplitude. However, our findings showed no differences in Nc amplitude between mother-face and self-face (H2) nor between mother-face and other-face (H3). Previous research indicates that the Nc is generally modulated by attention and stimulus familiarity (e.g., de Haan & Nelson, 1999; Guy et al., 2016, 2018) and larger amplitude has been reported in response to faces than objects in 6- to 8-month-old infants (Conte et al., 2020; Xie et al., 2019), overall pointing to the role of the Nc in the allocation of attention to novel or interesting stimuli (Conte et al., 2020). Our findings of no differences in Nc amplitude between face stimuli of varying degrees of familiarity may suggest that the mother-face, the self-face, and other-face are comparably novel or comparably interesting stimuli to infants at this developmental stage. An alternative possibility is that changes in ERP responses to familiar and unfamiliar stimuli in the first year of life may be the effects of developmental changes in cognitive abilities, repeated testing, or differences in novelty preference, as suggested by Webb et al. (2005). In line with this proposition, it is possible that infants' individual differences in our sample might have hindered an effect of face type on the Nc. For instance, the extent to which infants are exposed to their own reflection can vary based on the environment they grow up in. Similarly, the degree to which they

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exclusively bond with their mother as their primary attachment figure depends on the family's childcare circumstances. Relatedly, Scherf and Scott (2012) advanced the idea that the developmental trajectory of the formation of attachment relationships is associated with the strength and magnitude of face recognition biases in infancy. A possibility to explain the lack of effects on the Nc in our group of 6- to 8-month-olds is that, during this time window, infants are developing additional attachment relationships with other individuals (e.g., day care providers, other family members) which are not yet fully established. Indeed, in the UK (where the research was conducted), it is common for mothers to return to work when their baby is around 6 months old. Future studies should incorporate additional measures to better understand the relation between the Nc, individual infants' characteristics and circumstances, and clarify the variables that affect its response.

After visual inspection of Experiment 1 data, we identified an early P100 peak that showed significant differences between self- and other-faces, specifically driven by a larger amplitude to self-face than mother-face (visual inspection of Experiment 2 data showed no obvious differences in P100 peak amplitude across the experimental conditions; therefore, exploratory analyses were not run in this case). In adults, this early ERP component has been previously related to visual attention and encoding of physical characteristics of visual stimuli, such as spatial attention (Di Russo et al., 2003;

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Martinez et al., 1999) and variations in facial configurations (Halit et al., 2000; Itier & Taylor, 2004; Taylor et al., 2001). Some evidence also indicates that the P100 is modulated by low-level feature differences (e.g., luminance, local contrast, etc.) (Johnson & Olshausen, 2003; Rossion & Jacques, 2008; Rousselet et al., 2008), although other studies have found nonsignificant differences in P100 when controlling for low-level features (Desjardins & Segalowitz, 2013; Herrmann, Ehlis, Ellgring, et al., 2005). Critically, while it is still controversial whether P100 reflects face specificity (Elsabbagh et al., 2009, 2012; Luyster et al., 2014; McCleery et al., 2009; van Noordt et al., 2022), there is adult evidence of a P100 effect over the occipital lobes in response to faces versus objects (Herrmann, Ehlis, Muehlberger, et al., 2005; Itier & Taylor, 2004) and familiar versus unfamiliar faces (Butler et al., 2013). Specifically, a study by Butler et al. (2013) with dizygotic twins revealed that both self and twin faces evoked a larger P100 amplitude and longer latency compared to unfamiliar faces, indicating that familiarity can modulate the response on this component. Therefore, it is possible that, similar to the adult P100, the infant P100 may be sensitive to face familiarity.

Findings from developmental research are also conflicting as to whether P100 reflects a face-specific response. For example, some infant studies have found no differences in P100 between faces and non-face stimuli (Peykarjou & Hoehl, 2013), upright versus inverted faces (Peykarjou & Hoehl, 2013), and intact versus scrambled faces (Parise et al., 2010). In contrast, Conte et al. (2020) found significant differences in P100 amplitude to faces versus objects, and these remained stable across the first year of life. Interestingly, this difference was modulated by infant's attentional status, suggesting that top-down attentional control could influence early stages of face processing. Given that, in our study, stimuli were matched in low-level visual characteristics, it is possible that the P100 effect found in Experiment 1 may reflect increased attentional control for the self-face as early as 6 months of age. More recent adult research suggests that an additional attentional component, the P200, may represent an index of self-identification, whereby self-face processing is characterized by lower amplitudes reflecting the recruitment of fewer attentional resources (Alzueta et al., 2019, 2021). We propose that the attentional modulation of the P100 response in our infant sample may instead reflect the recruitment of additional resources to categorize the self-face as distinct from other (familiar and unfamiliar) faces. We speculate that this enhanced attentional mechanism may be due to a gradually developing neural sensitivity to the selfface during the first 2 years of life, eventually leading to overt mirror self-recognition. Future longitudinal studies should investigate amplitude variation in P100

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to self- versus other-faces during the first 2 years of life to directly examine the extent to which this component reflects self-specificity in infancy.

The registered report process adopted for this study ensured appropriate sample size and methodological rigor. Therefore, it is highly unlikely that our results can be explained by small sample size or inadequate data quality. We included controls both for familiarity (i.e., the mother's face) and for a potential own-age bias (another infant's face) (see also Stapel et al., 2017). However, we also acknowledge that null findings are hard to interpret, and it is important to consider other potential explanations for the nonsignificant differences observed, as well as limitations of our study. Firstly, it is possible that 6- to 8-month-old infants are too young and/or that the visual stimuli were too difficult to categorize the self-face as distinct from other faces. This developmental window was selected based on behavioral studies using visual preference paradigms, which have consistently demonstrated that infants (also as young as 4months) can discriminate between their own face and the face of an unfamiliar peer (Bahrick & Moss, 1996; Legerstee et al., 1998; Rochat & Striano, 2002). However, these studies have largely used colored stimuli and included full facial features (e.g., including hairline, ears, and neck). Therefore, a related possibility is that our grayscale stimuli that excluded the hairline, ears, and the neck of the infant might have been too difficult to process. Future research should employ more visually realistic stimuli to investigate the extent to which our nonsignificant differences in N290, P400, and Nc components could be attributed to stimulus choice.

Second, it is possible that the morphing selection adopted in Experiment 2 could have been too stringent for our participants. Using a visual preference paradigm, Nitta and Hashiya (2021) demonstrated that 12-month-old infants showed a visual preference for the self and unfamiliar faces over a morphed face comprising 50% of the self-face (while no difference in looking time was apparent between the self-face and the unfamiliar other-face). We chose the morphing percentages based on this behavioral evidence, but it could be argued that the featural differences between the 100% self-face and the 66% self-face and 44% self-face adopted in our Experiment 2 were still too subtle to be detected by the infants in our study. It would be important for future research to explore different morphing steps to examine at what point the self-face loses its own self-specificity and begins to be processed as "other."

To summarize, the current findings show that 6- to 8-month-old infants display an enhanced P100 in their ERP response to their own face compared to others' faces. There were no significant differences in N290 and P400 between self- and other-faces, suggesting that these components were not sensitive to the identification of the self-face. We also did not find significant differences in Nc amplitude between face stimuli of varying

degrees of familiarity. Taken together, these results highlight changes in how infants process faces during the second half of their first year. This period is crucially marked by increased exposure to different faces and the formation of new attachment relationships. The early attentional response to the self-face evidenced by the P100 might indicate an early neural sensitivity to the self-face, setting a foundation for later self-recognition. Our study suggests a possible progression in how infants process faces: Given the evidence that at 18 months of age infants show a greater P400 to self versus mother face (Stapel et al., 2017), we propose that the early attentional response to the self-face at 100ms may lead to a high-level face processing or categorization later in development-reflected by a positive peak in amplitude at around 400 ms. Longitudinal studies will therefore be essential to examine the developmental trajectories of selfrecognition by specifically exploring neural responses to the self- and other-faces across these different ERP components, and to identify how these responses emerge and change over time.

# **REGISTRATION OF APPROVED PROTOCOL**

The registered Stage 1 manuscript unchanged from the point of IPA can be found on the Open Science Framework: https://doi.org/10.17605/OSF.IO/2KHU6.

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#### DATA AVAILABILITY STATEMENT

The data necessary to reproduce the analyses presented here are publicly accessible on the Open Science Framework: https://doi.org/10.17605/OSF.IO/2KHU6. The code and materials necessary to attempt to replicate the findings presented here are available from the first author upon request.

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