EMPIRICAL ARTICLE

Theta power relates to infant object encoding in naturalistic mother-infant interactions

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Abstract
This study investigates infants' neural and behavioral responses to maternal ostensive signals during naturalistic mother-infant interactions and their effects on object encoding. Mothers familiarized their 9- to 10-month-olds ($N=35$, 17 females, mainly White, data collection: 2018–2019) with objects with or without mutual gaze, infant-directed speech, and calling the infant's name. Ostensive signals focused infants' attention on objects and their mothers. Infant theta activity synchronized and alpha activity desynchronized during interactions compared to a nonsocial resting phase (Cohen' d: 0.49–0.75). Yet, their amplitudes were unrelated to maternal ostensive signals. Ostensive signals did not facilitate object encoding. However, higher infant theta power during encoding predicted better subsequent object recognition. Results strengthen the role of theta-band power for early learning processes.

Caregivers intuitively use ostensive signals like gaze direction to help infants navigate the complex world (Abney et al., 2020; Reid & Striano, 2007). However, only little experimental neuroscience research has tested if and how ostensive signals facilitate infant learning. This study investigates neural processes underlying the putative facilitating effect of ostensive signals on infant learning during naturalistic mother-infant interactions in 9- to 10-month-olds.

By around 7–9 months of age, infants can attend to an object simultaneously with another person while both are mutually aware of attending to this object (Abney et al., 2020; Csibra & Gergely, 2006; Siposova & Carpenter, 2019; Striano & Bertin, 2005). Such naturalistic *joint attention* situations typically feature a range of ostensive signals, including calling the infant's name, infant-directed speech (IDS), and mutual gaze (Csibra & Gergely, 2006). Both calling an infant's name

and using IDS are known to enhance infants' attention (Frank et al., 2020; Parise et al., 2010; Peykarjou et al., 2020; Senju & Csibra, 2008; Spinelli et al., 2017), and addressing the baby in IDS combined with mutual gaze enhanced 9-month-olds' encoding of novel objects (Okumura et al., 2020). In addition, it was shown that it is the prosodic stress of IDS which facilitates neural speech tracking (Menn et al., 2022). Mutual gaze, on the other hand, has been shown to influence infants' object encoding. When an experimenter presented objects either with or without mutual gaze, 7- and 9-month-olds looked longer to a novel as compared to the familiarized object in an immediate recognition test only in the mutual gaze condition, suggesting facilitated object encoding (Cleveland et al., 2007; Cleveland & Striano, 2007). Computer-based studies with infants showed that a preceding moment of mutual gaze is necessary for effective referencing to an object by gaze (Okumura et al., 2020;

Thiele et al., 2021). Already 4-month-olds encoded objects which were cued by another person's head and/or gaze direction after a moment of mutual gaze more effectively than non-cued objects (Hoehl et al., 2013; Reid & Striano, 2005; Theuring et al., 2007; Wahl et al., 2013). In naturalistic mother-infant interactions, mutual gaze increased infants' attentiveness to objects (Wass, Clackson, et al., 2018).

These studies highlight the impact of ostensive signals on infants' attention and object encoding and recognition (see also Kopp & Lindenberger, 2011). Yet, when focusing only on behavioral parameters such as infant gaze, the cognitive and neural processes involved in bringing about these behavioral outcomes remain opaque. Studying infants' brain activities during joint attention can shed light on the neural processes that underlie the facilitated encoding through ostension. Alpha- and theta-band activities are promising candidates.

Activity in the infant alpha-band frequency range (6–9 Hz) is related to a range of different processes. A large amount of developmental literature linked desynchronization in the alpha-band frequency range over motor regions to action execution and action processing (e.g., Langeloh et al., 2018; Southgate et al., 2010; Stapel et al., 2010; van Elk et al., 2008). Additionally, activity in this frequency band is associated with sustained attention in infants as young as 10 months of age (Xie et al., 2018). Optimal task processing is reflected in an increase in alpha-band activity in task-irrelevant areas (thereby inhibiting these areas) and alpha desynchronization in relevant areas (Jensen & Mazaheri, 2010). Alpha-band activity may thereby facilitate the processing of relevant information also in social contexts which are most relevant for the current study: Lachat et al. (2012) found enhanced alpha desynchronization when two adults looked at the same compared to different objects. This was interpreted as reflecting attention mirroring and mutual coordination during joint attention. In 9-month-olds, a preceding moment of mutual gaze with the experimenter enhanced the negative central component and alpha desynchronization in response to subsequently presented objects (Hoehl et al., 2014; Striano et al., 2006). Moreover, alpha desynchronized in response to faces looking at objects compared to faces looking away in 4- and 9-month-olds (Michel et al., 2015, but see Angelini et al., 2022) and in instances when an actor's gaze followed the infant's gaze (Rayson et al., 2019). Thus, alpha-band activity seems to be involved in the processing of gaze-object relations early in life. Notably, alpha desynchronization has also been related to the process of accessing and integrating novel information into a semantic knowledge system (Klimesch, 2012). Combining these two aspects, we speculate that alpha desynchronization may reflect mutual coordination and the visual encoding of information (here objects) during social situations like joint attention based on gaze cues. However, this hypothesis can only be stated tentatively

as previous studies on alpha desynchronization and joint attention did not assess any actual learning outcomes (Hoehl et al., 2014; Lachat et al., 2012).

Infant theta power (3–5 Hz) was related to the processing of social interactions (Jones et al., 2015; Michel et al., 2015), sustained attention (Orekhova et al., 1999; Wass, Noreika, et al., 2018), and object encoding in 11-month-olds (Begus et al., 2015). This latter study measured not only infants' theta activity while infants explored objects on their own but also infants' recognition performance of this object in a subsequent object recognition test. It was found that the difference in theta activity between objects (objects eliciting high vs. low theta activity) during exploration predicted the difference in object recognition (high vs. low score). Object recognition was better for objects which previously elicited higher theta activity. Strikingly, infants' looking time at the object and the time infants manually handled the object did not predict their object recognition performance. This is in line with the assumption that theta power reflects learning in infants (Begus & Bonawitz, 2020; Köster et al., 2019). However, it remains unknown whether theta activity is related to infant encoding processes in social interactions.

Based on this background, we assume a functional relation between maternal ostensive signals, neural processes (infant alpha- and theta-band activities), and infants' object recognition. We expect that ostensive cues stimulate desynchronization of alpha band due to the processing of gaze-object relations and mutual attention coordination (Lachat et al., 2012; Michel et al., 2015). A synchronization in the theta-band activity may be stimulated through infants' neural entrainment to maternal speech (Menn et al., 2022). These altered brain processes may facilitate the encoding of novel information due to a facilitated access to a semantic knowledge system and memory formation. A critical test of this functional relation is missing to date.

The vast majority of findings on infant object encoding come from highly controlled experimental studies using two-dimensional objects on screen (e.g., Hoehl et al., 2012; Reid & Striano, 2005) or scripted interactions with strangers (Cleveland et al., 2007; Cleveland & Striano, 2007). Real social learning situations are tremendously different. Objects are experienced in 3D (Begus et al., 2015), interactions involve a large amount of movement, gestures, turn-taking, and contingent responses to an actively engaged infant, and caregivers are highly familiar interaction partners (Hoehl et al., 2012). To understand early social learning processes, studying naturalistic interactions with familiar interaction partners is necessary (Hoehl & Markova, 2018). This gap in the literature is even larger when it comes to the functional investigation of neural processes. The current study not only addresses the issue of ecological validity in letting infants interact with their mothers but also aims to examine the functional relation between maternal behavior,

infant neural oscillatory activity, and a highly relevant cognitive outcome, namely infants' object recognition performance.

We measured theta- and alpha-band power via EEG in 9- to 10-month-olds while mothers familiarized them with novel objects. We systematically varied maternal ostensive signals (i.e., IDS, mutual gaze, and calling the infant's name) within-subjects: the ostensive condition (OS condition) included a high level of ostensive signals, and the non-ostensive condition (NOOS condition) lacked these signals. We measured infants' object recognition via looking times to the familiarized 3D objects compared to novel objects several minutes after the interaction.

We expected infants to better encode objects in OS trials than in NOOS trials (Cleveland et al., 2007; Cleveland & Striano, 2007), thus looking longer to novel objects in the object recognition test. As theta power was related to better object encoding (Begus et al., 2015) and mutual gaze should lead to enhanced encoding, we expected higher theta activity during OS interaction than NOOS interaction. In line with Hoehl et al. (2014), we expected higher alpha desynchronization during OS interactions, reflecting higher levels of attention (e.g., Jensen & Mazaheri, 2010) and perhaps access to a generic knowledge system (Klimesch, 2012). To investigate how neural activity during familiarization predicts infants' object encoding, we related brain activity during encoding to infants' subsequent object recognition performance.

METHOD

Participants

We tested 81 mother-infant dyads. All infants except one were born full term, that is, in or after the 37th gestation week. We excluded this infant, another infant because of a broken EEG system, and two infants because they were too fussy to start at least one trial per condition. After applying our exclusion criteria (see Supplementary Material A), the final sample consisted of 35 infants (17 females; mean age: 9 months 14 days, age range: 9 months 0 days to 10 months 17 days; mothers' age at day of testing: mean age: 32.8 years, age range: 23.3 to 45.1 years). The exclusion rate of about 57% lies within the normal range for visual infant EEG studies (DeBoer et al., 2007). Data collection took place at the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig (Germany) between August 2018 and February 2019. Families were recruited from the database of the institute representing an urban Western, industrialized context. All participants came from Leipzig (Germany) or surrounding areas. The study procedure was approved by the local ethics committee and conforms to the Declaration of Helsinki. The experiment started after the caregiver gave their written consent to participate. Participants

received 7.50 € and a toy as reimbursement. The study was preregistered https://aspredicted.org/bc6s7.pdf. We aimed for a sample size of 30 based on previous studies using a similar paradigm or measures (Begus et al., 2015; Cleveland et al., 2007; Hoehl et al., 2014).

Materials

We used 12 pairs of novel pre-tested objects. The objects of each pair were of the same material, similar size, and complexity but of a different shape and color and had a range of width/length/height of 1.5–18 cm. None of the objects contained eyes or a face. The objects were wooden or stuffed toys, kitchen appliances like rubber oven gloves or tea infusers, plastic massagers, or dog toys made of ropes. These selection criteria differ from Begus et al. (2015) who presented highly similar pairs of objects. However, the participants in our experiment were younger (9-month-olds as compared to 11-month-olds), and we wanted to ensure that infants were able to discriminate the objects. Object pairs were pretested to ensure that both objects in one pair are equally interesting to 9-month-olds without any preceding interaction or familiarization (Michel et al., 2017). Therefore, we pre-tested 22 object pairs in advance. During that pretest, we presented up to 22 objects pairs to thirty-three 9-month-olds using the same setup as the object recognition test in our current experiment (i.e., 2 times 10 s looking times to the object starting at the first look of the infant to one object) without the preceding familiarization phase. For each object pair, we obtained valid looking time data of 20 or 21 infants. For the current experiment, we selected the 12 object pairs in response to which infants did not show any differences in looking times on average. In addition, mothers rated the objects with regard to how familiar they think the objects are to their infants on a scale from 1 (not at all familiar) to 5 (highly familiar). For the current experiment, we chose objects with mean ratings not significantly differing positively from 2. One object of each pair was presented during a familiarization phase, and the partner object was used as the novel object during the object recognition test. Each infant saw each object in only one familiarization phase and the respective recognition test. Over all participants, each object was presented as the familiar and as the novel object and in the OS and NOOS conditions in half of the infants, respectively. During the first phase of the object recognition test, each object was presented on the left and right sides equally often across infants.

Procedure

In the lab, mothers were familiarized with the setup and two experimenters (A and B) explained the study

structure and instructions verbally and in written form. The infant was then equipped with the EEG system. The experiment consisted of up to four blocks of three phases: a resting phase, a familiarization phase, and the object recognition test, containing two OS blocks and two NOOS blocks. Conditions were alternated between blocks, and the starting condition was counterbalanced between infants. The experiment ended whenever the infant felt uncomfortable, that is, whenever the infant started crying or became too fussy to pay attention to the interaction. Figure 1 presents the setting in each of the phases.

Resting phase

During the 20 s resting phase, infant and mother faced each other while an experimenter blew soap bubbles. The experimenter did not look at the infant or the mother. The 20 s started when the first soap bubble was visible to the infant.

Familiarization phase

Each block belonged to either the OS or the NOOS condition. In each block, infants were exposed to three
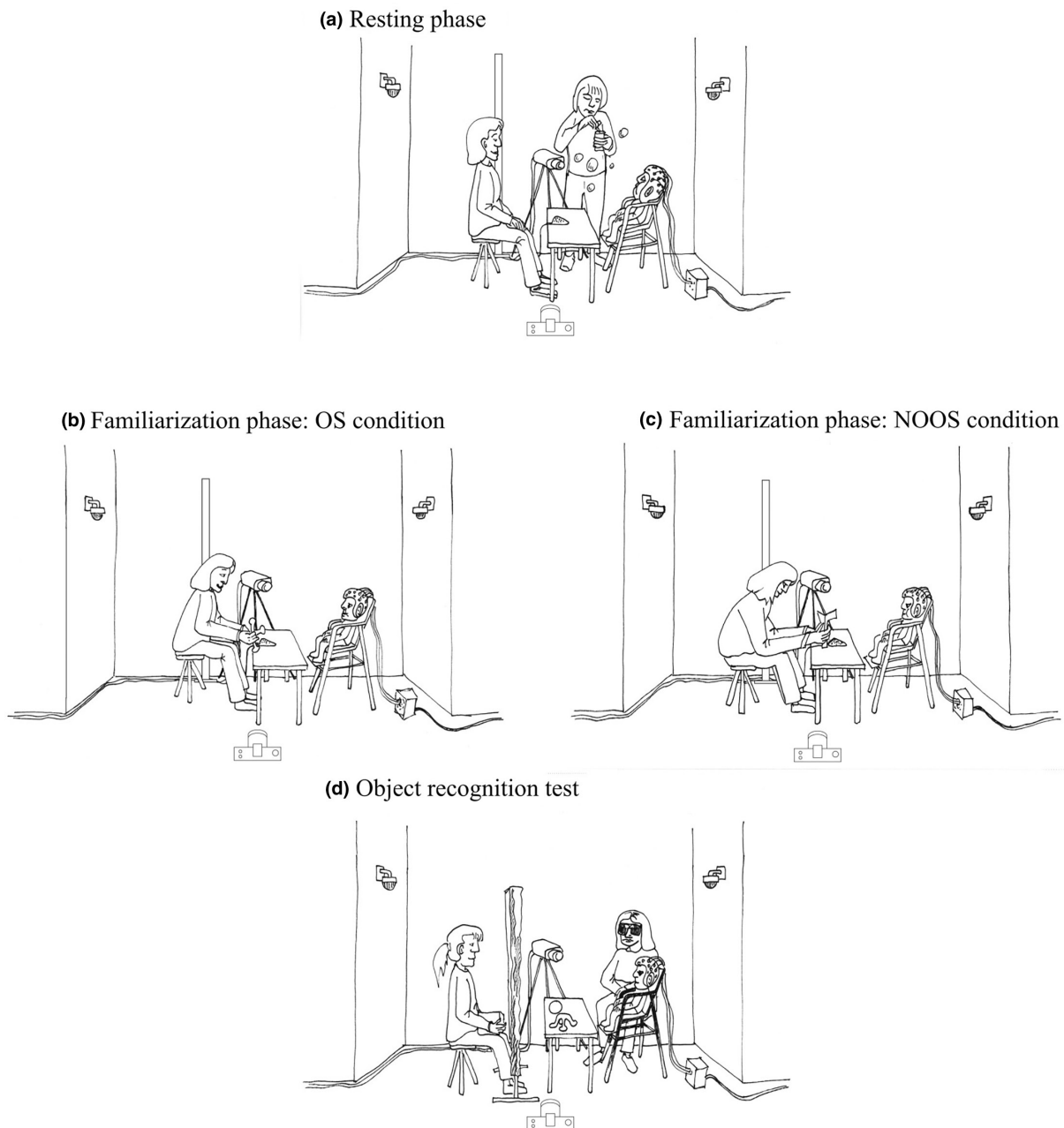

FIGURE 1 Schematic drawing of the setting in each of the phases of the experiment. The adult with the ponytail represents experimenter A.

different objects either exclusively in an ostensive or in a non-ostensive way. This sums up to a maximum of six objects per condition. To find a compromise between getting enough valid, artifact-free EEG data and keeping infants attentive, we had piloted the number of blocks and the number of objects within each block beforehand. Three objects per block and a maximum of four blocks turned out to be optimal in the sense that most infants stayed attentive while we would be able to collect and analyze the necessary amount of EEG data.

During the familiarization phase, mothers and infants faced each other. A microphone on the table recorded mother's speech. The familiarization phase of each object started with a gaze phase: during ostensive (OS) trials, there had to be mutual gaze between mother and infant. During non-ostensive (NOOS) trials, the infant had to look at the mother's face while the mother did not look at her infant (Hoehl et al., 2014). Experimenter B signaled experimenter A when the respective criterion was reached and the interaction could start. During the interaction, the infant was not supposed to touch the object to prevent EEG movement artifacts. Note that this necessary restriction presumably made the interaction slightly different from many real mother-infant interactions at home.

A familiarization phase lasted until the infant spent at least 20 s looking at the object to ensure that infants looked approximately the same amount of time at each object in both conditions (Cleveland et al., 2007; Cleveland & Striano, 2007). Therefore, experimenter B timed infants' looking time to the object, gave a visual signal to experimenter A who thanked mothers, took the object, and provided mothers with the next object. Infants' looking time to the object was later on re-coded based on video recordings.

In OS interactions, mothers were instructed to show the object to their infant as they would do at home. They could talk in IDS, call the infant by their name, and look at their infant. Mothers were instructed to keep the object above the center of the table and to engage in mutual gaze with their infant from time to time. During NOOS interactions, mothers were instructed to explore the object on their own: they were supposed to talk in adult-directed speech (ADS) as if they would talk to themselves, not to mention their infant's name and not to look at their infant. In both conditions, mothers were allowed to label the object. A translation of the written instructions mothers read before the experiment started can be found in Supplementary Material C.

Object recognition test

Infants subsequently saw the three objects from the familiarization phase each paired with their novel partner object for 10 s twice. The left/right position was switched after 10 s (Cleveland et al., 2007; Cleveland & Striano, 2007). The microphone was taken off the table. The 10 s started as soon as the infant initially looked at one of the two objects. Mothers sat next to the infant and wore sunglasses to prevent infants from detecting their mothers' gaze direction. Experimenter A hid behind a curtain and placed the objects on the table. Experimenter B judged infants' gaze, and a visual input was given to experimenter A when 10 s was over. This online judgment of experimenter A was later on verified offline, and the starting point of each recognition phase was adjusted on a frame-by-frame basis. After the last recognition test, the mother was asked to sit back opposite her infant. She was instructed for the next familiarization phase and the next resting phase started.

Behavioral coding and analyses

Video recording and coding were performed using the software VideoSync Pro and Interact by Mangold (Arnstorf, Germany). Video inputs from four synchronous cameras (infant from the front, mother from the front, infant and mother from the side, and infant from the side) were coded on a frame-by-frame basis. For reliability analyses, videos of 15 participants were coded by a second coder ignorant of the hypotheses. We calculated ICCs (two-way, random model, type = agreement and unit = single) using the software R.

Resting phase

For the resting phase, we coded the variables necessary for our exclusion criteria (see Supplementary Material A for an overview and the reliabilities). We only analyzed data of a resting phase if the resting was performed in accordance with our protocol, that is, it lasted at least 20 s, there were no external interruptions, and the experimenter did not interact or establish eye contact with the infant.

Familiarization phase

We coded the variables used to exclude trials (Supplementary Material A) and mothers' and infants' gaze. We coded each frame of the video as belonging exclusively to one of the following codes: look at object, at the face of the interaction partner (mother or infant), at the environment, or frame was not codable because of problems with the camera or the person's eyes were closed or covered. The reliability for mothers' and infants' looking behavior was excellent (for the duration of looks: ICC for mothers = 0.994, ICC for infants = 0.987; for the frequency of looks: ICC for mothers = 0.896, ICC for infants = 0.823). Based on these

codings, mutual gaze was defined as the synchronous look of infants and mothers to each other's face. Next, we calculated infants' attentiveness to the object (their mothers) as follows: (infant looking time to object)/(infant looking time to object + infant looking time to environment) and respectively for infants' attentiveness to their mothers. This calculation is based on Wass, Clackson, et al. (2018) and allows to include familiarization phases in which the infant always looked at the object (or mothers). To check whether the amount of mother's speech differed between conditions, we extracted segments of maternal speech in the audio (ICC based on 10 infants = 0.909). To analyze whether mothers stuck to the instruction to use IDS or ADS, we extracted segments from the audio in which only mother's speech was hearable, that is not masked by sounds in the environment or from the infant (ICC based on 10 infants = 0.885). These sound snippets were analyzed with regard to mean pitch and pitch range within the range of the 10th to 90th percentile using the software Praat (Boersma & Weenink, n.d.) (ICC based on 10 infants for mean pitch = 0.939, pitch range = 0.920) (Frank et al., 2020). We also coded infants' vocalization while they were looking at the object (ICC = 0.889) as infant vocalizations were related to object encoding in slightly older infants (Goldstein et al., 2010). These data will be reported elsewhere because here we focus on the effects of maternal communication. We only included data of a familiarization phase when the familiarization phase was performed in accordance with our protocol, that is, a valid gaze phase (mutual gaze in the OS condition; infant looking at mother in the NOOS condition), the infant looked at the object for at least 20 s, the mother did not mention that the infant knows the object, and the mother stuck to the instructions for each condition. We, therefore, did not include trials in the NOOS condition in which the mother called the infant by their name or mother and child engaged in mutual gaze.

Object recognition test

In addition to the variables used to exclude trials (Supplementary Material A), we coded infants' looking time to the familiarized, the novel object, to the environment or moments which were not codable (ICC = 0.949). To analyze infants' preference for the novel object, we calculated the novelty preference score (NPS): NPS = looking time to novel object/(looking time to novel + familiarized object) (Cleveland et al., 2007; Cleveland & Striano, 2007). To be included in the analysis, the infant had to look at least at one object during both object recognition phases for at least 500 ms. We included only trials in the analysis in which the recognition phase was performed in accordance with our protocol, that is, the infant did not touch the object, the mother wore sunglasses, the mother did not

name an object or point to an object, and the experimenter's hands were not visible.

EEG recording and analyses

EEG was recorded continuously using the actiCap system and the BrainAmp amplifier by Brain Products (Gilching, Germany) with a sampling rate of 500 Hz and 32 Ag/AgCl electrodes. The left mastoid served as the online reference. EEG analysis was done using in-house scripts based on FieldTrip version 3ba8125c1 (Oostenveld et al., 2011). First, we deleted channels of bad quality, that is, showing a high number of artifacts. We then band-pass filtered data from 1 to 30 Hz. Afterward, we interpolated the bad channels (maximum one channel in 11 of 81 infants) and re-referenced to the averaged mastoid electrodes. We excluded segments containing artifacts when the standard deviation within a sliding window of 200 ms reached 50 µV on at least one of the relevant electrodes (Fz, F3, FC3, FC1, Cz, C3, C4, FC4, FC2) (Hoehl et al., 2008). Eye movements were recorded via bipolar horizontal, and—if tolerated by the infant—vertical electrooculogram (EOG) electrodes. The vertical EOG was placed under the right eye. Eye movements were excluded manually (Michel et al., 2019). In addition, segments containing data of broken or saturated electrodes were excluded whenever the standard deviation within a sliding window of 200 ms was less than 1.5 µV.

For the analyses using the averaged data over all objects belonging to one condition, we concatenated data of valid trials (i.e., the objects which were not excluded based on any of the exclusion criteria) and calculated the power spectrum. For the analyses looking at the specific power during presentation of one object (i.e., in relation to the NPS for this specific object), we calculated the power spectrum based on the data of each object. The power spectrum [µV^2] was extracted for segments with a length of 2000 ms and an overlap of 87.5% (Wass, Noreika, et al., 2018) and averaged over all segments. Based on previous literature, we analyzed fronto-central electrodes Fz, F3, FC3, FC1, Cz, C3, C4, FC4, FC2 (Begus et al., 2015; Wass, Noreika, et al., 2018). Theta activity was analyzed in the frequency range of 3.5–5 Hz (Begus et al., 2015; Wass, Noreika, et al., 2018) and alpha activity in the frequency range of 6–8 Hz (Michel et al., 2015). As preregistered, we examined EEG data averaged over the complete familiarization phase and more selectively during moments in which infants looked at the object (Supplementary Material E). Therefore, the coding of the video data was synchronized with the EEG data. For every EEG analysis, our inclusion criterion was 10 s valid EEG segments per condition/object. Table 1 gives an overview of the number of valid EEG segments included in the different EEG analyses per

TABLE 1 Overview of the number of valid EEG segments included in the analyses per infant.

Phase/analysis	Condition	M	SD	Range
Resting phase		138	60	35–278
Familiarization phase				
Entire phase	OS	313	147	71–650
	NOOS	313	161	112–852
Infant looking at object	OS	209	113	41–521
	NOOS	174	74	49–371
Specific object	OS	74	31	13–35
	NOOS	81	41	18–35

Abbreviations: NOOS, non-ostensive; OS, ostensive.

infant. After applying all of our exclusion criteria, we only included a mother-infant dyad to the analysis if they provided valid data of at least two trials per condition. On average, infants contributed 3.11 (SD = 0.83, range = 2–4) trials to the analysis of the resting phase, 4.26 (SD = 1.29, range 2–6) trials in the OS, and 3.86 (SD = 1.06, range 2–6) trials in NOOS condition to the final analyses.

RESULTS

Analyses were pre-registered https://aspredicted.org/blind.php?x=at82rb. An overview and justification of pre-registered variables, which we did not include in the current paper, can be found in Supplementary Material B. Post hoc analyses which were not pre-registered will be marked as such.

Familiarization phase

(Descriptive) Statistics of ostensive signals

To describe how dyads differed in their use of ostensive signals, in the following, we averaged over the valid trials per mother per variable and report respective standard deviations and ranges. In the OS condition, mothers mentioned their infant's name on average 0.76 (SD = 0.86, range 0–4.5) times during the familiarization phase. A moment of eye contact was established on average two times (SD = 1.58, range 0–6.5) in the familiarization phase and at least one time during each gaze phase before the familiarization phase. The mean pitch was on average 225.7 (SD = 22.52, range 184.5–299.2), and the pitch range had a mean of 171.3 (SD = 31.56, range 115.0–239.3).

In the NOOS condition, as a consequence of the paradigm, mothers never mentioned their infants' name and there was no eye contact between mother and infant. The mean pitch was on average 202.9.18 (SD = 17.97, range 167.3–234.0) and the pitch range had a mean of 123.18 (SD = 34.07, range 69.34–225.93).

Infant looking time at the object during the familiarization phase was coded online by an experimenter, and the familiarization phase was stopped by the other experimenter whenever the infant looked at the object for 20 s accumulatively. However, this coding may have been inaccurate due to the demands of the testing situation, and the communication between experimenters took some time which may have extended the duration of the familiarization phase. To capture these inaccuracies, we re-coded infant looking time offline from the videos on a frame-by-frame basis. Infants' looking times at the object were on average longer than 20 s, but infants looked equally long to the objects in the OS condition (M = 25.09 s, SD = 2.74 s) and in the NOOS condition (M = 24.73 s, SD = 1.94 s), $t(34) = 0.97$, $p > .25$.

To give a broader overview of this rich data set, we present additional (pre-registered) descriptive statistics and analyses in Supplementary Material D.

Focused attention to object and mother

We exploratorily examined infants' attentiveness to the object and their mother (Wass, Clackson, et al., 2018). Infants showed significantly higher attentiveness to the object in the OS condition (M = .86, SD = 0.08) as compared to the NOOS condition (M = .75, SD = 0.13), $t(34) = 5.15$, $p < .001$, Cohen's $d = 0.87$ and significantly higher attentiveness to the mother in the OS condition (M = .42, SD = 0.21) as compared to the NOOS condition (M = .22, SD = 0.18), $t(34) = 5.11$, $p < .001$, Cohen's $d = 0.86$.

EEG analyses

Differences in theta- and alpha-band activities between experimental conditions during the familiarization phase
Infants' *theta-band* power during the familiarization phase did not differ between the OS condition (M = 9.83 μV², SD = 2.77) and the NOOS (M = 10.06 μV², SD = 2.88) condition, $t(34) = -0.84$, $p = .406$, Cohen's $d = 0.14$.

Infants' *alpha*-band power during the familiarization phase did not differ between the OS condition (M = 3.57 μV², SD = 1.13) and the NOOS (M = 3.70 μV², SD = 1.45) condition, $t(34) = -1.38$, $p = .176$, Cohen's $d = 0.23$. Additionally, no differences between conditions in alpha or theta-band power were found when analyzing only those moment in which the infant looked at the object (Supplementary Material E).

Differences in theta- and alpha-band activities between experimental conditions and resting phase
It may have been the case that the NOOS condition was perceived as a rather communicative interaction as it contained speech and movement. To further examine neural

activity during interaction and no interaction phases, we added an exploratory analysis which was not pre-registered and compared the experimental conditions to the rather non-interactive resting phase in a repeated-measures ANOVA with the within-subject factor condition: resting phase vs. OS vs. NOOS (see Figure 2).

Theta-band activity. We found a significant main effect of condition, $F(2, 68) = 12.78$, $p < .001$, partial $\eta^2 = 0.27$. Post hoc Bonferroni-corrected *t*-tests for paired samples revealed higher theta-band power in the OS condition (M = 9.83 μV², SD = 2.77) as compared to the resting phase (M = 8.51 μV², SD = 2.38), $t(34) = 3.61$, $p = .001$, Cohen's $d = 0.61$. In addition, theta-band activity was increased during the NOOS condition (M = 10.06 μV², SD = 2.88) as compared to the resting phase (M = 8.51 μV², SD = 2.38), $t(34) = 4.43$, $p < .001$, Cohen's $d = 0.75$.

Alpha-band activity. We found a significant main effect of condition, $F(1.15, 39.17) = 8.42$, $p = .004$, partial $\eta^2 = 0.20$ (Greenhouse–Geisser corrected). Post hoc Bonferroni-corrected t-tests for paired samples revealed decreased alpha-band power in the OS condition (M = 3.57 μV², SD = 1.13) as compared to the resting phase (M = 4.46 μV², SD = 2.58), $t(34) = -3.01$, $p = .005$, Cohen's $d = 0.51$. In addition, alpha-band activity was decreased during the NOOS condition (M = 3.70 μV², SD = 1.45) as compared to the resting phase (M = 4.46 μV², SD = 2.58), $t(34) = -2.91$, $p = .006$, Cohen's $d = 0.49$.

Relation between ostensive signals and EEG

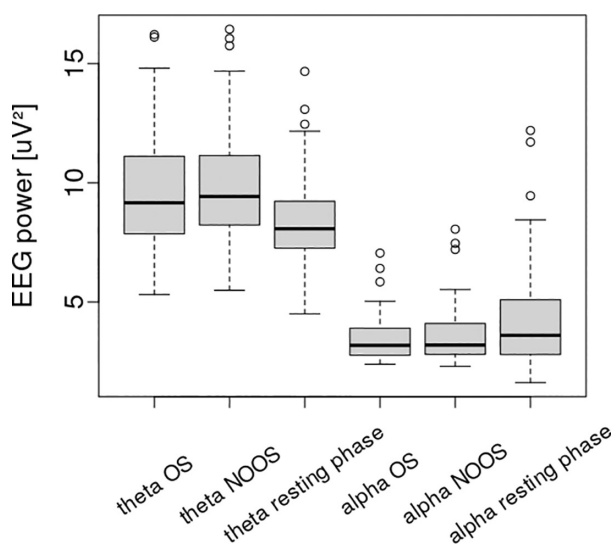To test whether the amount of ostensive signals (mean pitch, pitch range, frequency of mutual gaze, and calling the infant by their name) influenced theta- or alpha-band activities during the familiarization phase per trial, we fitted two generalized linear mixed model (GLMM), with a Gaussian error structure. In one model, theta-band activity served as the response variable; in the other model, alpha-band activity served as the response variable. We included data of the OS and NOOS conditions in this analysis. We used the R package lme4 version 1.1-23 (Bates et al., 2015). As alpha-band activity was not normally distributed, we log-transformed this variable. In both models, we included the mean pitch and the pitch range of mother's voice, the frequency of mutual gaze moments, and the frequency of mothers calling the infant by their name as fixed effects. To account for the differences in the duration of the familiarization phase, we divided the frequency of mutual gaze moments and the frequency of mothers calling the infant by their name by the duration of the respective familiarization phase. To control for the possibility that inattention or tiredness could increase during the experiment, we also included trial number as a fixed effect (control variable). All variables of the fixed effects were continuous and *z*-transformed. As random effects, we included subject as a random intercept and random slopes of all fixed effects on subject in the model.

To test for the influence of ostensive signals on theta- and alpha-band activities, we performed a significance test between these full models and corresponding reduced models excluding the four main fixed effects (ostensive signals) using a likelihood ratio test (Dobson & Barnett, 2002). The full-null model comparisons did not yield significance, neither when taking theta-band activity $\chi^2(4) = 5.41$, $p = .25$ nor when taking alpha-band activity as the response variable, $\chi^2(4) = 4.32$, $p = .37$. Thus, we found no evidence that the amount of ostensive signals influenced theta- or alpha-band activity during the familiarization phase.

Object recognition test

Comparison of NPSs between conditions

The NPSs did not differ between the OS condition (M = .51, SD = 0.08) and the NOOS condition (M = .51, SD = 0.09), $t(34) = -0.18$, $p = .862$, Cohen's $d = 0.02$ (see Figure 3).

Relation between familiarization phase and object recognition test

Influence of ostensive signals during the encoding on later object recognition

To test whether the amount of ostensive signals (mean pitch, pitch range, mutual gaze, and calling the infant by their
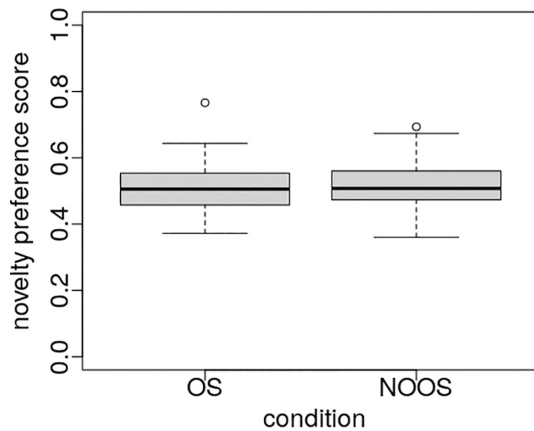

FIGURE 2 EEG theta- and alpha-band power during the familiarization phase in the OS and the NOOS condition as well as during resting phase.

FIGURE 3 The novelty preference score in the object recognition test did not differ between conditions.

name) influenced infants' object recognition in the object recognition test per trial, we fitted a GLMM. We included data of the OS and NOOS conditions in this analysis. The NPS served as the response variable. We used a beta error structure as NPSs were bounded between 0 and 1. We applied the R package glmmTMB version 1.0.2.1 (Brooks et al., 2017). For better model convergence, we transformed the novelty scores in a way that all values did not include 0 and using the formula: transformed NPS $= \frac{x \times (\text{length}(x) - 1 + 0.5}{\text{length}(x)}$ (Smithson and Verkuilen (2006) as cited in Cribari-Neto and Zeileis (2010)). As fixed effects, we entered the mean pitch and pitch range of mother's voice, the frequency of mutual gaze moments, and the frequency of mothers calling the infant by their name as covariates. To account for the differences in the length of the familiarization phase, we divided the frequency of mutual gaze moments and the frequency of mothers calling the infant by their name by the duration of the respective familiarization phase. To control for the possibility that inattention or tiredness could increase during the experiment, we also included trial number as a fixed effect (control variable). All variables of the fixed effects were z-transformed. As random effects, we included subject as a random intercept and random slopes of all fixed effects on subject. To test for the influence of ostensive signals, we performed a significance test between this full model and a reduced model excluding the main four fixed effects (ostensive signals) using a likelihood ratio test.

This full-null model comparison did not yield significance, $\chi^2(5) = 1.82$, $p = .87$. Thus, we found no evidence that the amount of the ostensive signals during encoding influenced infants' object recognition later on.

Influence of theta- and alpha-band activities during encoding on later object recognition

To test whether theta- or alpha-band activity during the familiarization phase, that is during the encoding of the

object, influenced infants' object recognition in the object recognition test per trial, we fitted two GLMMs. We included data of the OS and NOOS conditions in this analysis. The NPS served as the response variable. We used a beta error structure as NPSs were bound between 0 and 1.

We applied the R package glmmTMB version 1.0.2.1 (Brooks et al., 2017). For better model convergence, we transformed the novelty scores in a way that all values did not include 0 and 1 using the formula: transformed NPS $= \frac{x \times (\text{length}(x) - 1 + 0.5}{\text{length}(x)}$ (Smithson and Verkuilen (2006) as cited in Cribari-Neto and Zeileis (2010)). As fixed effects, we included theta- or alpha-band activity during the familiarization phase in the model. We included subject as a random intercept and random slopes of theta- (or alpha-) band activity on subject. We performed a significance test between this full model and a reduced model excluding theta- (or alpha-) band activity from the model using a likelihood ratio test. This full-null model comparison yielded significance, $\chi^2(1) = 7.45$, $p = .006$, estimate $= .04$, SE $= .02$, meaning that the higher theta-band power during the familiarization phase (encoding), the higher the NPS during the object recognition test (see Figure 4).

Applying the same analysis with alpha-band activity as the continuous predictor, the full-null model comparison did not yield significance, $\chi^2(1) = 2.05$, $p = .152$.

Influence of ostensive signals, infant looking time, and theta- and alpha-band activities on later object recognition

As a response to a reviewer comment, we have added this model including all behavioral and neurophysiological predictors: mean pitch, pitch range, relative frequency of mutual gaze, relative and frequency of calling the infants' name, and alpha and theta activities during the familiarization phase as predictors. Most important, we additionally included infant looking time to
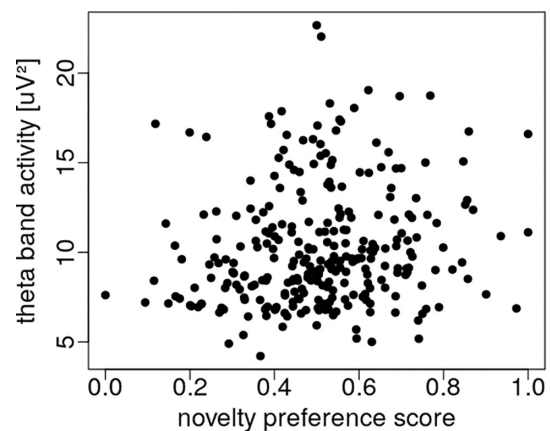

FIGURE 4 Scatterplot relating the novelty preference score during the object recognition test and the theta band activity during the familiarization phase on an individual trial level.

the object as another predictor (Begus et al., 2015). It is important to note that the duration of infants' looking time to the object during the familiarization phase was not fully infant-controlled because the familiarization phase was stopped by the experimenter whenever the infant looked for at least 20 s to the object as determined by the experimenter's online coding. Thus, variability in infants actual looking time to the object (determined by offline video-coding) was largely due to inaccuracies of this online coding (which would always conclude 20 s of cumulative looking). This is analysis was not pre-registered. To test whether any of the ostensive cues, infant's looking time to the object or theta- or alpha-band activity influenced infants' object recognition in the object recognition test per trial, we fitted a GLMM. We included data of the OS and NOOS condition in this analysis. The NPS served as the response variable. We used a beta error structure as NPSs were bound between 0 and 1. We applied the R package glmmTMB version 1.0.2.1 (Brooks et al., 2017). For better model convergence, we transformed the novelty scores in a way that all values did not include 0 and 1 using the formula: transformed NPS $= \frac{x \times (\text{length}(x) - 1 + 0.5)}{\text{length}(x)}$ (Smithson and Verkuilen (2006) as cited in Cribari-Neto and Zeileis (2010)). As fixed effects, we included all ostensive cues (mean pitch, pitch range, relative frequency of mutual gaze, and relative frequency of calling the infants' name), infant's looking time to the object, and infant theta- and alpha-band activities during the familiarization phase in the model. To control for possible effects of tiredness, we also added trial number as fixed effect.

We included subject as a random intercept. All variables of the fixed effects were continuous and z-transformed. As random effects, we included subject as a random intercept and random slopes of all fixed effects on subject in the model. We performed a significance test between this full model and a reduced model excluding all fixed effects except trial from the model using a likelihood ratio test.

This full-null model comparison yielded significance, $\chi^2(8) = 15.76$, $p = .046$. When analyzing the fixed effects individually, the significant estimates were theta power ($p \leq .01$, estimate $= .14$, SE $= .05$) and infant's looking time to the object ($p < .01$, estimate $= -0.23$, SE $= .08$). The results of this overall model show that—taking all ostensive and neural predictors and infant's looking time to the object into account—higher theta power and shorter looking times to the object during encoding predicted infant's object recognition performance.

DISCUSSION

In our study, we investigated neural processes underlying infant learning during rather naturalistic mother-infant interactions in 9- to 10-month-olds. Mothers familiarized their infants with novel objects in interactions containing the social signals mutual gaze, IDS, and calling the infant's name or lacking these signals. Previous studies on infant object encoding mainly used 2D screen-based setups or scripted interactions with strangers (i.e., experimenters), which contained less ecological validity. Compared to these studies, our study setup allowed for a much more naturalistic mother-infant interaction using 3D objects, thus better depicting learning processes taking place during infants' everyday experiences. It is important to note that our findings are restricted to a Western, educated, and industrialized culture.

Results show that 9- to 10-month-olds behaviorally discriminated between conditions: infants' attention was focused more to the object and their mothers in the OS condition as compared to the NOOS condition. These condition differences are not due to differences in the length of maternal speech (Supplementary Material D). This finding is in line with Wass, Clackson, et al. (2018) showing increased object-directed attentiveness in joint play situations as compared to solo play. We here expand this result showing that social signals also focused infants' attention on their mothers. Interestingly, infants did not increase their attention to their mothers in the NOOS condition. This suggests that infants well tolerated their mother's somewhat unusual behavior to not look at them during the brief period of the familiarization phase.

Besides these behavioral differences, we unexpectedly neither found differences between conditions in infants' neural theta- or alpha-band power during the familiarization phase nor did we find a relation between maternal ostensive signals and infants' EEG power. However, infants' theta-band power increased and infants' alpha-band power decreased during familiarization as compared to the rather nonsocial resting phase. As the goal of our study was to investigate the influence of three combined ostensive signals (mutual gaze, IDS, and infants' names), we only controlled for these signals but otherwise let mothers behave as they liked. Both experimental conditions presumably contained other social signals. For instance, mothers talked for an equal amount of time in both conditions (see Supplementary Material D) and moved in both conditions. As we did not control for movement and the visibility of mothers' hands, it may well be that mothers used motionese in both conditions and thereby attracted infants' attention with their hands (Brand et al., 2002; Brand & Shallcross, 2008; Hirai & Kanakogi, 2019; Yu & Smith, 2013, 2017). As alpha- and theta-band activities responded to the social interaction as compared to the resting phase, social interactions in both experimental familiarization phases presumably enhanced infants' attention.

On the group level, we did not find evidence for facilitated object encoding, and there was no statistically significant relation between the amount of ostensive

signals in the familiarization phase and infants' object recognition performance. One explanation may lie within the rather naturalistic setup of the study. While previous studies used computer-based experiments or scripted interactions, we let mothers interact quite freely with their infants rendering the situation more complex and potentially distracting. Previous live interaction studies investigating object encoding held on to more restricted, scripted interactions and were performed by a trained experimenter who was a stranger to the infant (Cleveland et al., 2007; Cleveland & Striano, 2007; Parise et al., 2007). In addition, due to the complex study setup, infants performed the object recognition test not directly after each familiarization phase of each object but after each block, that is, after three familiarization phases. Other studies which examined object encoding in this age group performed the recognition test immediately after the familiarization with only one target object (Cleveland et al., 2007; Cleveland & Striano, 2007; Okumura et al., 2020; Parise et al., 2007; Thiele et al., 2021). This change in our paradigm not only led to the fact that infants had to keep three (and not one) objects in mind but also increased the delay between encoding and recognition. Both factors may have impaired recognition processes. This delay was longest for the first object tested as the object recognition test of each trial lasted 2×10 s, a timing already used in previous live studies (Cleveland et al., 2007; Cleveland & Striano, 2007; Parise et al., 2007). Furthermore, as stated above, both conditions contained social signals like maternal talking or movements which may have increased the saliency of the objects. From a theoretical point of view, our results are in line with the altercentric hypothesis on early perspective taking (Southgate, 2020). Following this idea and assuming that young infants' perspective is altercentric, infants in our study may have encoded the objects in both conditions equally well as their mother attended to the object not only in the OS condition but also in the NOOS condition (however, see Thiele et al., 2021, showing that the mere attending of an actor to an object is not sufficient to promote object encoding in 9-month-olds).

As we can only interpret non-significant differences with great caution, it may still be that infants differently encoded objects during the OS and NOOS conditions; however, our recognition test did not capture such processes. For a more sensitive measure of recognition, future studies may relate infants' neural processing during encoding to their neural response during recognition. Although we measured infants' EEG continuously, the presentation time of the object recognition test was too short to get enough valid data to perform such analysis.

Two variables measured during the familiarization phase predicted infants' later object recognition performance: theta-band activity and looking time to the object. The higher infants' theta-band power during encoding in the familiarization phase, the more they preferred to look at a novel object in the recognition test. This finding is independent of the condition. It has been shown that theta power reflects states of (sustained) attention already in infancy (Orekhova et al., 1999; Wass, Noreika, et al., 2018). Social interactions in our familiarization phases seemed to suffice to increase theta power relative to a resting phase. This enhanced focus of attention may facilitate encoding of information such as the appearance of objects leading to the relation between theta power and the NPS. Our result is well in line with the finding by Begus et al. (2015) and the assumption that theta-band power is a neural marker for learning processes in infancy and adulthood (Begus & Bonawitz, 2020). In contrast to the study by Begus et al. (2015) which tested infants' learning from individual object exploration, we assessed infants' learning in a naturalistic live interaction with their mothers. Theta power, thus, is indicative of learning processes also in naturalistic interactions, but this learning—in our study—did not depend on mutual gaze, IDS, or mentioning the infant's name. Theta power thereby likely plays a crucial role in infants' daily learning.

It was not only theta power but also infants' looking time to the object, which was related to infants' later object recognition performance. Specifically, shorter looking times to the object during familiarization related to a higher object recognition performance later on. Note that the duration of looking times was not fully determined by the infant but was due to an experimenter online coding looking times and ending the familiarization phase whenever the infant reached 20 s. This negative relation between looking time and object recognition performance is rather unexpected. One would expect that infants who are more interested in the object would spend more visual attention on the object and presumably have a higher theta power, resulting in enhanced recognition of the object afterward. This was not the case. Instead, it seems that infants who encoded the object more easily showed higher theta activity and encoded the object faster which led to an earlier disengagement from the object and consequently to shorter looking times during familiarization as well as novelty preference at test. Is it only in combining behavioral and neurophysiological methods that we can get a clearer picture of the complex processes involved in early infant learning.

To our knowledge, our study is the first to vary ostensive signals while measuring infants' neural processes during encoding of novel objects and relating these processes to the learning outcome later on. Although it is a challenge to measure EEG in social interactions, this is the first study letting infants interact quite naturally with their mothers while measuring EEG in ecologically valid social learning situations. Infants' behavior showed that ostensive signals focused infants'

attention on the object and on the interaction partner. On the group level, we could not find evidence for successful object encoding. Collapsing across conditions, we found higher theta activity during encoding being related to infants' object recognition performance later on. Results confirm the functional role of theta oscillations for encoding and learning already in infancy (Begus & Bonawitz, 2020). Our results also speak to the notion that ostensive signals play a major role in shaping social interactions with infants, yet, their effective influence on infant learning in naturalistic live interactions warrants further research.

ACKNOWLEDGMENTS

DATA AVAILABILITY STATEMENT

The data and the analytic code necessary to reproduce the analyses presented here and the materials necessary to attempt to replicate the findings are not publicly accessible. The analyses presented here were partly preregistered. The preregistration is available at the following URL: https://aspredicted.org/bc6s7.pdf.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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